A STUDY ON DURABILITY OF CARBON FIBER REINFORCED POLYMERS IN CIVIL APPLICATIONS

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1 Introduction

Since carbon fibers were commercially available in 1970s, carbon fiber reinforced polymers (CFRPs) developments have mainly been driven by high-performance and low-volume production industries like aerospace and sports goods due to high production costs resulting from expensive raw materials and labor intensive fabrication processes [1]. However, recently, carbon fiber reinforced polymers (CFRPs) have received much attention as industrial materials due to their advantages such as high strength and stiffness to weight ratio, excellent corrosion resistance, and design flexibility. In particular, they are widely used in the construction and rehabilitation of civil engineering structures such as buildings and bridges. CFRPs can reduce the burden on the weight of the existing structure and increase stiffness, strength and enduring durability of the structures [2-3]. These reinforcements are readily available in several forms ranging from factory-made laminates to dry fiber sheets that can be wrapped to conform to the geometry of a structure before impregnation of polymer resins.

Although the CFPR tendons are widely used for externally bonded reinforcement (EBR) and externally non-bonded reinforcement (ENBR), the limited information of their durability restricts their applications. The lifetime prediction of CFRPs is very important for a practical application in various industrial sectors, particularly, architecture and civil engineering due to a greater concern of safety and durability. In this study, long-term durability and the safety life-time prediction were performed through the assessment of long-term effects on the properties of the CFRP tendons with the use of accelerated hydrothermal aging tests.

2 Experiments

2.1 Materials

T700 grade carbon fibers (CF) were used to manufacture unidirectional composites with a flat strip of the width of 50 mm and the thickness of 1.2 mm using a pultrusion process. These pultruded composites are commercially available and used for pretensioning and post-tensioning tendons for building and bridge repair.

2.2 Mechanical tests

The tensile specimens were prepared from a pultruded flat strip on basis of America Society for Testing and Materials (ASTM) with the dimension of 250mm × 13mm. Tensile tests were carried out with H100KS of a Tinus-Olsen's universal test machine using 100 kN loadcell, according to ASTM D3039, and were performed using gauge length of 150 mm at a crosshead speed of 2 mm/min.

The dynamic mechanical analyzer (DMA, TA Instrument Q-series) was used to determine glass transition temperature (T_g) with the 2°C/min heating rate and multiple frequencies of 0.3, 1, 10, 50, 100 Hz.

2.3 Hydrothermal aging tests

Hydrothermal aging tests were carried out according to “Standard Specification for Fiber Reinforced Polymer Composite Materials for Highway Bridge Applications, US Federal Highway Administration (FHWA) and ASTM” [4]. The test temperatures were determined based on a reference temperature (T_{ref}), taken as 80% of T_g, and ΔT ($[T_{ref}$-$40^oC]/3$). The four test temperatures are $T_1=T_{ref}$, $T_2=T_{ref} - \Delta T$, $T_2=T_{ref} - 2\Delta T$, and $T_3=T_{ref} - 3\Delta T$. The longitudinal and transverse samples with fiber direction along and perpendicular to the test span were immersed in de-ionized water at 40, 55, 70, 85°C for periods of 28, 56, 112 and 224 days.

3 Results and Discussion

3.1 Glass transition temperature

Table 1 shows the change in the glass transition temperatures measured by contact points of two tangent lines on storage modulus curves (G'), loss modulus (G'') and tan δ peaks, as shown in Fig. 1. The T_g increases with increasing frequency and the T_g of the longitudinal samples is higher than that in transverse direction due to reinforcing effects of carbon fibers. In contrast, the transverse samples are subject to the applied dynamic stress and stronger sensitivity of the matrix can accounts for the lower T_g. The apparent activation energy for glass transition, ΔE_a, can be used to characterize the relationship between the shift of glass transition temperature and frequency [5]. The activation energy represents the energy barrier of glass transition and can be calculated from the relationship between frequency and glass transition temperature through,

$$\Delta E_a = -R\left[\frac{d(\ln f)}{d(1/T_g)}\right] \qquad (1)$$

Where R is the Universal Gas Constant (1.9872 $\mathrm{cal\,mol^{-1}K^{-1}}$) and f is test frequency. The activation energy can be used as a means of monitoring material transition as a result of aging and/or environmental exposure [5]. As shown in Table 2, the longitudinal sample has much higher activation energy than that of the transverse sample, indicating that the latter is more susceptible to aging and can easily degrade under a certain environmental or service condition than the former.

3.2 Hydrothermal aging on CFRP tendons

The changes of T_g with time for the hydrothermally aged longitudinal samples are shown in Table 3. The T_g cannot be measured for the aged transverse samples due to the loss of stiffness for the DMA tests. The decrease in T_g can be attributed to the plasticization caused by the hydrothermal exposure [5], which is accelerated through the immersion at higher temperatures due to more moisture uptake, as shown in Fig. 2. As expected for a thermally activated process, the higher temperature accelerated moisture uptake, which in turn decreased the glass transition temperature.

The tensile modulus and strength of untreated longitudinal CFRP tendons are 172.2 GPa and 3605.5 MPa, respectively. According to the American Concrete Institute (ACI) guideline [6], the design ultimate strength, f_{fu}, for CFRP is suggested to ensure the effectiveness of the rehabilitation over the life of the structures, which can be expressed as,

$$f_{fu} = C_E f_{fu}^{*} \qquad (2)$$
$$f_{fu}^{*} = \overline{f_{fu}} - 3\sigma$$

where $\overline{f_{fu}}$ is the mean strength and σ is the standard deviation of the test population. C_E is the environmental reduction factor. For the exterior exposure with C_E of 0.85, the design ultimate strength is 3409.2 MPa and the stress limit is 1593.8 MPa to avoid the creep-rupture of the CFRP tendon under sustained stresses or fatigue failure due to cyclic stresses.

Table 4 and 5 show the effects of aging temperature and time on the tensile properties of the longitudinal CFRP tendons and on the flexural properties of the transverse CFRP tendons, respectively. The modulus and strength are significantly reduced as the temperature and aging time increase for both specimens. The most significant reduction was found for the transverse CFRP because the transverse flexural properties are one of matrix- and/or interface-relevant mechanical properties, indicating that the more the composite properties depend on the matrix or interface, the stronger the influence of the hydrothermal aging are. Such dependence can be explained by the removal of the matrix due to hydrolytic degradation and interfacial failure between matrix and fibers, which can be seen in the surface of the CFRP specimens, as illustrated in Fig. 3. Obviously, the reduction in the mechanical properties is due to the hydrolytic degradation in epoxy resins under humidity and elevated temperatures, leading to the weaker interface of the aged specimen because the failure mode changed from the matrix failure to more interface-relevant failure, as shown in Fig. 4.

The retention of the tensile strength for the hydrothermally aged samples is shown with time using a logarithmic scale in Fig. 5. As discussed before, the higher accelerated ageing can be seen at the highest temperature of 85°C. The Arrhenius method is applied to predict the service life. The 80, 70, 60, 50% data are plotted as a function of inverse temperatures in Fig. 6. The 80% retention can be predicted at 17.46°C (annual average maximum temperature in Seoul, Korea) over a hundred years through the extrapolated relationship, as shown in Fig 6. However, it must be borne in mind that the accelerated tests are only valid in the same degradation mechanisms between the accelerated and actual service conditions.

Table 1 Change in glass transition temperatures of CFRP tendons as a function of frequency

Specimen	Frequency	G'	G"	tan δ
	[Hz]	T_g [°C]		
Longitudinal	0.3	84	106	117
	1	89	113	123
	10	93	115	125
	50	95	120	129
	100	97	122	132
Transverse	0.3	58	75	86
	1	75	91	98
	10	66	86	97
	50	78	102	112
	100	70	93	112

Table 2 Activation energy of CFRP tendons

Specimen	G'	G"	tan δ
	Activation energy [kJ/mol]		
Longitudinal	516.3	475.2	549.2
Transverse	167.5	208.6	240.8

Table 3 Hydrothermal effects on glass transition temperatures of CFRP tendons

Days	Temperature (°C)			
	40	55	70	85
28	117.6	111.3	69.7	-*
56	116	77.8	65.6	-
112	97.7	71.7	59.1	-
224	87.7	-	-	-

*impossible to measure

Table 4 Hydrothermal effects on tensile properties of longitudinal CFRP tendons

Aging time [Days]	Temperature [°C]			
	40	55	70	85
	Modulus [GPa]	Modulus [GPa]	Modulus [GPa]	Modulus [GPa]
28	123.6	121.7	121.9	115.6
56	123.6	123.5	117.9	107.4
112	102.6	103.2	98.9	63.9
224	86	60.5	37.8	-
	Strength [MPa]	Strength [MPa]	Strength [MPa]	Strength [MPa]
28	3607.0	3473.6	3406.6	2744.0
56	3589.3	3330.9	3057.3	2040.1
112	3362.7	2592.6	2424.5	1153.3
224	3354.1	2952.6	2154.1	-

Table 5 Hydrothermal effects on flexural properties of transverse CFRP tendons

Aging time [Days]	Temperature [°C]			
	40	55	70	85
	Modulus [GPa]	Modulus [GPa]	Modulus [GPa]	Modulus [GPa]
28	14.9	10.8	16.3	11.2
56	9.9	9.2	10.1	2.8
112	7	5.6	4.1	-
224	4.7	4.3	0.6	-
	Strength [MPa]	Strength [MPa]	Strength [MPa]	Strength [MPa]
28	72.5	37.7	33.6	21.8
56	52.1	25.6	29.9	7.7
112	36	23.2	14	-
224	24.5	15.9	2.6	-

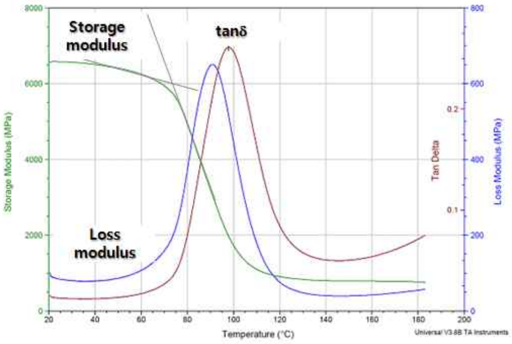


Fig.1. Typical DMA curves of UD CFRP tendons as a function of temperature.

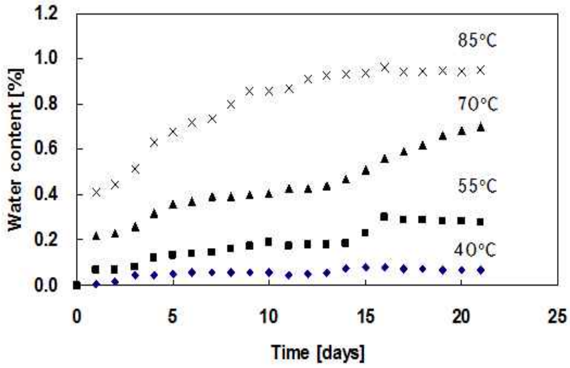
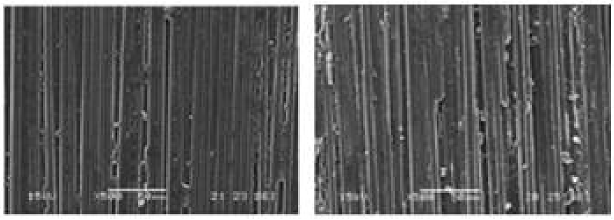
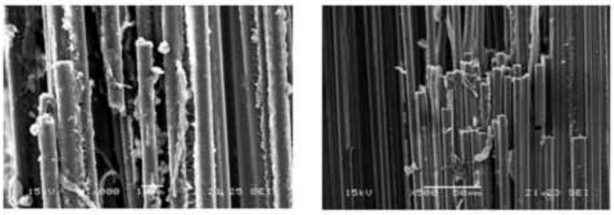


Fig.2. Water absorption of CFRP tendons as a function of temperature.



(a) (b)

Fig.3. SEM microscopes of CFRP tendons surfaces; (a) virgin and (b) hydrothermally aged specimens.



(a) (b)

Fig.4. SEM microscopes of fracture surfaces of CFRP tendons; (a) virgin and (b) hydrothermally aged specimens.

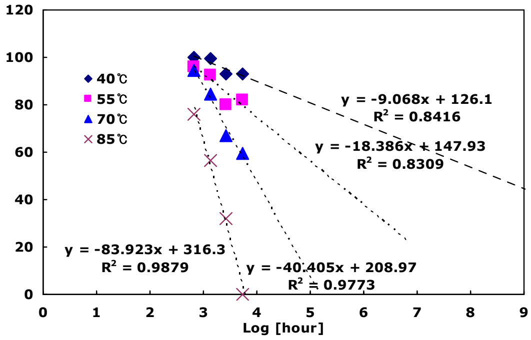


Fig.5. Property retention of CFRP tendons as a function of aging time.

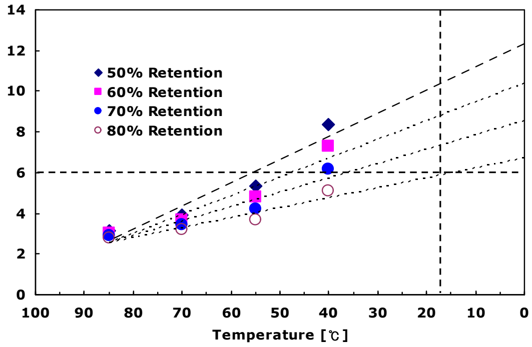


Fig.6. Arrhenius plot for prediction service life as a function of temperature and percent retention.

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