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Geosynthetics - 7th ICG - Delmas, Gourc & Girard (eds) © 2002 Swets & Zeitlinger, Lisse ISBN 90 5809 523 1

Long term tensile testing of polyolefin fibers in geotextiles

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ABSTRACT: With several types of geotextiles applied to steep slopes, e.g. geocomposite clay liners (GCL), polyolefin fibers intentionally sustain permanent tension. In many applications especially for permanent slope stability these load-bearing fibers may not break at relevant environmental conditions. Moisture and/or precipitation will occur in most cases and must be considered as important environmental factor. This is strongly emphasized by our results arising from long term tensile testing of fibers in water in a novel test design. It is shown that fiber rupture may occur not only after extended creep, as expected when tested in air. Instead, fibers immersed into water break after relatively small strains and load levels and virtually without any onset. In this case the times to failure cannot be estimated alone by the analysis of creep data, as usually assumed. It is possible, however, to characterize the performance of fibers using our long-term tensile load test.

1 INTRODUCTION

There are several geotextiles which are intentionally exposed to permanent shear forces when used in steep slopes e.g. in landfill caps, dams or other applications. This is especially true for sandwiched geotextiles like geotextile clay liners (GCL) and geocomposite drains (GCD). For some types of GCL the shear force is carried only by polyolefin fibers, which hold the top and bottom layers together. These fibers are therefore exposed to permanent tensional forces. Other geotextiles like geocomposite drains consist of a geospacer or geonet, sandwiched between a filter and a protective geotextile and the draincore must bear the shear forces over the entire operational lifetime. In order to investigate the limitations in the mechanical performance of geotextiles in permanent load-bearing situations there are some methods available: Besides frictional behavior other short-term properties (max. strength, max. elongation, peel resistance) as well as the creep performance are usually analyzed. Figure 1 shows creep elongation and creep rate curves typical for PE and PP geosynthetics (Kunz et al. 1999).

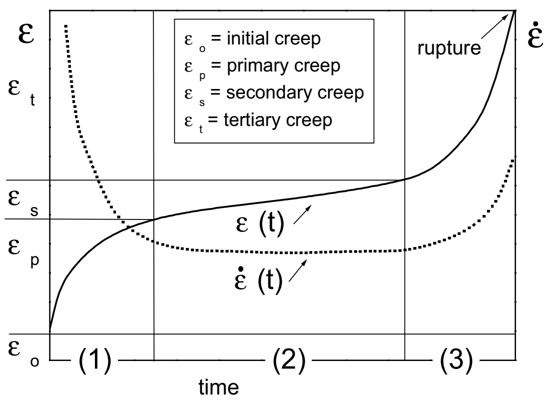

Figure 1. Schematic view of creep deformation ε and creep rate $\dot{\varepsilon}$ versus time.

As shown in Figure 1, after a short period (phase 1) the creep rate remains at a constant value (phase 2) which may be called a plateau creep rate (Ward 1995). The final accelerated increase (phase 3) of ε and $\dot{\varepsilon}$ is typical of PP and PE and precedes the rupture. The analysis of creep is frequently based on plots of creep rates versus strains, the so called Sherby-Dorn plots, see Figure 2.

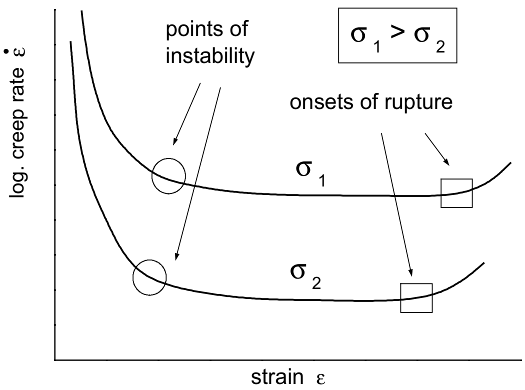

Figure 2. Schematic Sherby-Dorn plots (creep rate versus strain) for an oriented polyolefin fiber. For each load level (σ_1, σ_2) the point of instability and the onset of rupture are indicated.

As shown in Figure 2 two characteristic points are frequently dealt with in the literature in connection with the analysis of the creep behavior of polymer structures like fibers, geogrid strands etc.: The point of instability may easily be identified in a Sherby-Dorn plot as the onset of the plateau creep rate (Wrigley 1987), i.e. the horizontal section of the curve. The onset of rupture, however, is defined by some authors as the final increase in the creep rate, i.e. as an upturn of the Sherby-Dorn plot (Bush 1990). While the polymer structure is irreversibly deformed and damaged during creep, it is clear that at the latest at this stage its failure is obviously imminent.

With regard to load-bearing applications of geogrids or geotextiles the plateau creep rate must be essentially reduced to a very low level so that polymer strands or fibers under permanent tension may not reach the onset of rupture during the expected or planned service life (Ward 1995). Some investigations say neither a point of instability nor an onset of rupture is occurring for geogrids below a certain upper strain limit (Wrigley 1987, Bush

1990). Following this analysis a geogrid is safe from creep rupture provided its maximum strain during application remains below this limit. Summarizing, this is the usual way to give proof of a geotextiles or geogrids long-term suitability. When GCLs or geocomposite drains are applied in steep slopes, however, the slope stability in the long run may potentially be compromised by two other mechanisms: Besides premature aging environmental stress cracking could occur in load-bearing fibers or other polymer structures due to wetting media (moisture, precipitation) even though their creep resistance is sufficient when tested in the lab under dry conditions. With time each of these mechanisms could result in a total slope failure even though the geotextile passed all usual tests mentioned above. It is therefore not satisfactory that we lack knowledge about the significance of environmental influences on the lifetime of polyolefin fibers or polyolefin strands in load-bearing situations with respect to environmental stress cracking. To investigate this matter we developed and successfully operated a novel test equipment which enables us to measure the elongation and times to failure of polyolefin fibers or small strands immersed in a temperature controlled medium under permanent load

2 EXPERIMENT

For our investigation we selected fibers typically used for GCLs and other geotextiles. In Table 1 some properties are listed:

Table 1. Fiber Properties

Fiber	F1	F2	F3	F4	F5	F6
Polyolefin type	PP	PP	PE	PE	PP	PP
Resin label	a	a	b	b	c	d
Titer (dtex)	6.2	14.7	6.9	14	10.0	10.7
	± 0.2	± 0.5	± 0.2	± 1	± 0.2	± 0.5
Draw ratio	1:5	1:5	1:5	1:5	**	**
Strength (cN/tex)*	~50	~44	~31	~30	~25	~34
Strain (%)*	>50	>90	147	208	280	245

* at break, v = 80 mm/min, T = RT; ** Information not available

All fibers included in the experiment had been taken out of the production lines prior to curling and cutting. Sample fiber bunches had an original length of approximately 1 m. From these bunches single fiber samples for testing were taken and cut off to a length of 15 cm. The avivage was then removed from the specimen by rinsing for 24 h in ethanol. The linear density or diameter of all fiber samples (F1 to F6) was measured several times along individual fibers at 5 cm intervals as well as on a bunch of randomly selected fibers. By this we were able to characterize the variation in diameter of fibers as a whole and also individually. It turned out that F1, F3 and F5 are extremely good while the homogeneity of F4 is rather poor. Only those fibers were used for the long-term test, which fitted over their entire length into the respective titer range given in Table 1. Although it is likely that single fibers show variations in diameter within shorter intervals we successfully excluded at least fiber samples with large inhomogeneities from the test. For each fiber type up to eight tensile load levels were defined, ranging from 1 % to 17 % of the respective mean relative tensile strengths of Table 1. The loads were applied individually on each fiber sample, details of sample preparation will be given elsewhere (Seeger, in prep.).

The long term test equipment consists of a set of electrically heated basins, filled with deionized water at 60 ± 1 °C or 80 ± 1 °C respectively. The length of the sample fibers mounted in the basins is approximately 10 cm. Samples are completely immersed into the liquid. Immediately after mounting a sample its elongation is measured periodically, the time to failure, i.e. the time to rupture is also registered automatically. In the test stand more than two hundred fibers can be tested simultaneously. The number of completed tests exceeded 500 after approximately 1½ years testing. Details of the experimental setup will be published elsewhere (Seeger, in prep.). Investigations were complemented by microscope analysis of the fracture surfaces and by aging tests.

3 RESULTS

3.1 *Long-term tensile load test on fibers*

The long term tensile load tests on fibers reveal a clear relationship between the load level, the temperature and the times to failure, as shown for example in Figures 3, 4 and 5. To facilitate comparison all diagrams have the same scales. A comparison of fibers of the same resin but with different diameters reveals, that the geometrical influence of this parameter is relatively small: For fibers with ~ 7 and ~ 14 dtex the failure times at the same *relative load levels* are very close by, at least in the same decade.

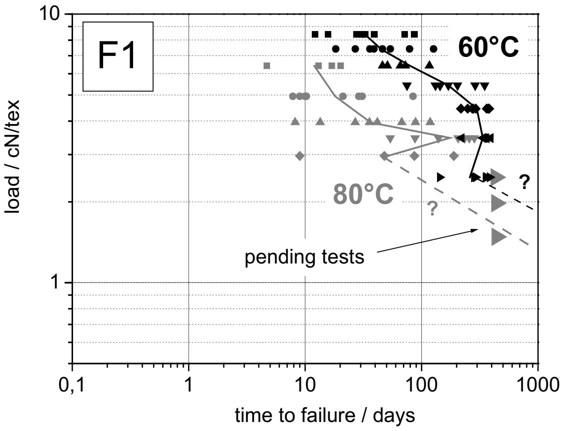

Figure 3. Results of the long term tensile load test on polypropylene fibers (F1) in water at 60°C and 80°C.

Fibers made of PP clearly differ from those of PE. All curves for PP-fibers, as shown for F1 & F2, seem to develop a "nose", i.e. a transition region, which resembles the curves from the long-term tensile test on thermoplastics (Ramsteiner 1990). All PE-fibers tested, however, do not reveal such a transition during the time period tested. The resistance to rupture (i.e. the tensile load at a given failure time) of PP-fiber F2 is at least three to five times higher compared to PE-fiber F3, whereas there is only a factor 1.4 in the *relative* short-term tensile strength. A comparison of PP- and PE-fibers with the same diameter (F1 & F3) shows that at the same load levels the mean failure times of the PP-fibers exceed that of the PE-fibers by at least one order of magnitude.

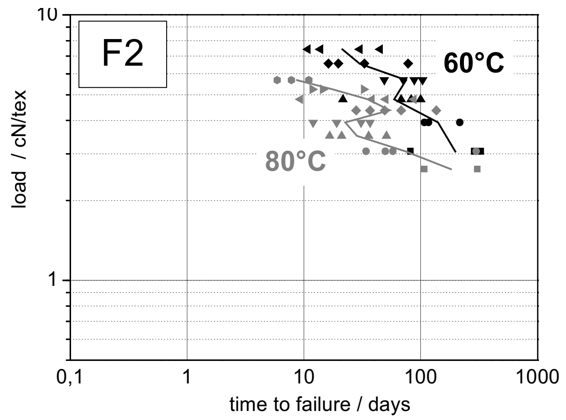

Figure 4. Results of the long term tensile load test on polypropylene fibers (F2) in water at 60°C and 80°C.

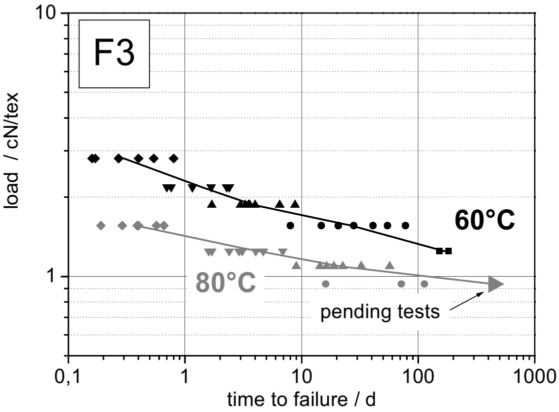

Figure 5. Results of the long term tensile load test on polyethylene fibers (F3) in water at 60°C and 80°C.

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In Figure 6 and 7 Sherby-Dorn plots of selected fiber samples are shown. The Sherby-Dorn plots reveal some remarkable features of the long term performance of PP and PE fibers in a load-bearing situation: We like to stress, that in Figure 6 and 7 the end point of each curve explicitly marks an actual rupture of a fiber, while this is not the case in other studies published (Wrigley 1987, Bush 1990). For PP fibers the instability point is easily detected in figure 6 from the curves at high loads as they clearly have plateau creep rates. There is no marked indication for a point of rupture, i.e. an upswing of the curve, however, as the actual rupture, as marked by the end of the curve, takes place without any marked onset. The space between the instability point and the actual rupture decreases systematically with the applied load level. At low loads the rupture of F2-fibers in water occurs after only slight strains. The points of rupture are extremely shifted to the left and therefore any indication of an instability point disappears. These findings apply qualitatively as well to PP-fibers F1, F5 and F6 at both temperatures tested.

For all PE-fibers, however, as shown for example in Figure 7, plateau creep rates or instability points cannot be identified at any load level tested. In water the vast majority of all PE-fibers, as shown here for the first time, fails while the creep rate is steadily decreasing, i. e. within primary creep (see Figure 1) or at the latest during the transition to secondary creep. Remarkably, at both temperatures tested fibers F3 and F4 seem to reveal an upper strain limit of only 10 % although this finding needs some further clarification in future measurements.

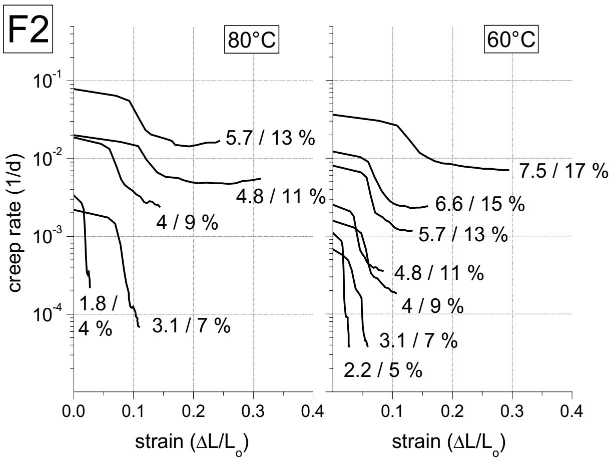

Figure 6. Sherby-Dorn plots of 14.7 dtex polypropylene fibers (F2) at 60 °C and 80 °C in water. End points of curves mark ruptures of fibers. The respective loads are given in cN/tex and percent of fiber strength according to table 1.

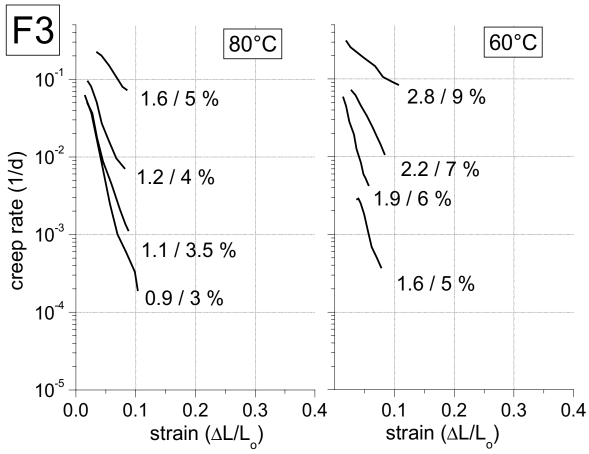

Figure 7. Sherby-Dorn plots of 6.9 dtex polyethylene fibers (F3) at 60 °C and 80 °C in water. End points of curves mark ruptures of fibers. The respective loads are given in cN/tex and percent of fiber strength according to table 1.

Figure 8 shows an electron microscope picture of the fracture surface of a PE-fiber as an example of a rather brittle fiber rupture with no indication for necking.

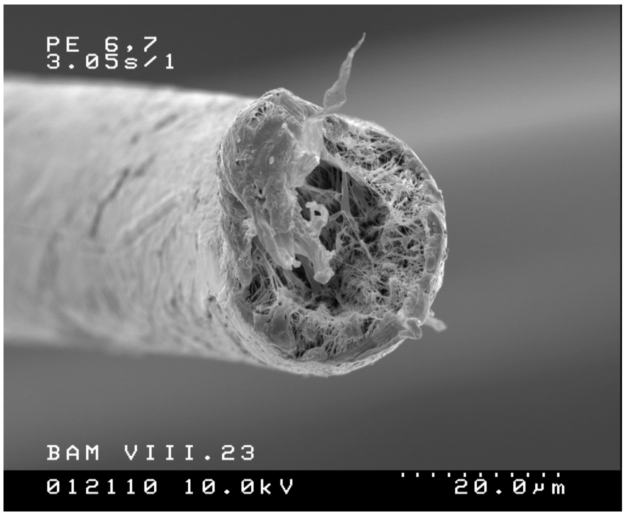

Figure 8. Example of a fracture surface of a PE-fiber (F3) ruptured after 180 days in water at 60 °C and 1.25 cN/tex load.

3.2 *Aging tests*

We performed long-term immersion tests in deionized water to study the thermal oxidative degradation of single PE- and PP-fibers. The immersion temperature was set to 80 °C, i.e. the highest temperature in the long term creep tests. Strength and strain at break are the most sensitive mechanical properties with respect to oxidative degradation. These parameters and also the change of high temperature OIT values (which reflect the change in the amount of stabilizer) were monitored during the aging.

For the tests fibers were tied to a bundle and the avivage was removed by the same method as described above. Each bundle was put in a closed glass flask filled with deionized water. The flasks were placed in a regulated oven at 80 ± 1 °C. The flasks were neither opened nor shaken and the water was not changed. Precipitation from dissolved components of the glass was observed and the pH-value increased steadily to a value of about 12 after half a year of immersion. At regular intervals some fibers were taken out and stored for 4 days in a standard climate (23 °C, 50 % rH). Afterwards the mechanical properties and the OIT-values were measured.

The strength was tested according to DIN 53816. High temperature OIT measurements complied with ASTM D 3895-95. For the PE-fibers F3 and F4 as well as for the PP-fibers F5 and F6 the OIT was measured at 170 °C. For the PP-fibers F1 and F2 the OIT temperature was 175 °C. Some of the experimental results are illustrated in Figure 9 and 10.

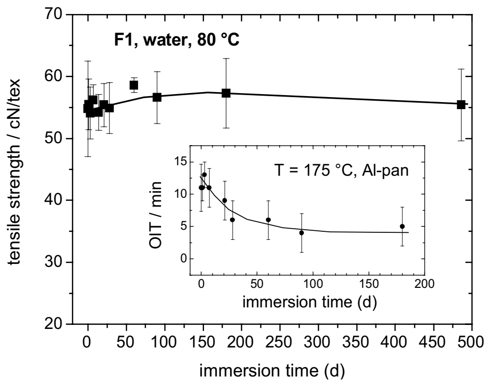

Figure 9. Strength and OIT (insert) for PP-fibers F1 during immersion in water.

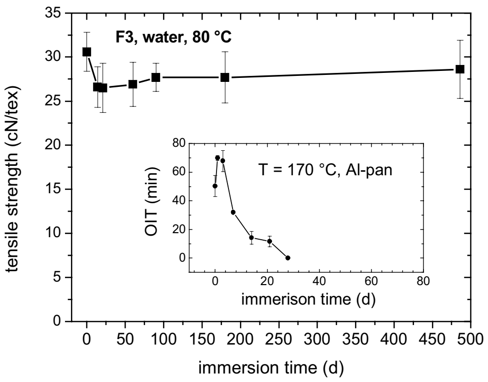

Figure 10. Strength and OIT (insert) for PE-fibers F3 during immersion in water.

After 486 days of immersion in water at 80 °C neither a steady nor a sudden significant change was observed in tensile properties of PP- fibers F1 and PE-fibers F3. Although both fiber samples reveal a decrease of their respective OIT-values there are no signs of embrittlement due to thermal oxidative degradation. As the failure times in the long term tensile tests do not exceed 500 days we may conclude that thermal oxidative degradation should not influence the observed failure of fibers. The results of thermal oxidative degradation fit nicely to the results obtained from long-term aging tests of various geotextiles reported elsewhere (Müller & Jakob 2000).

4 DISCUSSION

As thermal oxidative degradation and embrittlement of the polymers clearly can be ruled out, environmental stress cracking should be considered as most likely explanation for the observed failures of fibers. This is also supported by the appearance of brittle fracture surfaces at broken fibers as shown for example in Figure 8.

The fibers F1 and F2, made of the same PP-resin, seem to have the highest resistance to environmental stress cracking compared to the other PE- and PP-fibers in the test. The diameter of F2 is more than twice the diameter of F1. Therefore, the fiber F2 turns out to be the most crack-resistant, i.e. the one with the largest time to failure at any given absolute load level. This fiber seems therefore to give virtually no rise to doubts about its long term resistance against rupture at ambient temperatures. On the other hand one cannot be fully positive about the long-term performance of the thin PP-fiber F1, the PP-fibers F5 & F6 and also the PE-fibers, when used in a load-bearing situation, i.e. in very steep slopes. At a rough estimate the permanent *mean* tension acting on a fiber in a needlepunched GCL, installed in a steep slope, does rather not exceed 1 cN. Considering this, at first glance all fibers tested seem to have sufficient resistance to stress cracking, although they differ considerably. It must, however, be taken into account that the load limit was solely estimated on a theoretical base and there are no reliable information available on real peak tensile forces and their variations. Therefore large margins of safety are justified in the estimation of tolerable load limits for the application of geotextiles in load-bearing situations.

The above experimental findings clearly indicate that long-term tensile load tests in water should be considered for all geotextiles with load-bearing fibers in contact with water as potential trigger medium for environmental stress cracking. It has been shown that rupture and times to failure are not predictable when based solely on the analysis of short term strength/strain or creep behavior, usually measured in a neutral medium (air, oil).

The long term tensile load test turned out to be helpful in order to enable a comparison of the lifetimes of load bearing fibers. The results of this research are highly stimulating to further investigate details of the rupture behavior of fibers under permanent tension as a key property for the long term reliability of several geotextiles.

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