THE BEHAVIOUR OF GEOSYNTHETICS UNDER CYCLIC LOAD

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Abstract: Whenever geosynthetics are used to reinforce or stabilise infrastructural elements such as road- and railways, bridge abutments, run- and taxiways on airports or to protect coastlines of canals and other steep slopes they may be exposed to cyclic loads. Therefore, a reduction factor for dynamic effects on the geosynthetic tensile strength has been included into the calculation of the Long Term Design Strength (LTDS). An approach to assess the behaviour of geosynthetics is to adopt Woehler- or Smith graphs and Haigh-diagrams for polymers. This is because an endurance limit for polymers, which defines an infinite life under a defined cyclic load, has not been seen so far. A huge amount of mechanical testing is needed to predict the behaviour of geosynthetics against this particular background.

To reduce these efforts while getting an indication of the cyclic effect on geosynthetics, a combined method of mechanical and chemical analysis has been developed. The pure tensile strength tests to determine the residual strength after cyclic stress has been amended by IR-spectroscopy and Differential Scanning Calorimetry (DSC). In this context the chain change model of PET has been proven as valid for cyclic loads as well, which helps to define the endurance limit of materials made out of PET. For polyolefins such as PP and PE, a limit for the maximum alternating load has been identified at the point of the stress strain graph where the actual and the numerical stress of a material diverge from each other. Cyclic tensile strength tests have been carried out in a hydraulic test frame. The test parameters have been set to simulate the service life of a railway bed trafficked by high speed trains (ICE).

Keywords: cyclic load, dynamic loads, laboratory test, reduction factor, reinforcement, stiffness

INTRODUCTION

The German Society for Geotechnics is publishing recommendations for the design of geosynthetic reinforced structures (EBGEO 2008). Since the 1st edition was published in 1997, geosynthetics are used in many more applications than described and covered by the guideline. For this reason a new version of the EBGEO became necessary. A working group of experts was dealing with the effect of cyclic and dynamic loads on reinforced structures. Three design classes of exposure of reinforced structures to non-static loads have been defined.

Table 1. Design Classes for Dynamic Loads (Herold et al. 2008)

Design Class	Description	Design
1	• simple cases • only one load component acting orthogonally to the reinforcement • no soil dynamic effects expected • 2-dimensional problem	No special investigations needed. The use of static design procedures covers all cyclic and dynamic effects.
2	• simple cases • one essential load component acting orthogonally to the reinforcement • no soil dynamic effects expected • 2-dimensional problem • reinforcement affected by dynamic loads	Dynamic effects have to be taken into account. This can be done by using either quasi-static replacement loads or an approximation method. A more correct way is to follow a design according to class 3.
3	• complex cases • more than one essential load component acting not only orthogonally to the reinforcement • soil dynamic effects expected • 2-dimensional or 3-dimensional problems • data of acceleration, oscillation velocity and movements are required	Dynamic loads have an effect on the construction. The design has to be done with applicable procedures and methods considering time and frequency of the impact. This includes individual laboratory and field tests to determine all relevant properties for the design.

The behaviour of geosynthetics is important for designs according to class 3. This case can be divided in two different parts having an effect on the design results. First – the interaction behaviour of a cyclic stressed sandwich construction, second – the fatigue behaviour of a reinforcement sheet, affected by cyclic loads. (Nernheim 2005) has published his investigations on the effect of cyclic loads on the interaction behaviour between soil and geosynthetic reinforcements. This paper describes a laboratory test series to assess the performance of geosynthetics stressed by defined cyclic loads in their plane in air to determine the reduction factor for cyclic loads according to .

$$LTDS = \frac{UTS}{RF_{cre} \bullet RF_{ins} \bullet RF_{con} \bullet RF_{dur} \bullet RF_{dyn} \bullet SF}$$

where LTDS is the Long Term Design Strength of the reinforcement, UTS equals the Ultimate Tensile Strength of the virgin material, RF are Reduction Factors for creep, installation damage, connections, durability and dynamic effects respectively, and finally SF is safety factor for unspecified uncertainties.

THE STRESS-STRAIN BEHAVIOUR OF PET

Conventional analytical methods to determine the endurance/fatigue limits of materials are proved to be reliable with sufficient accuracy for metals. However these methods do not reflect the behaviour of polymers in an acceptable manner. This work is focussed on the morphology of polymers under mechanical stress.

The analysis of available sources of tests regarding the use of geosynthetics under dynamic and cyclic loads does not allow conclusions on the behaviour of geosynthetics subjected to high cycle fatigue. Hence the analysis of the state of knowledge has been expanded to applications of polymers under cyclic loads beyond geotechnics.

The model of (Heuvel et al. 1992) and (Heuvel and Lucas et al. 1992), which has been adopted by (Voskamp et al. 2001) and (Voskamp et al. 2006) to explain the stress-strain-behaviour and the creep-rupture behaviour of PET materials, was applicable when compared with test results.

For the assessment of PET materials the 2nd maximum of the modulus curve is essential. The modulus curve is the 1st derivation of the stress-strain-curve. The 2nd maximum is as a kind of limiting value and influencing factor on the failure probability of this kind of geosynthetics made of PET.

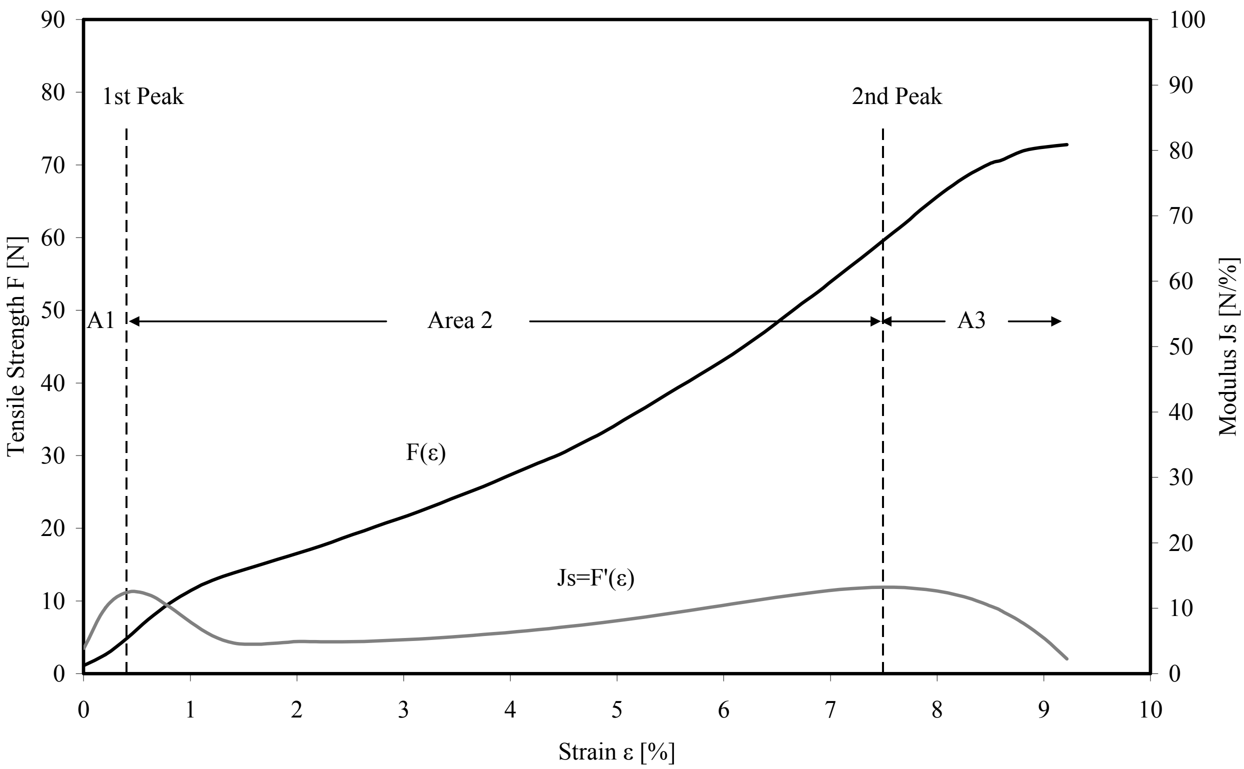

Figure 1. Scheme of a Stress-Strain-Analysis for PET-Yarn According to (Heuvel 92) and (Retzlaff 2007)

THE STRESS-STRAIN BEHAVIOUR OF PP AND HDPE

An effect of a tied up area and viscose yielding on the stress-strain-behaviour of materials out of polyolefin's has been confirmed with tests. It has to be separated between the actual stress (related to the actual cross-section) and the numerical stress (related to initial cross-section), which has been determined by tensile strength tests of these materials. Because the actual stress is higher than the numerical stress, the stress in the geosynthetics has to be limited to the area where the stress-strain-curve starts to defer (Figure 2). This is the point from where the two types of stress diverge from each other.

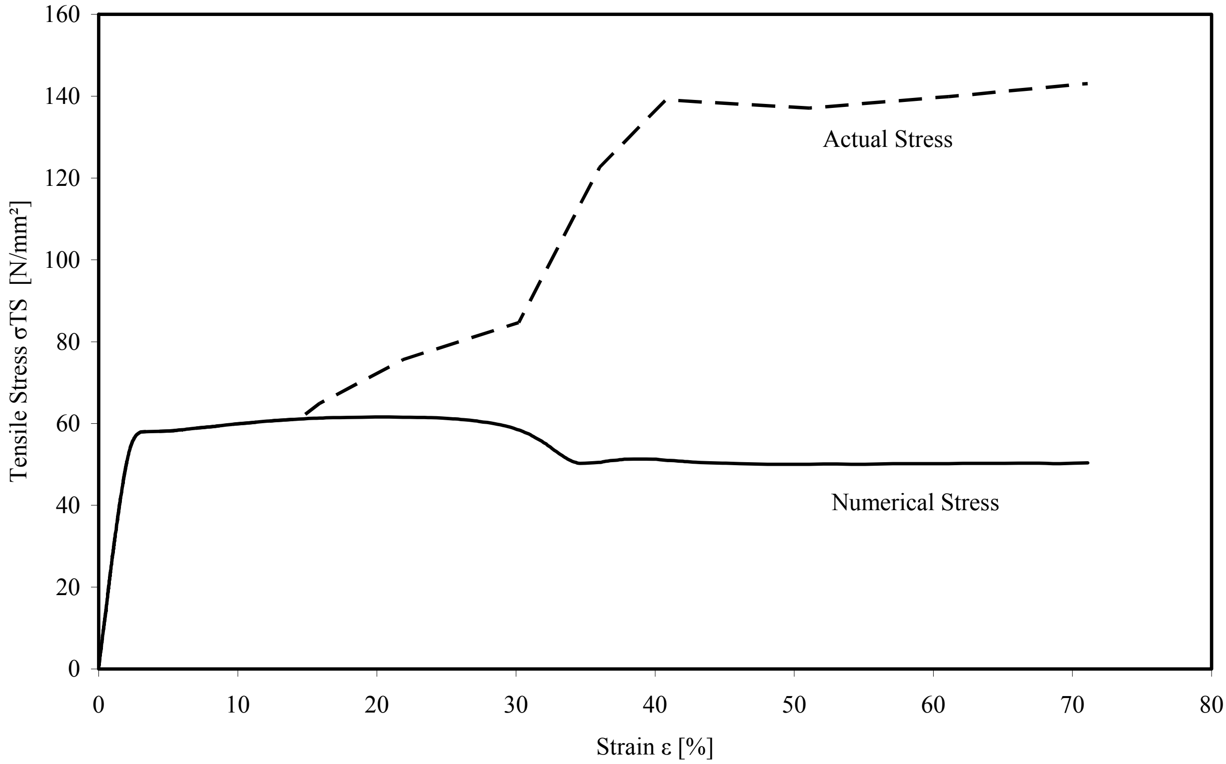

Figure 2. Examples of an Actual and Numerical Stress-Strain Graph Like for a Polyolefine

The investigated geosynthetics have been tested in a hydraulic test facility up to 10^7 load cycles. Conclusions on the effect of the cyclic loads on the geosynthetics have been drawn by comparing the residual strengths of the test samples after the cyclic loading to the original strength of the reference measurements. Using these two values a reduction factor can be calculated. The reduction of tensile strength of the tested specimens related to its original reference tensile strength was very small and did not exceed 10 %.

RESULTS OF THE CYCLIC TESTS

Training Effects

The training effect is a phrase that is commonly used for metals. Even if the mechanism is completely different the effect on the stress strain behaviour is comparable. It is assumed that a certain number of cycles at a suitable frequency leads to a change of the modulus and finally to a stiffer material. This can be assessed by evaluating hysteresis loops. The slope of the main secant of a hysteresis loop is an expression for the actual stiffness at the appropriate cycle.

The tracked hysteresis loops show a distinct training effect on geosynthetics made from PET. That goes along with an increase of their stiffness as the number of load cycles increases. This effect does not appear to be similar with polyolefin's. The graphs in Figure 3 have been based on the relative slope change of the hysteresis loops at the beginning and at the end of the test. Unfortunately the number of tests was not sufficient to provide a more general picture.

Temperature Effects

The applied load combinations did not cause any critical warming of the test samples. That includes the chosen dynamic ratio between the lower and the upper stress of 0.66, the frequency of 10 Hz and the material specific creep-rupture reduction factor RF_{cre} for the test period. The test temperature from Figure 4 was measured at the surface of the stressed sample. The reference temperature was measured at the surface of the sample taken from the same material and stored close to the clamped test sample. The higher temperature above the hydraulic cylinder was the reason for this procedure. Both test and reference temperatures were changing according to the room temperature. The difference between the tested specimen's and reference temperatures was less than 2 K. There was no remarkable temperature increase caused by the test.

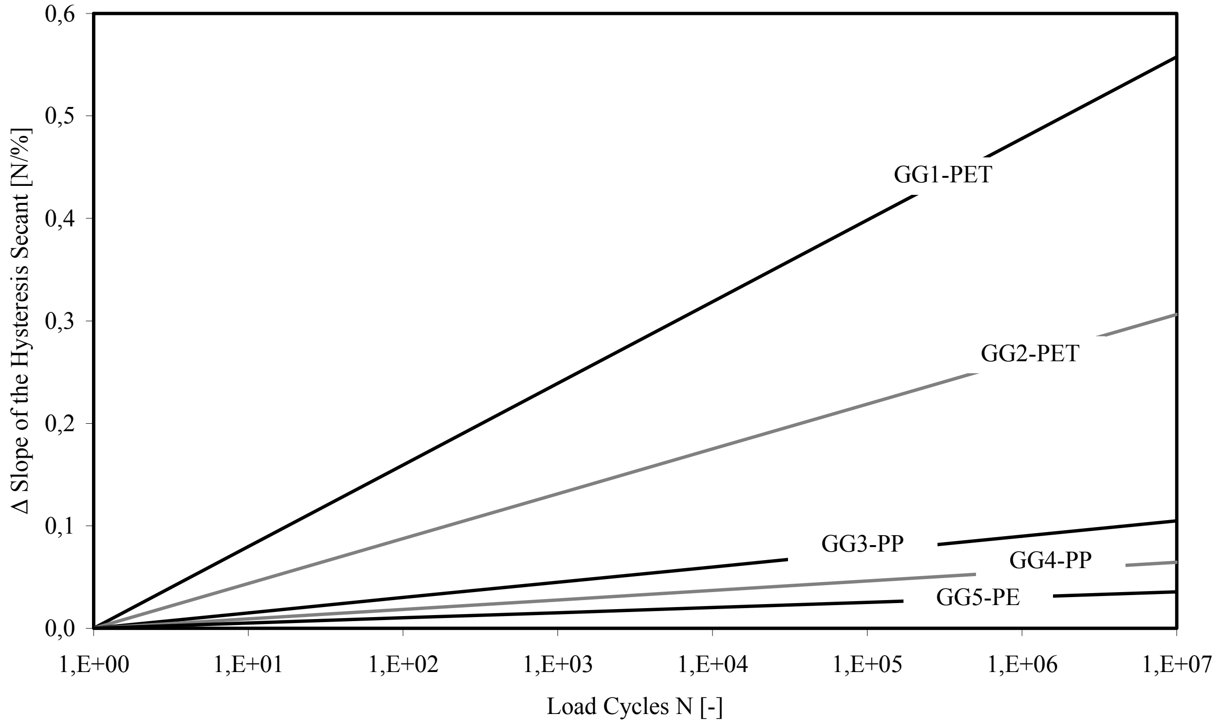

Figure 3. Training Effect of Cyclic Loads on Various Geogrids Indicated by the Slope Change of the Hysteresis Loops (Retzlaff 2007)

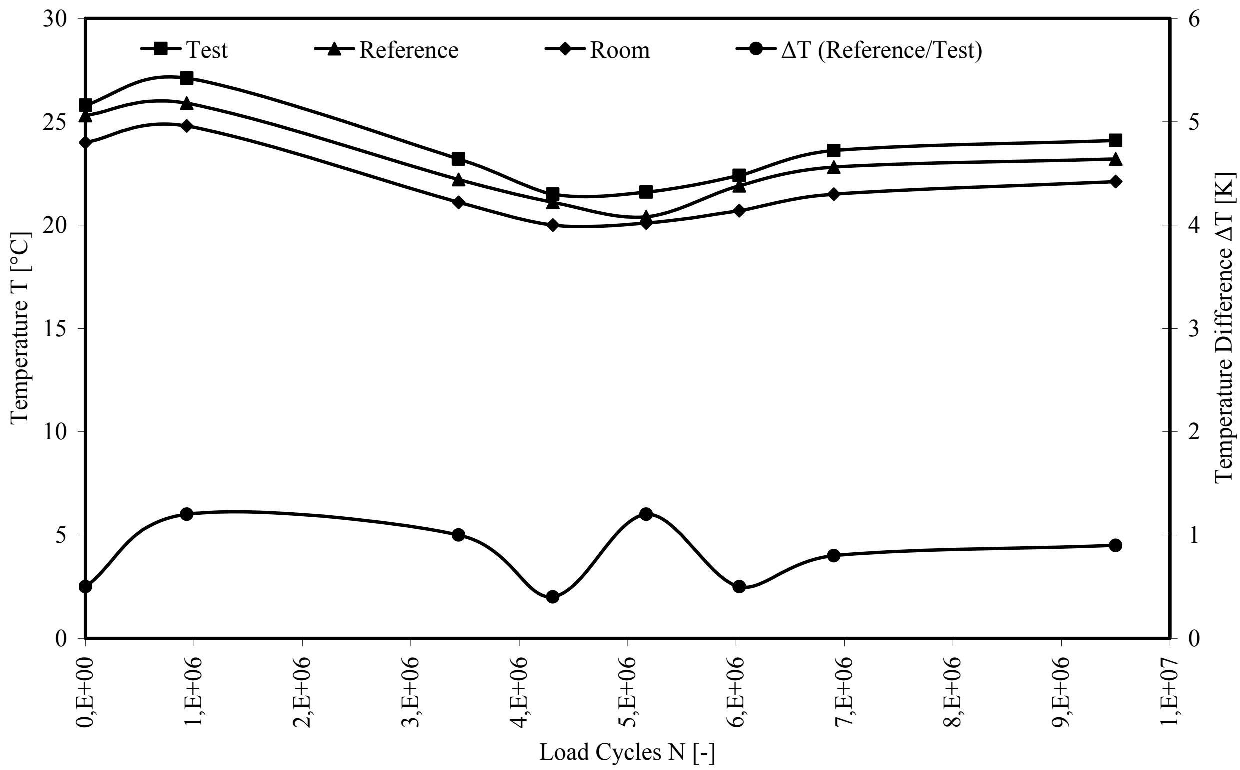

Figure 4. Temperature Profile of a Polyolefin During Cyclic Tensile Stress Testing

CHEMICAL ANALYSYS OF VIRGIN AND PRE-STRESSED SPECIMENS

After conducting a series of tests it can be concluded that a judgement of the fatigue behaviour of geosynthetics shall include the use of Infrared-spectroscopy (IR) and Differential Scanning Calorimetry (DSC) in addition to the determination of the mechanical properties. Both methods prove the tensile strength measurements. The IR-spectroscopy helps to quantify chemical changes of the materials. A combination of these results with the outcome of the Differential Scanning Calorimetry allows conclusions on the morphology, especially on the crystallinity of the polymers used to manufacture the geosynthetics.

Infrared-Spectroscopy (IR)

This method is using the excitation of molecules to move because of electromagnetical radiation in the range of the infrared spectrum. A typical behaviour of the molecules structures allows conclusions on the formation. For the PP tested, the results of an Attenuated Total Reflectance spectroscopy (ATR-IR) are shown in Figure 6. It was the purpose of these tests to get a first impression of a possible chemical change of the material that indicates a change in the morphology of the polymer. The difference between the base lines at smaller wave numbers was caused by the embossed structure of the surface of the test specimen, but in the area between 1,800 and 1,600 additional peaks have been recorded. These peaks are in the typical area for carbonyl bands which are the result of an oxidation.

Carbonyl bands are organic compounds that contain carbonyl groups:

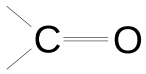

Figure 5. Carbonyl Group of Carbon (C) and Oxygen (O)

Because of the different electronegativity of the two elements the double connection results in a polar character of the group. That phenomenon provides a comfortable traceability with IR-spectroscopy. An IR-spectroscopy demonstrates changes of the chemical structure in the polymer. This method is limited to a qualification of the effects of the cyclic loads on geosynthetics.

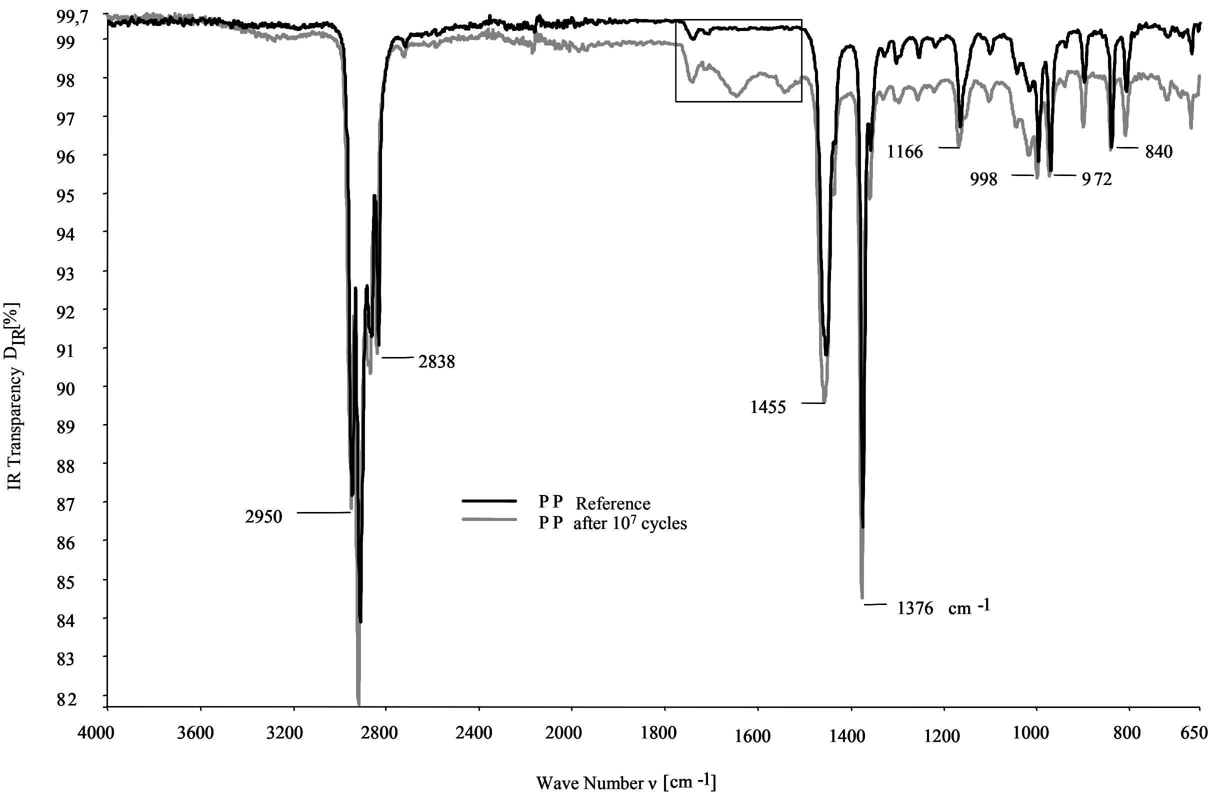

Figure 6. IR-Spectrum of a Polypropylene Material before and after 10^7 load cycles

Differential Scanning Calorimetry (DSC)

DSC is a thermo-analytical method to evaluate the dependence between temperature and time in the behaviour of the polymer to assess their physical and chemical properties. It is based on the heat flow volume that is measured during the test and plotted like Figure 7. The heat flow allows conclusions to be formed on the internal energy of a compound. The variation of the internal energy during the heating and cooling cycles of the DSC analysis is named enthalpy change. This can be calculated by integrating a section of the DSC-plot, which differs from a horizontal base line. The typical enthalpy change for some polymers is given in (Krevelen 2003). The analysis of the area connected to the melting point of the investigated polymers has shown a difference in the crystallinity before and after applying the cyclic stress for polyolefins. This difference in crystallinity went along with the strength loss during the cyclic tests up to 10^7 cycles.

Even though it is common practice to use only the second heat cycle of DSC for the evaluation, the first heat cycle was selected to be evaluated in this work. Because of the test circumstances of a DSC the first cycle shows much more variation than the second cycle. Nevertheless the first heat cycle was investigated to analyze the affected material immediately after the stress has been applied before any thermal handling that would change the structure of the tested thermo-plastics. Unfortunately the number of tests was too small to get statistically firm data. In any case it was surprising how close to each other the ratio for the change of the crystallinity and the ratio for the residual strength of the materials were.

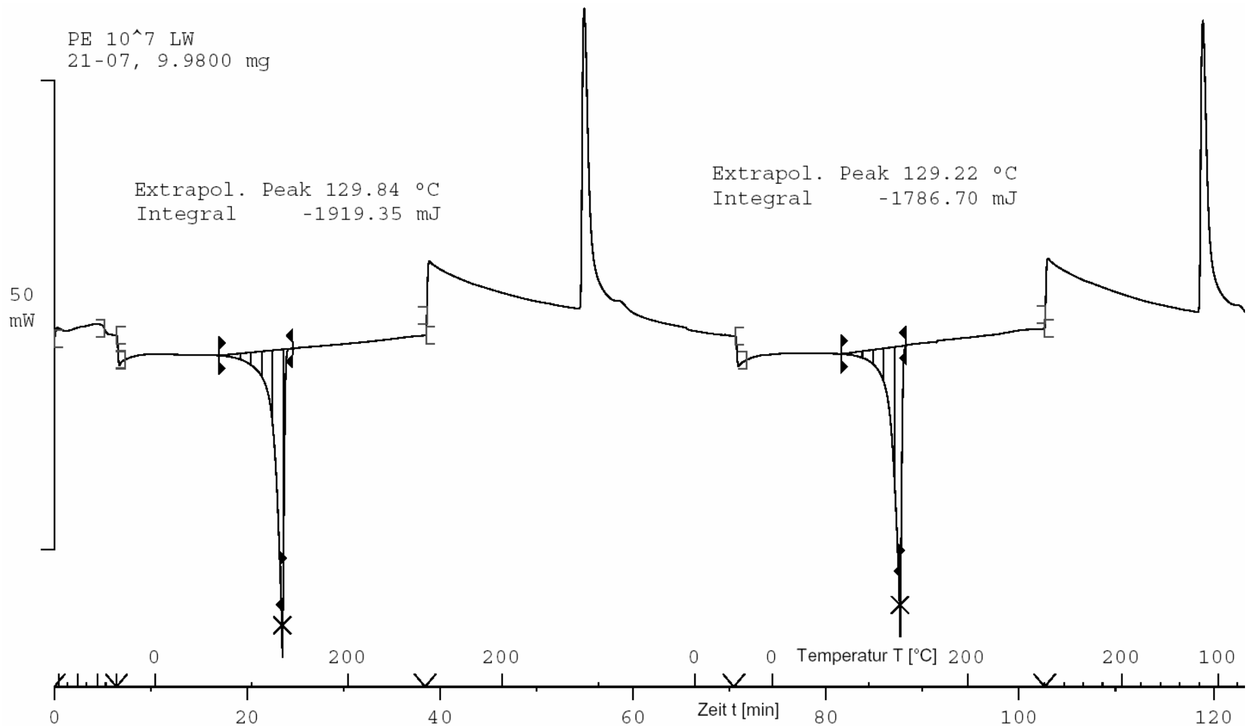

Figure 7. DSC-Plot of a HDPE Sample after Loading it for 10^7 Cycles

CONCLUSIONS

Finally, it can be noted that the test stress on the geosynthetics was much higher than the practical demands on site and the effect on the tested geosynthetics has been much smaller than expected. That may lead to an over dimensioning of reinforced structures. However it can be seen as a tolerable compromise to consider time dependent loads for designers as long as the limit state procedure is the standard and the serviceability can't be proven easily.

Extended formulations for a more realistic approach to identify the effect of cyclic loads are available from (Herold et al. 2006) and (Herold 2007), who has measured the elongation of geosynthetics under cyclic loads in an embedded state. These tests and measurements have resulted in the same dynamic ratio as used for the tests of this work but on a lower level of stress in the geosynthetics.

Once there is an acceptable theory of how the stress transfers from the loaded soil into the geosynthetic reinforcement, the in-air-tests of this work should be completed with in-soil-tests. This is important to realistically assess the cyclic stress in the geosynthetic layer. It will also help to determine the surface abrasion of the geosynthetics by oscillating soil particles.

Based on the recent state of knowledge, which is reflected in (Göbel et al. 2006) and (Nimmesgern et al. 2001), the possible surface abrasion is less than the installation damage.

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