Lifetime prediction of high tenacity polyester yarns for hydrolytic degradation used for soil reinforcement

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ABSTRACT: The long-term strength is considered the various degradation mechanisms in the design of the reinforced soil structure so that ISO TR 20432 provides guidelines for the determination of the long-term strength of geosynthetics for soil reinforcement. Geosynthetics using polyester and polyamide are susceptible to hydrolytic degradation due to ester and amide group by condensation polymerization. In this study, the accelerated hydrolysis test was carried out to predict service lifetimes of polyester filament yarns which are widely used in geosynthetics for soil reinforcement. Two types of filament yarns with different carboxyl end groups(CEG) were immersed in distilled water at elevated temperature at 80, 90 and 95°C up to 112 days for shortening the test times. The reduction in tensile strengths was evaluated as the rate of hydrolytic degradation along the time at each temperature. The failure times were estimated to reach 50, 60, 70, 80, 90% of retained tensile strengths by linear regression using time as an independent variable and retained strength as a response variable. The service lifetimes of polyester filament yarns were predicted at service temperature using Arrhenius relation of failure times and temperatures. The service lifetimes of both polyester yarns are exceeding 100 years up to 80% of retained strength at 20°C of service temperature. This can provide guidance to designers and manufacturers of geosynthetics in calculating the specific reduction factor of hydrolytic degradation at 100 years of design lifetime.

Keywords: Hydrolysis, Hydrolytic degradation, PET, Long-term performance, Durability, Lifetime prediction, Arrhenius Relation, Accelerated test

1 INTRODUCTION

High tenacity polyester yarns have advantages in price as well as excellent mechanical properties including a low creep strain rate and good chemical resistance to most of acids and solvents. For this reason polyester yarns are widely used for industrial purposes. In civil engineering application, polyester yarns are also applied in the form of geogrids, geostrips, non-woven and woven geotextiles. Geosynthetics have used the design and construction of embankment, slopes and waste landfill in the last 20 years, and most soil structure reinforced geosynthetics have been designed to last up to 100 years. Therefore, long-term performance of geosynthetics is important for securing the safety of soil structure. ISO TR 20432 and ISO TS 13434 provide guidelines for the determination of the long-term strength for soil reinforcement and the assessment of durability of geosynthetics. Polymers are susceptible to environmental degradation due to weathering, to chemical and to biological degradation. These degradation mechanisms are further influenced by temperature and moisture uptake for some polymers. Especially polyester is susceptible to hydrolysis in aqueous solutions or humid soil at all values of pH (internal hydrolysis).

BS EN 12447 is an index test method to assess the resistance to hydrolysis for polyester yarn which is applied to evaluate 25, 50 and 100 years of service lifetimes in the guidelines of long-term strengths for geosynthetics such as ISO TR 20432, ISO TS 13434 and CE-marking product standards such as BS EN 13249 and BS EN 13251. In this study, the accelerated hydrolysis tests were designed and carried out according to modified BS EN 12447 in order to predict service lifetimes of polyester yarns considering various applications.

2 MATERIALS AND TEST METHODS

2.1 *Samples*

The high tenacity polyester yarns were used for the accelerated hydrolysis test. Before immersion in water the polyester yarns were wound onto a stainless steel spinneret for accelerated hydrolysis test. The characteristics of two samples are given in Table 1. PET1 show the higher tenacity and elongation while lower number average molecular weight and CEG than PET2. According to ISO TR 20432, ISO TS 13434 and FHWA-NHI-10-024, the number average molecular weight and CEG are required minimum of 25,000 and maximum of 30mmol/kg. PET1 meets all requirements while CEG of PET2 is higher than 30mmol/kg.

Table 1. Characteristics of high tenacity polyester yarns

Materials	High tenacity polyester yarns	
	PET1	PET2
Linear density (denier)	1,522	1,001
Measured tensile strength (N) (Standard deviation)	153.0 (1.8)	95.5 (0.82)
Tenacity (g/d) (Standard deviation)	10.2 (0.12)	9.7 (0.08)
Measured elongation at Maximum load (%) (Standard deviation)	11.2 (0.14)	10.3 (0.11)
Number average molecular weight	33,077	35,882
Carboxylic end group contents (mmol/kg)	25.7	36.7

2.2 *Accelerated hydrolysis tests*

BS EN 12447 specifies a screening test method for determining the resistance of geotextiles and geotextile-related products to hydrolysis by exposing test specimens to water at elevated temperatures. We performed the accelerated hydrolysis test under the modified conditions (temperatures and test durations) from BS EN 12447 in order to shorten the test times to predict 100 years of service lifetime. The polyester yarns were immersed in an autoclave filled with water at elevated temperatures of 80, 90, 95°C for 2,688 hours. The water was stirred during the test with magnetic stirrer.

2.3 *Tensile properties*

The hydrolyzed specimens were tested for tensile properties at eleven time intervals; 1, 24, 72, 168, 336, 504, 672, 1,008, 1,344, 2,016, 2,688 hours according to KS K 0412. Tensile strength tests were run using a strain rate of 300mm/min, tensile strains were measured via cross-head displacement using a 250mm gauge length. The control specimen which is exposed to same environment for one hour is determined to establish the base line for the tensile strength of the specific materials being tested. The ten specimens at each test condition were prepared by 8 twists per 10cm before tensile testing.

2.4 *Molecular weight and carboxyl end group content*

The number average molecular weight and carboxyl end group content of polyester yarns were measured according to GRI GG8 and ASTM D7409 respectively. GRI GG8 covers the calculation procedure to obtain the number average molecular weight from an inherent viscosity value which is produced based on the ASTM D4603 test procedure using a solvent of phenol/1,1,2,2-tetrachloroethane (40/60 weight % mixture) and at a test temperature of 25°C. This guide can determine the relative viscosity value following the test procedure described in ASTM D4603, the relative viscosity value is converted into intrinsic viscosity using the Billmeyer relationship. The number average molecular weight is calculated with intrinsic viscosity using the Mark-Houwink-Sakurada equation.

ASTM D7409 can be used for determining the CEG content, the method uses o-cresol as the solvent to dissolve polyester yarns at a temperature of 80°C. The polyester solution is titrated using potassium hydroxide via automatic titrator. The amount of potassium hydroxide that is required to complete the titration with the polyester solution is measured and subsequently used in the calculation to determine the content of CEG.

3 RESULTS AND DISCUSSIONS

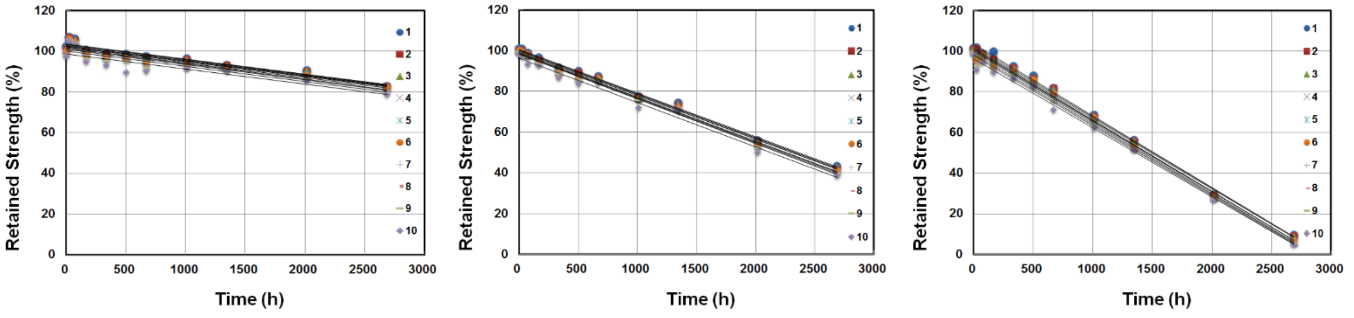
3.1 *Reduction in tensile strength*

The rate of hydrolysis was determined by the reduction in tensile strength. The tensile strengths of hydrolyzed polyester yarns are shown in Table 2. The tensile strengths decrease as the test temperature and time increase. Figures 1 and 2 show the reduction in tensile strengths along the time and the relationships between the retained strengths and test times are linear for both samples at all test temperatures.

The retained strengths of PET1 are slightly higher than those of PET2 after accelerated hydrolysis test for 2,688 hours at each test temperature. It is found that the CEG of polyester yarns show the significant effect on hydrolytic degradation.

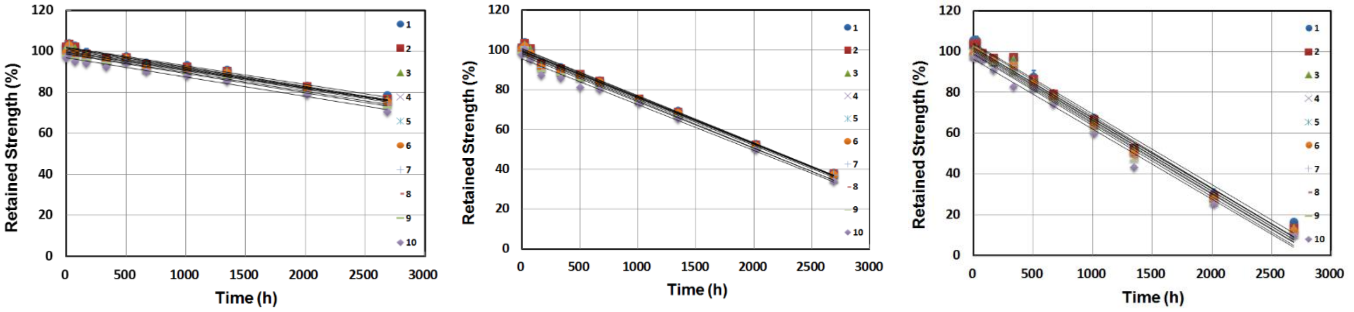
Table 2. Average tensile strength of polyester yarns after accelerated hydrolysis test at each test temperature.

Specimen	Test Temperature (℃)	Average tensile strength (N) after accelerated hydrolysis test										
		1h	24h (1d)	72h (3d)	168h (7d)	336h (14d)	504h (21d)	672h (28d)	1,008h (42d)	1,344h (56d)	2,016h (84d)	2,688h (112d)
PET1	80	154	163	161	151	149	148	145	145	141	136	125
	90	158	157	154	149	141	137	136	120	115	85	65
	95	149	143	145	140	135	127	117	100	80	42	10
PET2	80	97.2	99.6	96.5	94.5	92.6	93.4	89.7	88.3	86.6	79.2	72.9
	90	100.1	102.1	98.4	91.4	89.0	86.2	83.0	74.8	67.7	51.6	36.6
	95	92.4	93.3	90.2	87.9	86.1	77.9	71.3	59.1	45.9	25.5	11.2



(a) 80℃ (b) 90℃ (c) 95℃

Figure 1. Reduction in tensile strengths of PET1 at 80, 90, 95℃



(a) 80℃ (b) 90℃ (c) 95℃

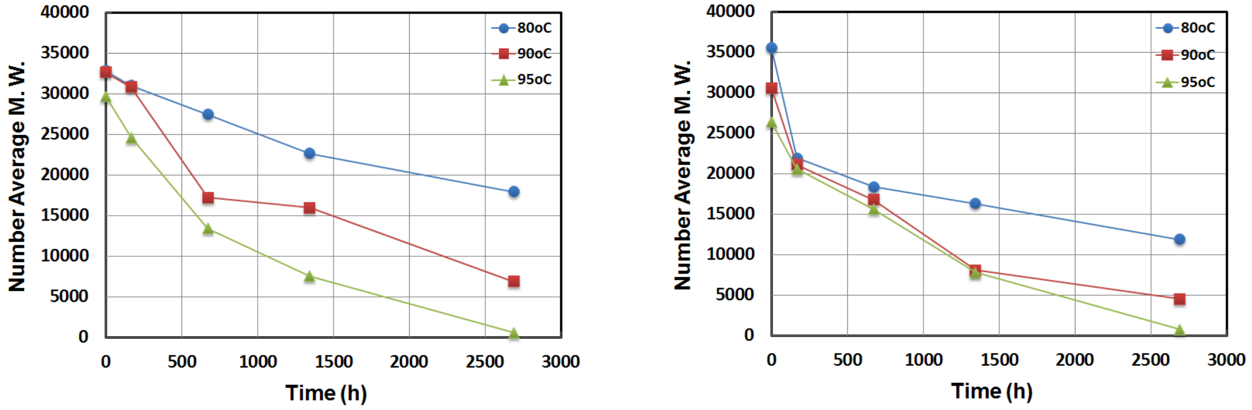
Figure 2. Reduction in tensile strengths of PET2 at 80, 90, 95℃

3.2 *Reduction in molecular weight*

PET molecular weight can affect the mechanical properties of polyester yarns by influencing the physical state. The number average molecular weights over test times at each temperature are shown in Table 3. The number average molecular weight decreases as the test temperature and time increase. Figure 3 shows the reduction in number average molecular weight for PET1 (Figure 3(a)) and PET2 (Figure 3(b)), respectively. In the initial state, the number average molecular weight of PET2 is greater than that of PET1, while the number average molecular weight of PET 2 decreases more significantly than that of PET1 as the test time increases. For PET1, the number average molecular weight decreases linearly at 80°C while the reduction rate increases exponentially at 90 and 95°C. For PET2, the number average molecular weight of polyester yarns decreases exponentially along the time at all test temperatures.

Table 3. Number average molecular weight of polyester yarns after accelerated hydrolysis test at each test temperature.

Specimen	Test temperature (℃)	Number average molecular weight after accelerated hydrolysis test				
		1h	168h	672h	1,344h	2,688h
PET1	80	32,856	31,017	27,468	22,632	17,935
	90	32,647	30,829	17,200	15,958	6,879
	95	29,707	24,635	13,407	7,568	589
PET2	80	35,583	21,945	18,362	16,291	11,892
	90	30,576	21,134	16,800	8,067	4,544
	95	26,419	20,610	15,643	7,794	805



(a) PET1 (b) PET2

Figure 3. Reduction in number average molecular weight of polyester yarns at 80, 90, 95℃

3.3 *Estimation of failure times*

The hydrolysis rate of polyester yarns is commonly evaluated by the reduction of tensile properties which can be used to predict the long-term performance of the products, particularly for reinforcement applications. CE-marking product standards require 50% of tensile strength retention as a failure criterion while the lifetime prediction was performed at various failure criteria including 50% of retained strength in order to simulate the various applications. The failure times were estimated to reach 50, 60, 70, 80 and 90% of retained tensile strengths by linear regression as given in Table 4.

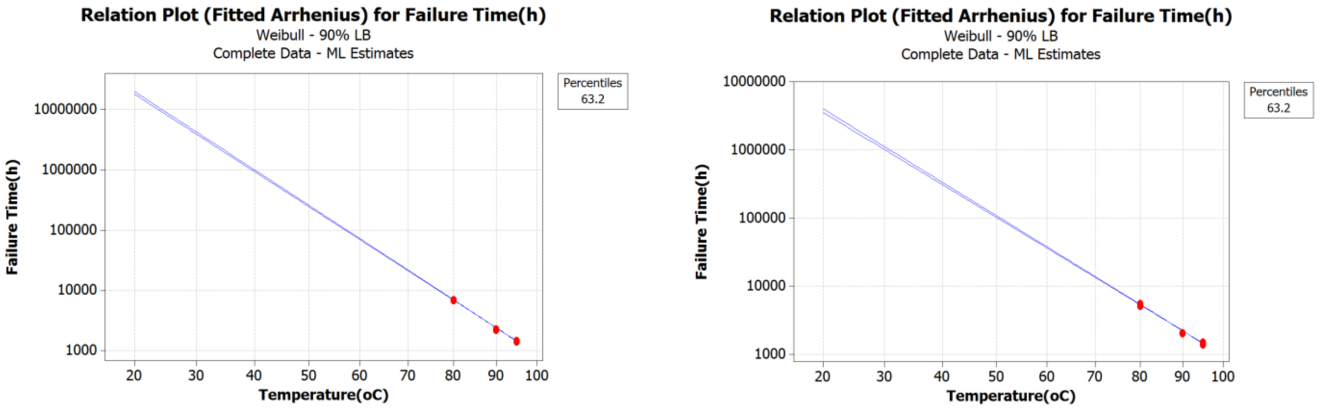
Table 4. Average failure time of polyester yarns at various failure criteria

Specimen	Test temperature (℃)	Average failure time (h) at various failure criteria (percent of retained strength)				
		50%	60%	70%	80%	90%
PET1	80	7,004	5,648	4,292	2,936	1,580
	90	2,267	1,805	1,343	881	419
	95	1,446	1,159	872	584	297
PET2	80	5,428	4,343	3,258	2,173	1,088
	90	2,085	1,657	1,230	803	375
	95	1,463	1,175	887	599	310

3.4 *Lifetime prediction*

The service lifetimes were predicted using Arrhenius relation between failure times and test temperature under the assumption that the failure times follow Weibull distribution as shown in Figure 4. This means that the degradation rate at a given field ambient temperature can be extrapolated from the accelerated test temperatures, if activation energy of the hydrolysis reaction is known. In this study, we obtained the activation energies of polyester yarns which are 114.6kJ/mol for PET1 and 95.6kJ/mol for PET2. It means that the higher the activation energy, the less the hydrolytic degradation.

The MTTFs (mean times to failure) of polyester yarns are estimated at various failure criteria and service temperatures in Table 5. The PET1 show longer MTTFs than PET2. This is due to the higher CEG of PET2 than that of PET1. The service lifetimes of both polyester yarns are exceeding 100 years up to 80% of retained strength at 20℃. It also means that both polyester yarns are suitable for use in civil engineering applications required by ISO TR 20432 and CE-marking product standards.



(a) PET1

(b) PET2

Figure 4. Arrhenius diagram of high tenacity polyester yarns at 50% retained strength.

Table 5. Service lifetimes at each service temperatures.

Specimen	Service temperature (℃)	Service Lifetimes (years, MTTF) at various failure criteria (percent of retained strength)				
		50%	60%	70%	80%	90%
PET1	20	2,290	1,892	1,492	1,101	741
	25	1,044	861	676	495	326
	30	489	402	315	229	147
	40	115	94	73	53	32
PET2	20	466	364	263	164	70
	25	242	190	138	86	37
	30	129	101	74	46	20
	40	39	30	22	14	6

4 CONCLUSIONS

In this study, we have predicted the service lifetimes of high tenacity polyester yarns for hydrolysis used for civil engineering application through evaluating the retained tensile strengths and reduction in molecular weight. The accelerated hydrolysis tests were carried out for high tenacity polyester yarns with different CEG content at 80, 90, 95℃ for 2,688 hours in order to shorten the test times.

The reduction in tensile strengths shows linear along the time for both samples while the molecular weight decreases exponentially for both samples except that of PET1 at 80℃. The activation energy of PET1 is higher than PET2 so that the service lifetime of PET1 for hydrolysis is shown 5 times longer to reach 50% of retained strength than that of PET2. This implies that the CEG of the polyester yarns has significant influence on the hydrolysis resistance of the geosynthetics. The lower the value, the higher the hydrolysis resistance of the polyester yarns.

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