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Residual strength of PET after more than 12 years creep loading

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ABSTRACT: The residual strength of PET material after being loaded for more than 12 years at various load levels has been established. It turns out that no significant reduction in strength has taken place, however, the elongation at break has reduced significantly. An earlier published description of the changes at molecular level during stress-strain tests of PET yarns has been used to explain the results of this test and based on the system also the long term effects could be explained. A method has been developed to determine the rest of the available service life of a material/structure after continuous loading. This method has been validated and a practical example is shown. With this method we can determine at any time and with good accuracy the remaining service life of a structure and therefore we can control the safety of any reinforced soil structure using PET reinforcement material perfectly during its service life. Using this method any uncertainty about the lifetime of a soil reinforcing structure can be eliminated.

1 INTRODUCTION

At the second Kyushu Conference in 1997, a paper was presented by W. Voskamp entitled "Proposed method to determine the safety capacity of reinforced soil structures". In this paper it was indicated that the residual strength of PET after having been loaded for some time is much higher than was expected when the stress rupture model is used for design. A typical stress rupture model is shown in figure 1.

T_{cr} = the extrapolated creep rupture strength at the end of the selected design life and at a maximum operational temperature.

t_{design} = the selected design life.

T_{ult} = the ultimate strength measured during the short-term tensile strength test.

In the literature and based on experience it is anticipated that the residual strength of a material is higher than the T_{cr} according to the stress-rupture line (Schardin-Liedtke, H, 1990). A method to calculate the effect was proposed by J. Greenwood, 1997. At the laboratories of Colbond Geosynthetics, formerly known as Akzo Nobel Geosynthetics a creep testing program is on its way since 1987. Intermediate reports of the results have been made. We have decided to stop this program and to measure the residual strength of these samples. The samples were tested at various load levels and many have reached rupture in the past, however, a number of them have been loaded for about 13 years.

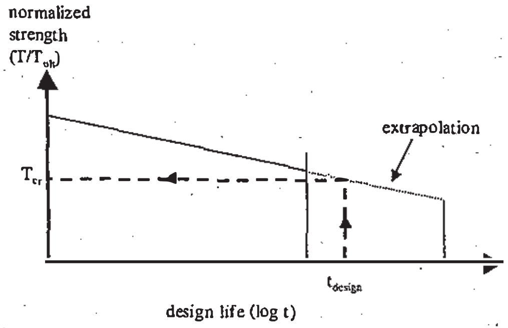

Figure 1. Creep rupture graph.

The samples were taken of different PET yarn types and from at least two different suppliers. They were taken from spools, from woven fabrics and even a part of the program was on samples taken from fabrics damaged in a controlled way which resulted in the same amount of damage in all samples. In this paper we will report on the residual strength measurements made on various samples. Some test results have already been published by J. Greenwood in the discussion on his paper (Geosynthetics International, 1997).

2 TEST RESULTS

In 1987 we started with a creep-testing program on yarns. The yarns were loaded with a constant load which varied between 20% and 70% of the ultimate tensile strength (UTS). At regular times the strain in the sample was measured between 2 marks on the sample. The measurement was made by means of an optical device. The temperature in the test area was 20 °C at average. The time to rupture was recorded independently. The samples had a length of at least 80 cm and the strain measurements were made over a length of 60-70 cm. The strain was recorded with an accuracy of 0.01 cm.

Five groups of samples were tested:

Category 1: Virgin yarn taken from the spool, not woven into a fabric (Diolen 770).
Category 2: Yarn taken out of a Stabilenka 150 fabric (Diolen 770).
Category 3: Yarn taken from a damaged Stabilenka 150 fabric (Diolen 770); the damage was applied in a controlled way.
Category 4: Virgin yarn from the spool, made by another process (Diolen 776).
Category 5: Virgin yarn from the spool, made by another company (type A).

In 1997 we recorded the following results:

Table 1. Test results after 55500 hrs.

Yarn type	Initial strength (N)	Loading (N)	Residual strength (N)	Retained strength (%)
Cat. 1	76.6	38.61	77.2	100.7
Cat. 2	77.2	38.61	75.2	97.3
Cat. 3	66.7	41.53	64.9	97.4
Cat. 4	75.0	38.77	74.4	99.3
Cat. 5	74.0	40.26	76.9	103.9

Yarn type	Initial strain %	Creep Strain %	Time of loading (hrs)
Cat. 1	5.28	0.86	55575
Cat. 2	5.23	0.73	55573
Cat. 3	5.79	0.82	55578
Cat. 4	5.16	0.71	55071
Cat. 5	5.73	1.16	55572

In 2001 we completed the testing and the following results were recorded:

Table 2. Test results after 104800 hrs.

Yarn Type	Initial-strength (N)	Loading (N)	Residual strength (N)	Retained strength (%)
Cat. 1	78.33	33.22	74.86	95.6
Cat. 2	74.20	30.89	74.30	100.1
Cat. 3	63.54	30.89	67.34	105.9
Cat. 4	74.84	31.02	73.36	98
Cat. 5	76.33	32.21	72.02	94.4

Yarn Type	Initial strain %	Creep strain %	Hrs.
Cat. 1	4.39	0.95	104832
Cat. 2	4.32	0.45	104832
Cat. 3	4.43	0.40	104832
Cat. 4	4.51	0.57	104832
Cat. 5	5.20	0.54	104832

In some cases the residual strength is higher than the initial strength. This is caused by the variations in strength between the individual yarns. We have made a statistical evaluation and will use in our analysis for all materials the mean value. In general it can be concluded that, if there is a reduction in strength, it is very limited and it is within the accuracy of the tests. The loading of the samples was checked at the end of the test. The values of the load are given in the table. Uncertainty remains about the initial strength of the samples. We have records that indicate strength levels which are lower than the mentioned ones. We had stored virgin samples of the test material and after completion of the test program we checked the initial strength again. These values are mentioned. During the test program we found strange results: some yarns broke within 1000 hrs. while they actually were loaded at load levels which are related to a service life of 100 years. Detailed investigations have been made and the conclusion was that the transfer mechanism of the load to the yarn and the application of the load to the yarn could be too sensitive for the sample. This means that some uncertainty remains about the correctness of the calculated normalized load (probably the percentages are too low compared to the actual loads). These uncertainties have no influence on the use of the samples for determination of the residual strength.

Although the strength of the yarns has not changed so much, the elongation at break has reduced considerably. Table 3 gives an overview of the results.

The reduction in strain is significant in all loading cases and types. The standard deviation is small so it may be concluded that although the strength does not vary so much, the strain has reduced considerably. This means also that the modulus of the material has increased.

3 MOLECULAR CHANGES OF PET YARNS DURING STRETCHING

In 1992 a study was made at Akzo Nobel Research Laboratories in Arnhem on the molecular changes of PET yarns during stretching measured with rheo-optical infrared spectroscopy and other techniques. This study is reported in the Journal of Applied Polymer Science (V.d. Heuvel C.J.M. c.s., 1993).

They developed a method to measure infrared spectra during the mechanical deformation of yarns. With this rheo-optical technique they were able to study the molecular processes during loading of PET yarns. These results were combined with data obtained from Size Exclusion Chromatography and tensile measurements at elevated temperatures. In summary it was found that the stress-strain curve of a PET yarn or other PET material the modulus of the

Table 3. Residual strength results.

Yarns	N	S.d.	Strain %
DIOLEN 770			
Cat. 1 spool	78.33	1.40	11.55
Spool loaded residual	74.86	3.97	9.98
Cat. 2 fabric	74.20	1.43	9.76
Fabric loaded residual	74.30	3.73	9.84
Cat. 3 fabric damaged	63.54	1.37	8.20
Fabric damaged loaded residual	67.34	4.64	7.56
DIOLEN 776			
Cat. 4 spool	74.84	0.27	10.68
Spool loaded (40-50% residual)	73.36	1.66	9.01
Spool loaded (20%) residual	74.41	--	8.34
TYPE A			
Cat. 5 spool	76.33	1.18	12.47
Spool loaded residual	72.02	3.06	8.95

Yarns	S.d.	n
DIOLEN 770		
Cat. 1 spool	0.78	10
Spool loaded residual	1.05	6
Cat. 2 fabric	0.21	10
Fabric loaded residual	0.97	6
Cat. 3 fabric damaged	0.19	10
Fabric damaged loaded residual	0.75	6
DIOLEN 776		
Cat. 4 spool	0.39	10
Spool loaded (40-50% residual)	0.63	6
Spool loaded (20%) residual		2
TYPE A		
Cat. 5 spool	0.63	10
Spool loaded residual	0.74	6

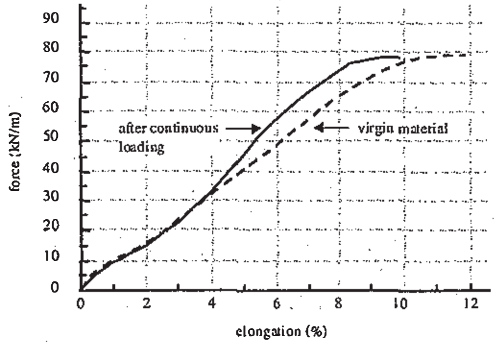

Figure 2. Stress-strain curve before and after testing Diolen 770 spool.

material, which is the first derivative of the stress-strain curve, varies a lot (see figure 3).

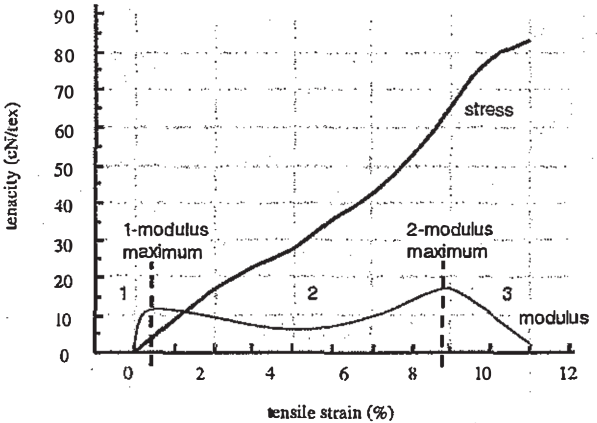

Figure 3. Typical stress-strain curve with modulus (V.d. Heuvel, 1993). Note: tenacity is factor * load/specific strength

Clearly 2 maxima can be found in the modulus curve: one around 0.5 – 1% strain and the other at about 7 - 8% strain. These stress-strain curves can be divided in 3 regions using these maxima. The molecular deformations which take place in these 3 regions are clearly different from each other.

Region 1: up to the first maximum in the modulus (around 0,5 – 1%).

Region 2: between the first and the second maximum in the modulus (between 0.5 – 1% and 7 - 8%).

Region 3: after the second maximum in the modulus.

To understand the processes which take place in the 3 regions it is necessary to look at the physical structure of PET, a two phase model with amorphous and crystalline domains (Den Hoedt, 1986, v.d. Heuvel, 1992).

During straining the PET molecules will uncoil. The ethylene groups in the amorphous domains of semi-crystalline PET occur in 2 conformations, gauche and trans conformation. Molecule chains with a lot of gauche will be coiled strongly, trans conformers in series give rise to extended chains. The crystalline zones consist only of trans conformers. So we have to concentrate on what happens in the amorphous domains.The study of Van den Heuvel had as result a description of the uncoiling of processes which take place. In region 1 entanglements (amorphous chain-chain interactions) of the molecular chains contribute substantially to the mo-

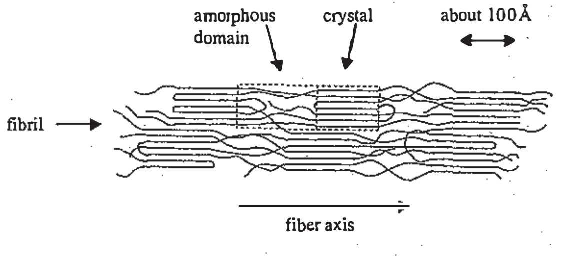

Figure 4. Physical structure of PET yarn (V.d. Heuvel).

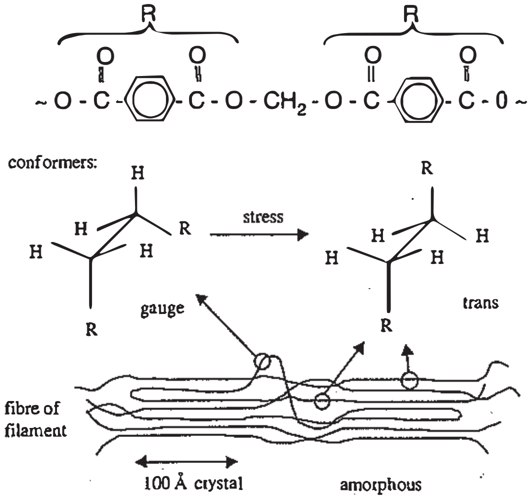

Figure 5. Molecular and physical structure of PET (V.d. Heuvel).

dulus. This leads to a maximum in modulus. In region 2, after the first maximum, the modulus reduces, which is caused by the break down of the entanglement network and the start of the uncoiling by gauche → trans transitions. This uncoiling takes of course place in the amorphous domain. The uncoiling effects a lowering of the non-elastic modulus, while in region 2 the elastic modulus increases.
The uncoiling in region 2 leads to straining of the tie-molecules. The chain modulus of the taut-tie molecules is relatively high, which results in increase of the tensile modulus of the yarn. This increase continues up to the next maximum. When the modulus reaches its second maximum some of the taut-tie molecules begin to break, this is the start of region 3. The number of molecules that break is limited. (It is measured to be maximally 3%). The increased reduction of the modulus in region 3 is the result of chain scission in the amorphous zone where much more local stress concentrations are generated, which lead to further accumulation of molecular breakdown and which lead to rupture of the filament.

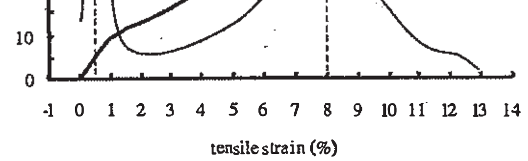

Figure 6. Molecular processes in the 3 regions.

We can summarize this process as:
Region 1: entanglement of molecular chains result in high modulus.

Region 2: uncoiling of the molecular chains with gauche-trans transformation and straining of the taut-tie molecules.

Region 3: chain scission in amorphous zones leading to rupture.

This process has been measured and verified by means of various techniques as have been described by Van den Heuvel (1992). The process describes what happens during short term loading of a PET sample. Analysis of the residual strength measurements and especially of the stress-strain curves of the residual strength test indicate that the mentioned process is not only taking place during short term loading, but that the same processes take place during long term, creep loading. Figure 7 describes the loading pattern of the sample Diolen 770, spool.

Phase 1, loading of the sample
Phase 2, constant loading and creep
Phase 3, unloading
Phase 4, loading up to rupture.

The sample is loaded to a level that it is clearly in region 2: uncoiling of the molecules and straining of the taut-tie molecules. The modulus pattern of the yarn at the begin of the test and at the end is indicated in the figure. The second maximum of the modulus has moved to a lower strain level during the creep loading in 12 years. As can be seen the modulus of the yarn is higher at the end of the test compared to the begin (while the strength remains at the same level). It can be concluded from these results that during the 12 years loading the modulus strain of the yarn has increased which indicates that the molecules have become more stretched during the loading. This is also described as the mechanism in region 2 during the short term test.

Further it is logical that, when during constant loading a further increase in stiffness or modulus takes place, it also will not influence the strength of the material. The strength is determined by passing the second maximum in modulus because then tie-breaks and scissions of molecules take place. This mechanism has been verified with the results of the tests on the other type of PET materials and at various load levels. They all show the same pattern, therefore it may be concluded that the molecular

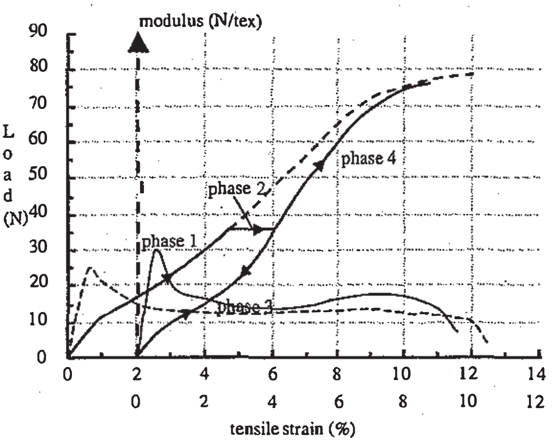

Figure 7. Loading during creep test Diolen 770, spool.

change mechanism which was described by Van den Heuvel (1992) is also applicable for long term loading. In a separate paper to this conference the model is verified with creep measurements on various types of PET materials: different yams, straps and at various loading levels. A different behavior of creep is shown for region 1 and 2.

4 VALIDATION METHOD OF BUILD STRUCTURES

The described mechanisms give us a unique method to establish the long term reliability of a build reinforcement structure. We have seen that the second maximum of the modulus moves to lower strain levels during the continuous loading of a structure in region 2. The PET reinforcement material ruptures when the second maximum is passed. This rupture takes place within 3 months after passing the second maximum as we have observed in our rupture measurement tests. It can easily be established (even with a short term test) what the creep rate will be during the further loading of a structure. The practical method is:

1. Take a sample of the PET reinforcement material from the loaded structure.
2. Execute a stress-strain test on this sample.
3. Calculate the modulus curve from the stress-strain curve and indicate the 2 maximums.
4. Determine the creep rate at the loading level for the rest of the service life of the structure. This could even be at a higher load level, when the structure will get an increase in service load.
5. Calculate the available rest service life by dividing the strain at the second modulus minus at the required load level in the residual strength stress-strain line, by the creep rate.

$$t_{rest} = \frac{\Sigma_{2nd\,mod} - \Sigma_{load}}{creeprate}$$

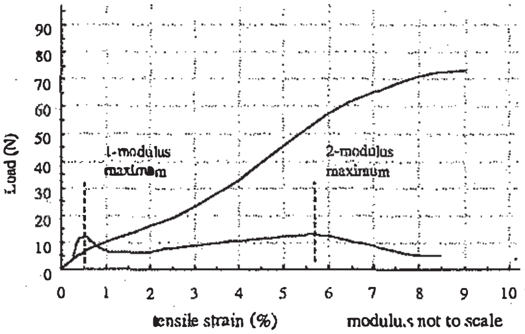

Figure 8.1. Diolen 770 – fabric, after continuous loading.

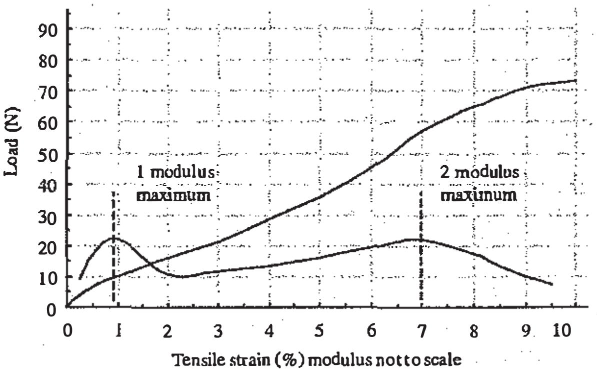

Figure 8.2. Diolen 770 – virgin fabric.

Example:

The test on the Diolen 770 'blanc fabric' is taken as an example.

We have loaded the sample at 30,89N. The corresponding strain in the stress-strain curve (residual strength test after 83664 hrs) is 3,7%. The second maximum of the modulus has moved from the original material (at 7%) to 5,7% at this test . This means that we have 5,7 – 3,7 = 2% to go before the second maximum equals the loading strain. The creep rate is: 0,03% / 2,1836 yr.

$$t_{rest} = \frac{2\%}{0{,}03\%} \cdot 2{,}1836\,years = 145{,}6\,years$$

t_{rest} = time before rupture

Note: the creep rate is decreasing in time and can be better described with a log formula. We took here simply the last measured interval, which also would be done in practice. When we use the log formula we find in this case a creep rate of 0,98% per decade.

$$\log t_{rest} = \frac{2\%}{0{,}98\%} = 2{,}04$$

$$\log t_{tot} = 2{,}04 + \log 104832 = 7{,}06$$

$$t = 11.481.536\,hrs = 1.310\,years$$

According to the normal stress-rupture line of PET yarns we may expect a service life of 1,000 years (8760000 hrs. or log t(hrs.) 6,94 for 54% and 10,000 year (87600000 hrs, log t(hrs.) = 7,94) for 50% loading.The corrected load value for this sample is 43 x 1,2 = 52%, this means a service life according to the stress-rupture line of log t = 7,44. On the log scale measured this is of the same order as has been calculated with the described rest strength calculation method.

5 CONCLUSIONS

1. The residual strength of PET materials after being exposed to loads for more than 12 years has not decreased significantly.
2. The elongation at break of the PET materials after the 12 years loading has reduced significantly leading to the conclusion that the modulus of the material is increased.
3. The earlier developed description of the molecular changes of PET material during stress-strain loading with the 3 regions, clearly divided by the 2 maxima in the modulus of the material can also be applied to the creep process which has been shown by means of the results of various long term tests.
4. With this process description a method is developed to calculate the time period left until rupture of a loaded reinforcement material.
5. This method has been validated with the results of long term test measurements and the results are comparable to the results of the stress-rupture analysis.
6. The described system of molecular changes during short term loading has been extended to also long term loading which gives us detailed insight in the creep process of PET and allows us to make a good prediction of the safety of executed soil reinforcement systems.

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