Time-Dependent Behavior of Geosynthetic Reinforcement – A Review of Experimental Work

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1. Introduction

The popularity of soil structures reinforced with mechanical inclusions has brought to light the important issues of service life and durability. Unlike other civil structures, the load bearing elements of reinforced soil structures are difficult to inspect, and essentially impossible to maintain. In addition, they are buried in soil, a complex environment with physical and chemical characteristics that may vary greatly from site to site.

Geosynthetics are generally manufactured from polymer materials that exhibit a load, load rate, and temperature dependent elastic-viscoplastic behavior. Of particular interest to the present discussion are the following three families of geosynthetics: geotextiles, geogrids, and geomembranes.

Geotextiles are textiles in the traditional sense, but consist of synthetic fibers rather than natural ones such as cotton, wool, or silk (Koerner, 1994). Consequently, biodegradation is not a problem. These synthetic fibers are made into a flexible, porous fabric by standard weaving machinery, or are matted together in a random or non-woven manner (Koerner, 1994). A wide range of processes are used to manufacture geotextiles. This imparts quite different load-extension properties to the materials. With woven geotextiles, the properties of the constituent fibers may dominate the overall behavior. With non-woven and composite geotextiles the dominant factor is their internal structure (McGown et al. 1982). Geotextiles always perform at least one of the following five discrete functions (Koerner, 1994): 1) separation; 2) reinforcement; 3) filtration; 4) drainage; and/or, 5) liquid barrier (when impregnated).

Rather than being a tightly woven, non-woven or knit textile fabric, geogrids are plastics that are formed into a very open, gridlike configuration; i.e., they have large apertures (Koerner, 1994). Geogrids are either stretched for improved physical properties, or are made on weaving machinery by unique methods. Geogrids function almost exclusively as reinforcement materials (Koerner, 1994).

Along with geotextiles, geomembranes represent two of the largest groups of geosynthetics (Koerner, 1994). Geomembranes are impervious thin sheets of rubber or plastic material used primarily for linings and covers of liquid- or solid storage facilities (Koerner, 1994). Their primary function is thus always as a liquid or vapor barrier.

For geotechnical structures with a long design life (e.g., 70 to 120 years), long-term behavior is obviously of importance. In the design of such structures, *stability* and *serviceability* considerations require that the reinforcement: (1) Not attain its ultimate state of collapse; i.e., tensile rupture (this is a strength criterion); and, (2) Not develop excessive strain over their design life (this is a strain criterion). In the case of polyester geogrids, long-term design strengths are usually governed by tensile rupture; for polyethylene, the long-term design strengths may be governed by either strain or rupture (Ingold et al. 1994).

The more significant conclusions found amidst the literature pertaining to the experimentally determined long-term behavior of geosynthetics are reviewed in this report. This is achieved in the following manner: In Section 2 the findings of past creep tests on geosynthetics are discussed. This is followed, in Section 3, by a similar discussion of the results of stress relaxation tests. A brief summary of temperature effects on geosynthetics is presented in Section 4; this serves as background information for the discussion of acceleration and superposition techniques presented in Section 5. This is followed, in Section 6, by a summary of the more significant points from this chapter. Discussion of the various macroscopic models proposed to mathematically describe the creep and stress relaxation response of geosynthetics is presented elsewhere [report 2].

2. Creep

Creep is defined as the time dependent development of shear- and/or volumetric deformations under a constant state of force or stress. Creep occurs at a rate that either remains constant, or varies with time. In typical laboratory creep experiments, specimens are loaded to a prescribed force level. This force is then maintained constant throughout the remainder of the test, and the resulting deformations of the geogrid recorded.

The creep response of geosynthetics, as well as that of other engineering materials, can typically be separated into one of three stages. Primary creep denotes a period of transient response during which deformation accumulates at an ever decreasing rate. This may be followed by a period of fairly constant strain rate called secondary creep. The duration of secondary creep varies widely, and for some materials is practically nil. At sufficiently high levels of stress this steady-state period is succeeded by a period of strain rate acceleration (termed tertiary creep) leading to failure or “creep rupture.”

2.1 Creep of Geotextiles

Allen et al. (1982) investigated the mechanical properties of geotextiles used in cold regions applications. In particular, the influence of freeze-thaw cycles in fresh and saltwater on the load-strain characteristics of five geotextiles was studied. In addition, they investigated the load-strain-strength and creep characteristics of geotextiles at sub-freezing temperatures. The investigation involved both tensile tests of normal duration and creep tests. Based on the results presented, it was concluded that, for a range of temperatures commonly associated with cold region applications, the load-strain-strength and creep characteristics were not adversely affected by sub-freezing temperatures. Also, freeze/thaw cycling in a dry, distilled water, and/or saline water environment had no appreciable influence on the load-strain-strength characteristics of the geotextiles tested.

Based on the results of the tensile tests of normal duration, it was observed that the needle-punched geotextiles (continuous filament, *polyester*; continuous filament *polypropylene*) exhibited high elongation and intermediate strengths. The woven geotextile (slit film *polypropylene*) had the highest strength but the lowest elongation. The heat bonded (continuous filament, non-woven *polypropylene*) and resin bonded (continuous filament, non-woven *polyester*) geotextile had strength and elongation characteristics intermediate to those of the needle-punched and woven geotextiles. The modulus and strength of the heat bonded geotextiles increased with decreasing temperature. The elongation at failure decreased significantly for the heat bonded and all polypropylene geotextiles. Concerning the behavior at small strains, the effects of geotextile construction appeared to be much greater than the effect of temperature.

From the results of creep tests, it was determined that for geotextiles with *polypropylene* fibers, a reduction in temperature resulted in a decrease in creep strains. The influence of temperature on creep strains was apparently related to filaments and not to the geotextile construction. All of the *polypropylene* materials exhibited tertiary creep and failed at load levels of 50 or 65 percent of the wide strip tensile strength at 22^{o}C. All other factors being equal, the *polyester* geotextiles were found to have the lowest creep rates and highest thresholds of tertiary creep. Finally, the geotextile construction process appeared to dominate the magnitude of the short-term creep strain at any time. At a given load, needle punched geotextiles were found to have the greatest short-term creep strains. Heat bonded and woven geotextiles were found to have the lowest short-term creep strains.

Holtz et al. (1982) evaluated the triaxial creep behavior of woven and non-woven *polypropylene* geotextiles reinforced specimens of Lafayette Concrete sand. It was found that specimens reinforced with non-woven geotextiles exhibit creep behavior similar to ones reinforced with woven geotextiles.

The first in-depth study of geotextile response under confined (in soil) conditions was presented by McGown et al. (1982). The confining soil used was Leighton Buzzard sand. From the results of strain-controlled tests of standard duration, it was concluded that when tested in-soil (100 kPa confinement), structured non-woven

(67% *polypropylene*, 33% *polyethylene* with melt bonded filaments; *polyester* with needle punched filaments) and composite woven (needle-punched *polypropylene*) geotextiles exhibited significant changes in the shape of their load-strain curves. The woven geotextile (*polypropylene* with woven tapes) did not exhibit much change, as it depends for its strength on aligned tapes that are not greatly affected by embedment in the sand used.

Creep test data obtained from unconfined in-isolation and from confined in-soil tests on two non-woven geotextiles indicated a reduction in initial and long-term strains in the confined specimens. This is obviously due to the soil-geotextile interaction; i.e., the rather significant effect of soil confinement on creep response. Significantly different shapes of the load-strain curves were observed for specimens tested in isolation and in-soil. The creep strain increased as confining pressure or strength of geofabrics increased. McGown et al. (1982) claimed that creep behavior of geotextiles was influenced by confining condition, temperature, fiber type and fiber structure.

The work of Shrestha and Bell (1982) is significant in that not only were experimental results generated, but an attempt was made to analytically describing the observed response. Shrestha and Bell (1982) performed creep tests on 200 mm wide by 100 mm long specimens of six different geotextiles, tested under load-controlled conditions. The durations of the creep tests ranged from 1400 to 1600 minutes. The lowest creep was exhibited by a non-woven, resin bonded, and continuous filament *polyester* geotextile. The highest creep was exhibited by non-woven, needle punched, staple and continuous filament, *polypropylene* geotextiles. Intermediate between these results (in order of increasing creep) were the following materials: woven (with needle nap), slit film, *polypropylene*; woven, monofilament *polypropylene*; and, non-woven, heat bonded, and continuous filament *polypropylene*. Creep was most sensitive to load levels for the continuous filament *polypropylene* geotextiles (creep increased 3 to 5 times when the sustained load was doubled). For the polyester geotextile, and for the polypropylene one with staple filaments, creep increased by only 1 to 2 percent for increases in sustained load levels from 50 to 57, and from 33 to 56 percent, respectively.

The load-strain-time-temperature relationship of several geotextiles was investigated by Andrawes et al. (1986). Using a single-step loading apparatus, they performed both loading and unloading tests on four geotextiles for durations of up to 10,000 hours; their goal was the prediction of service life of geotextiles and geogrids. The specimens measured 200 mm wide by 100 mm long. The tests were performed at constant temperatures of 5, 10, 20, and 40^{o}C. Referring to the instantaneous strains upon loading and unloading as the “plastic” and “elastic” components, respectively, Andrawes et al. (1986) noted that in general the magnitudes of the elastic and plastic instantaneous strains are similar. The elastic strains appeared to exhibit a greater sensitivity to temperature.

The notion of *isochrones* was used, and the isochronous stiffness (secant slope of isochronous load-strain curve) was quantified. The latter was observed to decrease with time. From the isochrones generated, the stiffest response was that associated with a composite woven and needle punched *polypropylene* geotextile. Exhibiting substantially lower stiffness and strain at failure were the following geotextiles: *polypropylene* woven tape, non-woven needle punched *polypropylene* (exhibited somewhat unstable material response), non-woven melt bonded filaments consisting of 67% polypropylene/33% polyethylene.

Den Hoedt (1986) presented creep data for a number of commonly used *polyester*, *polypropylene* and *polyamide* geotextiles loaded to 20% and 60% of the short-term tensile strength. He also attempted to predict lifetime behavior based on the experimental creep data generated.

The time dependent response of three geotextile fibers was reported by Greenwood and Myles (1986). The creep testing was carried out by suspending lengths of fiber under load. The testing of *polyester* yarn (1100 denier polyester) showed that the material has a relatively high elongation on loading and subsequently during the first hour. The subsequent strain is, however, quite low. By contrast, the testing of *polypropylene* yarn (9000 denier polypropylene) exhibited relatively little strain upon loading, but showed rather continuous creep. Not only the initial loading, but also the subsequent creep behavior depended upon stress in a non-linear manner. Finally, the creep testing of *polyaramid* fiber (1500 denier Kevlar) indicated that the overall strain level and the creep are both extremely low.

Greenwood and Myles (1986) concluded that the creep measurements on different geotextile fibers show no direct relationship to the short-term stress/strain relationship, but are rather dominated instead by the polymer composition. Furthermore, they noted that in general, it appears that the less the creep in the yarn, the greater the effect of the weave. Most of the reported values for the creep of woven polyester are considerably higher than the values for the yarn. For polypropylene, the creep results quoted for woven and non-woven fabrics are of the same general appearance.

The focus of Kaber's (1988) was the calibration and use of the multiple integral method of Onaran and Findley (1965) in predicting the response of four geotextiles: *non-woven melt-bonded* (Terram 1000), *non-woven* (Bidim U24), *woven tapes* (Lotrak 16/15), and *composite woven and needle punched* (Propex 6067). Similar to the work of Andrawes et al. (1986), Kabir (1988) quantified the isochronous stiffness, and concluded that isochronous plots could be used to obtain safe allowable loads for design.

Jailloux and Segrestin (1988) studied the effect of the environment on geotextile performance. Increases in temperature seemed to accelerate the degradation of geotextiles. Jailloux and Segrestin (1988) found that *polyester* geotextiles were vulnerable to hydrolysis at normal temperatures. *Polyethylene* was found to resist many chemicals, but it was prone to brittle failures. The latter were accelerated by being in an environment that causes cracks in the geotextile.

In their short paper, Duvall and Egan (1990) focus on the subject of creep rupture of geosynthetics, but more from a molecular level. They state that a change in the slope of log (applied stress) vs. log (time to failure) plot creates a “knee” in this plot. This phenomenon is attributed to a change in the molecular or atomic-scale mechanism causing material creep and fracture. The authors point out that for polymer-based geosynthetics, before establishing design stress and/or strain limits, it is necessary to determine not only creep, but also stress-rupture behavior. They also note that some products will exhibit a change in failure mode, like the ductile-brittle transition in isotropic polyethylene (PE); others will not (e.g., elevated temperature testing of oriented high density polyethylene or HDPE).

Greenwood (1990) investigated the creep and, to a lesser degree, stress relaxation of geotextiles. The materials tested included: *polypropylene* (plain weave; two strengths), *polyester*, *polyester* strip, and *polyethylene* grid. The creep tests were carried out to rather long times (in some cases greater than 10,000 hours). Both 200 mm and 50 mm wide specimens were used. The author discussed, at length, the benefits and drawbacks of roller grips. Greenwood (1990) is a proponent of in-isolation tests; he correctly states that tests performed in soil are quite dependent upon the test parameters, and that in-isolation tests are more reproducible and represent “maximum or conservative” values. Comparing the creep behavior of yarns versus that of the woven material, the author states “not only the initial loading strain but also the rate of creep is greater for the woven material.” This finding is in agreement with the conclusions of Greenwood and Myles (1986). Concerning the prediction of stress relaxation results, Greenwood (1990) states that in absence of experimental data, one must estimate such response from creep data. The notion of *isochrones*, described by Andrawes et al. (1986), is used by Greenwood (1990) for the purpose of predicting stress relaxation data from creep data.

Matichard et al. (1990) have investigated the “in-isolation” creep behavior of six geotextiles (two non-woven *polyesters*, two non-woven *polypropylenes*, one woven *polyester*, and one woven *polypropylene*). The results obtained confirmed earlier creep experiments. In addition, the authors also investigated the effect of confining pressure (without a soil specimen present; air pressure was used) on the creep rupture of three (one non-woven *polyester*, one non-woven *polypropylene*, and one woven *polypropylene*) geotextiles. The effect of confining pressure (up to 200 kPa) was found to be rather minimal, although the ultimate strain of one of the non-woven geotextiles was significantly reduced by a confinement pressure of 50 kPa.

The “plane strain” behavior of spun-bonded non-woven fabrics (*polyester* and *polypropylene*) has been investigated by Miki et al. (1990). From normal duration tests on these materials, the authors determined the best sample widths, pin confinement (to present lateral “necking”), chuck spacing and tensioning speed to be used. From the results of creep tests, concluded that the spun-bonded, non-woven fabrics tested exhibited behavior in which the secondary phase of creep predominated. It was also determined that the polypropylene fabrics exhibit a rapid increase in the creep when the applied load exceeded 10-20% of its ultimate tensile strength. The polyester fabrics did not show much creep deformation even when a load exceeding 60% of its tensile strength was applied. As a general trend, for both materials the strain rate is reduced during transition between primary and secondary creep. Both materials ruptured suddenly in the secondary range, before the minimum value of the strain rate was reached.

Viezee et al. (1990) investigated the effects of mechanical damage and chemical aging on the long-term performance of polyester (PET) fibers and fabrics. They noted that the creep and time-to-break behavior of PET yarns from woven fabrics was completely different at lower loadings than at higher ones. The macroscopic creep phenomenon was thought to be related to the yield and relaxation processes as developed in the (macromolecular) morphology theories for highly oriented polymers. At loads 60%

of ultimate and greater, creep gradients were seen to increase sharply. They did not spread significantly as a result of yarn treatment. Finally, mechanical damage did not effect the creep gradient; neither did it effect the initial elongation. It did, however, effect the elongation at break.

Blivet et al. (1992) present the results of in-isolation and in-soil tensile and creep tests on four geotextiles. The confining soil is not specified. Concerning the tensile tests, the authors erroneously conclude that “for some geotextiles there is a great influence of a confining pressure on modulus.” For the creep tests they correctly conclude that “The effect of confinement seems to have no influence on the creep strain whatever the type of geotextile, woven or non-woven.”

Levacher et al. (1994) performed short and long-term (creep) tests on four different specimens: woven and non-woven polyester and polypropylene. The creep tests were performed unconfined as well as confined. Unconfined creep test results (performed at 20^{o}C) revealed that the creep of polypropylene is approximately 10 times that of the polyester. Except for the initial strain, there is no significant influence of the structure (woven or non-woven) of the material. Confined creep test results were performed at 20^{o}C and at 40^{o}C. The creep of polypropylene was again found to be approximately 10 times that of the polyester; this indicates that the level of confinement does not seem to influence this ratio. The temperature increase to 40^{o}C affected only the polypropylene specimens. The largest effect of confinement appears to be at the beginning of the creep tests.

2.2. Creep of Geogrids

Studies of the creep of geogrids are similar in scope to such studies for geotextiles. According to Koerner et al. (1993):

> “It appears as though the most extensive data base on time dependent geosynthetic mechanical properties is available for creep in geogrid materials. Since geogrids are generally used in reinforcement applications,

> such as retaining walls and steep slope stabilization, this is understandable."

McGown et al. (1985) studied the load-strain-time behavior of two Tensar geogrids. In particular, a uniaxial geogrid (SR2) manufactured from co-polymer grade *HDPE*, and a biaxial geogrid (SS2) manufactured from homo-polymer *polypropylene* were tested. When tested under constant rate of strain, the load-strain behavior of these geogrids was significantly influenced by the test temperature and strain rate. Rapid loading creep tests were shown to be suitable for the measurement of the load-strain-time relationship of the geogrids. The associated data allow the identification of the performance limit strains for the geogrids at any time during the lifetime of the soil-geogrid structure.

The use of isochrones was advocated. The maximum load that may be sustained by a geogrid without approaching creep rupture was proposed to be the product of the "performance limit strain" and the isochronous stiffness at the given time.

The load-strain-time-temperature relationship of two geogrids (heat stretched biaxial *polypropylene* grid & a heat stretched uniaxial *HDPE* grid) was investigated by Andrawes et al. (1986). Using a single-step loading apparatus, they performed both loading and unloading tests at constant temperatures of 5, 10, 20, and 40^{o}C. Referring to the instantaneous strains upon loading and unloading as the "plastic" and "elastic" components, respectively, Andrawes et al. (1986) noted that in general the magnitudes of the elastic and plastic instantaneous strains are similar. The elastic strains appeared to exhibit a greater sensitivity to temperature.

The family of creep curves generated at different stress levels was converted to isochronous stress-strain curves; i.e., curves drawn at equal time intervals. These isochronous curves represent the decrease in geogrid stiffness with time. From such curves, the stiffest and strongest specimen was found to be a heat stretched uniaxial

HDPE geogrid. The second grid tested, a heat stretched biaxial *polypropylene* material was slightly less stiff and exhibited a substantially lower strength.

Wrigley (1987) presented creep data for polyethylene geogrids and discussed the issue of time-temperature superposition. He found that a temperature increase from 10 to 20°C increases the time scale by a factor of ten; i.e., at higher temperatures, the effects occur ten times faster. This finding is in agreement with the literature survey conducted by Jewell and Greenwood (1988), who found that for similar geogrids, the same temperature increase gives a factor of eleven.

Kutara et al. (1988) reported the results of displacement-controlled, short-term pullout tests and load-controlled long-term tests on polymer grids. All grids were confined in Toyoura sand. The results are not at all surprising. In particular, the displacement and deformation vary depending upon the density of the sand, the confining pressure, on the magnitude of the pullout force and on the testing method. Kutara et al. did show that creep of the geogrid, rather than slip along the soil-reinforcement interface, is the factor controlling long-term response.

Bush (1990) investigated the creep response of three *polyethylene* geogrids (Tensar SR55, SR80 and SR110) in-isolation, at 10, 20 and 40°C. At a given temperature, the creep response was typical of HDPE grids. Bush (1990) found that the effect of load level was more of a significant factor than the effects of elevated temperature. In particular, the effect of doubling the load was much greater than a 30°C increase in temperature. From plots of strain versus log of strain rate (i.e., from Sherby-Dorn (1956) curves), it was seen that the rate of strain at each temperature is similar and that the largest effect of temperature on total strain is seen during the application of load and during the early part of the test. Finally, Bush (1990) was able to establish a unique relationship between isochronous stiffness, time and temperature. Consequently, the HDPE grids were found to be relatively insensitive to temperature changes.

The work of Rimoldi and Montanelli (1993) focused on the creep response and associated acceleration techniques for geogrids. The geogrids tested included six different HDPE grids (integral, extruded, cold punched or hot formed, uniaxially or biaxially drawn), and one PET grid (woven, with PVC coating). Rimoldi and Montanelli (1993) confirmed the observations of Greenwood and Myles (1986) and Greenwood (1990) that creep tests on single strands of woven geosynthetics were not representative of the behavior of the entire product. Rimoldi and Montanelli (1993) also investigated the effect of loading time (i.e., the amount of time in which the sustained creep load is applied) on the response of geogrids. They found that the HDPE geogrids were more sensitive to the loading time than the PET grid; both types of geogrids showed significant differences in the instantaneous elongation even when loading time was changed from instantaneous to only 3 minutes. For the HDPE geogrids, the effect of loading time disappeared after about 50 hours; for the PET geogrid, this occurred after only 2 hours.

Wu (1994) and Wu and Helwany (1996) demonstrated that in-soil creep deformations greatly depend upon the type of confining soil, and upon the properties of the soil-geogrid interface. In sand, the interface was shown to have a restraining effect on creep. However, in clay the creep rate of the confining soil was faster than that of the geosynthetic, thus inducing an accelerating creep in the reinforcement. Overall, these tests demonstrated that creep of embedded polymers depends also on the properties of the confining soil and on the soil-geosynthetic interface characteristics.

Although focusing on the advancement of their own Fortrac¨ PET geogrids at elevated temperatures, den Hoedt et al. (1994) noted the following useful conclusions concerning PET yarns (which have a complex semicrystalline structure in which the molecules are arrayed along the fiber axis in crystalline and amorphous domains): (1) short-term tensile properties of PET are largely unaffected by temperature increases from 20 to 40°C. At 60°C a significant drop in tensile strength occurs; and, (2) Creep testing does not induce large permanent changes in physical structure. This is unlike PE, where only weak Van der Waals interactions are present, thus facilitating molecular slipping.

The results of an experimental study of the behavior of geogrid under static and repeated long-term tensile (pull-out) loads in granular soils were presented by Min et al. (1995) and Min (1995). The creep strain rate of the geogrid was found to be a function of load amplitude, number of load cycles (duration of loading), types of loading (static or repeated) and other factors. By considering the soil-geogrid interface friction, the creep strain rate was determined by Min et al. (1995) to be an intrinsic property of the geogrid, and therefore independent of the confining pressure. Consequently, for a given tensile load at a point in the grid, the resulting creep will be the same regardless of confinement. Provided creep failure does not occur, the long-term ultimate pullout resistance is approximately the same as that of the short-term pullout resistance. In long-term tests, the repeated load reduced the ultimate pullout load by about 20% when compared to the sustained load. When the amplitude of the repeated load was equal to the magnitude of the sustained value, the creep strain rate under repeated load was less than that under sustained load. A similar study, but involving a cohesive soil, was performed by Pamuk (1997).

Moraci and Montanelli (1996) investigated both the short-term (cyclic) and long-term (creep) behavior of an *HDPE* and a *polyester* geogrid. The results of the cyclic tests (with incremental loads) showed that even for at low tensile force levels, irrecoverable strains appear and increase with temperature. The creep test results confirmed earlier findings that, as compared to polyester specimens, creep strains are higher in HDPE geogrids. Employing the notion of isochrones, Moraci and Montanelli (1996) confirmed the fact that the secant “tensile creep modulus” decreases with time.

The effect of thermo-mechanical treatment of PET yarns on their load-deformation behavior was studied by Müller -Rochholz et al. (1998). It was determined that such treatment can lead to significant changes in the level of admissible deformations associated with typical design criteria.

2.3. Creep of Geomembranes

Very little research has been done to investigate the creep of geomembranes. Koerner at al. (1993) note that:

> "There is no work in the literature on creep of geomembranes, per se, but there is in similar polymers used for other applications."

In particular, they cite the work of Findley (1987), Crissman (1991), and Clements and Sherby (1987).

In a subsequent study, Duvall (1993) performed "biaxial" (axisymmetric) creep and stress rupture tests of specimens of one medium density polyethylene (MDPE) geomembrane liner. The creep tests were performed at room temperature (23^{o}C). The stress rupture tests were performed not only at room temperature, but also at elevated temperatures of 60 and 80^{o}C. For the specific MDPE, a transition from a ductile to a non-ductile (slow crack growth) failure mode was observed. In addition, the strains immediately prior to failure decrease as time to failure increases. It was emphasized that such response depends on the specific PE product being tested. Although he created isochronous stress-strain curves from his creep data, Duvall (1993) did not associate them with any form of stress relaxation data.

3. Relaxation

Relaxation tests attempt to duplicate the behavior of loaded geosynthetics whose dimensions are held constant in situ. In such tests specimens are strained to a desired level, which is subsequently maintained constant. During this time, changes in stress, acting in the direction whose dimension is maintained constant, are recorded.

Stress relaxation in geosynthetics has not been studied nearly as extensively as creep. One reason for the scarcity of stress relaxation data is the difficulty associated with performing such tests. In particular, the “elastic” strain developed immediately after load application must be maintained constant by reducing the tensile load with time. Such a test inevitably requires a rather sophisticated device, though a rather simple experimental approach has been developed by Leshchinsky et al (1997).

3.1. Stress Relaxation in Geotextiles

Greenwood and Myles (1986) appear to have performed some stress relaxation tests (though no details are given). From isomeric curves, it appears that *polyester* exhibits little relaxation, while *polypropylene* relaxes significantly.

Greenwood (1990) described the stress relaxation of geotextiles. The materials tested include: *polypropylene* (plain weave; two strengths), *polyester*, *polyester* strip, and *polyethylene* grid. As compared to polyester, a larger stress relaxation was observed in polyethylene and polypropylene specimens. The associated experimental results were used to compare isochronous stress-strain curves obtained from creep experiments at various stresses with those from stress relaxation tests at various strain levels. The agreement between predicted and measured stress relaxation results is deemed acceptable below about 5 percent strain; Greenwood (1990) concludes that “prediction of stress relaxation performance from creep tests provides a reasonable estimate.”

3.2 Stress Relaxation in Geogrids

The work by Greenwood (1990) represents the first reference on stress relaxation of geogrids. HDPE geogrids were evaluated, and the duration of relaxation was one week. From the associated data isochronous stress-strain curves were plotted. These were compared with similar curves obtained from creep data on the same geogrids. At strain levels below 5 percent, the agreement was deemed reasonable, and led Greenwood to conclude that in the absence of actual data, one can estimate the stress relaxation response in this manner.

In addition to creep tests, Leshchinsky et al. (1997) performed stress relaxation tests on polyester and HDPE geogrids of varying ultimate strengths. Both sets of tests were performed at 40, 60 and 80 percent of the geogrid’s ultimate short-term strength. The stress relaxation results showed that the polyester and HDPE relaxed a maximum of 30 and 50 percent, respectively. This data indicated that a smaller creep reduction factor could potentially be used when designing multi-layer reinforced soil structures, though more testing was deemed necessary before any firm conclusions could be made.

Additional work related to the testing program was performed by Heffernan (1998), who tested additional polyester and HDPE geogrids at 30 percent of their ultimate short-term strength, as well as a polypropylene geogrid. Insight into the relation between creep and stress relaxation response was sought.

3.3. Stress Relaxation in Geomembranes

The stress relaxation response of geomembranes has not been extensively studied. In one of the few papers on the subject, Krupin et al. (1982) presented limited data on the stress relaxation in polyvinyl chloride and polyethylene geomembranes.

Koerner at al. (1993) presented some stress relaxation test results on HDPE geomembranes. In addition, they attempted to develop a generalized relationship between creep and stress relaxation.

Soong et al. (1994) performed stress relaxation tests on HDPE membranes at temperatures of -10, 10, 30, 50 and 70^{o}C. Initial loading was applied in one of two ways: (1) Initial stress via stress-controlled loading; and, (2) Initial strain via strain-controlled loading. The initial force and amount of stress relaxation was seen to increase at lower temperatures. The stress relaxation modulus (instantaneous stress / constant strain) was found to be independent of the initial stress level (stress-controlled loading) and initial strain level (strain-controlled loading). Finally, the time-temperature principle of polymer viscoelasticity was found to be valid for HDPE geomembranes. This implied that long-term data could be extrapolated from short-term data by using a time-temperature shift on the modulus versus time curves.

4. Effect of Temperature

The effect of temperature on the creep of non-woven (*PE/polypropylene*, *polyester*, *HDPE*) and woven (*polypropylene*) geotextiles has been investigated by Müller -Rochholz and Kirscher (1990). It was observed that the creep of polyester geotextiles was dependent mainly on stress/strength ratios, while that of polyolefines (PP and PE) showed a rather significant temperature dependence. The former finding was confirmed by Levacher et al. (1994), who concluded that creep of polyester geotextiles is not affected by the nature of the polymer.

The creep response of three *polyethylene* geogrids (Tensar SR55, SR80 and SR110) in-isolation, at 10, 20 and 40°C was investigated by Bush (1990). At a given temperature, the creep response was typical of HDPE grids. Bush found that the effect of load level was more of a significant factor than the effects of elevated temperature. In particular, the effect of doubling the load was much greater than a 30°C increase in temperature. From plots of strain versus log of strain rate (i.e., from Sherby-Dorn (1956) curves), it was seen that the rate of strain at each temperature is similar and that the largest effect of temperature on total strain is seen during the application of load and during the early part of the test. Finally, Bush was able to establish a unique relationship between isochronous stiffness, time and temperature. Consequently, the HDPE grids were found to be relatively insensitive to temperature changes.

Den Hoedt et al. (1994) performed creep experiments that involved an increase in temperature. They found that the long-term geogrid properties were affected by a temperature increase of 20°C, while the short-term properties remained the same. In particular, the long-term properties were reduced by 4% in their experiments. It was also seen that for a 40°C temperature increase, there was a significant drop in the tensile strength of the geogrid.

The effect of temperature on creep behavior is greater for polypropylene or HDPE than for polyester (Allen 1991; Ingold 1994). Indeed, Moraci and Montanelli (1996) found that the creep behavior of polyester is primarily a function of the applied load and that a temperature increase barely effects the creep behavior. They also found that HDPE's creep behavior is a function of both the applied load and temperature, and is more creep sensitive than the polyester geogrid.

Cazzuffi et al. (1997) note that temperature effects are directly influenced by the nature of the polymer and the polymer structure. In addition, citing the work of Müller-Rochholtz and Reinhart (1990), Rimoldi and Montanelli (1993), and den Hoedt et al. (1994), they note that (1) Temperature has a pronounced influence on the strain-time behavior of HDPE and for PP. However, the temperature effect may be minimized for HDPE by increasing the molecular weight and molecular draw ratio (Bush 1990); and, (2) Temperature has a negligible effect on the strain-time behavior of PET geosynthetics.

5. Acceleration and Superposition Techniques in Testing

By their very nature, creep and relaxation tests require relatively long periods of time to complete. It is not surprising, therefore, that over the years various extrapolation techniques have been investigated.

A very common method of extrapolating creep data is time-temperature superposition. This approach is based on the premise that a certain increase in temperature is equivalent to a ten-fold (say) increase in the time scale under ambient temperature. Time-temperature superposition was used by Andrawes et al. (1986) on geotextile creep data gathered for 10,000 hours. Andrawes et al. (1986) also stated that a combination of time-temperature superposition and a mathematical model should be used if data is to be extrapolated for more than one log time cycle. The mathematical model used by Andrawes et al. (1986) was based on the multiple integral technique discussed by Onaran and Findley (1965).

Wrigley (1987) and Bush (1990) used time-temperature superposition to extend their geogrid creep data. Wrigley (1987) determined that a ten degree centigrade increase in temperature caused a ten-fold increase in the time scale.

Thorton et al. (1997) also used time-temperature superposition to extend eight months of data to three years worth of data. An acceleration factor was also applied along with time-temperature superposition to account for the ramp rate of loading. Thorton et al. (1997) compared the predicted long-term results from the high temperature short-term test with results from longer-term tests that were run at a lower temperature. The results again compared favorably.

Shelton and Bright (1993) attempted to predict creep behavior with the Arrhenius equation, which is usually used to represent the temperature dependency in a rate equation. The predicted data was compared with accelerated creep test data. It was concluded that the Arrhenius equation might not be a good choice for predicting creep behavior. This is because the activation energy term appearing in the equation should remain constant no matter what changes in the test environment. However, Shelton and Bright's (1993) conjecture was that the activation energy may not remain constant when the temperature is increased during a test.

Farrag (1997) also used the Arrhenius equation to predict creep behavior. He compared predicted results with the results of accelerated creep tests and concluded that one must be careful to use the correct activation energy at all times. Farrag (1997) also used a temperature shift prediction procedure based on the so-called "WLF equation" proposed by Williams, Landel, and Ferry (Ferry, 1955). Applying this shift factor to creep strain curves at elevated temperatures, Farrag (1997) extended 1,000-hour data to 10,000 hours. The predicted data was in good agreement with experimental creep results.

Ingold et al. (1994) presented examples of extrapolation techniques for tensile creep rupture strength of geogrids. In particular, they extended data from 10^4 hours to 10^6 hours demonstrated the numerical range of extrapolated results obtained for different assumptions.

Rimoldi and Montanelli (1993) performed standard and accelerated creep tests on geogrids. The standard tests were performed at 20°C and the accelerated tests were performed at 30° and 40°C. They concluded that the time-temperature superposition approach was “quite reliable and simple.”

6. Concluding Remarks

Based on the information appearing in the literature, some general conclusions can be drawn concerning the time-dependent behavior of geosynthetics.

6.1 Factors Affecting Long-Term Behavior

Effect of confinement

Numerous creep tests on geosynthetics (e.g. Finnigan 1977; Allen et al. 1982, to name a few) were performed in-isolation; i.e., unconfined. In an effort to better simulate the effects of soil confinement on creep, in-soil tests have also been performed (e.g., McGown et al. 1982; Holtz et al. 1982). However, the results of such tests were somewhat inconclusive. For example, McGown et al. (1982) showed a drastic effect of soil confinement on the creep of geotextiles. Conversely, Matichard et al. (1990) and Blivet et al. (1992) demonstrated insignificant effects. Furthermore, the in-soil tests are complicated by the presence of soil/reinforcement interfaces. For example, Kutara et al. (1988) used a pullout test to show that creep, rather than slip along the soil/reinforcement interface is the factor controlling long-term response. To complicate the issue, Wu (1994) demonstrated that creep deformations greatly depend on the type of confining soil. He constructed a device that allows the geosynthetic and confining soil to deform in an interactive manner, presumably simulating plane strain conditions. In sand, Wu (1994) showed the interface to have a restraining effect on creep. However, in clay the creep rate of the confining soil was faster than that of the geosynthetic, thus inducing faster creep in the reinforcement. Clearly, these tests demonstrate that creep of embedded polymers depends also on the properties of the confining soil and on the interface characteristics between the two. The above conclusions concerning creep behavior of geosynthetics embedded in sands were supported by the work of Min et al. (1995).

Nature of Polymer : concerning their tendency for time-dependent response, the following general trend appears to be applicable: PE > PP > PET.

Structure of Polymer : the molecular weight, molecular orientation, crystalline volume fraction, degree of branching and draw molecular ratio all affect the time-dependent response (Ward 1985; den Hoedt et al. 1994)

Structure of Geosynthetic : concerning their tendency for time-dependent response, the following general trend appears to be applicable: integral structures > woven > non-woven structures.

Loading Rate

Temperature : temperature effects are directly influenced by the nature of the polymer and the polymer structure (Cazzuffi et al. 1997). Temperature changes have a pronounced effect on the strain-time behavior of HDPE and PP geosynthetics; however, for HDPE geogrids, the temperature effect may be minimized by increasing the molecular weight and molecular draw ratio (Bush 1990). Also, for all polymer materials, the effect of load is many times greater than the effect of temperature (Cazzuffi et al. 1997).

Soil Environment : chemical and mechanical characteristics of the backfill soil also influence the time-dependent response of geosynthetics. An example of the mechanical effects on the time-dependent response is the presence/absence of time-dependent response of the backfill soils.

6.2 On Lateral Contraction

As noted by den Hoedt et al. (1994), *non-woven* geosynthetics exhibit high lateral contraction, low strength, and high strain at rupture. On the other hand, geosynthetics commonly used for reinforcement exhibit negligible lateral contraction, low strains, low creep, and high tensile strength. Consequently, for purposes of modeling common reinforcement, uniaxial constitutive models appear to be justified.

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