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Mechanical properties and fracture behavior of nonwoven fabric reinforced plastics for rehabilitation of sewage pipes

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Trenchless construction of repair works on sewage pipes has been developed. In such methods, fiber reinforced plastics (FRP), especially nonwoven fabric composites with polyester felt, have been used. In order to reduce pressure to force the reinforcements on the wall of a pipe, low weight FRP have been expected. In the present study, FRP using polypropylene (PP) felt and banana-polyester felt which have lower density comparing with conventional polyester poly(ethylene terephthalate) (PET) felt were developed for alternative reinforcement. Three-point bending and creep tests were conducted to evaluate the mechanical properties of the composites. In static bending, PET and banana composites showed brittleness, whereas PP composites failed in a stable manner. Especially, PP composites with thicker layers showed higher load-bearing capacity. Creep test results indicated that modulus retentions of PET and PP composites are comparable. It was found that the composites using thicker PP nonwoven fabric was a candidate material for the rehabilitation of sewers.

Keywords: FRP; polypropylene felt; sewage pipes; nonwoven fabric composites

1. Introduction

In recent years, the number of repair works of sewerage pipes has been increasing with increasing decrepit pipes. Previously, a replacement of an old pipe with new one has been performed for the works of pipes. This work requires higher cost and longer time because of excavation work of the ground. In order to overcome the problem, nonexcavation works to reinforce the old pipe from the inside with fiber reinforced plastics (FRP) have been developed and performed.

Nonwoven fabric composites have been used for the repair works. The reinforcement in the FRP used for a repair work of pipe is polyester felt because of high water resistance and good moldability, and the resin used in the FRP is thermosetting plastics (e.g. unsaturated polyester and vinylester resin) because of higher corrosion resistance and good moldability. In a repair work, a continuous resin-impregnated polyester felt tube is inserted into an existing pipe. The tube is inverted against the inner wall of the pipe and allowed to cure [1]. In this process, high-pressure air or water is required for inverting a longer tube. In order to reduce working pressure and also the cost for a work, an alternative material with lower specific

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weight is desired, whereas similar strength comparing to that of conventional one is also necessary.

For discussing the alternative material, information about micro-fracture process of a material is also important because it dominates final fracture. As for the microscopic fracture process in short fiber reinforced composites, Youjiang et al. investigated the effect of texture on the fracture process of carbon fiber mat reinforced composites [2]. Karger-Kocsis, Harmia, and Czigany studied the micro-fracture process of chopped long glass fiber and continuous glass fiber composites [3]. Bussiba characterized micro-fracture process of various composites consisting of short glass fiber, carbon particles, etc. with acoustic emission measurements [4]. These studies are limited on the composites with inorganic material fillers and there is little study about nonwoven polymer fabric composites used for repair works of sewages.

In this work, we focused on a nonwoven fabric composite using PP or banana fiber non-woven fabric and epoxy, because they have lower densities and reasonable costs comparing with conventional polyester felt and vinylester resin, as shown in Table 1. In order to evaluate the mechanical properties of the composites as an alternative material for rehabilitation works of a sewage pipe, three-point bending tests, with *in situ* observation of damage progress, and creep tests were conducted. Modulus retention after 50-year usage, which is a requirement for a material used for sewer rehabilitation, was also estimated with time–temperature superposition principle. From experimental results, the alternative FRP applied for rehabilitation of sewage pipe were discussed.

2. Experiments

2.1. Materials

In preparing of nonwoven fabric composite in this study, mixture of Epikote 828 (Mitsubishi Chemical Co.) of 130 g and triethylenetetramine of 14.3 g (Wako Co.) was used as a matrix and poly(ethylene terephthalate) (PET), polypropylene (PP), and mixture of banana fibers and polyester (banana) felts were used as nonwoven fabrics.

Fabricating process of PP felts was as follows. First, PP fiber flocks were opened by a rag machine and cotton-like PP was obtained. Then, the fibers were carded into fleece with a carding machine. Thin PP fleeces were laminated with eight, four, two, and one layers. With conducting a needle process on the surface of laminated PP fleeces, felts with different thicknesses were fabricated. In order to obtain composites with same thickness, one, two, four, and eight felts were laminated, respectively. As a result, laminated felt composites including different number of layer interfaces were obtained, as shown in Figure 1. In the present study, specimens are described as one, two, four, and eight layers, respectively. PET and banana felts were fabricated in a same manner, whereas only one-layer composites were fabricated.

The felt and the epoxy resin were put in a polyethylene bag and the bag was sealed up. Then, a small metallic tube connecting to a vacuum pump was stuck into the bag and the felt was impregnated with the resin in vacuum. After impregnation, tube entry point on the bag was closed and the bag was set in a metallic mold. Impregnated PP felt in the bag was cured at 50 °C for 1 h and at 100 °C for 1.4 h in an oven. After being cured, it was cut into a rectangular specimen of 4 mm × 10 mm × 80 mm.

Table 1. Densities of materials.

PET fiber	PP fiber	Banana fiber	Vinylester	Epoxy
1.36	0.99	0.80	1.19	1.12

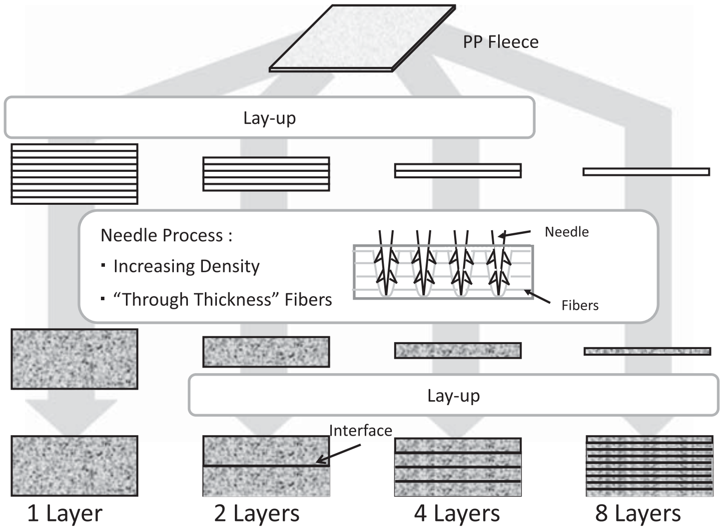

Figure 1. Schematics of laminations.

2.2. *Three-point bending test*

In order to estimate mechanical properties of nonwoven fabric composites, three-point bending tests were performed at a cross-head speed of 2.0 mm/min. AG50-KNISD (Shimadzu Co.) and LU-50KE (Kyowa Electronic Instruments Co.) were used as a test machine and a load cell, respectively.

2.3. *Observation of damage mechanism and crack propagation*

In order to clarify damage behavior of the composites, macroscopic and microscopic *in situ* observations were conducted during the three-point bending test. For the macroscopic and microscopic observations, a digital video camera (HFM-31, Canon Co.) and a video microscope (VW-5000, Keyence Co.) located around the loading point were used, respectively.

2.4. *Creep test at elevated temperature*

To estimate modulus retention after 50-year usage of the nonwoven fabric composites, three-point bending creep tests were performed at the temperatures of 30, 40, 50 and 60 °C for 2 h. Test load was selected as loading of 0.25% strain to specimen. Tests were performed in an oven and deformation of specimen was measured using the dial gauge (DT-10, Kyowa Electronic Instruments Co.).

In the present study, bending stress, σ_0, strain, ε, and creep compliance, D, were calculated as:

$$\sigma_0 = \frac{3PL}{bh^2} \tag{1}$$

$$\varepsilon = \frac{6hd}{L^2} \tag{2}$$

$$D(t,T) = \frac{\varepsilon}{\sigma_0} = \frac{1}{E} \tag{3}$$

where, P is load, L is loading span, b is specimen width, h is specimen thickness d is displacement, t is time, and T is temperature.

2.5. *Time–temperature superposition principle and long-term creep property*

In the present study, modulus retention after 50-year usage was estimated according to the time–temperature superposition principle. For various nonwoven fabric composites, master curves at 30 °C were drawn by translating creep curves at higher temperature to longer time. If the relation between shift factor and reciprocal temperature can be approximated by Arrhenius equation:

$$\text{Log } a(T) = \frac{\Delta H}{2.303G}\left(\frac{1}{T} - \frac{1}{T_0}\right) \tag{4}$$

where, Log $a(T)$ is shift factor, ΔH is activation energy, G is gas constant, and T_0 is reference temperature. Shift factor and reciprocal temperature is estimated as a linear relation by the method of least squares. If a correlation coefficient between experimental results and the least squares approximation is more than 0.97, the time–temperature superposition principle is applicable for estimation of creep deformation [5]. We evaluate modulus retention of the composite after 50-year usage based on the extrapolation of a master curve and discuss the applicability for sewage rehabilitation.

3. Result and discussion

Figure 2 shows the bending stress–strain curves of PET and banana composite and P–P composite with different layers. For PP composite, rapid stress decrease and subsequent stress increase with increasing strain were observed, which is caused due to crack formation. For eight layers, stress decreases with increasing strain. Compared with PP composites, the PET and the banana composites were fractured at lower strain in a brittle manner, which indicates brittle characteristics of the composites. Figures 3 and 4 show the bending strength and modulus of the composites. In the bending strength, the stress at an initial crack formation and the maximum stress up to strain of 10% are shown. PET, banana, and eight-layer composites

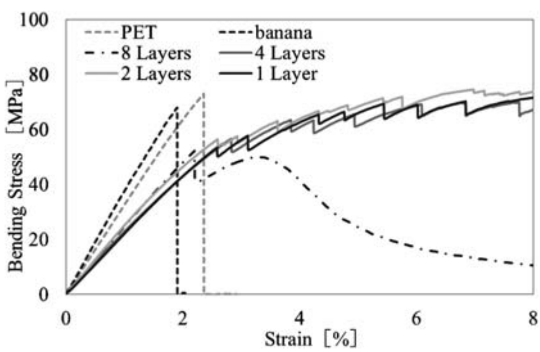

Figure 2. Bending stress–strain curves of composites.

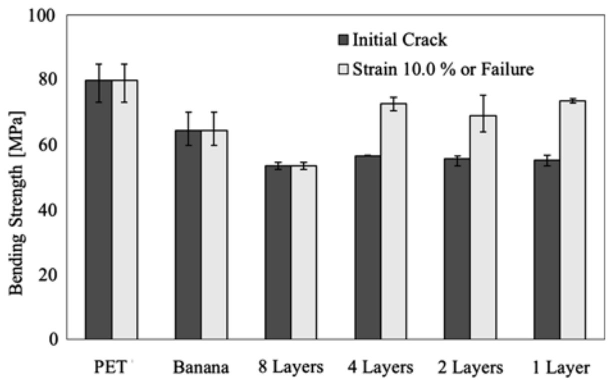

Figure 3. Bending strength of composites.

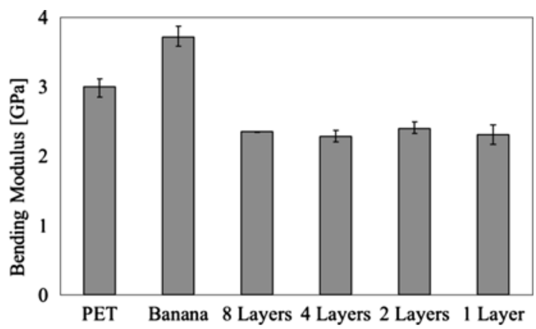

Figure 4. Bending moduli of composites.

did not recover the stress at initial cracking. For maximum stress up to strain of 10%, there were no differences for one-, two-, and four-layer composites. Bending modulus of the banana composite was highest, followed by the PET composite. Bending strength and modulus of PP composite were comparable for one, two, and four layers.

Figure 5 shows the result of macroscopic observation on the eight-layer composite which shows stress decreasing with increasing strain. An initial crack formed at strain of 2.36%. With increasing strain, the initial crack propagated extensively without other crack formations, and then the specimen failed. Figure 6 shows the result of microscopic observation on the eight-layer composite. In this composite, process zone formation which includes fiber/matrix debondings preceded crack propagation. This was due to lower fiber–matrix interfacial strength. For eight-layer composite, crack propagation was stable because process zone decreased stress concentration near crack tip.

The one-, two-, and four-layer composites, which show no stress decreasing with increasing strain, failed in the same manner. Figure 7 shows the result of macroscopic observation on the one-layer composite. An initial crack formed at strain of 2.67%. With increasing strain, the initial crack did not propagate extensively and multiple cracks formed in the axial direction. The composites did not fail up to strain of 10%. Figure 8 shows the result of microscopic observation on the two-layer composite. The results indicated no process zone formation and less crack propagation. This was due to crack arrest by fiber aggregation entangled during needle process, which results in multiple cracking at the tensile side during bending.

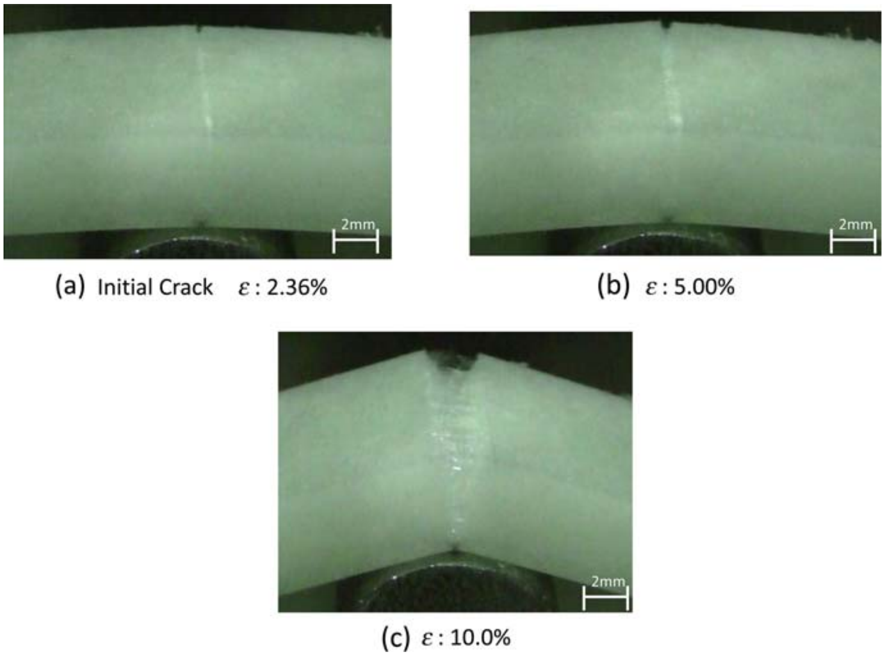

Figure 5. Macroscopic observation results of eight-layer composites.

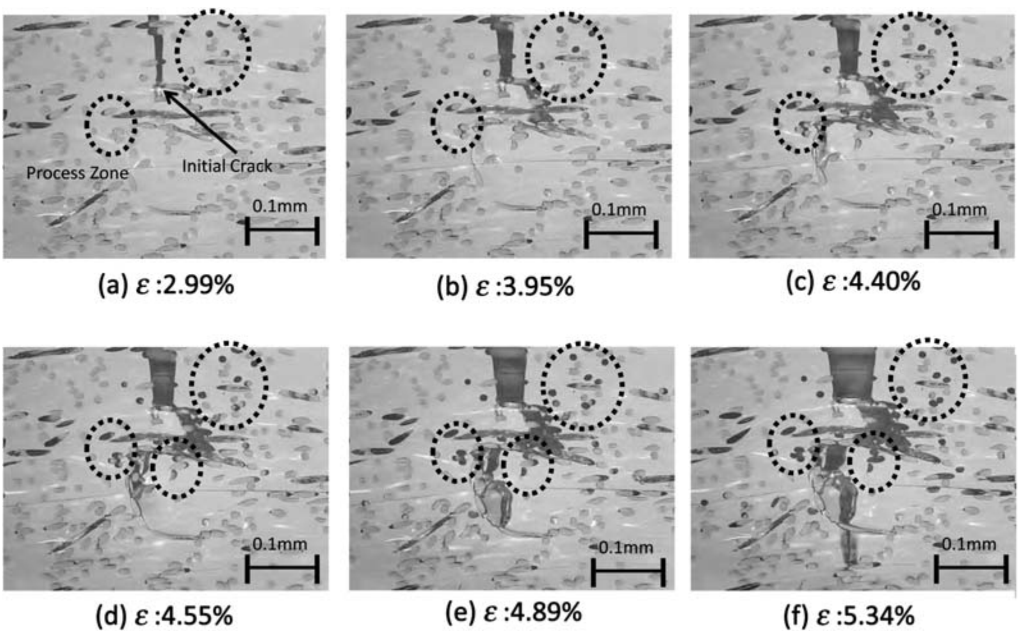

Figure 6. Microscopic observation results of eight-layer composites.

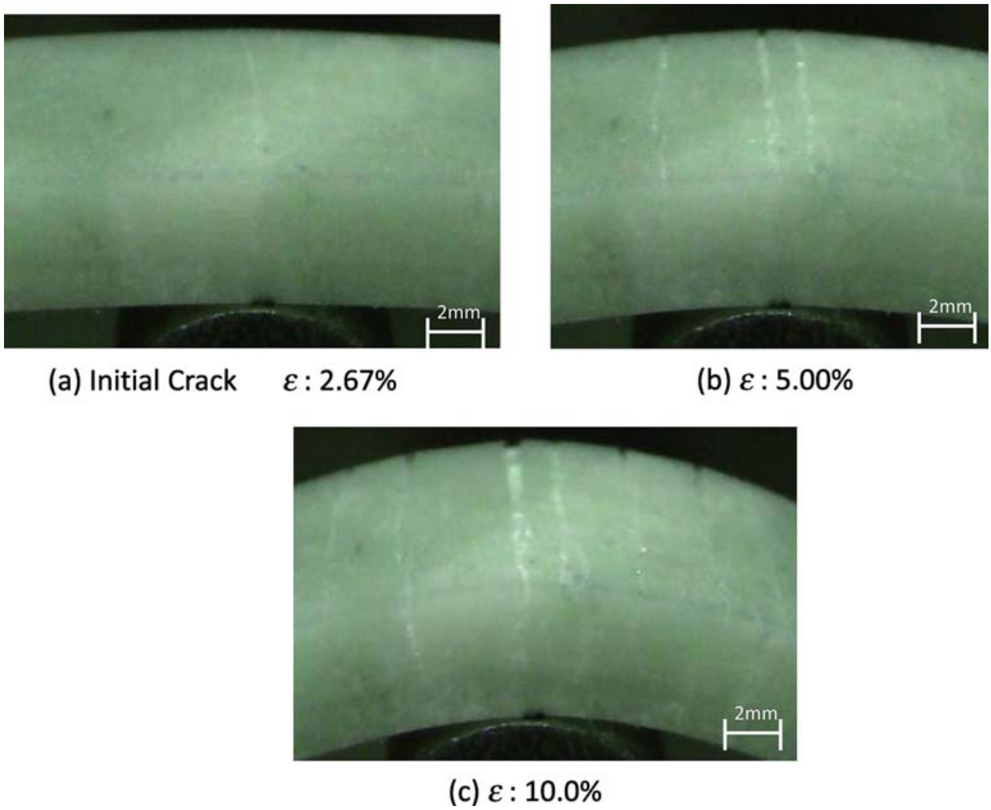

Figure 7. Macroscopic observation results of one-layer composites.

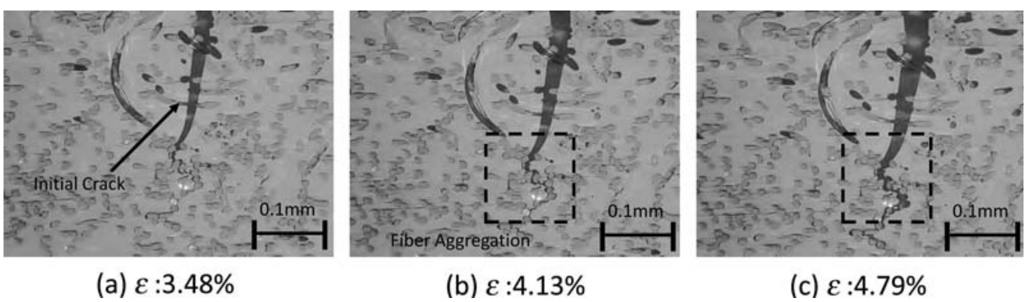

Figure 8. Microscopic observation results of two-layer composites.

Figure 9 shows the result of microscopic observation on the PET composite which shows brittle fracture behavior. An initial crack formed at strain of 2.74% and then the specimen fractured in an unstable manner. As shown in the photograph, after fracture it is found that no process zone formed. This was due to higher fiber–matrix interfacial strength between PET/Epoxy. The banana composite failed in a similar manner to the PET composite.

Considering the brittle fracture behavior and lower strength, the banana composite is not adequate for the rehabilitation works of sewage pipes. From this point, creep tests were

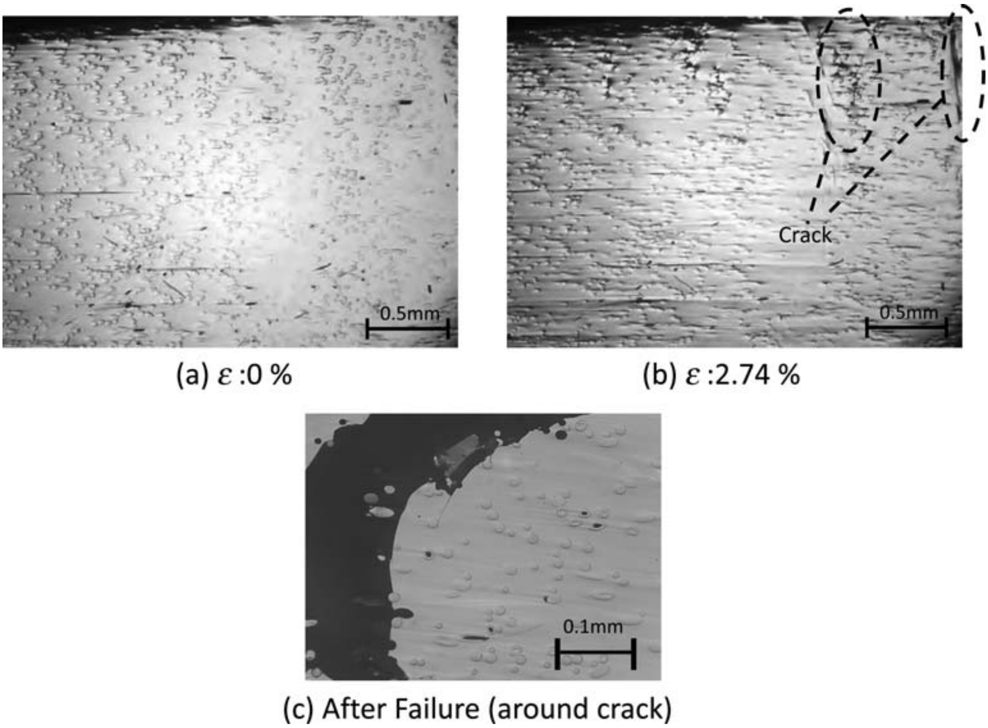

Figure 9. Microscopic observation results of PET composites.

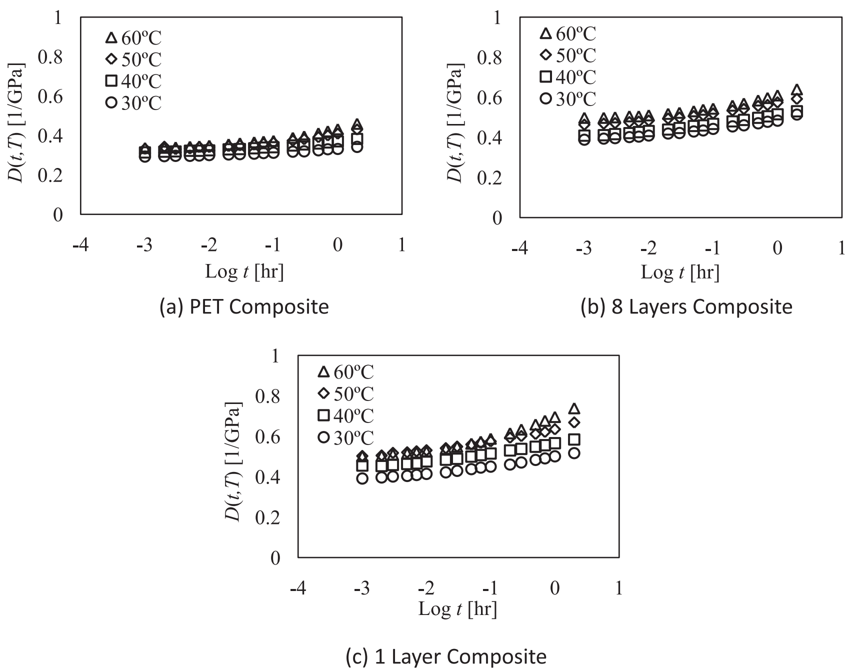

Figure 10. Creep compliances as a function of time.

conducted on the PET, one- and eight-layer composites. Figures 10–12 show creep compliances as a function of time, master curves, and relations between shift factor and temperature. From Figure 11, it was found that master curves were smooth and were approximated as one curve. In addition, Figure 12 shows that temperature–shift factor plots were able to be

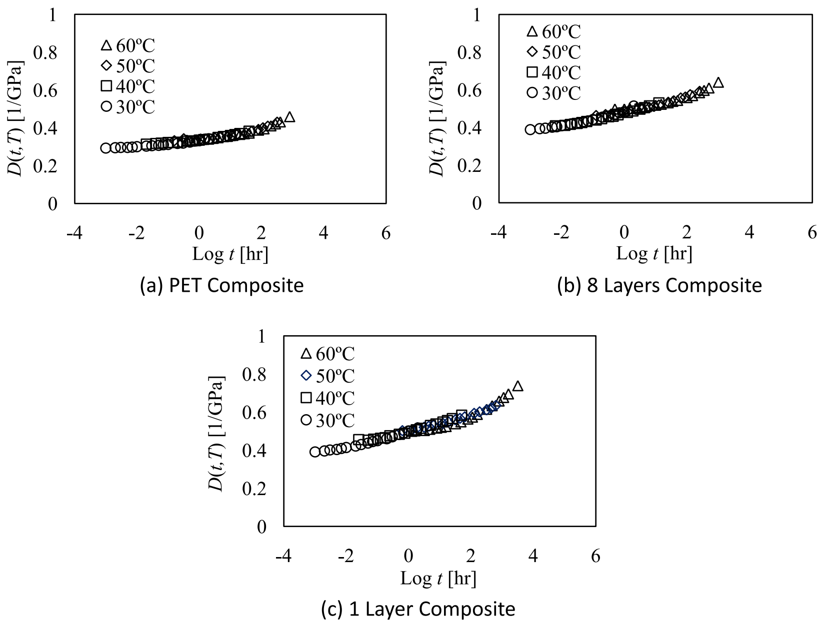

Figure 11. Master curves obtained from Figure 10.

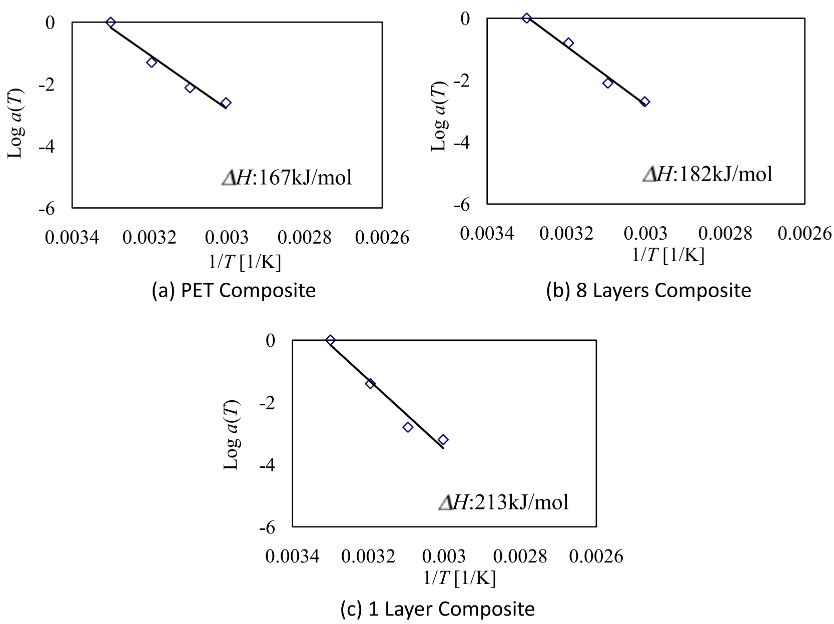

Figure 12. Relations between shift factor and temperature (Arrhenius plots).

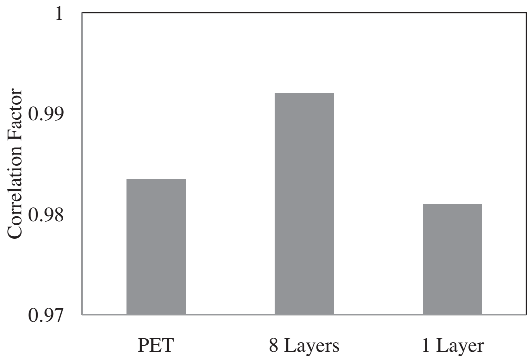

Figure 13. Correlation factor (linear approximation of Figure 12).

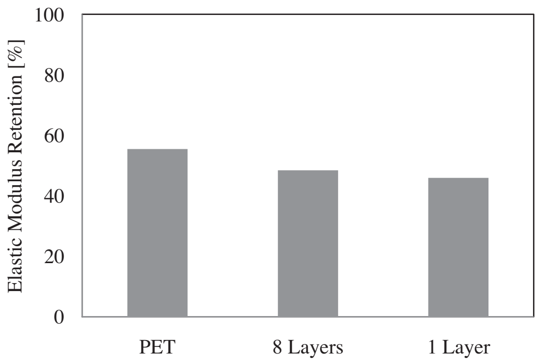

Figure 14. Modulus retentions after 50 years.

approximated as a straight line. Figure 13 shows correlation coefficients between shift factor and reciprocal temperature, which indicate that the values were more than 0.97. These results suggest that the time–temperature superposition principle is applicable for the present material systems. Thus, we use Figure 11 to evaluate the modulus retention of the composites after 50-year usage. Figure 14 shows the modulus retention after 50 years calculated from master curve for each composite using the time–temperature superposition principle. The modulus retentions after 50 years for PP composites were a little lower than that for the PET composite. This was attributable to lower glass transition temperature of PP fiber. There is little difference in modulus retention between one- and eight-layer composites. Considering the density, fracture process and comparable modulus retention, we can conclude that the PP composites consisting of thicker layer are one of the candidate materials for sewage rehabilitation.

4. Conclusion

In the present study, PET, banana, and PP nonwoven fabric reinforced epoxy composites were developed as alternative materials for a sewage pipe rehabilitation work. Static and creep bending tests were conducted on the composites to evaluate the possibility as a candidate. Bending strength of the one-, two-, and four-layer composites were same with that of the

PET composites and bending moduli for one-, two-, and four-layer composite were slightly lower than that for PET. Bending modulus of the banana composite was larger, whereas strength was lower. The PET and banana composites showed brittle fracture manner at lower strain, while the one-, two-, and four-layer composites had larger load-carrying capacity and stable fracture manner. The modulus retentions after 50 years for the PP composites were slightly lower than that of the PET composites. From these results, it was found that the PP composite with thicker nonwoven fabric is a candidate material for the rehabilitation of sewage pipes.

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