Technical Report

Development of Reinforcement Method for Canal Tunnels Using Carbon Fiber Strand Sheet and Abrasion Resistance Epoxy Resin

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Abstract

An inner lining reinforcement method using carbon fiber strand sheets and ceramic-mixed epoxy resin mortar was developed for an agricultural canal tunnel lining with bending cracks on the inner surface of the lining. Various elemental tests were conducted on this method, and it was confirmed that the method exhibited excellent water adhesion resistance and abrasion resistance. As a field demonstration test, an actual waterway tunnel that had been damaged was reinforced using this method, and the applicability of this method to the field was confirmed. The results of monitoring for five years after construction showed no deformation of the reinforcing layer, no decrease in the bond strength between the resin material and concrete, and no change over time of the resin mortar by chemical analysis. These results indicate the validity of this method.

1. Introduction

The main agricultural canal in our country spans approximately 50 000 km, which includes about 2 000 km of agricultural canal tunnels. For many canal tunnels, 50 or more years have passed since their construction, and various deformations and/or water leakages of the concrete lining have been reported.[1] For such canal tunnels, countermeasures aimed at restoring the function by reinforcement employing the steel plate bonding and pipe rehabilitation method, and reinforcement employing lattice shaped carbon fiber are being applied. However, as compared with the cross sections of rail and road tunnels, those of the agricultural canal tunnels are smaller, and therefore the access to the inside of such tunnels is difficult. Adoption of reinforcement employing the steel plate bonding and pipe rehabilitation method which requires a large-scale temporary construction is also difficult sometimes. In the case of reinforcement employing the lattice shaped carbon fiber, although access to the inside of the tunnel is easier because of the light weight of the materials used, since a cementitious mortar is used as the bonding agent, there remain the issues of abrasion resistance in relation to the flow of water, and the required covering depth increases, while the sectional area for the water flow decreases. Depending on the method, water stagnates on the rear side, and it causes peeling-off of the reinforcing layer. Furthermore, in the case of reinforcement employing the carbon fiber, in addition to the unnecessary reinforcement applied in an unnecessary direction, the amount of reinforcement is limited in the cross-sectional direction. Thus, in the existing canal tunnel reinforcement method, there are issues in terms of workability, back-of-lining water, abrasion resistance, and life cycle cost.

In this study, firstly, a ceramic-mixed type epoxy resin mortar excellent in abrasion resistance and applicable to canal tunnels (hereafter referred to as resin mortar) was developed. Then, the carbon fiber strand sheet (hereafter referred to as CFSS) as the reinforcing material and the epoxy mortar as the adhesive material were utilized, and the elemental tests of both materials were conducted. Next, using an actual size tunnel model, the reinforcing effect and the deformation performance of this method were evaluated.[2, 3] Furthermore, a water drainage anchor pin was developed in order to provide actual tunnels with long-term durability using this method. Finally, for an actual tunnel, a reinforcement design was conducted based on the results obtained from the actual size tunnel models test, the construction workability on the trial construction was confirmed, and long-term monitoring after the construction was performed.

This paper reports the results of the elemental tests conducted at the time of the development of the reinforcing material, and the

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monitoring results after the trial construction.

2. Main Body

2.1 Overview of this method

In this method, after the surface treatment of the inner surface of the concrete lining of the canal tunnel, a coating of a wet-surface applicable epoxy resin primer is applied, then the CFSS is temporarily fixed by the water drainage anchor pins to match the direction of its fibers to the periphery direction of the tunnel, and then is adhered by the epoxy mortar having the functions of an adhesive agent and a lining material. The properties of the CFSS and the resin mortar used in this study are shown in **Table 1** and **Table 2**, respectively. The high strength type CFSS having a tensile strength of 4000 N/mm^2, a tensile modulus of 270 kN mm^2, and a fiber weight of 600 g/mm^2 was used. As compared with a steel re-bar, the CFSS is about 1/4 the mass in terms of weight, and more than 10 times higher in terms of tensile strength, even in a narrow canal tunnel, which makes human transportation and installation easy. For the primer material, an epoxy resin primer which is effective in adhesion to a wet concrete surface was selected. For the binding material which adheres CFSS to concrete, and stays in contact with the water flow, the ceramic-mixed epoxy resin mortar was employed to secure the abrasion resistance performance for a long period of time. Owing to these factors, an actual scale temporary construction requiring heavy machinery and rails has become unnecessary, and the construction consists of materials which allow for manual construction work. **Photo 1** shows the cross section of the reinforcing layer.

2.2 Overview of elemental test and result

2.2.1 Water adhesion resistance test

Since the canal tunnels are in contact with water for a long period of time, a water adhesion resistance test between the reinforcing layer and the concrete was conducted. The test conditions are shown in **Table 3**. Two types of plain concrete having different compressive strength (nominal strength 20 N/mm^2 and 30 N/mm^2) were prepared, and surface treatment was applied by a high pressure water washing machine. Then a coating of a wet-surface applicable primer was applied, and CFSS was adhered using the resin mortar. The test conditions were as follows: specimen (S): completely submerged in water, specimen (HS): only the rear side submerged in water as the rear side of concrete contacts water, and specimen (DR): maintained in the dry state. The respective specimens were laid in a covered water tank or in a covered air space to avoid the influence of ultraviolet rays. After laying for a predetermined period of time, the samples were taken out of the water tank, and the adhesion tests provided by the Japan Society of Civil Engineers were conducted.[4)]

The results of the tests are shown in **Table 4**. Up to the 27th month, all specimens exhibited values exceeding the reference threshold of 1.5 N/mm^2.[5)] Compared with the specimens under surface dryness of the concrete surface, the two water-submerged specimens showed no significant change in values. Furthermore, all observed fracture modes occurred within the concrete substrate, demonstrating that the resin material employed in this method possesses excellent water adhesion resistance.

2.2.2 Water jet with sand abrasion test

The material used to reinforce the inside of the canal tunnel lining was subject to abrasion concerns due to flowing water. In order to evaluate the abrasion resistance performance of the resin mortar, the sand abrasion test was conducted using a water jet at Shimane University. Pursuant to the study of Ueno et al.[6)], the test time period was set at 20 hours at which an abrasion equivalent to that of 40 years is developed. The abrasion resistance performance of the resin mortar was evaluated based on the relative evaluation with respect to the JIS standard mortar.[7)] **Figure 1** shows the results of the water jet sand erosion test, and **Photos 2** (a) and (b) respectively show the abrasion situations of the resin mortar specimen and the standard

Table 1 Properties of CFSS

	Unit	Value	Test method
Weight	g/m^2	600	–
Thickness	mm	0.333	–
Tensile strength	N/mm^2	4000	JIS K 1191
Tensile modulus	kN/mm^2	270	JIS K 1191

Table 2 Properties of resin mortar

	Unit	Value	Test method
Bending strength	N/mm^2	48	JIS K 7181
Bending modulus	N/mm^2	2100	JIS K 7181
Share strength	N/mm^2	20	JIS K 6850
Specific gravity	–	1.55	JIS K 7112

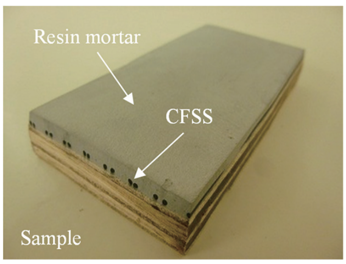

Photo 1 Cross section of the reinforcing layer

Table 3 Test conditions

Subject	Compressive strength (N/mm^2)	Immersion conditions
20-S	26.7 (Average)	Submerge
20-HS		Half-Submerge
20-DR		Dry
35-S	37.8 (Average)	Submerge
35-HS		Half-Submerge
35-DR		Dry

Table 4 Test results of adhesive strength

Subject	Adhesive strength (N/mm^2)			
	3 months	9 months	18 months	27 months
20-S	2.17	2.19	3.17	3.03
20-HS	2.16	2.25	3.04	4.00
20-DR	2.78	2.14	2.63	2.51
35-S	2.89	2.10	2.33	3.37
35-HS	2.49	1.71	3.98	4.28
35-DR	2.26	2.13	2.80	2.46

mortar specimen after the erosion test. The abrasion volume of the standard mortar specimen used for comparison purposes is 16 880 mm^3 on average after 20 hours while the abrasion volume of the resin specimen is 1 120 mm^3 on average, which is about 6.7% that of the standard mortar. Furthermore, the ratio of the depth of the abrasion of the epoxy resin with respect to that of the standard mortar is 0.07, and is confirmed to be significantly below 0.2 which is provided as the criteria for the organic-system material by the Canal Tunnel Repair Manual issued by the Ministry of Agriculture, Forestry and Fisheries. Based on this result, the excellent abrasion resistance performance of the resin mortar was confirmed.

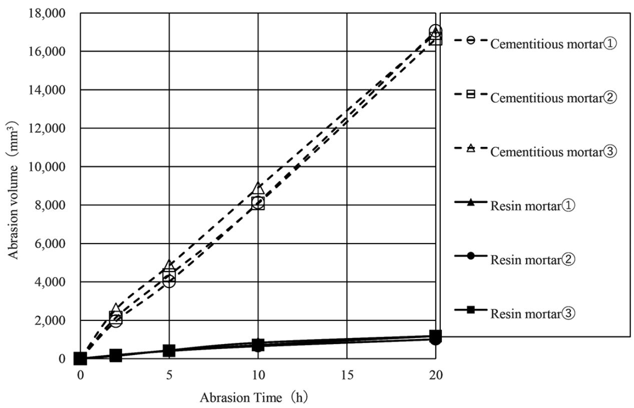

Fig. 1 Result of water jet sand erosion test

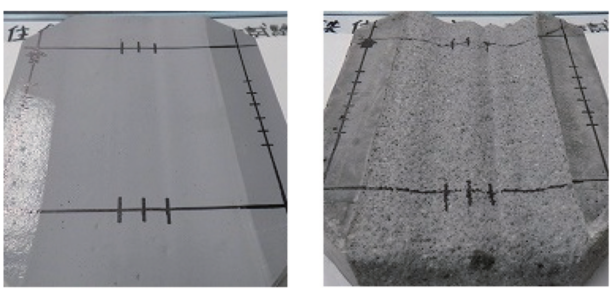

Photo 2 Post test situation (a) Resin mortar (b) Standard mortar

2.2.3 Development of water drainage anchor pin

The internal surface of the tunnel lining covered by the reinforcing layer is unable to let the rear side water flow to the inner side, and as a result, delamination and/or peeling-off of the reinforcing layer may be caused. In order to avoid such a defect, and further, to exert the effect of the mechanical fixation when an excessive load operates, a mechanical anchor as shown in **Photo 3** having a drainage function was developed. This water drainage anchor pin is equipped with a check valve, which does not allow the water in the tunnel to flow to the rear side, while allowing the drainage of the rear side water to the inside. The water drainage anchor pin so developed was evaluated in a field demonstration test described below.

2.3 Field demonstration test

2.3.1 Overview

In a canal tunnel in the jurisdiction of the Tohoku Regional Agricultural Administration Office of the Ministry of Agriculture, Forestry and Fisheries, the workability of the method, the water drainage function of the developed water drainage anchor pin, and the water adhesion resistance performance of the resin mortar were evaluated, and the validity of the monitoring system employing an optical fiber type sensor was examined. The tunnel was of the 2r standard horse shoe type. As shown in **Photo 4**, bending cracks developed on the internal lining surface, and this method was applied to a distance of 15 m including the area where cracks developed.

2.3.2 Reinforcement design

1) Design condition

The allowable stress design method was adopted for the reinforcement material. The allowable stress of the CFSS was determined from the delamination strain obtained in a full-scale tunnel loading test, combined with an appropriate safety factor, and was set to 245 N/mm^2 (corresponding to a strain of $1\,000 \times 10^{-6}$). The number of CFSS layers was specified to ensure that the tensile stress remained below this allowable limit. The design parameters are summarized in Table 1.

For the analysis, a frame analysis software of FRAME (in-plain) ver.6 of the FORUM8 Co., Ltd. was used, and referring to the Deformed Tunnel Countermeasure Design Manual,[8] the axial force and the bending moment of the checking section were sought, and the CFSS stress intensity was obtained from the cross-sectional calculation based on the following assumptions.

- Fiber strain being proportionate to the distance from the neutral axis.
- Tensile strengths of concrete and resin mortar to be disregarded.
- Young's modulus ratio of CFSS vs. concrete to be calculated by Equation (1).

$$n_{cf} = \frac{E_{cf}}{E_s} \cdot n_s \quad = \frac{E_{cf}}{E_s} \cdot 15 \qquad (1)$$

Where,

n_{cf} : Ratio of Young's modulus of strand sheet vs. concrete
E_{cf} : Young's modulus of CFSS (N/mm^2)
E_s : Young's modulus of steel reinforcing bar (=200 000)
n_s : Ratio of Young's modulus of steel reinforcing bar vs. concrete

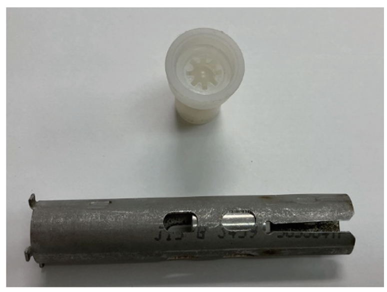

Photo 3 Water drainage anchor pin

Photo 4 Crack state

2) Overview of frame analysis

The model frame employed in this analysis is shown in **Fig. 2**. The frame model was developed referring to the Deformed Tunnel Countermeasure Design Manual.[8] In this method, only the lining is modelled since the tunnel base is not the subject of reinforcement. The dead weight and the ground pressure are taken into consideration of the load. As bending cracks developed on the inner surface of the side wall of the subject tunnel, the ground pressure mode was estimated to be a ground plastic pressure having a cavity on the rear side of the top (in the angular range of 100 degrees). As the presence of cracks on the outer side of the side wall of the bottom part is presumed, the constraint condition is that, admitting the rotation of the tunnel, the tunnel is fixed in the horizontal direction and spring-supported in the vertical direction. Furthermore, the ground is modeled by a ground spring, and the calculation of the ground spring coefficient followed the method of estimation from the N value provided in the Deformed Tunnel Countermeasure Construction Manual. The value calculated on the basis of the N value of 50 was employed.

The design load P was determined in such a way that the concrete tensile stress intensity agrees with the concrete tensile strength 1.58 N/mm^2 (design standard strength intensity 18 N/mm^2) at the crack-developed position when the dead load and the design load P are considered to be exerted effectively on the entire non-reinforced cross section.

3) Analysis result

Figure 2 shows the results of the bending moment analysis, the bending moment, and the axial force at the crack-developed position. From the analysis results, under the assumptions 1) based on the balance of force and the balance of moment wherein the axial force is taken into consideration, the neural axis of the one layer of CFSS was sought, and the CFSS tensile stress intensity was calculated. As a result, since the CFSS tensile stress intensity became 229 N/mm^2 which is lower than the allowable stress intensity (245 N/mm^2), the number of the CFSS layers was determined to be one. The CFSS adhesion was applied to the entire perimeter of the inside of the tunnel based on the actual size tunnel model test, excluding the inverted section.

2.3.3 Construction method

1) Surface preparation

Removal of dirt and/or degraded parts by high-pressure water jet washing was conducted.

2) Water cutoff

Water cutoff operation was applied to water leaking positions of the lining such as cracks and/or damages by pouring in rapid hardening cement and/or water cutoff agent of the polyurethane injection system, and by using a water drainage hose. After the water cutoff operation, the inner side of the lining was dried by air blowers.

3) Marking work

Positions of the water drainage anchor pin installation and the positions of the CFSS adhesion were marked.

4) Installation of water drainage anchor pin

Anchor pin holes were drilled by an electric hammer drill for the fixation of water drainage anchor pins. The water flowing out of a water drainage anchor pin was conveyed by a hose so that the lining was kept dry. The drilling depth was set at 180 mm so that the drill hole would not penetrate through the rear side of the lining.

5) Sheet adhesion

A coating of the wet-surface applicable epoxy resin primer was applied with a paint roller, followed by an under coating of the resin mortar before the primer became hardened, and then one layer of CFSS was adhered in a continuous process. In this process, the CFSS was temporarily fixed to the curved surface of the concrete lining by the water drainage anchor pins. After the installation of the CFSS, a coating of resin mortar was applied, and then trowel-finished. The CFSS adhesion procedure, and the work that finished condition are shown in **Photos 5** and **6**, respectively.

2.3.4 Monitoring method and result

1) Measurement of strain

In order to evaluate consecutively the reinforcement effect in the field demonstration test, an optical fiber type strain sensor was installed in alignment with the direction of the CFSS fiber, and adhered to the concrete surface with the epoxy resin mortar (**Photo 7**). **Figure 3** shows the reinforcement area reinforced by this method and the strain measurement points. The sensor was installed at three locations in the longitudinal direction of the canal tunnel. The optical fiber type sensor employed is an optical cable coated with a glass fiber reinforced plastic. A sensor so installed enables the measurement of strain at any arbitrary point. As the sensor does not need

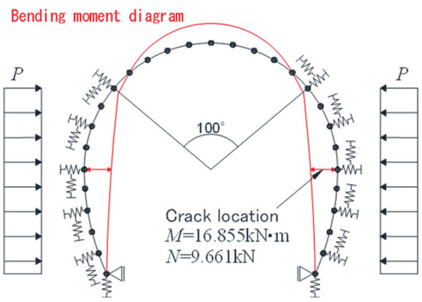

Fig. 2 Model frame and moment diagram

Photo 5 Adhesion work of CFSS

Photo 6 After completion of work

any electricity supply source, it was judged to be the most appropriate for monitoring in the canal tunnel. In this study, five measurement points were provided per optical fiber sensor.

Table 5 shows the strain measurement results of the past five years. The values taken on the 1st day after the completion of the construction work were assumed as the initial values, and the strain data were taken on-site after the elapse of predetermined numbers of years. The positive values of the strain data indicate the tensile strain, and the negative values indicate the compressive strain. Overall, negative values are shown as compared to the initial values, which is considered to be attributed to the measurement of the resin mortar contraction hardening strain because the initial values were taken a day after the completion of the construction work. After the elapse of one year, no remarkable strain changes were observed, and even after the elapse of five years, no separation of the reinforcing layer was detected by the hammering test. Since the optical fiber type sensor used this time realized the consecutive monitoring of the strain despite being immersed for a long period of time in the water in a canal type tunnel, the validity of the long-term monitoring for the construction method was confirmed.

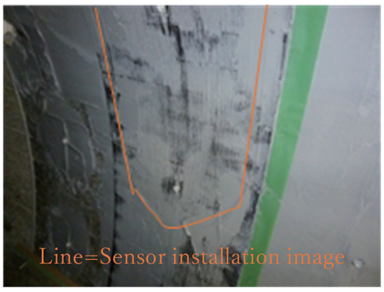

Photo 7 Installation of an optical fiber sensor

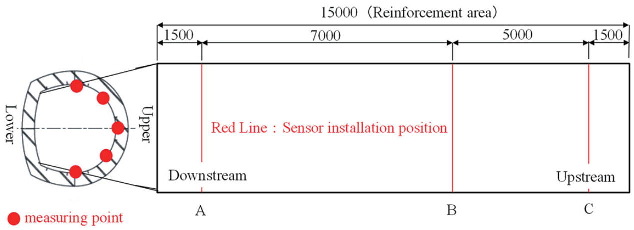

Fig. 3 Reinforcement area and strain measurement points

Table 5 Test results of strain measurement

Measuring point	Elapsed year	Strain ($\times 10^{-6}$)				
		①	②	③	④	⑤
A (Downstream)	0	0	0	0	0	0
	0.5	−97	−55	−81	−61	−70
	1	−43	14	−20	−5	−14
	2	−34	−2	−48	−21	−20
	3	−48	−36	−81	−52	−42
	5	45	28	−32	0	21
B (Center)	0	0	0	0	0	0
	0.5	−125	−98	−93	−108	−82
	1	−84	−59	−72	−82	−29
	2	−83	−65	−90	−90	−24
	3	−105	−87	−112	−109	−55
	5	−99	−77	−92	−97	−48
C (Upstream)	0	0	0	0	0	0
	0.5	−86	−85	−103	−82	−81
	1	−60	−81	−110	−73	−65
	2	−43	−88	−111	−70	−60
	3	−87	−141	−155	−118	−112
	5	−57	−105	−133	−82	−68

2) Water drainage anchor pin

Photo 8 shows the water flow situation of the water drainage anchor pin after the completion of the construction work. The flow of the water on the rear side of the lining to the inside of the lining was confirmed from immediately after the completion of the construction work. The water drainage anchor pins function satisfactorily even after the elapse of five years. As aforementioned, no delamination and/or peeling-off of the reinforcing layer due to the rear side water were recognized, and therefore the suppressing effect of the water drainage anchor pin against the delamination and/or peeling-off of the surface covering material using a fiber sheet was confirmed.

3) Adhesion strength with respect to substrate concrete

In order to evaluate the long-term water resistance adhesion performance of this method, the adhesion test provided by the Japan Society of Civil Engineers[4] was conducted at the field demonstration construction site. An exclusive use jig was adhered to the construction work surface with a two-component rapidly curable hardening epoxy resin adhesive agent, and after the hardening of the adhesive agent, a 40 mm square was cut out around the jig, and the test was conducted using a jack. **Photo 9** shows the test situation. This test has been conducted for five years, and the entire test results obtained at each year of elapse are shown in **Table 6**. Although the variation is large, the results obtained at the measurement points at each elapse of year show that the values exceeding the standard criteria of 1.5 N/mm^2 provided by the open canal repair manual[5] were confirmed, and furthermore, all fracture modes exhibited the fracture developed at the base material of concrete. An example of the


Photo 8 Water flow situation after 5 years


Photo 9 Adhesion test at canal tunnels

state of the fracture at the adhesion test conducted after the elapse of five years is shown in **Photo 10**. Based on the data obtained from the field demonstration test combined with the results of the elemental tests, the excellent water resistance adhesion performance of the resin materials used in this method with respect to concrete was confirmed.

4) Chemical analysis of resin mortar

In order to confirm the secular change of the resin mortar used to adhere the CFSS, the chemical analysis of the resin was conducted using the Fourier transformation infrared spectrophotometer (FT-IR) and differential scanning calorimetry (DSC). The sample for analysis was taken from the resin mortar portion which remained on the exclusive-use jig at the time of the adhesion test conducted five years after the completion of the construction work, and for reference, the hardened resin not exposed in the canal tunnel was used.

Table 6 Test result of adhesion strength

Elapsed year	Test result	(1)	(2)	(3)	Average
0	Maximum tensile load (kN)	3.92	5.06	5.19	
	Adhesive strength (N/mm^2)	2.45	3.16	3.24	2.45
	Destructive position	Concrete	Concrete	Concrete	
1	Maximum tensile load (kN)	3.01	3.8	2.94	
	Adhesive strength (N/mm^2)	1.88	2.38	1.84	2.03
	Destructive position	Concrete	Concrete	Concrete	
2	Maximum tensile load (kN)	3.1	6.01	4.38	
	Adhesive strength (N/mm^2)	1.94	3.76	2.74	2.81
	Destructive position	Concrete	Concrete	Concrete	
3	Maximum tensile load (kN)	5.16	2.69	3.72	
	Adhesive strength (N/mm^2)	3.24	1.68	2.33	2.45
	Destructive position	Concrete	Concrete	Concrete	
5	Maximum tensile load (kN)	2.58	3.18	2.76	
	Adhesive strength (N/mm^2)	1.61	1.99	1.73	1.80
	Destructive position	Concrete	Concrete	Concrete	

Photo 10 Destruction state

The measurement results of FT-IR are shown in **Fig. 4** and **Fig. 5**, respectively. In the spectrum range measured, the peak positions of the spectrum of the resin mortar five years after the completion of the construction work are almost the same as those of the reference, and no newly developed peak was recognized. Furthermore, it was confirmed that there is no difference between the spectrum intensity ratios of the C-H stretching and contraction vibration around 2800 to 3200 cm^{-1}. The DSC measurement was conducted twice at heating rate 20°C/min within a measurement range of −10 to 200°C, and the analysis was conducted in the range of 30 to 170°C. **Figure 6** and **Fig. 7** show the results respectively. The value of the heat absorption peak top of DDSC which is the differential of DSC is assumed to be the glass transition temperature, and comparing the result of the 1st scan, there is a slight difference observed in the peak positions around 60°C of the glass transition temperature of the resin mortar, which is considered to be the difference in the extent of hardening of the resin caused by the difference in the curing circumstance. Comparing the results in the 2nd scan, the complete agreement of the heat absorption peak positions is confirmed. From the above analysis results, no remarkable secular change of the resin mortar even under the condition of immersion in water in the canal tunnel was confirmed.

3. Conclusion

Regarding the reinforcing method for the plain concrete lining of a canal tunnel using CFSS and a resin mortar, the following issues have been confirmed.

(1) Based on the results of the immersion test conducted as an ele-

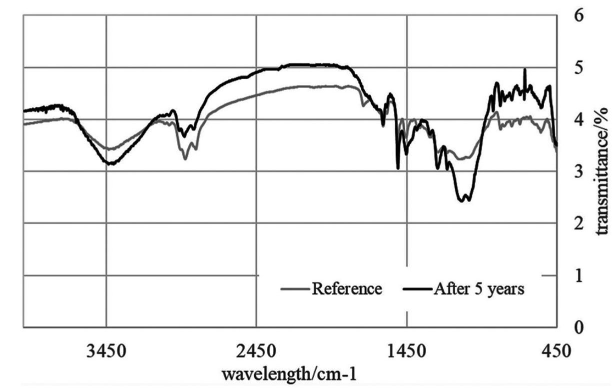

Fig. 4 Result of FT-IR measurement

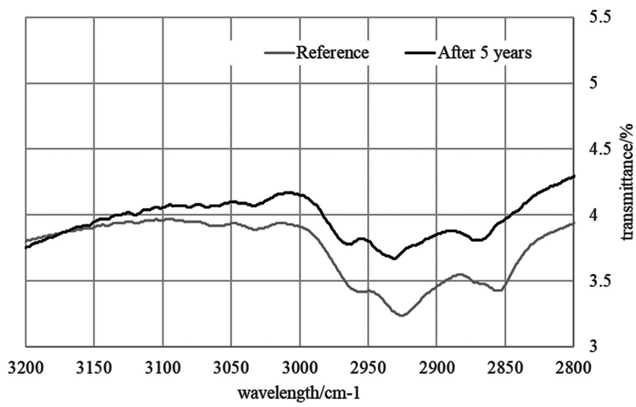

Fig. 5 Spectrum around 2800–3200 cm^{-1} (C-H stretching)

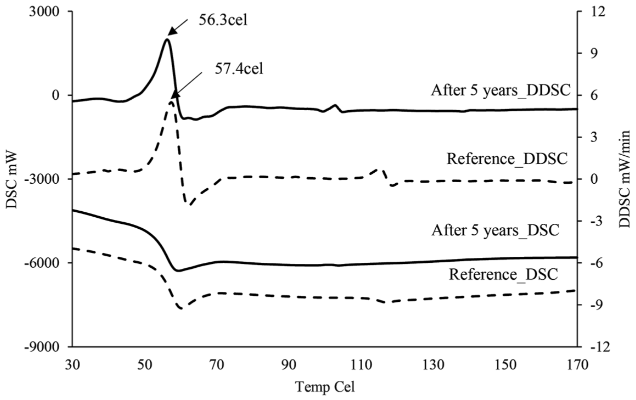

Fig. 6 Result of DSC measurement (1st SCAN)

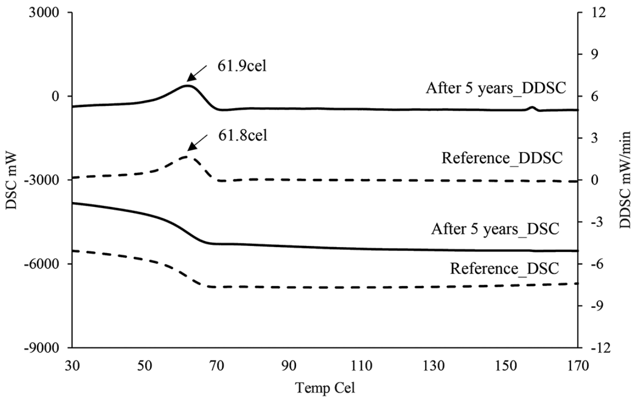

Fig. 7 Result of DSC measurement (2nd SCAN)

mental test, and the results of monitoring of the adhesion strength in the actual canal tunnel, long-term durability of the adhesion with respect to the concrete structure has been confirmed.

(2) Since the resin mortar employed in this method is superior to the ordinary mortar in terms of abrasion resistance, reduction in the life cycle cost of the canal tunnel is expected.

(3) Based on the results of the field demonstration test conducted in an actual canal tunnel, the water flow performance of the water drainage anchor pin and the suppressing effect thereof on the reinforcing layer against the delamination and/or peeling-off have been confirmed.

(4) The monitoring employed in this method using the optical fiber type sensor has been confirmed as a valid method which enables the consecutive strain measurement despite long-term immersion in water in the canal tunnel.

(5) Based on the results obtained from the FT-IR measurement and the DSC measurement conducted for the resin mortar exposed to the canal tunnel for five years, and since no secular change has been observed as compared with the result of the reference, it has been confirmed that the sound state of the resin mortar is maintained even under long-term exposure to water.

Acknowledgements

This study has been conducted as the "Study on the development of reinforcing method most optimized to the plain concrete canal tunnel lining", a subject of the research and development of new technologies under the public-private partnerships of the Ministry of Agriculture, Forestry and Fisheries.

Furthermore, the authors also wish to express deep appreciation to their joint study partners of the Institute for Rural Engineering of the National Agriculture and Food Research Organization of the National Research and Development Agency, Shimane University, and Oriental Shiraishi Corporation.

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