

Degradation behavior of stressed polyester reinforcing products under alkaline conditions embedded in eluates and soils

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Abstract. The use of geosynthetic reinforcements in different applications has been proven over the last decades to be a very beneficial and valid technique. For a safe design of such structures the long-term behavior and especially the available resistant tensile force over the time under variable boundary conditions, such as temperature, chemical influences or loading conditions, has to be well known and understood. The known effects, which lead to a reduction in tensile strength, are considered in the design by applying so called reduction factors. So far, those reduction factors are determined separately without considering a possible interdependency. Latest research results are indicating that this can lead to major misjudgements. The main mechanism of the chemical degradation of polyester in high alkaline environment is the so called alkaline or “external” hydrolyses. In contrast to the internal hydrolyses, which provokes an evenly distributed, very slow degradation of the whole cross-section of the synthetic material, the external degradation generates a much faster “surface corrosion” with creation of fissures or cracks. If this does occur while the material is loaded, the fissures are widened, and their propagation are dramatically accelerated. The understanding and consideration of chemical degradation under mechanical stress is from crucial importance. This research will present results for products made of PET with different production technologies, where above-described mechanism has been investigated in more detail and conclude with a recommendation, how to proceed based on those findings. Tests have been conducted with samples embedded in eluate as well as in partially and fully saturated soils.

1 Introduction

In general engineering design practice, knowledge of material properties, especially those responsible for the stability of a structure, is fundamental. This naturally includes understanding the effect of degradation mechanisms on the material properties with the corresponding boundary conditions of the structure (external influences). A reliable prediction of e.g., the strength development over time, considering e.g., temperature, mechanical load, or chemical action, is therefore required. This requires that the degradation

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mechanisms for different raw materials and the interdependence of the different degradation mechanisms are known.

Geosynthetic reinforcement products are susceptible to different degradation mechanisms resulting from creep (strain under constant load), chemical action or cyclic loading. The short-term tensile strength is therefore reduced by various reduction factors to account for the reduced long-term tensile strength. The tensile strength is not only reduced by the degradation mechanisms, but also by the effect of installation damage, which is considered by a further reduction factor.

These reduction factors are determined independently of each other, which indirectly implies the assumption that there are no mutual dependencies between the different degradation mechanisms. In fact, it is quite difficult to identify dependencies when several factors are involved and especially when only certain combinations lead to a change in the degradation behaviour of certain mechanical properties. This article deals with such a behaviour, which occurs when geosynthetics made of polyethylene terephthalate (PET) are exposed to pH values above 9 in a humid environment under loading.

2 Internal and external hydrolysis of PET in alkaline environment

Hydrolysis is the process of splitting a chemical bond by reaction with water. Two types of hydrolysis can be observed in PET. The so called internal and external hydrolysis. Internal hydrolysis occurs in neutral conditions with pH-values in-between 4 and 9. The corresponding mechanical degradation occurs evenly over the entire cross-section. Degradation by internal hydrolysis is relatively slow, and strength loss over a 120-year period is low. For geosynthetic reinforcing products in general around a few percent.

Under alkaline conditions with pH values above 9, external hydrolysis also sets in. In contrast to internal hydrolysis, external hydrolysis progresses much faster and causes surface corrosion leading to voids, cracks, and perforation. The loss of strength is disproportionately higher. Figure 1 shows a PET strand which was stored unloaded (no tensile force) in a saturated $\text{Ca}(\text{OH})_2$ solution (lime water). The red lines indicate the original width of the PET strand. Furthermore, the damage caused by external hydrolysis is clearly visible from the holes and cracks.



Fig. 1: PET strand after 4 years immersion in $\text{Ca}(\text{OH})_2$ at 50 °C without load (Greenwood et. al, 2016)

Müller-Rochholz and Bronstein (1994) analysed the influence of high pH-values in combination with stress (tensile load) on the degradation process of PET fibres. They found that the degradation process does speed up significantly under these conditions. This is because the tensile forces widen the microcracks and the cracks propagate, which leads to a reduction in the cross-sectional area and thus to a lower tensile strength. Figure 2 to 4 show the mechanism described.

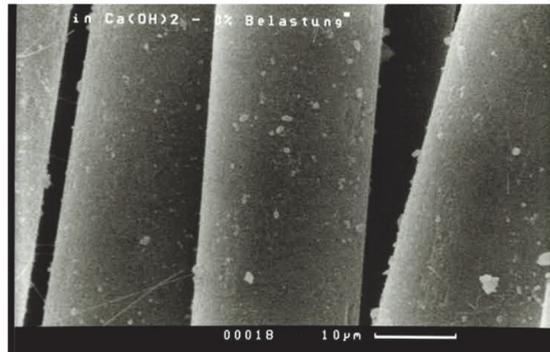


Fig. 2. PET fibres after being stored for 91 days in $\text{Ca}(\text{OH})_2$ without stress at 40°C (Müller-Rochholz and Bronstein 1994)

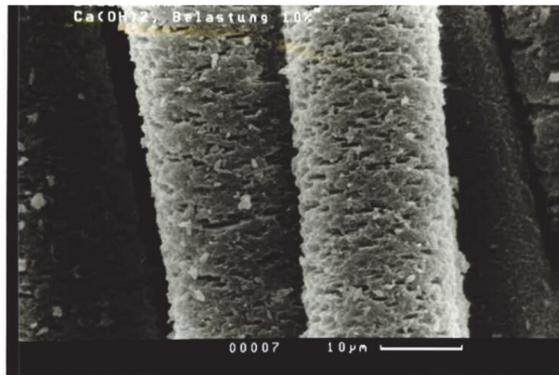


Fig. 3. PET fibres after being stored for 55 days in $\text{Ca}(\text{OH})_2$, stressed with 10% of the maximum tensile strength at 40°C (Müller-Rochholz and Bronstein 1994)

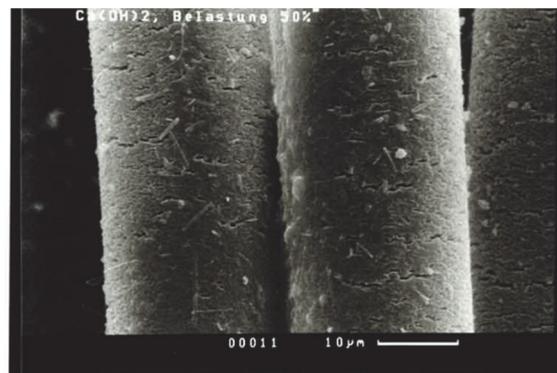


Fig. 4. PET fibres after being stored for 14 days in $\text{Ca}(\text{OH})_2$, stressed with 50% of the maximum tensile strength at 40°C (Müller-Rochholz and Bronstein 1994)

The images in Figure 2 to Figure 4 are taken with a scanning electron microscope (SEM). They show the surfaces from PET fibres that were simultaneously exposed to an alkaline environment (lime water, $\text{pH} = 12.6$ measured at 20°C) at 40°C and mechanical stress over a short period of time (Müller-Rochholz and Bronstein 1994).

The damage patterns show the influence of mechanical stress on the formation of notches and cracks during external hydrolysis. As a result of these investigations, a causal relationship

was established between the surface structure of the PET fibres examined during external hydrolysis and the applied stress. The surface damage in (Figure 3) occurred after just 55 days at a relatively low mechanical tensile stress of 10 % of the maximum tensile strength of the material in an alkaline environment. The damage is significantly higher compared to the unstressed stored fibre after 91 days in the same eluate (Figure 2).

Besides the pH-values and temperature, also the specific surface area has an influence on the degradation process. To analysis this, geogrids made of PET strands have been tested. The samples have been tensioned by 35% of their ultimate strength, which corresponds approximately to the design strength of the material. In a first test series the samples have been placed in an eluate at 50°C and a pH value of 11,7. Figure 5 shows the geogrid sample before and after testing. It can be observed that the former transparent strands became milky, which is because micro cracks occurred in the material and changed the light refractive index. The whiter the surface the more micro cracks have appeared. After 28 days under these conditions the geogrid failed.

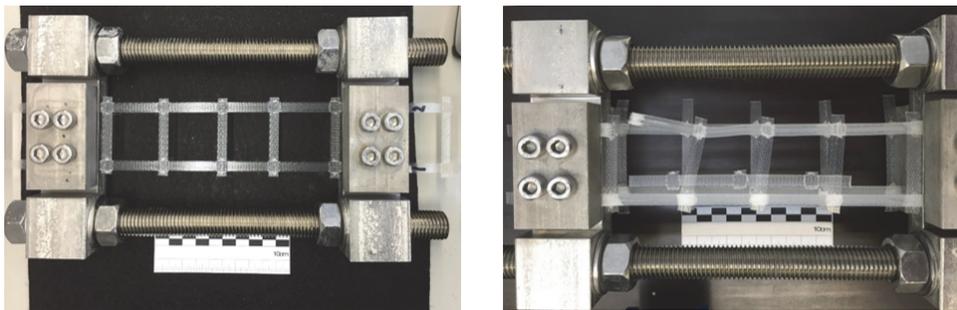


Fig. 5. PET strands loaded by 35% (approximately the design strength) at 50°C in an eluate with a pH value of 11,7 (left picture before testing, right picture after 28 days in the eluate)

To understand better the influence of temperature, those tests have been repeated at 20°C and a pH-value of 12,6. The degradation process decreases in speed but still occurs. After 64 days in those conditions the residual strength reduced by 45%.

All those tests have been executed by placing the samples in an eluate. This might not reflect the real conditions, where the material is embedded in soil. Therefore, further test series have been developed, where the samples are embedded in soil and loaded at the same time. Within a master thesis at the TU Deggendorf a test set-up has been developed (Figure 6), which allows the testing of the samples embedded in partially saturated and saturated soils (Strahberger, 2023).



Fig. 6. Test device for testing loaded geogrid samples embedded in soil

Figure 6 shows the test set up. The geogrid sample is fixed at the bottom of the right container and to the horizontal bar at the top of the device. The grey container is then filled with soils. Via the horizontal bar and a counterweight, the geogrid sample is then stressed. The tensile load in the geogrid sample is measured via a load cell which is located between the horizontal bar and the geogrid sample. To compensate for deformations and tilting due to (creep) deformation and to keep the load constant, the fixings on the horizontal bar are designed to be movable. The container with the soil is then partially filled with water, so that the lower half of the soil is saturated and the upper half of the soil partially saturated. The water level is controlled by an overflow pipe in the centre of the tank. To reduce the water evaporation, a cover folie is attached to the container. A displacement transducer is attached to the device to determine the exact time of breakage. The pH value in the tank can be continuously monitored via a PVC pipe.

In total 4 tests have been executed so far. A lime-sand mixture was used as soil material. The pH-value of this material was in between 12,6 and 12,7 and the temperature in between 13°C and 19°C over the duration of the tests. In test 1 the load ratio was 50% in test 2, 3 and 4 40%. Tests 1, 3 and 4 were with soil and test 2 only with the eluate. Tests 3 and 4 are identical. The results can be seen in figure 7.

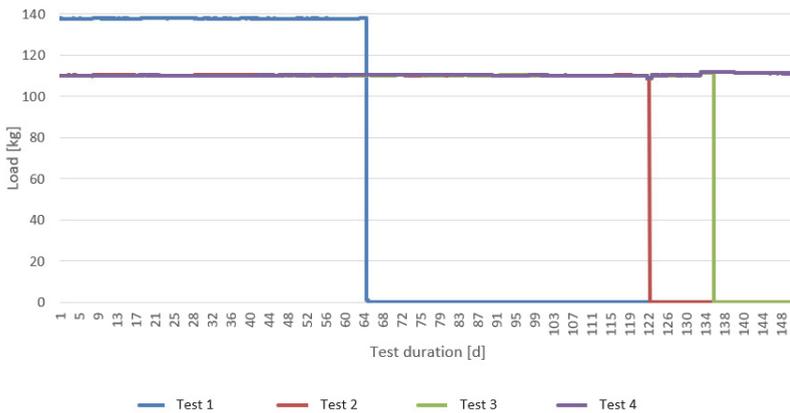


Fig. 7. Test results for test 1 to 4 – time until rupture

In figure 7 the load of the geogrid is shown over the time. At the moment of rupture, the load drops down to zero. As expected, test 1 breaks first due to the higher utilisation degree. The difference between test 3 and 4 and the difference between test 2 (only eluate) and 3 are in the same range, so that therefore no differentiation between those three tests can be done. The rupture of the embedded samples occurred in the partially saturated zone as well as in the saturated zone of the soil, as shown in figure 8.

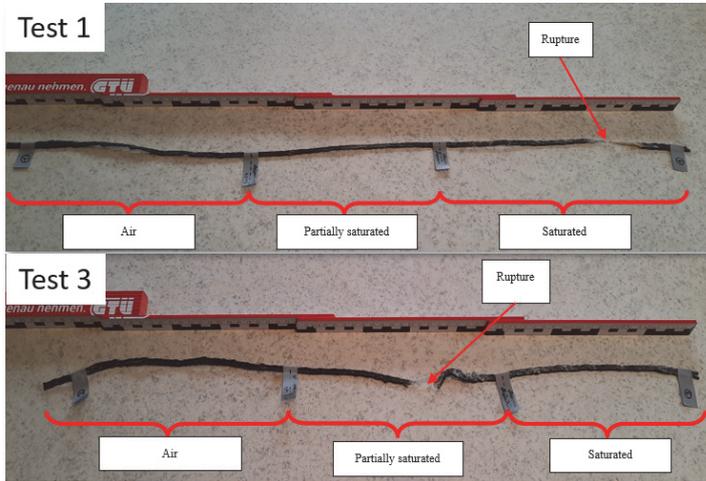


Fig. 8. Location of the rupture in the soil

Based on the limited number of tests it seems, that it does not play a role if the geogrid is embedded in the partially saturated or saturated soil or just in the eluate. As soon as the pH value is high and the geogrid under tension a degradation process of PET elements starts.

3 Recommended procedure to evaluate on the suitability of PET products in high alkaline conditions

In case reinforcing PET products are planned to be used within high alkaline environments their suitability should be tested in combination (embedded) with the planned material. ISO TR 20432 (2022) recommends performing a short-term creep test on a sample of geosynthetic that is immersed in the chemical or soil. Those tests can be done as described above or with small modifications also with standard laboratory devices, which are used to estimate the in-air creep behaviour of reinforcing materials. The test program can be designed analogue to the WSDOT Standard Practice T 925 (2017) procedures for comparison of creep and creep rupture behaviour of two products, for example. The results obtained in this way must then be compared with test results, obtained in a neutral environment. If no statistically significant difference in creep behaviour can be determined and there are no other objections, the product can be used with the tested soil material, otherwise suitable materials must be used.

4 Conclusion

The paper reports on the inner and outer hydrolysis of PET with special focus on reinforcement applications. Whereas the inner hydrolysis is a relatively slow and homogeneous degradation process, the degradation due to external hydrolysis can have a major impact on the safety level of the structure. Different research results are presented and

show that this degradation process occurs with PET fibres as well as with PET strands, which are placed under tension in an eluate or embedded in partially saturated or saturated soils. If reinforcing PET products are planned to be used within high alkaline environments their suitability should be tested under tension and embedded in the planned material. A possible test set-up is presented, and reference is made to a test procedure.

References

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