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Swing up in creep curves at high loadings of PET bars – further proof of the molecular chain change model

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ABSTRACT: The paper discusses the results of creep measurements on PET geogrids bars at high load levels. These measurements complete the series of earlier published data on creep at lower load levels. The tests have been executed with continuous measurement of the elongation of the geogrids over time. The results obtained were used to further support the model which describes the process that takes place at molecular chain level. It is shown that the 2^{nd} maximum modulus point of the tested PET bars is the point where the swing up starts. At 8–9% total elongation (elastic and plastic) the tested bars progressive failure indicated by a swing up of the graph takes place.

This strain is lower than the ultimate strain measured during the short term tensile strength test. The measured data was compared with earlier published data, This gave further proof of the validity of the model.

1 INTRODUCTION

Long term constant load testing is done to measure the creep in a geosynthetic material. Creep of geosynthetics can be defined as a continuous extension of material as result of a tensile load applied to it. The rate of elongation is not constant with time and depends on the magnitude of the applied load. The elongation of the geogrids is measured with time and the results can be presented in the form of a stress-rupture curve, in which the creep is presented as the increase in elongation against the time on a logarithmic scale. In general there are 3 phases in a creep curve with different creep rates.

The first part of the curve is a straight line obtained during the initial loading. After that the elongation continues to increase while the load is kept constant. Phase 1 describes the phase directly after initial loading when the creep rate decreases to level which is constant with the logarithmic of time. Phase 2 is the period in which the creep rate is constant against log. time and Phase 3 is the swing up, when the creep rate increases continuously up till rupture takes place.

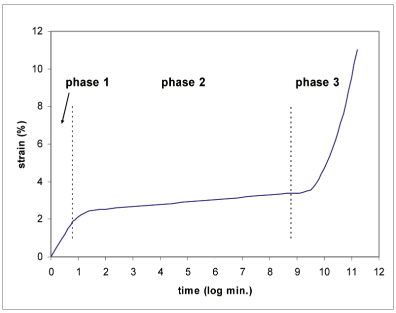

Figure 1. Typical creep curve.

The creep of polymeric material, especially of PET, has been investigated in the past 30 years by many researchers (Van den Bleek I.M.C., 1985, Voskamp W., 1985, 1996, 2001, Den Hoedt G., 1986, Viezee D.J., 1990, Greenwood J.H. 1997). The creep in a polymeric material influences the service life of a reinforcement material, and can result in additional deformations of the completed structure. Therefore the creep data is an essential base for the design of soil reinforcement structures.

The use of the stress-rupture line as a design tool for service life design of soil reinforcement structures was suggested by Voskamp W, 1985 and Den Hoedt G., 1986, followed by extensive long term tests on virgin and damaged fabric (yarns) by Viezee D.J. et al, 1990. Residual strength measurements on specimens that were subjected to 12 years creep loading (Voskamp. W, 2001) proved that during the lifetime of a structure no gradual reduction of strength takes place, but the strength remains constant in time up to the moment the swing-up in the creep curve takes place near rupture. The present soil reinforcement design is based on the assumption of a gradually reducing strength. A study of the changes which take place at molecular level during the short term loading of PET yarns up to rupture was executed by Van den Heuvel, C.J.M. et al. 1993. The changes in molecular level were investigated using a.o. rheo-optical infrared spectroscopy. With the results of the residual strength study and long term creep tests, it was possible to conclude that the model developed for changes at molecular level during the short term test, was also applicable to describe the behavior of molecules at continuous loading (Voskamp W., 2001). The constant residual strength and a concave and convex shape of the creep curves can be explained with the model. It shows that the 2nd maximum modulus of the stress strain curve is the point which not only determines the start of progressive failure in a short term stress-strain curve, but also determines the start of rupture failure in a creep curve. The results of creep which takes place is a decrease of the distance between the 2 maximum modulus points or in other words as results of creep the modulus of the stress-strain curve increases. After continuous loading the elongation at break is reduced and the 2 maximum modulus points have moved to each other. A typical curve is given in Figure 2.

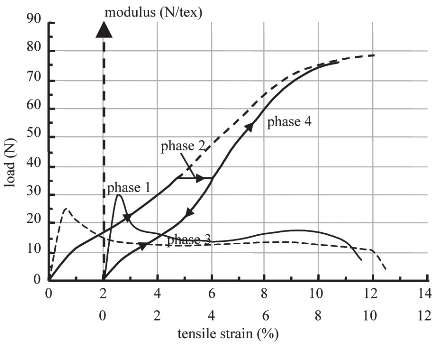

Figure 2. Loading path during creep tests, with phase 2 as continuous loading path (Voskamp 2001). Phase 1 and 2 cover the initial loading and creep phase. Phase 3 and 4 are the unloading and loading phase up to break . These last phases equal a stress strain curve with an origin at 2%.

The last phase of the creep-strain curve, in Figure 1 indicated as phase 3, is the swing up. Details of this phase are not well known. This is because during the execution of the creep tests on geogrids normally no continuous measurement of the elongation is made due to the length of time of the experiment.

In an earlier study (Voskamp W., 2001), the variation of creep rate at constant loading of PET geogrid strapping, showed the start of a swing up at a normalized load level of 75%. It is very important to know at what elongation the swing up starts, because at that moment the progressive collapse of the reinforced soil structure takes place. It is also important to investigate if the strain at which the swing up starts is actually the same for all load levels.

The purpose of this study was to investigate the swing up at various load levels and to compare the starting points of the swing up in terms of elongation with the 2nd maximum modulus point in the stress-strain curve.

In this study it has been found that the 2nd maximum modulus point indicates the elongation at which the swing up and collapse starts. With this known the extrapolation of creep curves can be made correctly and the service life times for various creep load levels can be determined.

This means that not only accelerated tests at higher temperatures (like SIM tests) can predict the life time (Thornton, J.S. 1997, Greenwood, J.H., 1997), but also the service life at lower load level can be predicted by extrapolation of (steady) creep lines up to the level of the elongation of the 2nd maximum modulus, which can be found with the normal stress-stain test.

2 DESCRIPTION OF THE MOLECULAR CHANGES MODEL OF PET YARNS DURING SHORT- AND LONG TERM LOADING

The previous studies have showed that the earlier measured and described molecular changes during short term loading of PET yarns (Van den Heuvel C.J.M., 1993) also take place during long term loading. The changes were measured using rheo-optical infrared spectroscopy. It was found that the modulus of the stress-strain curve of PET material varies and that it has typically 2 maxima.

For clearness sake we quote in the following section the description of the molecular changes during loading, as we have written in our paper "Variation in creep rate at constant loading of PET geogrid strapping", (Voskamp W. and v.Vliet F., 2001).

A typical stress-strain curve for PET material is given in Figure 3. In the same figure the modulus of the stress-strain curve, which is the first derivative of the stress-strain curve, is given.

Clearly 2 maxima can be found in the modulus curve: one around 0.5-1% strain and the other around 8-9% strain. The stress-strain curve can be therefore divided in three 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 70 maximum modulus (between 0.5-1% and 8-9%).

Region 3 : after the second maximum in the modulus.

To understand the processes which take place in these regions it is necessary to look at the physical

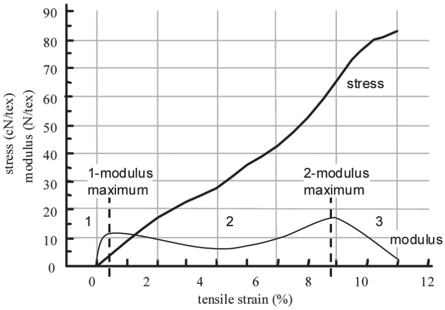

Figure 3. Typical stress-strain curve with modulus values (v.d. Heuvel C.J.M., 1993).

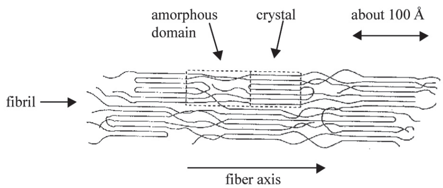

Figure 4. Physical structure of PET yarn (V.d. Heuvel, C.J.M.).

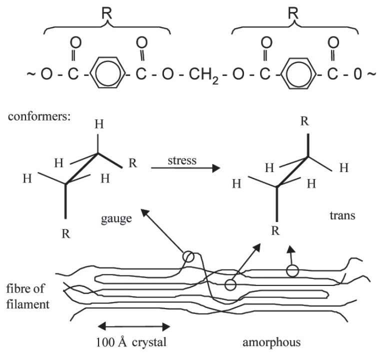

Figure 5. Molecular and physical structure of PET (V.d. Heuvel, C.J.M.,1993).

structure of PET, a two phase model with amorphous and crystalline domains (Den Hoedt G., 1986, v.d. Heuvel C.J.M., 1992).

During straining the PET molecules uncoil. The ethylene groups in the amorphous domains of semicrystalline PET occur in 2 conformations, gauche and trans conformation. Molecule chains with a lot of gauche will be coiled strongly; whereas trans conformers in series give rise to extended chains. The crystalline zones consist only of trans conformers. The creep takes place in the amorphous domains. The study by Van den Heuvel C.J.M. (1993) resulted in a description of the uncoiling processes which take place. In region 1, entanglement (amorphous chain-chain interactions) of the molecular chains contributes substantially to the modulus. 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. tensile strain (%) This uncoiling takes place in the amorphous domain. The uncoiling results in a lowering of the non-elastic modulus.

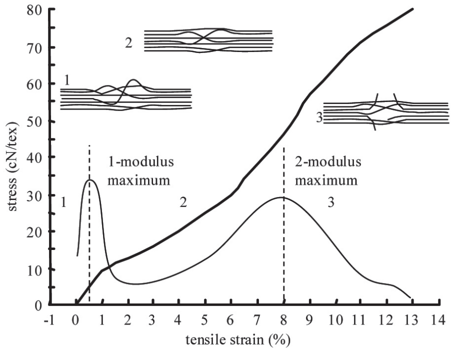

Figure 6. Molecular processes in the 3 regions (Voskamp W, 2001).

The uncoiling in region 2 leads to straining of the tie-molecules. The chain modulus of the taut-tie molecules is 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, which is the start of region 3. The number of molecules that break is limited. (It is measured to be maximally 3%). The increasing reduction of the modulus in region 3 is the result of chain scission in the amorphous zone, where more local stress concentrations are generated, which lead to further accumulation of molecular breakdown and which lead to rupture of the filament.

The process can be summarized as:

Region 1: entanglement of molecular chains resulting 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.

The changes of molecular level in the various regions take also place during creep loading as shown in the earlier mentioned papers (Voskamp W., 2001).

In Figure 2 we have seen that the 2 maximum modulus points move closer together as result of the creep taking place.

The phases in this figure are:

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 is clearly in region 2: uncoiling of the molecules and straining of the taut-tie molecules take place. The modulus pattern 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 is higher at the end of the test compared to the beginning (while the strength remains at the same level).

Based on the results of earlier investigations it was concluded that the swing up would start at the same elongation level: the elongation at the 2nd maximum modulus where rupture starts in the stress-strain test. This hypothesis is checked in a test program with extensive creep measurements at high loading.

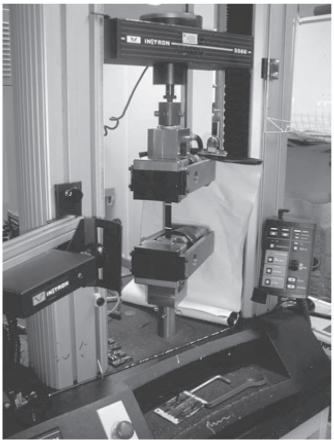

Figure 7. Creep measurements with tensile loading device.

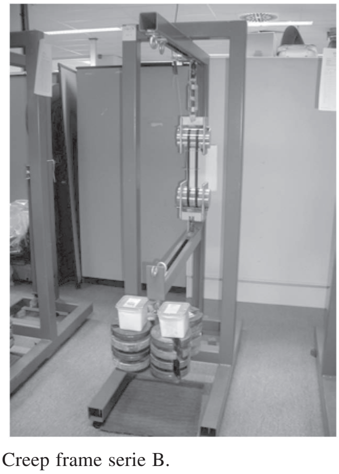

Figure 8. Creep frame serie B.

3 TEST PROGRAM

Creep tests were executed on the strapping of Enkagrid PRO 90. The virgin straps had strength of 6882 N and an elongation at break of 11%. A typical stress-strain curve is shown in Figure 11.

The strength of the welded straps is 6700 N and the elongation at break is 9.6%.

Two series of tests have been executed.

Series A:

Creep measurements were executed with an Instron tensile test equipment with continuous loading and continuous strain measurements.

The loads applied were between 90 and 83% of UTS, the measurements took between 1 and 10 hours.

Long duration testing was not possible with this type of equipment because execution of the test with constant load and increasing elongation was very sensitive and difficult to execute with this equipment.

The measurements are and shown in Figure 9 in the top 4 curves.

Series B:

Creep measurements were carried out using a creep frame.

In this set up the measurement of the elongation is done manually, measuring the distance between 2 markers on the geogrid strap with a digital length measuring device.

The load levels were between 78 and 81% and the results were also shown in Figure 9 in the second group of measurements.

Figure 9 shows the creep strain vs. time. The results of the stress-strain test (UTS) are indicated in Figure 9 as "100% load". This gives the initial elongation after application of the load. The series tests of an earlier investigation (10%-75% of UTS) have been shown in the same figure to have a consistent overview.

The last series is done on 2 strap wide, welded samples while the high load series is done on single virgin straps as result of the test equipment required limitations. A stress-strain curve of these earlier tests is also shown (Figure 11).

When we compare both stress-strain curves in Figure 10 it can be observed that the 2nd maximum modulus point of the welded geogrids (point with the highest gradient in the curve) is between 6-7% and that of the virgin material is between 8-9%. This is an effect of the welding.

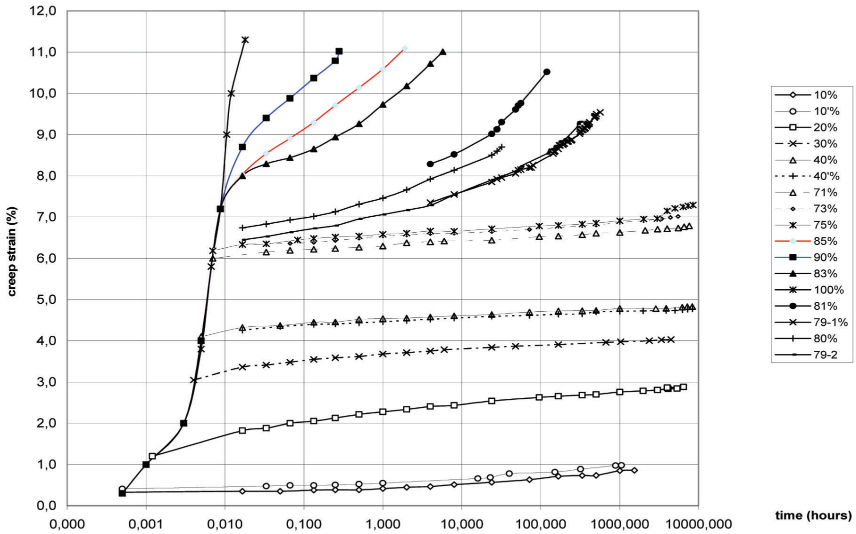

Figure 9. Typical stress-strain figure.

4 DISCUSSION OF THE RESULTS

In series A specimens were loaded up to strain levels higher than the strain of the 2nd maximum modulus point. We see that the curves of 90% and 85% loading do not reach a steady creep level but after reaching the test load level the swing-up takes directly place. Normally the increase in strain per unit time during the loading reduces after the test load level has been reached and the loading is kept constant. It reduces up till a steady level is reached. This does not happen in the series A tests, which shows that the strain rate/ time in these tests is already higher than the constant creep rate. So the swing-up has started immediately after the initial loading. At this load level the gauche–trans molecular chain transformation has already taken place and straining of the tauttie molecules has already taken place. So chain scission in the amorphous zones starts immediately leading to rupture.

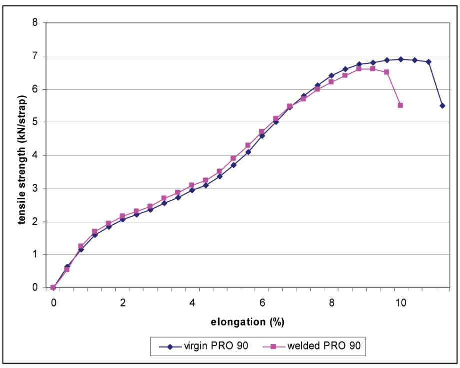

Figure 10. Typical stress-strain figure.

At 83% there is a very short period of constant creep rate at a strain level of just above 8%.

The series B with load levels between 80% and 83%, a period of constant creep up till the strain level of 8-9% is reached was observed. The 2nd modulus point of virgin straps is between 8-9% strain. The swing-up in the creep curve in Figure 10 starts above this level. This further confirms the molecular chain model, in this period the straining of the taut-tie molecules takes place, at 8-9% the chain scission in the amorphous area starts.

It can further be observed that the time period during which the swing-up takes place is not for all load levels the same. The higher the load level is, the shorter the swing-up time.

Further the creep-rupture line of these materials which is the result of another test program, shows that rupture in 100 years is expected to take place at the load level of about 70%. This correlates with the 6-7% strain area at which the swing-up in Figure 9 starts.

Comparing the results with the SIM (stepped isothermal method) tests of the same material shows that the upswing of these curves start between 6 and

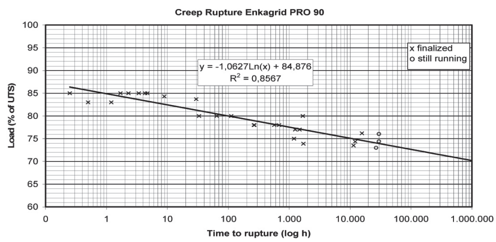

Figure 11. Creep-rupture of 2 strips Enkagrid PRO90.

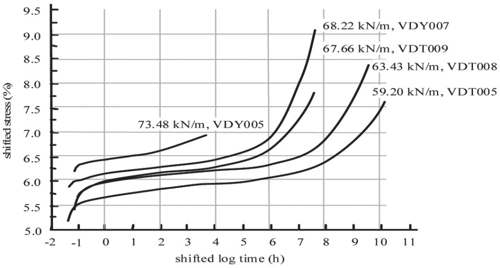

Figure 12. Creep at high loads using SIM testing method.

7% strain, which is at the same level as the test results of Figure 9.

5 CONCLUSIONS

1. Detailed strain measurements during creep loading at high load levels show that the swing-up in the creep curve of these PET geogrids bars start at a strain level of 8-9%, which is the level of the 2nd maximum modulus in the stress-strain curve.
2. The time at which the swing-up starts, depends on the load level.
3. The time span of the swing up varies between 300 hrs at load levels close to the ultimate tensile strength and 4000 hrs at 75%.
4. Based on these measurements, together with the test results reported in the earlier papers (Voskamp. W., 2001) it can be concluded that the molecular chain change model describes the creep of PET accurately. It can safely be used to predict the remaining service life time of PET soil reinforcement material, after it has been used for a longer time period or in case the load of the soil reinforced structure is increased later.

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