Assessment of Hydrolysis in Historic Polyester Yarn Recovered From 20 - 30 Year Old Reinforced Soil Structures

PJ Naughton. School of Engineering, Institute of Technology, Sligo, Ireland. naughton.patrick@itsligo.ie
GT Kempton. Consultant, London, United Kingdom. geoffkempton@f2s.com
R Lozano. Linear Composites Inc, USA. lozanoreng@aol.com
M Scotto, Officine Maccaferri, Bologna, Italy. moreno.scotto@infinito.it
J Meadows. Maccaferri Southern Africa, Durban, RSA. joseph.meadows@maccaferri.co.za

ABSTRACT
Laboratory data indicates that hydrolysis of polyester is not a significant issue provided the correct grade of polyester fibre is used in the manufacture of the geosynthetic reinforcement. No reduction in strength or stiffness was measured in samples of reinforcement recovered from 20 to 30 year old structures (Naughton et al, 2005 and Kempton et al, 2008). The polyester fibres recovered from these structures were assessed for possible degradation due to hydrolysis using a scanning electron microscope. No discernible change in the visual appearance of the fibres was evident indicating that hydrolysis was not significant and was in fact less than that predicted by laboratory testing. The data indicated that hydrolysis of polyester will not affect its performance for several centuries in the extreme case of a constant soil temperature of 40 ^{o}C and pH between 4.0 and 11.0 in fully saturated conditions.

1. INTRODUCTION

Soil reinforcement techniques are widely used in the construction of walls, slopes and embankments. The inclusion of geosynthetic reinforcement increases the stability of the structure and when correctly designed restricts the deformations of the structure to acceptable pre-defined limits. Modern soil reinforced structures were first built during the late 1960's and early 1970's. In the 1970's polymeric reinforcement elements appeared on the market and these now account for the majority of reinforcement materials used in this technique.

The polyester used in the reinforcing of geosynthetics in the 1970's was initially developed by Imperial Chemical Industries, ICI, for use in the rubber cord, car seat belts and ropes industries. Polyester was ideal for soil reinforcement applications due to its high tensile strength and modulus properties. The factors that were unknown at that time were the long-term durability characteristics of the material for use in soil structures, which had a typical design life of 120 years. Considerations for the design of stressed soil applications required information on the creep-rupture performance and environmental durability. This papers deals with the effects of hydrolysis, which is considered the principle mode of environmental degradation in polyester.

Samples of reinforcing elements have been recovered from two structures, one in the UK and the second in Turkey, which were constructed in the late 1970's and late 1980's respectively. The retained strength of the recovered samples was determined to assess the magnitude of degradation. A visual inspection of the polyester fibres was also undertaken to determine if there was damage or degradation to the fibres surface. A detailed study of the hydrolytic properties of the polyester used in these two structures was undertaken at the University of Cambridge (Burgoyne and Merii, 1993 & 2007).

The results of the residual strength testing, visual inspection using the scanning electron microscope (SEM) and the Burgoyne and Merii study are brought together to understand the degradation of polyester in reinforced soil structures.

Naughton et al (2005) provided an extensive discussion on the initial and long-term characteristics of a family of geosynthetics (grid and linear reinforcing elements used in steep slopes, reinforced soil wall and basal reinforcement applications) of which the reinforcement elements in this paper are members.

2. DESCRIPTION OF RECOVERED SAMPLES

Samples of the geosynthetic reinforcement were recovered from two structures; the first was the Transport Research Laboratory (TRL) trial wall constructed in 1977 in the UK. The second structure was the Kinali – Sakarya Motorway, Turkey. This wall was constructed in 1987 and was demolished in 2007 to make way for a redesigned motorway intersection. This structure also experienced a magnitude MW 7.4 earthquake in August 1999, which did not affect its performance. Further details on this wall are contained in Kempton et al. (2008).

2.1 The Transport Research Laboratory Trial Wall, United Kingdom

In July 1977 the construction of a full scale, 6 m high, trial reinforced soil wall commenced at the Transport and Roads Research Laboratory (now called the Transport Research Laboratory) Berkshire, United Kingdom (UK). The primary objectives of that trial were to optimise the use of the reinforcing elements in terms of length, spacing and orientation and to investigate the possible use of reinforcements other than those in use at the time.

While the trial wall consisted of several reinforcement types, this paper is only concerned with the geosynthetic reinforcement, consisting of high tenacity polyester encased in a polyethylene sheath. Further information on the properties of the reinforcement is given by Naughton et al. (2005). Details on the extensive instrumentation and measured values recorded in the wall are given by Boden *et al. (*1977). A photograph of the polymeric section of the trial wall taken in March 2005, after 28 years of service, is shown in Figure 1(a).

Samples of the polymeric reinforcing straps have been exhumed at intervals, over the past 28 years, and their retained strength determined. The polymeric reinforcing straps were passed around steel pins that were cast into the concrete facing panels, Figure 1(b). The white strip around the geosynthetic was merely to keep the straps in position during assembly and did not provide any reinforcement. Current construction methods have replaced the steel connection assembly to the facing panel with a polymeric system.

For practical reasons the samples of geosynthetic recovered were from the upper layers of the wall at depths of approximately 1 m. The backfill soil in this region consisted of silty clay, with a relatively high clay content. It can be reasonably assumed that this soil layer was partially saturated and would have a degree of saturation in the range 40 – 70 %.

The exhumed samples were visually inspected before having their retained tensile strength determined. The samples were generally in good condition although some physical damage was evident, which was attributed to the excavation process. Samples retrieved in 1984, 1990 and 1994 exhibited cracking of the polyethylene sheath on the reinforcement at the location where it wrapped around the pin attachment to the concrete facing panel. The most recent sample exhumed in March 2005 showed no evidence of this type of cracking, Figure 1(c).

2.2 The Kinali – Sakarya Motoway, Turkey

The Turkish section of the Trans-European Motorway runs from Edirne, near the Bulgarian/Greek border to Istanbul (Thracian Motorway) and then on to the capital city Ankara (Anatolian Motorway). The motorway consists of two main sections: Edirne to Kinali; and Kinali to Sakarya. Construction of the Kinali-Sakarya section commenced in 1987 and was completed in 1993. Further information on the design and construction aspects of this structure is contained in Kempton et al (2008).

All the wing walls of the overpasses and the retaining walls of the connecting roads from the motorway to the existing circular road were constructed with a reinforced soil system using polymeric strips on a 30 km stretch starting from Bahcesehir to the Second Bosphorus Crossing (Fatih Sultan Mehmet Bridge). The wall area constructed was more than 60,000 sq.m.

Rapid developments along the motorway route lead the Istanbul Metropolitan Municipality to construct new junctions and widen connecting roads at Seyrantepe. Construction of a new junction required the demolition of the existing reinforced soil walls and opened the possibility of recovering segments of the polymeric reinforcements. The location of the overpass was on a section of the motorway where there was heavy traffic 24 hours a day. Unfortunately there was not enough time to recover strips with hand excavation so the fill was excavated behind the panels with the help of a backhoe, Figure 2(a), and the polymeric strips at the connections to the panels were cut and the panels were removed letting the fill flow. Therefore only the strips that were hanging from the embankment could be recovered with minimal damage, Figure 2(b).

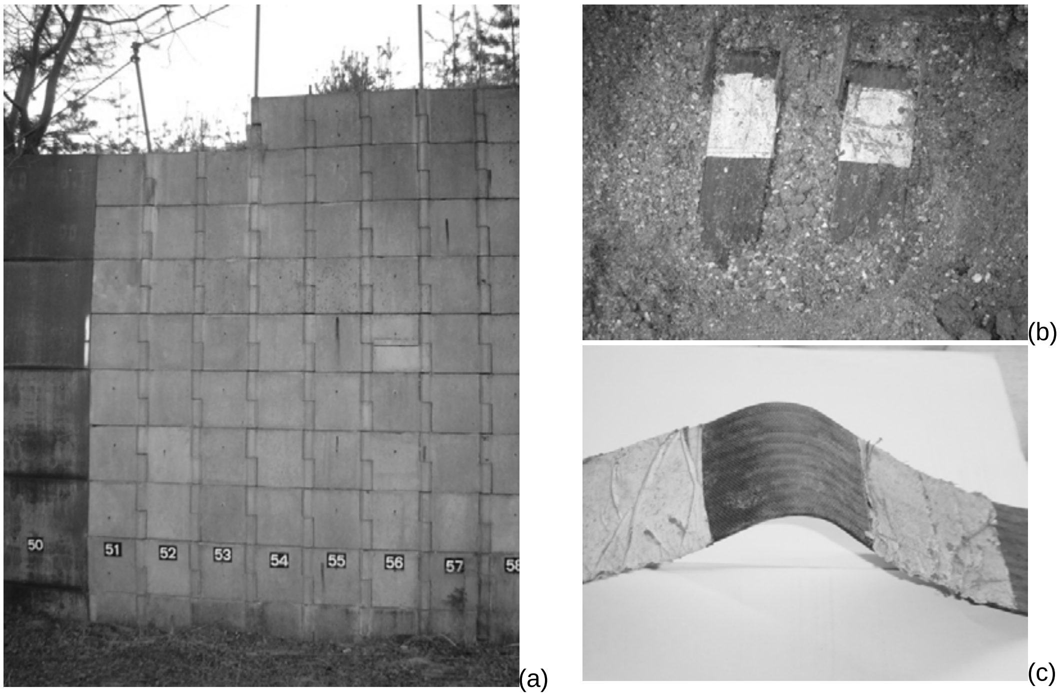

Figure 1. (a) 2005 view of polymeric section of the 1977 TRL experimental wall, Sample exhumed March 2005 (b) before removal of samples, (c) after removal.

2. (a) Demolition of the polymeric reinfor il wall (b) Recoverable polymeric strips from the ıkment.

3. OVERVIEW OF HYDROLYSIS

Hydrolysis occurs when H^+ ions, from water, react with the polyester molecules; resulting in chain scission, reduced molecular weight and strength loss (Koerner *et al.,* 1992). Pioneering research on hydrolysis of polyester by McMahon et al (1959) indicated that rates of hydrolysis were low, but in the context of civil engineering structures were not negligible. Moreover the rate of hydrolysis is affected by the relative humidity, degree of saturation and ambient temperature in the soil around the polyester. For partially saturated soil the predicted strength loss may only be a fraction of that in saturated conditions. The effect of temperature, above 20 ^{0}C, is to increase the rate of hydrolysis. The rate of hydrolysis is also influenced by the molecular weight and carboxyl end group count. FHWA (2000) recommends that high molecular weight (Mn >25000) and low carboxyl end group (CEG < 30) polyesters should be considered for long-term reinforcement applications, as these are more resistant to hydrolysis.

There are two types of hydrolytic reaction which run independently of each other (Hsuan et al., 2008). The first is referred to as inner hydrolysis, since it takes place mainly inside the polyester. Inner hydrolysis depends on the presence of water molecules in the polyester product. Even if the surrounding medium does not contain water, the presence of water vapor is sufficient to start the reaction. The second kind of hydrolysis is called outer hydrolysis, since it is a surface reaction leading to pits and holes on the surface. It only takes place when the polyester is in contact with alkaline liquids.

4. HYDROLYSIS OF POLYESTER USED IN HISTORIC STRUCTURES

Burgoyne and Merii (1993 & 2007) reported on the hydrolysis of uncoated polyester fibres. Two fibres were studied, PET 1 and PET 2, Table 1. PET 1 meets the FHWA (2000) requirement on both the number average molecular weight and carboxyl end group count and was very similar to the polyester used in the reinforcement elements in the TRL trial wall and the Kinali – Sakarya Motorway. PET 2 does not meet the FHWA (2000) requirements and is considered poor grade polyester for reinforcement applications.

The Byrgoyne and Merii (1993 & 2007) study is particularly important at it provides information on the variation of several properties, tensile strength, intrinsic viscosity, and number average molecular weight for both relaxed (unloaded) and loaded specimen of polyester fibres exposed to water and chemical solutions at various pH, ranging from H_2SO_4 at pH 4 to $Ca(OH)_2$ at pH 11. The samples were tested at various temperatures, including 50, 70 and 85 ^{o}C.

Table 1. Properties of PET 1 and PET 2 fibres (after Burgoyne and Merii, 1993).

	PET 1	PET 2
Number average molecular weight, M_n	30,700	39,500
Weight average molecular weight, M_w	113,000	109,000
Carboxyl end group count	15	30
Tensile strength (N)	85.5 ± 2.5	82.3 ± 2.8
Elongation at break (%)	10.23 ± 0.59	11.32 ± 0.51

Burgoyne and Merii (2007) found that at ambient temperature (20 ^{o}C) there was little loss of strength anticipated for several centuries. The application of tensile force to the specimens does not appear to have a measurable effect on the strength. Furthermore replacing water with mild solutions of acid (pH 4) and alkali (pH 11) has no significant effect on the strength.

Müller-Rochholz et al. (2008) in assessing the hydrolysis of polyester under alkali like environments examined the pH in soil subjected to lime treatment. It was found that the maximum pH was 12.5 and it was expected that this value would reduce with time. Martin and Dachroth (1994) reported that most natural soils would have their pH between 4.5 and 6.5.

5. RETAINED STRENGTH OF REINFORCEMENT ELEMENTS

5.1 The Transport Research Laboratory Trial Wall, United Kingdom

The retained tensile strength of the exhumed material was determined using a modified ISO EN 10319 (1996) test procedure at the University of Leeds, UK. The samples were cleaned to remove the silty clay residue and thoroughly dried before testing.

The mean stress-strain relationship indicated that no significant reduction in the mean tensile strength occurred over the intervening 28 years, Figure 3(a). The results were also consistent with the results of tensile testing on previously recovered samples reported by Greene and Brady (1999). Where individual test results are below the original short-term strength of the reinforcement, 30 kN, the reduction in strength can be attributed to damage inflicted during installation or extraction of the specimens, in-service degradation and experimental error in the testing process between all time periods (Greene and Brady, 1999).

5.2 The Kinali – Sakarya Motorway, Turkey

The tensile strength was determined in accordance with ISO EN 10319 (1996), which was a very similar technique to that used in the 1980's. The mean tensile test results are shown in Figure 3(b) and compared with the expected behaviour of the original material as shown in BBA Certificates' No's 82/22 and 88/38, both entitled 'Websol Frictional Anchor System'. The Paraweb exhumed was grade 50 which would have had a Nominal Breaking Load (NBL) of 50 kN but an actual breaking load of closer to 60 kN with a strain at NBL of around 11%. A small discrepancy between the BBA Certificates values and the actual retained strength is evident. However, this in part is due to the adjustment of the BBA Certificate stress-strain relationship to reflect the nominal breaking load, rather than the actual breaking load of the material. There is no reduction in the ultimate strength of the reinforcement.

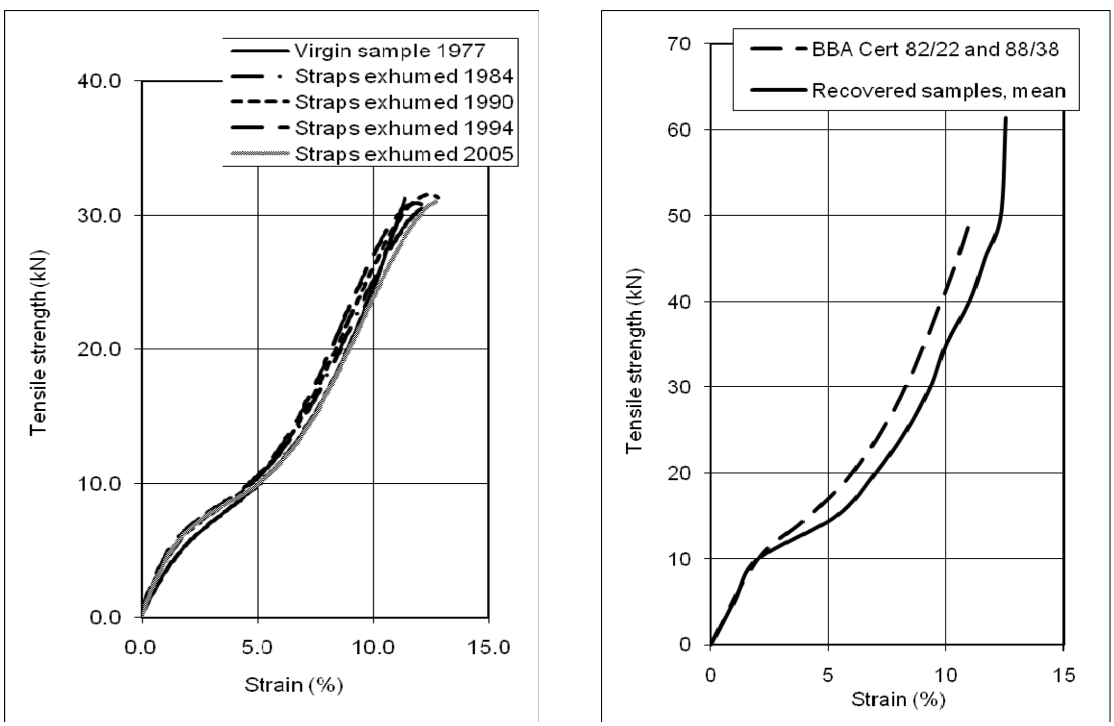

Figure 3. Results of tensile tests carried out on exhumed samples compared with virgin material, (a) TRL wall and (b) Kinali – Sakarya Motorway.

6. SCANNING ELECTRON MICROSCOPE ANALYSIS OF FIBRES

A Scanning Electron Microscope (SEM) technique was selected to examine the surface profile of the polyester fibres and to asses if any damage or degradation to the surface of the fibre due to hydrolysis was visible. The SEM technique was selected as it would identify surface pitting and holes which would indicate outer hydrolysis of the polyester. This technique was chosen over chemical analysis as it is difficult to prepare recovered fibres for chemical testing; the fibres can become contaminated with soil and polyethylene from the outer sheath of the reinforcing elements.

Three types of fibre were examined; the first were samples of the original polyester fibre used in the manufacture of the reinforcement elements for the TRL wall in 1977, the second was fibres from the recovered elements from the TRL wall, and the third were fibres recovered from the Kinali – Sakarya Motorway site, Figures 4, 5, 6. The recovered samples from the TRL wall at 500x and 1000x do show some contamination with flecks of unknown material clearly visible in the scans, Figures 4(b) and 5(b). The recovered samples from both the TRL wall and the Kinali – Sakarya Motorway, at a magnification of 4000x, show no evidence of pitting or surface damage, resulting from outer hydrolysis, Figure 5 (b) and 6(c), respectively.

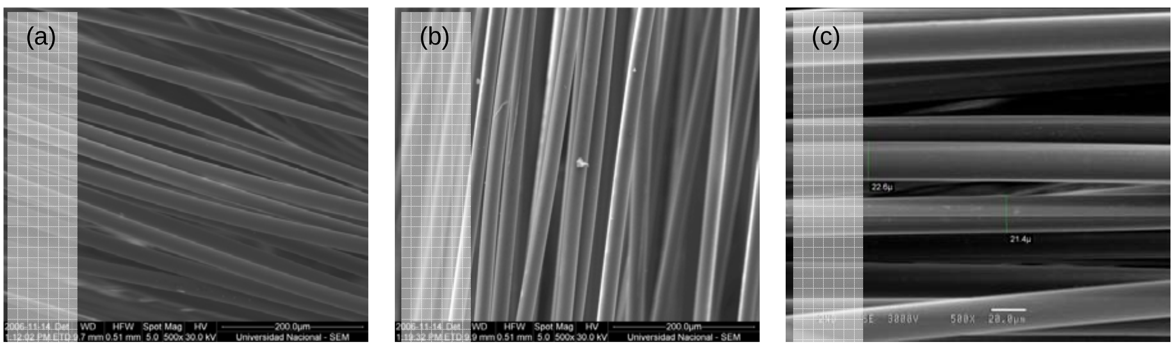

Figure 4. SEM images of (a) the original polyester fibre used in the manufacture of the reinforcement, (b) the recovered polyester fibre from the reinforcement in the TRL wall and (c) the recovered polyester fibre from the reinforcement in the Kinali – Sakarya Motorway at a magnification of 500x.

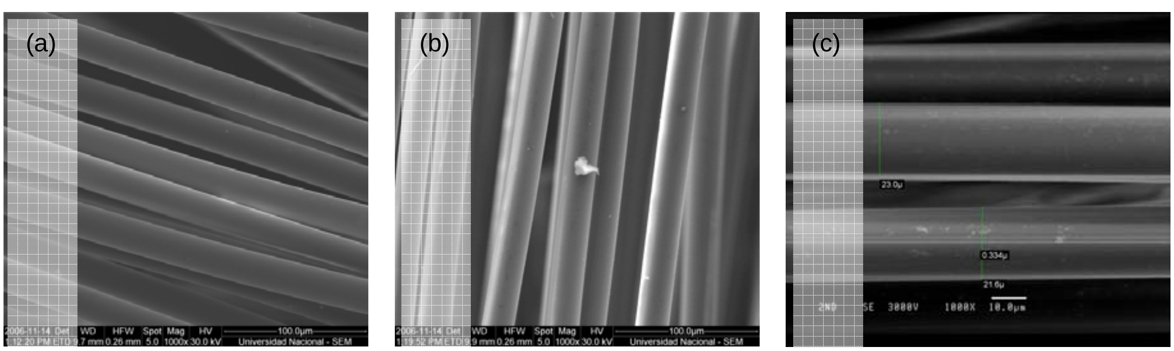

Figure 5. SEM images of (a) the original polyester fibre used in the manufacture of the reinforcement, (b) the recovered polyester fibre from the reinforcement in the TRL wall and (c) the recovered polyester fibre from the reinforcement in the Kinali – Sakarya Motorway at a magnification of 1000x.

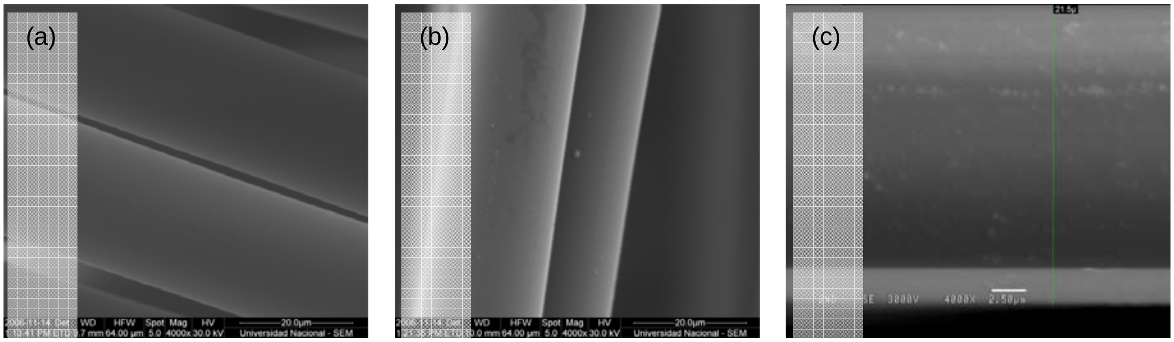

Figure 6. SEM images of (a) the original polyester fibre used in the manufacture of the reinforcement, (b) the recovered polyester fibre from the reinforcement in the TRL wall and (c) the recovered polyester fibre from the reinforcement in the Kinali – Sakarya Motorway at a magnification of 4000x.

7. DISCUSSION AND SIGNIFICANCE OF RESULTS

Polyester based reinforcing elements retrieved from structures in the UK and Turkey, which were in service for 20 - 30 years, showed no reduction in strength or stiffness. SEM images of the polyester fibres showed no physical changes or degradation had occurred and the retrieved samples had the same profile and cross section as the original virgin polyester fibre.

The majority of investigations into hydrolysis in polyester are conducted in saturated conditions and at elevated temperatures. These conditions are selected as they are an extreme case and allow the predictions of further strength loss at lower temperatures through appropriate models. To understand the weather environment at both sites examined in this study, data from the UK Met Office (Anon, 2009a) and the International Station Meteorological Climate Summary (Anon, 2009b) was used to estimate the relative humidity and mean temperature close to the two structures, Table 2. It is reasonable to assume that the temperatures quoted in weather reports are shade temperatures and significantly higher temperatures could occur locally (Burgoyne and Merii, 2007). The values of maximum mean temperature given in Table 2 can therefore be considered lower bound temperature values for exposed structures facing south in the Northern Hemisphere.

Table 2. Met Office UK (Anon, 2009a) and International Station Meteorological Climate Summary (Anon, 2009b) temperature and relative humidity values for the United Kingdom and Turkey

	United Kingdom		Turkey	
	Relative humidity (%)	Mean temperature (°C)	Relative humidity (%)	Mean temperature (°C)
Maximum	94	22	82	32
Minimum	60	1	70	3

Data from Murray and Farrar (1988), Howells and Pang (1989) and Jones (1995) showed that the constant soil temperature may vary from 10 °C in temperate climates to 20 °C in tropical climates. Müller-Rochholz et al. (2008) reported that the mean yearly temperature at 1 cm, 5 cm and 35 cm below ground surface was less than 15 °C and that the maximum temperature recorded in the soil never exceeded 25 °C for a site in Munich, Germany. Temperature measurements behind a reinforced soil wall near Tuscon, Arizona (USA) varied from a maximum of 18 °C in winter to a maximum of 36 °C in summer (Jones, 1995). For this discussion two temperatures will be used; 20 °C, representing the mean temperature in a soil mass and 40 °C representing the maximum temperature likely to be experienced in arid desert conditions. The temperatures are assumed to remain constant, resulting in a very conservative analysis as temperatures generally vary considerably through the year.

Determining the allowable load in the reinforcement using a BS 8006 (1995) / SANS 207 (2005) type calculation and the relevant partial material factors and creep limited strength from the current BBA Certificate No. 09/R146, (BBA, 2009) for these reinforcement elements suggest that the load in the reinforcement should be limited to 63 % and 39 % of ultimate strength for design temperatures of 20 ^{o}C and 40 ^{o}C, respectively, in fully saturated conditions with $4 \leq pH \leq 11$.

Based on the predicted life spans of PET 1 from Burgoyne and Merii (2007), which was a similar grade of polyester to that used in the two structures, an estimate of the life expectancy of the polyester at different percentages of ultimate load and different ambient temperatures can be made, Table 3. The experimental results from Burgoyne and Merii are for fully saturated conditions, and are therefore likely to be more severe than that found at high soil temperatures (40 ^{o}C) in desert conditions, where the degree of saturation of the soil could be low. At 20 ^{o}C the life expectancy is greater than a millennium, even for 70 % of ultimate, and therefore it is reasonable to assume that hydrolysis is insignificant and can be ignored. At 40 ^{o}C the rate of hydrolysis has increased, but for practical purposes hydrolysis will not affect the performance of the structure inside a normal design life of 120 years. For a reinforcement loaded to 40 % of ultimate, based on the BBA partial factors (Anon, 2009a) for these conditions, the life expectancy is 320.8 years, resulting in a factor of safety (based on time) of 2.67.

Table 3. Predicted life expectancy of the polyester used in the TRL wall and Kinali – Sakarya Motorway based on data from Burgoyne and Merii (2007).

Temperature (^{o}C)	Strength % ultimate	Life expectancy (years)
20	70	1,681
	60	2,738
	50	4,297
40	60	144.9
	50	227.3
	40	320.8

8. CONCLUSION

Retrieved samples of polyester based reinforcement, from structures in the UK and Turkey and which had been in service for 20 to 30 years, showed no reduction in tensile strength or stiffness.

A scanning electron microscope analysis of the surface of the retrieved fibres showed no evidence of surface pits or holes, which would be indicative of outer hydrolysis.

A laboratory study of hydrolysis on very similar polyester fibres to that used in the historic structures indicate that the life expectancy of polyester based reinforcements is well outside the typical design life of 120 years, even at for the extreme case of constant soil temperatures of 40 ^{o}C, $4 \leq pH \leq 11$ and fully saturated conditions. Where a structure is constructed from free draining material in a hot region there is likely to be no water in the fill and the hydrolysis mechanism will not be activated, irrespective of the temperature or pH level.

Degradation due to hydrolysis of polyester should be included in design codes. However, for good quality high tenacity polyester, hydrolysis of the polyester will not limit the design life of a structure nor will it cause failure of the structure, even at elevated temperatures in a fully saturated soil over a wide range of pH levels normally found in soils.

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