Field and laboratory based studies on the hydrolysis of polyester fibres

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ABSTRACT: Hydrolysis is often portrayed as a significant problem in polyester based geosynthetics. Liquids, such as water, provide the H^+ or OH^- ions necessary for hydrolysis. The rate of hydrolysis is accelerated by temperature. Analysis of the strength, stiffness and surface profile of exhumed samples of polyester from reinforced structures in the UK and Turkey showed no degradation of the fibres had occurred. A review of soil temperatures measured in reinforced soil applications indicate that a maximum temperature is recorded immediately behind the facing and that further back in the fill the temperature is significantly lower. The maximum temperature recorded behind the facing was never above ambient temperature and in most cases was at least 10 ^oC below ambient. A design temperature calculated in accordance with ISO TR 20432 (2007) showed good correlation with the maximum temperature measured in the soil backfill. The design temperature never exceeded about 35 ^oC. Measurements of moisture contents in reinforced structures (Hsuan et al., 2002) did not exceed 5 % in coarse grained, free draining fill and varied between only 20 % and 10 % in fine grained backfills. Natural soils have pH in the range 4.5 - 6.5. Where values outside of this range occur it is unlikely that they will be maintained for any extended period of time. Analysis of experimental data, conducted in saturated conditions, indicates that hydrolysis of polyester is not a problem for design temperatures in the range 20 – 40 ^oC and design lives of 100-120 years in normal soils.

1 INTRODUCTION

Soil reinforcement techniques are widely used in the construction of walls, slopes and embankments. Polyester has been used in reinforcement applications since the mid 1970's. The combination of strength, stiffness and low creep makes them suitable for a number of applications where steel would be either too heavy or too susceptible to corrosion.

Polyester fibres are prone to neutral, acid or alkali hydrolysis resulting in a reduction in both molecular weight and tensile strength. Neutral hydrolysis occurs in the presence of water. Acid hydrolysis is the same as neutral hydrolysis since both involve the H^+ ion. Burgoyne & Merii (2007) suggested that attack by alkaline species is different since it involves attack by the OH^- ion and takes place by removing material from the surface of the fibre.

Reinforced soil structures are typically designed for minimum life spans of 100-120 years. Therefore the effects of hydrolysis, which is both time and temperature dependent, are of major interest. This paper deals with the effects of hydrolysis, which is considered the principle mode of environmental degradation in polyester and, in particular, the effect of temperature in actual reinforced soil structures.

2 PROPERTIES OF RECOVERED SAMPLES

Naughton et al (2005) and Kempton et al (2008) analyzed the retained strength of polyester based reinforcements retrieved from reinforced soil walls in the UK and Turkey, respectively, which had been in service for over 25 years.

The retrieved samples of reinforcement showed no reduction in tensile strength or stiffness (Naughton et al, 2005 & Kempton et al, 2008). 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 hydrolysis. A detailed discussion on these findings is given in Naughton et al (2009).

3 MEASURED TEMPERATURES IN REINFORCED SOIL STRUCTURES

Very little information is published in the literature on the measured temperatures in reinforced soil structures. Data reported in the literature include Murray & Farrar (1988), Segrestin & Jailloux (1998), Jones (1995), Hsuan et al. (2002) and measurement reported by Müller-Rochholz et al. (2008) and Brady (1987) and Brady et al. (1995). Hong Kong Geoguide 6 (2002) and ISO TR 20432 (2007) provide guidance on the selection of appropriate design temperatures for assessing reinforced soil structures.

3.1 *Murray & Farrar (1988)*

Murray & Farrar (1988) reported seven years of temperature measurements observed at different locations in a reinforced earth retaining wall, with northern aspect, on the M25 near Waltham Cross, UK.

The observed temperature within the reinforced fill followed an annual cyclical pattern, varying between 0 ^{o}C and 19 ^{o}C with the seasons. Within about 0.3 m of the face of the structure the recorded temperatures were fairly close to ambient and attained a maximum value of 19 ^{o}C. Mean temperatures increased up to a distance of about 4m from the face after which they appeared to remain approximately constant to the rear of the reinforced fill.

Two dimensional analysis of temperature variation, reported by Murray & Farrar (1988) showed that apart from close to external surfaces where the temperature was close to ambient conditions, a maximum value of 16 ^{o}C can be expected, and towards the rear of the wall fill a maximum predicted temperature of 13 ^{o}C can be expected.

3.2 *Segrestin & Jailloux (1988)*

Segrestin & Jailloux (1988) presented temperature measurements recorded over a nine month period in a reinforced soil structure along the road to the Frejus tunnel in the French Alps.

At a particular point in the wall, located 3 m below the road surface and 2 m behind the wall facing the measured temperature varied between 0 ^{o}C and 21 ^{o}C over the monitoring period. A temperature of 30 ^{o}C was recorded a small depth below the road surface at the top of the wall. The external air temperature was recorded at 22.5 ^{o}C. However, temperature fluctuations have also been recorded by Robinson (1986), where temperatures in the range -15 ^{o}C to + 45 ^{o}C were measured at a depth of 250 mm beneath flexible road pavements in southern and central England.

Calculated maximum temperature variations in a soil mass behind a concrete facing unit during the summer months were determined using a finite difference technique, which was calibrated against the field measurements by Segrestin & Jailloux (1988). The model shows that a maximum temperature of 30 ^{o}C was predicted at a short distance behind the facing and that the temperature drops down to a value of about 20 ^{o}C further back in the soil mass. Segrestin & Jailloux (1988) also indicated that the maximum summer temperature behind the wall had a daily variation between 20 ^{o}C and 30 ^{o}C and that the yearly variation was between -5 ^{o}C and +25 ^{o}C, with a yearly average of 10 ^{o}C.

3.3 *Jones (1995)*

Jones (1995) presented temperature variations recorded in a reinforced soil wall in Arizona, USA. In summer values as high as 35 ^{0}C were recorded. However in winter soil temperatures reduced to between 13 ^{o}C and 16 ^{o}C.

3.4 *Hsuan et al. (2002)*

Hsuan et al. (2002) reported temperature measurements recorded in the backfill of three segmental block walls located in the northeastern United States. Details of the wall geometries and construction details are given in Hsuan et al. (2002). In all locations the measured soil temperature tended to be 10 ^{o}C to 20 ^{o}C below ambient. The maximum temperature recorded in any of the walls was 23 ^{o}C.

3.5 *Müller-Rochholz et al. (2008)*

Müller-Rochholz et al. (2008) reported that the mean yearly temperature, at a site in Munich Germany, at 1 cm, 5 cm and 35 cm below ground surface was less than 15 ^{o}C and that the maximum temperature recorded in the soil never exceeded 25 ^{o}C.

3.6 *Brady (1987) and Brady et al. (1995).*

Monitoring of reinforced soil structures on the Carmarthen bypass built in 1981 indicated that the mean temperature of the backfill was about 12 °C. As anticipated, the daily and seasonal variations in temperature reduced with increasing distance from an exposed surface.

3.7 *Geoguide 6 (2002)*

Geoguide 6 (2002) states that in Hong Kong, the difference in temperature experienced by the reinforcement throughout the year can be in excess of 15°C. The majority of the temperature differential occurs in the first 0.5 m behind the wall face, which was also observed by Segrestin & Jailloux (1988). Although the transient maximum soil temperature immediately behind the wall face could reach 35 ºC, the mean soil temperature beyond 0.5m from the wall face is approximately 26 °C (Geoguide 6, 2002). Geoguide 6 (2002) specifies a design temperature of 30 ºC that is intermediate between the average soil temperature and the transient maximum soil temperature.

3.8 *ISO TR 20432 (2007)*

ISO TR 20432 (2007) suggested that in the absence of site specific data that the design temperature can be taken as the mean of the average yearly air temperature and the normal daily air temperature for the hottest month.

3.9 *Summary of design temperatures*

Measurements and predications of soil temperatures indicate that soil temperatures cycle with seasonal variation (Murray & Farrar, 1988 and Jones, 1995) and that maximum temperatures develop in close proximity (within 1 m) of the concrete facing unit during summer (Segrestin & Jailloux, 1988). Measured values also indicate that the maximum soil temperature, immediately behind the face, is somewhere between the ambient and 10 ^{o}C less than ambient. Outside of this zone the soil temperature is considerably lower.

Estimates of design temperatures for the case histories and design guides discussed in this paper were made using air temperature data available from the BBC Weather website (Anon, 2009). Where the exact site location was not available the nearest city with data was used. The normal daily air temperature was assumed to be the maximum temperature during any month (effectively the hottest month) and the average yearly air temperature was taken as the average of the mean monthly temperature average over the year. The estimated design temperatures at the different locations are presented in Table 1 and a comparison of estimated design temperatures and maximum measured soil temperature values presented above is presented in Table 2.

The design temperatures vary from 21.7 ^{o}C in Cardiff to a maximum of 35.5 ^{o}C in Death Valley, one of the hottest and driest places on the planet. Very good correlation between the estimated design temperature and the maximum measured temperature was found.

Table 1. Estimated design temperatures at different location

Location	Normal daily air temperature (^{o}C)	Average yearly air temperature (^{o}C)	Estimated design temperature (^{o}C)
London	38	10.6	24.3
Cardiff	33	10.3	21.7
Lyon	40	11.5	25.8
Munich	36	8.3	23.2
Hong Kong	36	22.5	29.3
Phoenix	48	21.3	34.7
Death Valley	46	25	35.5
Philadelphia	41	12.3	26.6

Table 2. Comparison of estimated design temperature and maximum measured soil temperature

Location for estimated design temperature	Case study	Estimated design temperature (^{o}C)	Maximum measured soil temperature (^{o}C)
London	M25, Murray & Farrar (1988)	24.3	19
Cardiff	Carmarthen by pass, Brady (1987) and Brady et al (1995)	21.7	12*
Lyon	Frejus Tunnel, Segrestin & Jailloux (1988)	25.8	30^{+}
Munich	Munich, Müller-Rochholz et al. (2008)	23.2	25
Hong Kong	Hong Kong (Geoguide 6, 2002)	29.3	30
Phoenix	Arizona, Jones (1995)	34.7	35
Death Valley		35.5	
Philadelphia	Hsuan et al. (2002)	26.6	23

* mean value recorded
$^{+}$ measured in the road surface at the top of the wall

4 IMPLICATIONS OF DESIGN TEMPERATURE ON HYDROLYSIS OF POLYESTER

For hydrolysis to occur H^{+} or OH^{-} ions must be present. In soil neutral hydrolysis, in the presence of water, is the most common form of hydrolysis in soil reinforcement applications. The concentration of the H^{+} or OH^{-} ions is also important. However, in soil applications Martin and Dachroth (1994) reported that most natural soils would have their pH between 4.5 and 6.5. Where values outside of this range occur it is unlikely that they will be maintained for any extended period of time. In the absence of H^{+} or OH^{-} ions, i.e. water or other liquid, hydrolysis will not occur irrespective of the soil temperature.

Hsuan et al. (2002) also reported measured moisture contents inside the backfill of three segmental block wall constructed from different fill types, including coarse grained and fine grained fill. In the coarse grained backfills the moisture content never went above 5 %, indicating free draining material. One wall was constructed using fine grained fill. The initial moisture content was recorded as a maximum of 20 %, but this value decreased to 10 % within 70 %, due to drought conditions. The moisture content remained relatively constant, even after a prolonged wet period. Hsuan et al. (2002) concluded that the rainwater was unable to reenter the soil mass.

Burgoyne and Merii (2007) reported on the hydrolysis of uncoated polyester fibres in saturated conditions. Fibre PET 1 was very similar to the polyester used in the reinforcement elements in the TRL trial wall and the Kinali – Sakarya Motorway.

The Burgoyne and Merii (2007) study is particularly important as it provides information on the variation of several properties; tensile strength, intrinsic viscosity, and number average molecular weight for both relaxed (unloaded) and loaded specimens 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 °C.

Figure 1 is adapted from Burgoyne and Merii (2007) and indicates, for different design temperatures under saturated conditions, the percentage of ultimate load that can be applied continuously to a reinforcement element for a design life of 100 years. At 20 °C a polyester based reinforcement could carry over 90 % of its ultimate strength for 100 years. At 30 °C, 35 °C and 40 °C the reinforcement could carry 90 %, 80% and 70 % of its ultimate load for a 100 year period, respectively.

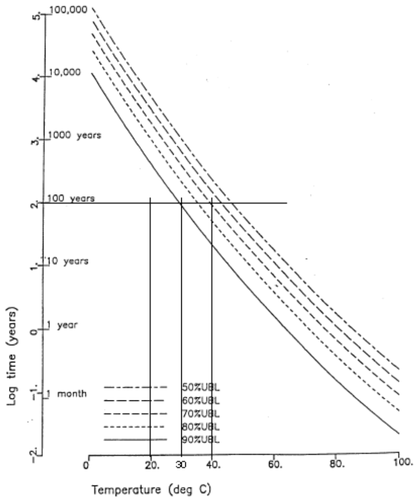

Figure 1. Percentage of ultimate load a polyester reinforcement can carry for different temperatures under saturated conditions (adapted from Burgoyne and Merri, 2007).

5 CONCLUSIONS

A review of temperature measurement from case histories indicates that the soil temperature reaches a maximum immediately behind the facing and then decreases further into the soil mass. The maximum temperature is never greater than the ambient temperature and is typically up to 10 °C below ambient Good correlation between calculated design temperatures, using the procedure in ISO TR 20432 (2007) and maximum measured temperatures was found. Maximum soil temperatures are unlikely to exceed 35 °C, even in hot arid locations like Death Valley.

H^+ or OH^- ions must be present, in the form of liquids in soil, before hydrolysis can occur. Measured concentration of these ions are generally in the range 4.5 ≤ pH ≤ 6.5. Where pH values outside of this range are found it is unlikely that they will be maintained for any significant period of time.

Moisture contents in coarse grained, free draining fill never exceeded 5 %. Even in fine grained fill the moisture content varied between only 20 % and 10 %.

An experimental study on hydrolysis of polyester under saturated conditions indicates that at a design temperature of 35 °C the polyester can safety carry 80 % of its ultimate strength for a 100-120 design life.

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