Technical Paper by S.R. Boyle, M. Gallagher and R.D. Holtz

INFLUENCE OF STRAIN RATE, SPECIMEN LENGTH AND CONFINEMENT ON MEASURED GEOTEXTILE PROPERTIES

ABSTRACT: In-isolation and in-soil tests were performed on four woven and two nonwoven geotextiles to investigate the effect of strain rate, specimen length, and confinement in soil on the measured strength characteristics. It was determined that woven geotextiles are affected by strain rate but not by confinement. Nonwoven geotextiles were found to be influenced by both confinement and specimen gauge length. It was concluded that different manufacturing techniques influence measured strength properties, and a standardized wide-width strip tensile test, such as ASTM D 4595, may not be an appropriate method for all types of geosynthetic reinforcement products.

KEYWORDS: Geotextile, Testing, Wide-Width strip tensile test.

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1 INTRODUCTION

As part of an ongoing research project on the deformation prediction of geosynthetic reinforced soil (GRS) retaining walls, the in-isolation and in-soil strength properties of geotextiles were investigated. The study included an investigation of the effects of strain rate on woven geotextiles and specimen length on nonwoven geotextiles using in-isolation tests. In-soil tests were also performed to determine the effect of confinement on these same geotextiles. The appropriateness of the standard wide-width strip tensile test, ASTM D 4595, for characterization of the engineering properties of these geotextiles is also discussed.

Preliminary results of this research have been reported by Boyle and Holtz (1994) and Boyle (1995b). Details of the in-isolation and in-soil testing programs are presented by Gallagher (1995) and Boyle (1995a), respectively.

2 IN-ISOLATION TESTS

2.1 Introduction

The ASTM D 4595 standard test, is widely used to obtain the ultimate strength and stiffness of geosynthetic reinforcement products. In this test, a 100 mm long by 200 mm wide specimen is loaded to failure in tension at a strain rate of 10%/minute. Initially, a limited number of ASTM D 4595 standard tests were to be performed on the geotextiles in the program for comparison with in-soil test results. However, early in the in-soil testing program it was discovered that the response of the woven geotextiles was very sensitive to strain rate, more so than anticipated after performing a literature review (Rowe and Ho 1986; Wang et al. 1990). Additionally, the operational mode of the in-soil testing device (described in Section 3) caused the normal stress acting on the nonwoven geotextiles to increase during tests, thus making correlation with in-isolation tests difficult. Consequently, to characterize the geotextiles in more detail the in-isolation testing program was expanded to include:

- a series of ASTM D 4595 tests on woven geotextile specimens, conducted at strain rates from 0.01 to 10%/minute, to study the strain rate effect; and
- a series of ASTM D 4595 tests on nonwoven geotextile specimens, with gauge lengths ranging from 25 to 115 mm, to determine if an in-isolation zero gauge length test would be appropriate for predicting confined, in-soil stiffness values.

2.2 Geotextiles

The geotextiles used for the in-isolation ASTM D 4595 tests included: three polypropylene woven slit-film geotextiles, PP1, PP2 and PP3; one polyester woven multifilament geotextile, PET2; and, two polypropylene nonwoven needle-punched geotextiles, NW1 and NW2 (Table 1). Geotextiles PP2 and PP3 were manufactured by stitch-bonding together two and three layers of geotextile PP1, respectively. Geotextiles PP1, PP2, PP3 and PET1 are the same materials that were used in the construction of the Rainier Avenue wall in Seattle, Washington, USA (Allen et al. 1992).

Table 1. Geotextiles tested.

Geotextile	Description	Mass/unit area (g/m^2)	Thickness (mm)	Wide Width Strength (kN/m) (ASTM D 4595)	Elongation (%)[*] (ASTM D 4595)
PP1	Woven, slit-film	-	0.4	26	15[**]
PP2	Woven, slit-film, 2 layer stitch-bonded	-	0.7	49	15[**]
PP3	Woven, slit-film, 3 layer stitch-bonded	-	1.4	77	15[**]
PET1	Woven, multi-filament	-	-	215	10[††]
PET2	Woven, multi-filament	-	1.8	175	10[**]
NW1	Nonwoven, needle-punched	268	2.6	16	95[†]
NW2	Nonwoven, needle-punched	532	4.3	26	95[†]

Notes: [*]Manufacturer's published data from Industrial Fabrics Association International (1989, 1992). [**]Minimum average roll values. [†]Typical roll values. [††]Average value from Allen et al. (1992). PP = polypropylene; PET = polyester; NW = nonwoven.

Geotextile PP1 specimens were cut from geotextile samples exhumed from the Rainier Avenue wall site during its demolition. Tests for PP2 and PP3 geotextiles were performed using new material. Geotextile PET2 is manufactured using the same materials and procedures as geotextile PET1 which was also used in the Rainier Avenue wall project. However, PET2 specimens were used in the in-isolation tests because geotextile PET1 is no longer being manufactured and insufficient quantities had been exhumed from the Rainier Avenue wall site to permit its use for both the in-soil and in-isolation tests.

Nonwoven geotextiles were included in the laboratory program because they have been effectively used in several early full scale GRS walls. If the behavior and reinforcement characteristics of nonwoven geotextiles were better quantified they would likely be used more often in GRS walls because they are less expensive than many other geosynthetics. Nonwoven geotextiles, NW1 and NW2, were selected as being representative of the lightest weight and typical weight nonwoven geotextiles, respectively, for GRS wall applications.

2.3 In-Isolation Test Apparatus, Instrumentation and Specimen Preparation

In-isolation tests were performed using an MTS testing machine which was fitted with hydraulically operated clamps. In an attempt to eliminate end effects, elongation of the geotextiles was measured using a "scissors" type of displacement device (Figure 1). The scissors were attached to the geotextile specimen by puncturing the specimen with needles, which are mounted at the end of each scissor arm. The distance between the needles at the beginning of each test (approximately 60 - 75 mm for 100 mm gauge length specimens) was used as the initial gauge length for calculating strains in the woven geotextile specimens. No measurable reduction in strength resulted from insertion of the needles. The scissors gave erratic and unreliable readings and were difficult to

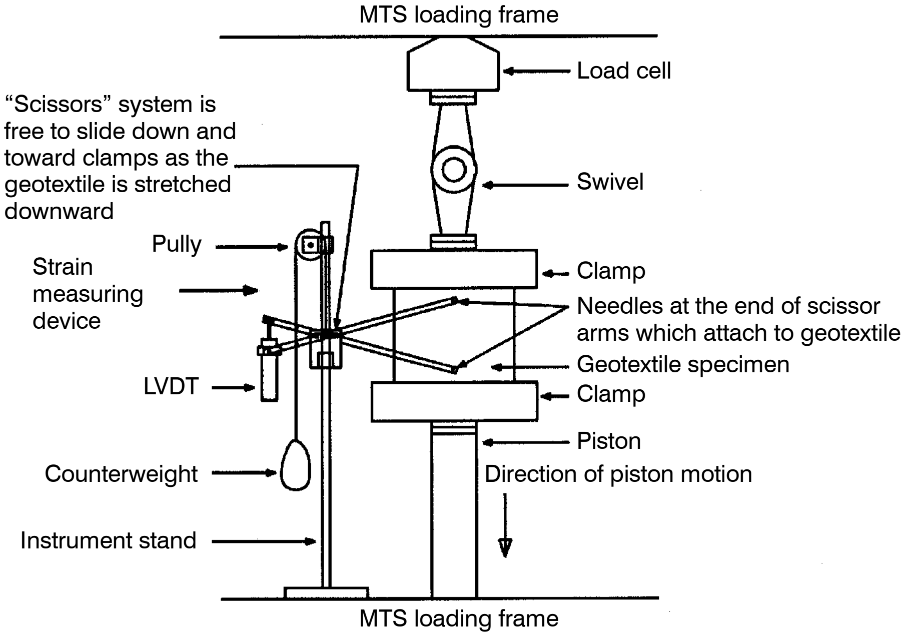

Figure 1. In-isolation test setup and the "scissors" system used to measure displacement.

use on specimen gauge lengths less than 75 mm. Hence, strains in NW1 and NW2 specimens were computed using cross-head displacement data.

Polypropylene woven geotextile specimens were 200 mm wide by 200 mm long. The 50 mm lengths on each end of the specimen used to clamp the specimen was reinforced with an epoxy resin to prevent damage by the clamps. This resulted in a test specimen 200 mm wide with a 100 mm gauge length between the clamps as required by ASTM D 4595.

Testing of the PET2 specimens presented some difficulties. Full 200 mm wide specimens could support loads exceeding the structural capacity of the clamps (Table 1). Furthermore, slip between the clamps and the specimen occurred at these large loads. Thus, to reduce the maximum applied load, PET2 specimen widths were reduced. This approach was supported by the work of Leshchinsky and Fowler (1990) and Paulson (1993) who reported that specimen widths could be reduced with no effect on the measured wide-width strip tensile properties for geotextiles of the type tested in the current study; i.e. geotextiles with little interaction between the structural filaments oriented in the direction of loading and the cross-weave fibers. With the exception of two 50 mm wide specimens, PET2 specimens were 100 mm wide. No differences in strength or stiffness, per unit width of the geotextile specimens, was observed for the different width PET2 specimens. Since the polyester filaments were easily damaged, both ends of the PET2 specimens were impregnated with an epoxy resin, and a 0.3 mm thick sheet of stainless steel was glued on the outside of the epoxy for additional protection from the clamp teeth. The PET2 specimen gauge length between the clamps was 100 mm.

Table 2. Number of tests and loading condition for woven geotextiles.

Geotextile	Constant strain rate (%/minute)				Constant load (creep test)
	10.0	1.0	0.1	0.01	
	Number of tests				
PP1	7	3	6	6	0
PP2	10	5	4	7	2
PP3	11	5	4	8	2
PET2	10	2	2	5	3

All NW1 and NW2 specimens had widths of 200 mm, and since these are lower strength materials, it was not necessary to apply epoxy to the ends. However, to prevent filament damage from clamp slippage the clamp faces were roughened.

2.4 Constant Strain Rate Tests

The effect of strain rate on the strength properties of the four woven geotextile specimens, PP1, PP2, PP3 and PET2, was investigated using a series of wide-width tests conducted at strain rates of 10, 1, 0.1 and 0.01%/minute (Table 2). The stiffness and strength values of PP1, PP2 and PP3 specimens were found to be very sensitive to strain rate and followed the same general pattern that was reported by Yeo (1985): i.e. a decrease in strength and stiffness values was observed with decreasing strain rate (Figure 2). The PET2 specimens were not as sensitive to strain rate as were PP1, PP2 and PP3 specimens, and occasionally it was difficult to distinguish between tests conducted at different strain rates. The 5% secant stiffness values (secant stiffness value determined at 5% strain) decreased by approximately 50% for PP1, PP2 and PP3 specimens when the

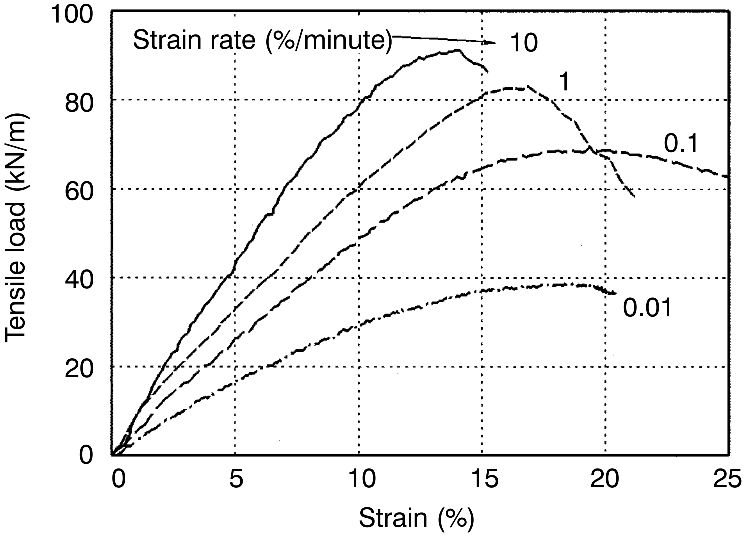

Figure 2. Tensile load versus strain for PP3 geotextile specimens.

strain rate was decreased from 10 to 0.01%/minute, whereas the 5% secant stiffness values for PET2 specimens decreased by only 15 to 20% for the same decrease in strain rate (Figure 3).

In this study the average strength values and the average corresponding strain values for the woven geotextile specimens were less than those reported by Allen et al. (1992) (Table 3). In fact, the strength values were closer to the minimum average roll values (Koerner 1994 pp. 91-93) reported by the manufacturers (Industrial Fabrics Association International 1989, 1992; Table 1), while the corresponding strain values were less (with the exception of PET2 specimens). Strengths below those previously reported may be partially attributed to difficulties in clamping the geotextile specimens in a manner which did not damage them. However, the epoxy specimen end protection may not have been sufficient as the specimens typically failed near the clamps. Even though different types of specimen protection and clamps with smaller teeth were tried, the method used appeared to be the best. The application of the epoxy may itself have influenced the failure mode of the specimens by causing a stress concentration at the transition point from the epoxy coated geotextile specimen to the uncoated geotextile specimen. A better means of clamping, especially for high strength geotextiles, is required and comparison with tests performed using roller clamps is suggested.

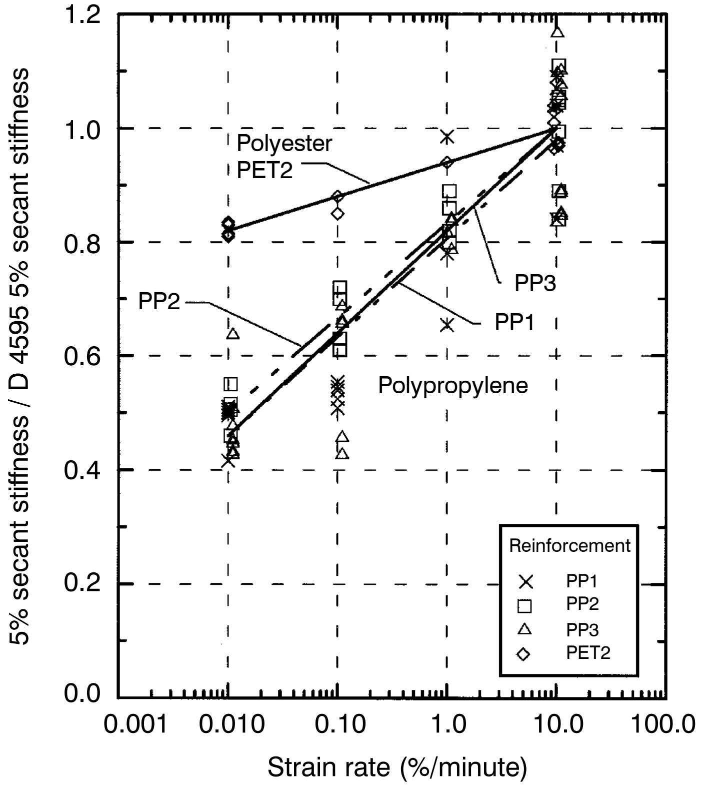

Figure 3. Normalized 5% secant stiffness versus strain rate for woven geotextiles.

Table 3. Comparison of wide-width strip tensile test results (ASTM D 4595) performed by Gallagher (1995) with those reported by Allen et al. (1992) for the woven geotextiles.

Geotextile	Gallagher (1995)			Allen et al. (1992)		
	Strength (kN/m)	Strain at failure (%)	5% secant stiffness (kN/m)	Strength (kN/m)	Strain at failure (%)	5% secant stiffness (kN/m)
PP1	24.3	10.5	260	31 (21)	21 (15)	198 (181)
PP2	53.3	12.7	470	62	16	453
PP3	77.6	13.6	780	92	17	662
PET1	NA	NA	NA	186	18	1068
PET2	162	12.4	1000	NA	NA	NA

Notes: Values in parentheses are test values for specimens exhumed from Rainier Avenue wall site (Allen et al. 1992). NA = not available.

The differences in strain values at failure may also be attributed to failure of the geotextile specimens near the clamps. This failure zone, which corresponds to the zone of highest localized strain, was outside of the region measured by the "scissors" (Figure 1). Therefore, the "scissors" did not measure overall specimen strain values at failure, but only measured the strain between the two needles. To exclude this failure zone would underestimate the overall geotextile specimen strain values at failure. Again, a better geotextile clamping method is required to ensure that the failure zone will fall within the region bounded by the strain measuring device (i.e. the scissors).

Even though the strength values measured using ASTM D 4595 were less than those reported by Allen et al. (1992), the stiffness values measured for PP1, PP2 and PP3 specimens were greater (Table 3). (The stiffness values for PET2 specimens could not be used in this comparison because PET2 geotextiles were not used in the Rainier Avenue wall project and no manufacturer's data was available.) Since the stiffness values were calculated at strain values much less than the strain values at failure, geotextile specimen clamp damage should not be the cause of greater stiffness values. The overall geotextile specimen strain should also be more accurately measured by the scissors since stress concentration effects should have less effect at the lower stress conditions associated with these strains. Therefore, the stiffness values measured in this program should be close to the stiffness values that would be obtained if clamp damage is not a factor.

2.5 Variable Gauge Length Tests

Wide-width strip tensile tests were conducted on 200 mm wide NW1 and NW2 specimens using gauge lengths of 25, 50, 56, 75, 100 and 115 mm (Table 4). All tests were conducted at strain rates of 10 %/minute by adjusting the loading piston displacement rate for the specimen length. These tests were performed to determine if a correlation could be established between in-isolation, and confined, in-soil stress-strain behavior. If such a relationship could be established it would simplify testing of nonwoven geotextiles by eliminating the need to perform confined tension tests (McGown et al. 1982; Wilson-Fahmy et al. 1993). These tests assumed that shorter gauge lengths would more closely approximate the plane strain conditions of confinement in soil and would

Table 4. Number of tests conducted at each gauge length on nonwoven geotextiles.

Geotextile	Gauge length (mm)					
	25	50	56	75	100	115
	Number of tests					
NW1	5	5	2	4	6	5
NW2	5	4	4	4	4	3

approach the near “zero” gauge length between soil particles in GRS systems (Christopher et al. 1986; Resl 1990). The assumption that zero gauge length strength and stiffness values obtained from in-isolation tests might approximate those values obtained from in-soil tests was based upon:

(1) the conclusion by Ling et al. (1992) that the stress-strain response of nonwoven geotextiles confined between two membranes was similar to the response when confined in soil;

(2) the conclusion by Resl (1990) that geotextile reinforcement is effectively “clamped” by soil particles on either side of the failure (“tear”) in model GRS wall tests;

(3) the observation by Christopher et al. (1986) that “zero span” tests produced results similar to the confined tests reported by McGown et al. (1992); and

(4) reports by Wang et al. (1990) and Resl (1990) that strength values measured from in-isolation tests on nonwoven geotextiles increased with decreasing gauge lengths.

In this study, contrary to the results reported by Wang et al. (1990) and Resl (1990), the strength values of NW1 and NW2 specimens were approximately the same for all gauge lengths tested (Figure 4). Wang et al. reported an increase in strength values of 25 to 33% for decreases in gauge length from 200 to 50 mm. Resl reported an increase in strength values from 65% to greater than 130% for decreases in gauge length from 200 to 3 mm. One possible explanation for the difference between the writers’ results and those reported by Resl and Wang et al. is the strain rate. The strain rate for tests conducted in the current study remained constant at 10%/minute regardless of specimen gauge length. In the study by Wang et al., a constant loading piston *displacement* rate was maintained, not a constant *strain* rate. Thus, for a decrease in gauge length from 200 to 50 mm the strain rate would increase by a factor of four. Although Resl does not indicate if the strain rate or loading piston displacement rate were held constant, the similarity between Resl and Wang et al. data, and the 30% increase in the strength values of woven geotextiles tested by Resl using the same procedure, suggests that Resl also held the displacement rate constant. If the polypropylene filaments in the nonwoven NW1 and NW2 specimens behave similarly to those in the woven PP1, PP2 and PP3 specimens tested in this study, an increase in strength values with increasing strain rate would be expected. Thus, Wang et al. and Resl were combining variable strain rate tests with variable gauge length tests, and their results should not be used for projecting a “zero” gauge length strength. The test method chosen for this program, whereby the strain rate was held constant regardless of geotextile specimen gauge length, more closely models an in-soil load-elongation test conducted at that same strain rate and is

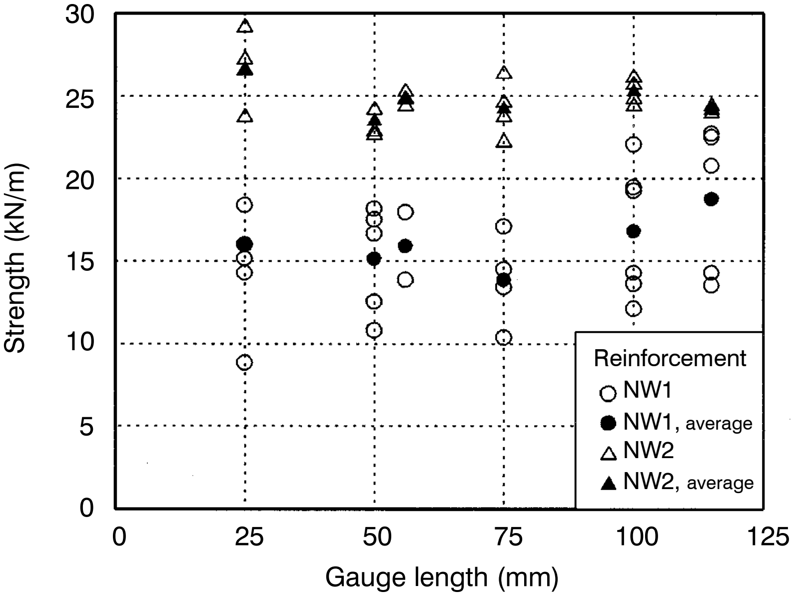

Figure 4. Strength versus gauge length for nonwoven geotextiles.

the more appropriate test method for comparison of "zero" gauge length in-isolation specimen tests with in-soil specimen tests.

Although no increase in NW1 and NW2 specimen strength values was recorded, the stiffness values appear to have increased with decreasing gauge length (Figure 5). The 5% secant stiffness values for NW1 and NW2 specimens increased by approximately 130 and 65%, respectively, when the gauge length was reduced from 115 to 25 mm. Since neither Wang et al. nor Resl reported stiffness data, no comparison with their results could be made. If the relationship between stiffness and gauge length is assumed to be linear, the extrapolated "zero" gauge length 5% secant stiffness values for NW1 and NW2 specimens were approximately 200 and 160% of the stiffness values determined using the ASTM D 4595 specified gauge length of 100 mm for NW1 and NW2 specimens, respectively. These increases are less than the 200 to 300% increase in stiffness values of nonwoven geotextiles with confinement in soil reported by McGown et al. (1982). Some of the difference between our extrapolated "zero" gauge length increase in stiffness values and those reported by McGown et al. (1982) may result from the assumption of a linear relationship between geotextile specimen stiffness and gauge length. The actual relationship may not be linear; however, given the scatter and limited number of data points, anything other than a linear extrapolation would be inappropriate. Further discussion on the relationship between the "zero" gauge length stiffness values and the in-soil stiffness values for NW1 and NW2 specimens is presented in Section 3.

There was significant scatter in NW1 and NW2 specimen test results (Figure 5). This was more pronounced for the lighter weight NW1 specimens than for the NW2 specimens, which have approximately twice the mass per unit area (Table 1). Some of the scatter of the data points can be attributed to test method variability, inaccuracies in test-

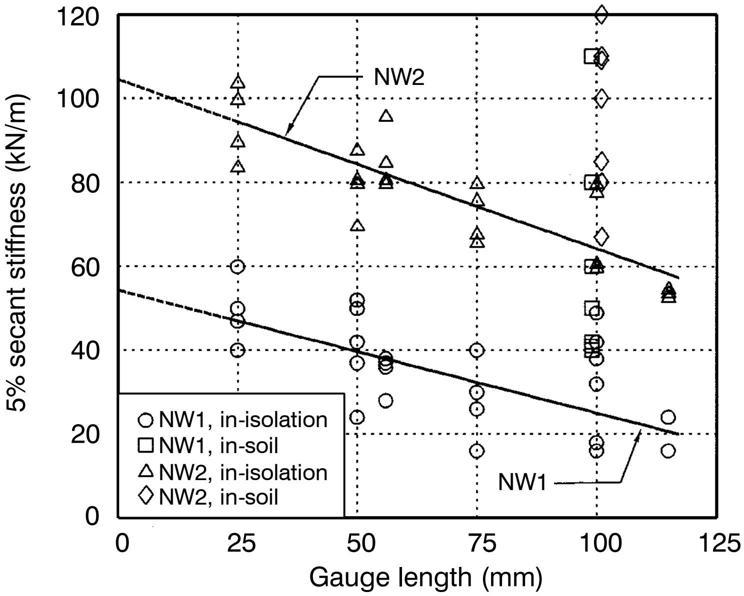

Figure 5. Secant stiffness versus gauge length from in-isolation tests for nonwoven geotextile specimens compared with secant stiffness values obtained from 100 mm gauge length confined tests on the same type of geotextile specimens.

Note: Lines in the figure are linear regressions of in-isolation test results.

ing, and the method used to measure the strain in the NW1 and NW2 specimens. However, much of the scatter seems to be due to material variability, despite the fact that both nonwoven geotextiles were produced by the same manufacturer using the same manufacturing process. Visual inspection and weighing of individual NW1 and NW2 specimens revealed substantial variability in the density and distribution of fibers (Figure 6), and the variation in mass per unit area had a noticeable influence on the measured geotextile specimen strength. There was significantly more variability in mass per unit area values for NW1 specimens, which also showed more variability in strength than was observed for NW2 specimens. The importance of the minimum average roll value in design is highlighted by the significant variability of mass per unit area values observed for the nonwoven geotextiles tested. This variation in geotextile properties could create difficulties if not appropriately considered when these products are specified for use in GRS walls or other applications.

3 CONFINED TESTS USING THE UNIT CELL DEVICE (UCD)

3.1 Introduction

An investigation of fundamental GRS behavior was performed using a plane strain unit cell device (UCD) in which a geotextile reinforced soil specimen (UCD specimen), representative of an element within a GRS wall or slope, is tested (Figures 7 and 8). The

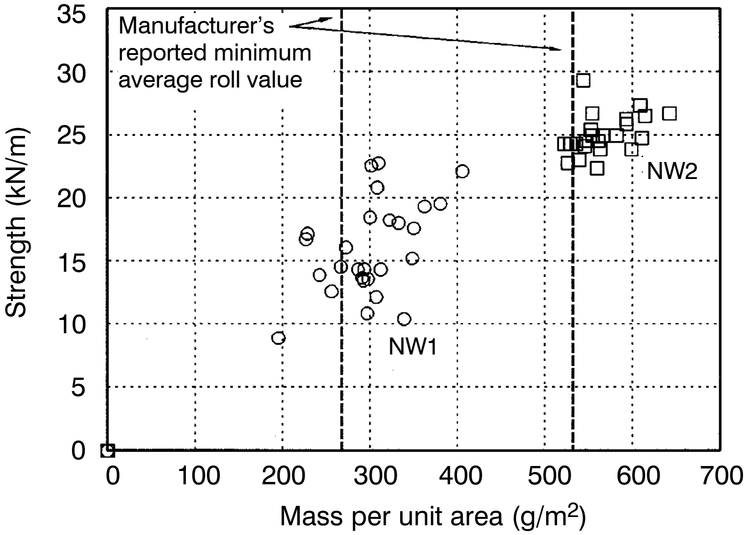

Figure 6. Strength versus mass per unit area for the nonwoven geotextiles.

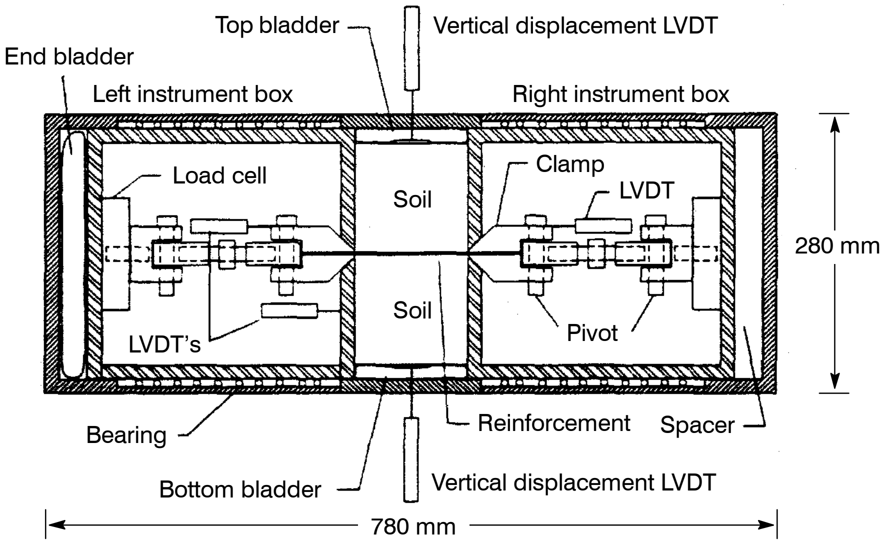

Figure 7. Profile cross-section schematic of the unit cell device (UCD).
Note: Reaction frame not shown.

UCD is a load control test apparatus; as the vertical pressure, σ_1, on the top and bottom surfaces of the UCD specimen is increased, the left instrument box is free to displace horizontally. Horizontal deformation of the soil is resisted by an applied lateral confin-

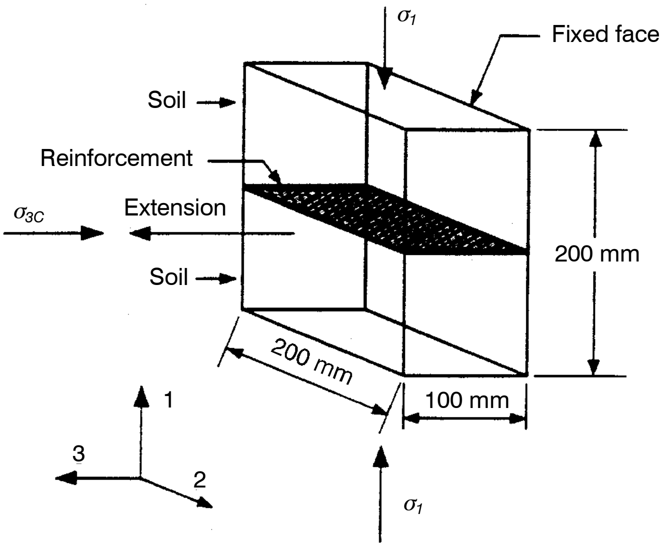

Figure 8. UCD principle of operation and specimen dimensions.
Notes: σ_1 = vertical pressure; σ_{3C} = lateral confining pressure.

ing pressure, σ_{3C} , and by tensile loads induced in the geotextile specimen (Figure 8). The loads in the geotextile specimen are measured directly by load cells connected to clamps which grip the geotextile specimen on both ends. Stiff end plates, to which the clamps are mechanically linked, ensure that the geotextile specimen and the soil displace equally in the lateral direction during loading and that the surfaces of the geotextile specimen remain orthogonal. Since the UCD is a load control device, which vertically loads the UCD specimen, neither the vertical nor horizontal (geotextile specimen) strain rate could be controlled. The lateral confining pressure applied to the UCD specimen was maintained constant for each test, and for any given test it was between 10 and 100 kPa. A graded Ottawa sand (Soil O) and a local glacial outwash sand (Soil R) were used in the test program (Table 5).

Table 5. Soil properties.

Soil	D_{60} (mm)	C_u	C_c	Specific gravity	Minimum void ratio	Maximum void Ratio	ϕ_{ps}*
Soil O	0.28	1.6	1.0	2.65	0.51	0.75	42
Soil R	0.61	4.1	1.0	2.73	0.46	0.76	55

Notes: * ϕ_{ps} = plane strain angle of internal friction; C_u = coefficient of uniformity = D_{60}/D_{10} ; C_c = coefficient of curvature = $D_{30}^2/(D_{10} \times D_{60})$; and D_{10} , D_{30} and D_{60} = the particle size such that 10, 30 and 60%, respectively, of the particles are smaller than that size; Soil O = Ottawa sand; and Soil R = local glacial outwash sand.

Prior to placing specimens in the UCD, the interior was lubricated with a silicon grease and lined with a 0.3 mm latex membrane. Unit cell device specimens were constructed by placing two approximately equal weight layers of soil below the geotextile specimen, installing the geotextile specimen, and placing two more equal weight soil layers above the geotextile specimen. Since the soil used in GRS walls are generally compacted, Soils O and R were compacted in the UCD to relative densities of 96 and 101%, respectively (relative density was determined in accordance with ASTM D 4253). Each soil layer was compacted by 25 blows of a 2.27 kg mass dropped from a height of 300 mm. All UCD specimens were constructed with dry soils.

Before loading, each UCD specimen was nonhydrostatically consolidated by applying a vertical pressure, σ_1 , which was equal to the lateral confining pressure, σ_{3C} , that was applied to the UCD specimen during the test. The lateral confining pressures, σ_2 and σ_{3C} , could not be controlled during consolidation and were dependent upon the applied vertical pressure, σ_1 , and the soil properties. After a minimum consolidation period of 150 seconds, the vertical pressure on the specimen was manually increased in 10 kPa increments every 30 seconds until: the geotextile reinforcement failed; the lateral displacement limit of the UCD was reached; or, the upper limits of the measuring devices were approached. In some tests, loading was discontinued prior to reaching one of the above conditions and the vertical pressure held constant so that the response of the UCD specimen under sustained loading could be monitored. The UCD design, operation, and test procedure are presented in more detail in the paper by Boyle (1995a).

Since the tension in each end in the geotextile specimen was measured throughout each test, the “apparent” in-soil geotextile specimen stiffness values could be computed by dividing the tension by the corresponding strain values. Due to frictional interaction between the soil and geotextile specimen, the loads measured at each end of the geotextile specimen were not necessarily equal throughout each test. The difference between the two loads increased with decreasing geotextile specimen stiffness, increasing soil friction, and increasing strain. The distribution of tensile strain was measured in a few tests by attaching strain gauges to the geotextile specimen. The strain was observed to decrease approximately linearly from the left clamp to the right clamp (Boyle 1995a). The confined stiffness values were computed by averaging the tensile forces measured in each end of the geotextile specimen. Unfortunately, due to the UCD mode of operation, direct comparison of the stiffness values obtained from UCD tests with stiffness values obtained from tests performed with other in-isolation or in-soil devices may be difficult for the following reasons:

- The confined stiffness of geosynthetics has often been measured using devices which apply a constant pressure normal to the geosynthetic during load application (McGown et al. 1982; Ling et al. 1992). For the UCD tests in this study, the normal pressure on the geotextile specimen was not constant but increased continually during each test. This process models the conditions that occur during the construction of GRS walls. However, the apparent stiffness, of geosynthetics sensitive to confinement, changes as the normal pressure increases during testing. Arriving at a single stiffness value for the geotextile specimens from the UCD test results is difficult because for each test the geotextile specimen strain and normal pressure differ depending on the soil properties and the effective lateral confining pressure.
- Other in-soil geosynthetic testing devices maintain a constant strain rate throughout each test (McGown et al. 1982; Wu 1991; Ling et al. 1992). For the UCD device however, the load is applied to the soil and the rate of lateral expansion is dependent on

the soil response and may vary during testing. Any variation in the geosynthetic strain rate may cause the apparent stiffness values of strain-rate-sensitive geosynthetics to vary during a test.

3.2 Nonwoven Needle-Punched Geotextiles

Although more than 17 UCD tests were carried out on NW1 and NW2 specimens, a meaningful stiffness value could not be determined in all of the tests. No stiffness values were computed if the difference in tension measured at the two ends of the geotextile specimen was deemed excessive, or if the UCD specimen exhibited odd (i.e. very different than that observed in other tests) behavior during the test. It was virtually impossible to determine a single stiffness value for either of the NW1 and NW2 specimens due to: low specimen tensile loads; variability of specimen strength due to the manufacturing process; variability in specimen preparation; and the nonuniform tension in the specimens.

However, even with limited data, it can be implied that the apparent stiffness values increased above the stiffness values obtained from ASTM D 4595 standard tests on 100 mm gauge length specimens when confined in soil (Figure 5). The NW1 and NW2 specimens had confined stiffness values one to four times larger than the standard, 100 mm gauge length, in-isolation tests. This increase in stiffness values for the NW1 and NW2 specimens due to confinement in soil and the application of a normal pressure was anticipated since this effect had been reported by others (McGown et al. 1982). The extrapolated “zero” gauge length in-isolation 5% secant stiffness values were within the range of in-soil stiffness values determined from the UCD tests (Figure 5).

Developing a correlation between in-isolation and in-soil stiffness was not possible because the normal pressure on the geotextile specimens changed throughout each UCD test and was dependent on both the soil strength and the confining pressure applied to the soil. The relationship between NW1 and NW2 specimen stiffness values and normal pressure prevents the development of an exact correlation between UCD determined stiffness values and the projected zero gauge length stiffness values of nonwoven geotextile specimens determined through in-isolation tests, as was suggested by Christopher et al. (1986) and Resl (1990). A different confined testing program, perhaps utilizing one of the devices reviewed by Wu (1991), is recommended for determining the confined stiffness values of needle-punched nonwoven geotextile specimens at specific normal pressures. The projected zero gauge length stiffness values could be compared to the confined stiffness values to determine how closely they approximate the confined stiffness values, if at all, and for what normal pressures.

The limited tests performed in this study, and the scatter in the test data, are insufficient to confirm or rule out the potential for a “zero” gauge length test to adequately predict the in-soil stiffness values of nonwoven needle-punched geotextiles. Further research is recommended as the monetary and time savings associated with performing in-isolation tests instead of in-soil tests would be significant. Any research undertaken for this purpose, using nonwoven needle-punched geotextile specimens similar to NW1 and NW2, should use a large number of specimens because of the high degree of manufacturing variability observed in these geotextiles.

3.3 Woven Geotextiles

An increase in stiffness values with confinement was not observed for PP1, PP2, PP3, PET1 and PET2 specimens; instead, the stiffness values decreased significantly in comparison to the in-isolation ASTM D 4595 test values (Figure 9). The stiffness values computed for PP1, PP2 and PP3 specimens were between 40 and 80% of the 5% secant stiffness value (stiffness values taken at 5% strain) determined from ASTM D 4595 tests. The PET1 specimens were not as greatly affected by confinement; with stiffness values near 90% of the ASTM D 4595 5% secant stiffness value. One notable difference between tests conducted in the UCD and ASTM D 4595 tests is the rate at which the geotextile specimens were strained. Standard ASTM D 4595 tests are conducted at strain rates of 10%/minute while UCD specimens experienced average strain rates between 0.5 and 0.035%/minute, 20 to 300 times slower than the standard test (Figure 9). Scatter in the normalized stiffness values for the in-soil tests is principally attributed to variability in the geotextile specimens, as the values determined for in-isolation tests have similar ranges. Also, the use of an “apparent” stiffness value for the in-soil tests, soil variability, and specimen preparation problems associated with clamping the geotextile specimen outside the soil specimen boundaries contributed to the scatter in the normalized stiffness values.

A reduction in stiffness values of geosynthetics with decreasing strain rate has been reported by Rowe and Ho (1986), Wang et al. (1990), Nothdurft and Janardhanam

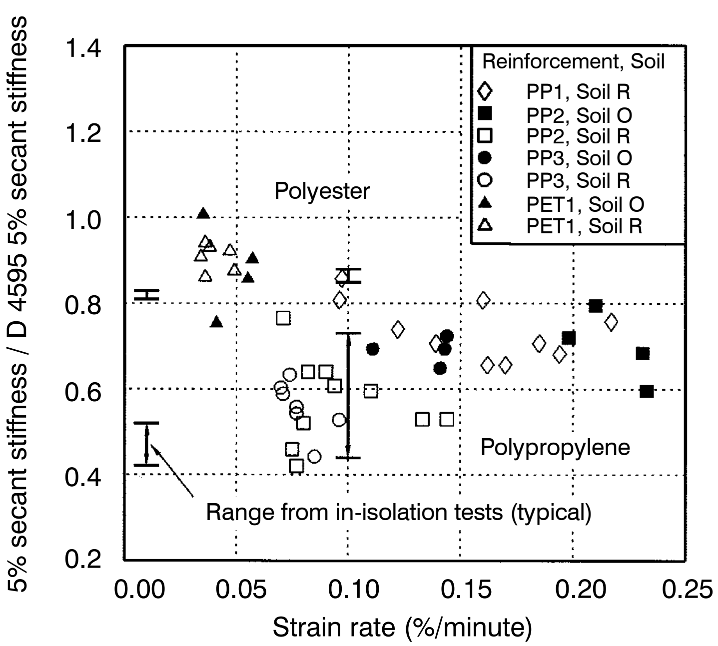

Figure 9. Normalized 5% secant stiffness values versus strain rate for woven geotextile specimens.

Note: Ranges shown were determined from in-isolation tests performed at the indicated strain rate.

(1994) and Nothdurft (1995). A decreasing strain rate is the suspected cause of the reduction in stiffness values observed in this study. The increase in the rate at which tension developed in the woven geotextile specimens when the lateral strain rate was increased verified that woven geotextiles display substantial strain rate dependency. This is in agreement with the in-isolation tests conducted in this study (Figure 9). This fairly close relationship between strain rate and woven geotextile stiffness values, especially for PP1, PP2 and PP3 specimens, suggests that neither the stiffness values nor the strain dependency of the woven geotextile specimens measured in the UCD were influenced by confinement. The slight difference in strength reduction with decreasing strain rate for PET1 specimens, when compared with the in-isolation tests, may be due to confinement in soil but is more likely due to differences between PET2 specimens, which were tested in-isolation, and PET1 specimens which were exhumed from the Rainier Avenue wall site. Provided the strain rate effects are known, this decoupling of woven geotextile stiffness values from confinement effects should simplify testing of woven geotextiles, since only in-isolation testing is required. This is in agreement with the in-soil load-elongation tests reported by Wilson-Fahmy et al. (1993) who concluded that only nonwoven geotextile specimens require confined testing. In-isolation testing should be performed to define the relationship of strength and stiffness to strain rate.

4 ASSESSMENT OF ASTM D 4595: WIDE-WIDTH STRIP TENSILE TEST

The ASTM D 4595 standard test specifies that strength and stiffness values of geotextiles be determined, regardless of the material properties and the manufacturing technique, by conducting an in-isolation load-elongation test on 100 mm gauge length by 200 mm wide specimens strained at 10%/minute. The tests conducted on both the woven and nonwoven geotextile specimens in this study illustrate the problem of applying such a universal standard to geotextiles which are manufactured using a variety of materials and techniques. Material properties, manufacturing process, specimen size, strain rate, and, in the case of the nonwoven geotextiles, confinement, affect the measured performance of these geotextiles. While a universal standard may be appropriate for quality control testing by manufacturers, it appears that the ASTM D 4595 standard is inappropriate, in its current form, for obtaining engineering properties of geotextile reinforcement.

The effect of strain rate on the computed stiffness values of the woven geotextile specimens (PP1, PP2, PP3 and PET2) implies that the stiffness values determined from ASTM D 4595 are actually “apparent” stiffness values and are not an intrinsic property of the material (Nothdurft and Janardhanam 1994; Nothdurft 1995). For strain rate susceptible geotextiles not influenced by confinement in soil, a better approach for obtaining the engineering properties may be to perform a series of in-isolation tests at various strain rates and plot the 5% secant stiffness values versus gauge length (Figure 5). When designing or evaluating a GRS wall, the “apparent” stiffness values, which depend on the strain rate anticipated during construction, could be obtained from interpolation or extrapolation of the strain rate test data from such a plot. Since a series of tests which define the influence of strain rate on engineering properties would take less time to perform than creep tests, the engineering data needed for the design of GRS structures could be quickly obtained for any particular geosynthetic reinforcement. While each designer could commission testing for each geosynthetic in the design, it would be easier and reduce repetition, if manufacturers, suppliers, or independent research facilities provided charts or tables which address the influence of strain rate on each specific geosynthetic.

A similar situation exists for testing nonwoven geotextiles that have apparent stiffness values dependent on gauge length, strain rate, and normal pressure. Although the ASTM D 4595 standard test may be appropriate for manufacturer quality control, and while conservative if used directly in design, it is all but useless for obtaining "actual" engineering properties without a correlation to account for gauge length, strain rate, and normal pressure. Furthermore, the substantial variation in the mass per unit area of the nonwoven geotextile specimens (NW1 and NW2) tested, emphasizes the importance of testing a statistically significant number of specimens in any program performed to characterize nonwoven geotextiles. A large number of tests may be required to determine with confidence the minimum average strength and stiffness values (i.e. two or more standard deviations below the mean) for these materials so that sufficiently conservative values may be used in design.

The laboratory program reported here was of insufficient scope to make more specific recommendations with regard to modification of the ASTM D 4595 standard than those made above. The findings do, however, highlight the problems which accompany the universal application of a single standardized test procedure to geotextiles that behave differently depending on the geotextile composition and the manufacturing process. Further research is needed.

5 PRACTICAL IMPLICATIONS

The importance of a clear understanding of geosynthetic reinforcement behavior, developed through appropriate testing, when designing GRS structures or modeling their behavior can be illustrated by comparing the findings reported above with the conclusions reached by Zornberg and Mitchell (1993, 1994). Zornberg and Mitchell performed a finite element method (FEM) analysis of the Rainier Avenue wall, the same wall from which PP1, PP2, PP3 and PET1 samples were obtained (Allen et al. 1992). Zornberg and Mitchell used backfill soil properties determined from triaxial tests and geosynthetic reinforcement properties determined using the ASTM D 4595 standard (STS 1990) to model the soil and the geosynthetic reinforcement behavior. To calibrate their FEM model and thus adequately model the behavior observed in the Rainier Avenue wall, Zornberg and Mitchell had to increase the stiffness of the woven geotextile. Since this action was necessary, Zornberg and Mitchell concluded that the stiffness of the woven geotextiles must have increased due to confinement. The results of the writers' laboratory investigation contradict the conclusion drawn by Zornberg and Mitchell. The Rainier Avenue wall was constructed in approximately two months and the woven geotextile reinforcement generally experienced strain values less than 1% (Allen et al. 1992). Strain rates were, therefore, of the order of 0.00001%/minute - 1 million times slower than the ASTM D 4595 specified strain rate. Extrapolating the data presented in Figures 3 or 9, the stiffness values corresponding to this strain rate would fall between 30 to 50% and 70 to 90% of the ASTM D 4595 determined stiffness values for the polypropylene and polyester woven geotextiles, respectively. Since confinement was not shown to influence the geotextile specimens in the laboratory tests of this study, it is unlikely that confinement resulted in *doubling* of the ASTM D 4595 geotextile specimen strength values for geotextiles used in the Rainier Avenue wall, as Zornberg and Mitchell concluded. A different factor associated with the method which Zornberg and Mitchell used to model the wall must have been responsible for the increased stiffness values of the geotextile reinforced soil.

The writers' suggest that plane strain soil behavior was likely responsible for the reduction in deformations below those computed by Zornberg and Mitchell with the unadjusted reinforcement properties. The plane strain friction angles for dense cohesionless soils have been shown to be greater than the friction angle obtained from triaxial tests, and reach their peak strength values at lower strain values in plane strain tests than in triaxial tests (Marachi et al. 1981). Both of these factors were confirmed for the soil used in the Rainier Avenue wall (Boyle 1995a), and would account for decreased deformations. Thus, the conclusion reached by Zornberg and Mitchell that the stiffness values of the woven geotextiles must increase with confinement is incorrect.

It should be acknowledged that adjustment of the soil data (i.e. the stress-strain curves), instead of the geotextile reinforcement data, would have been much more complicated since no plane strain soil data was available to Zornberg and Mitchell. Also, no technique is available for converting triaxial stress-strain curves to plane strain stress-strain curves. Furthermore, Zornberg and Mitchell did not have access to variable strain rate test results for the four woven geotextiles, which were produced as part of this study, and thus they could not incorporate the reduction in stiffness values with decreased strain rate into their model.

6 CONCLUSIONS

The following conclusions from this study can be made:

(1) In-isolation wide-width strip tensile tests (ASTM D 4595) on woven geotextile specimens (PP1, PP2, PP3 and PET2) conducted at different strain rates determined that the strength and stiffness values of these geotextiles decreased with decreasing strain rate. The decrease in the 5% secant stiffness values associated with a decrease in strain rate from 10 to 0.01%/minute was approximately 50 and 15% for the polypropylene and polyester geotextiles, respectively.

(2) No increase in strength values was observed with reductions in specimen length for the nonwoven geotextile specimens (NW1 and NW2), although the stiffness values of these geotextiles did increase. The "zero" gauge length 5% secant stiffness values for the NW1 and NW2 specimens increased by approximately 130 and 65%, respectively, above the stiffness values measured using the standard 100 mm gauge length. Confinement of NW1 and NW2 specimens in soil resulted in an increase in stiffness values above the in-isolation stiffness values measured on 100 mm gauge length specimens using ASTM D 4595, but no correlation between the "zero" gauge length in-isolation stiffness and the confined stiffness could be made.

(3) The stiffness values of the woven geotextile specimens did not increase with confinement in soil, and confinement did not influence the strain rate effect. The woven geotextile specimens tested in soil exhibited reductions in stifffness with decreases

in strain rate similar to those observed in in-isolation tests on the same type of geotextile.

(4) The ASTM D 4595 wide-width strip tensile test was found to be deficient for the determination of the engineering properties of geotextiles used in reinforcement applications. The cause of this deficiency is the universal application of standardized strain rates and specimen dimensions to geotextiles that are strain rate sensitive and influenced by specimen dimensions. To determine the engineering properties of geotextiles that may be used in the design and evaluation of GRS structures it is recommended that modifications be made to ASTM D 4595 which account for material variability.

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