

FUNDAMENTAL STUDY ON IMPROVEMENT OF WATER TIGHTNESS AND BOND STRENGTH AT INTERFACE OF SPRAYED MORTAR FOR REPAIRING OF TUNNEL LINING CONCRETE

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ABSTRACT

The effects of surface treatment methods at the interface between repairing mortar and original concrete on bond strength and on watertightness were investigated. The repairing mortar for RC underground tunnel structures severely deteriorated by chloride induced corrosion was used. Two kinds of mechanical processing for the surface of concrete and two kinds of chemical bonding agent were applied. Compared to the treatment only by wetting with water, chemical bonding agents remarkably improved bond strength and watertightness at the interface.

Keywords: interface, surface treatment, watertightness, bond strength, repairing mortar

1. INTRODUCTION

In recent years, large attention has been paid to the maintenance of severely deteriorated underground railway tunnels in the area of reclamation in Tokyo metropolitan area. Some RC underground tunnels are severely damaged by chloride induced corrosion caused by leaking water including chloride [1]. The third author, et al. have developed repairing mortar using shotcrete method for patch repairing of those deteriorated RC tunnels [2]. The newly developed repairing method is expected to extend the service life of existing structures at a low cost without causing re-degradation.

It has been pointed out that the interface between original concrete and repairing material tends to become a weak point due to low resistance against mass transfer [3]. If the mass transfer resistance at the interfaces is extremely low, it may lead to deterioration of interface causing spalling of repairing material and corrosion of steel at the interface.

In this study, the repairing mortar developed by the third author, et al. is used and the effects of treatment methods for the interface between the mortar and the original concrete on bond strength and on watertightness will be investigated.

For the surface treatment of the original concrete before applying sprayed mortar, two kinds of mechanical processing methods will be provided. After the mechanical processing, several chemical agents will be used to strengthen the interface.

Bond strength at the interface will be investigated by pull-out test. The watertightness will be investigated by the test device developed by the authors applying high-water pressure to the interface.

2. EVALUATION OF ADHESIVE BOND STRENGTH BY PULL-OUT TEST

2.1 Experiment overview

In the current study, the authors tried various specimen shapes for conducting appropriate bond strength test for sprayed mortar and obtaining reliable data. Finally, the specimen with large indentation (150×300×40mm (length×width×height)) was provided for 60mm first concrete layer, as illustrated in Fig. 1. This indentation was necessary due to the restriction (length of the coring drill) of the coring machine for bond strength test. Fig.2 shows the situation of coring from the indented part of concrete layer.

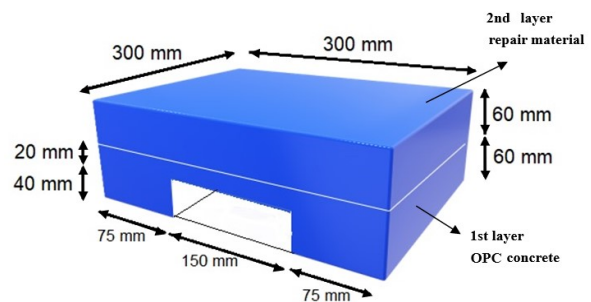


Fig.1 Design of rectangular specimen for bond strength test

The specimens were designed to have two different layers. The first layer simulating the original tunnel lining concrete, made with ordinary Portland cement (OPC), was placed in the laboratory condition using the material described in Table 1.

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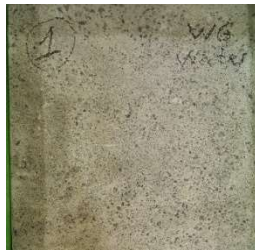
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Fig.2 Coring for bond strength test

Table 1 Conditions of concrete (1st layer of specimen)

Slump (cm)	Air volume (%)	W/C (%)	Maximum size of coarse aggregate (mm)	Water content of sand (%)	Water content of aggregate (%)	Sand to aggregate ratio (%)
12±2.5	4.5±1.5	55	15	2.76	0.8	45



Less rough surface (Wire grinder)



Rough surface (Jet chisel)

Fig.3 Two methods for interface processing

Table 2 Six specimens with different treatment methods for construction joint

Name of specimen	Mechanical processing method for interface	Treatment with chemical agent for the interface
Water-L	Less rough surface (by wire brush grinder)	Wet with water only
Water-R	Rough surface (by electric chisel)	
EP-L	Less rough	Silicate-based Surface Penetrants
EP-R	Rough	
EVA-L	Less rough	Primer of ethylene-vinyl acetate adhesive
EVA-R	Rough	

The methods of processing the surface of the first concrete layer are explained. Firstly, the surface processing of the first layer involved two methods: roughening using an electric chisel for a rougher surface and less roughening using a wire brush grinder as shown in Fig.3. Secondly, the treatment of the concrete surface before casting the second layer underwent three types of treatments: 1. no treatment but wetting with water only, 2. A silicate-based surface penetrants called Ever Prolong (main components are sodium silicate and

potassium silicate), and 3. a primer of ethylene-vinyl acetate (EVA based) adhesive.

The surface of the first layer for construction joint with the second layer was processed at the age of 7 days. The methods of the joint surface processing are described in Table 2.

The second layer, made of the repairing mortar of 60mm thickness described in Table 3, was applied by shotcrete method as demonstrated in Fig.4.

The repairing mortar developed by the third author, et al. [3] was made using the materials shown in Table 3. Ordinary Portland cement, lime-crushed sand, vinylon fiber were used for the mortar. Polyacrylic ester was added as a polymer. Two calcium aluminate admixtures were used: hydration accelerator, a mixture of $12\text{CaO}\cdot 7\text{Al}_2\text{O}_3$ and anhydrite, and a salt-fixing material consisting mainly of $\text{CaO}\cdot 2\text{Al}_2\text{O}_3$. Liquid plasticizers were also used, mainly composed of aluminum sulfate.

Table 3 Mix proportions and constituent materials of repairing mortar

Water (kg/m ³)	Ordinary Portland cement (kg/m ³)	Sand content (kg/m ³)	W/C (%)	Short fiber (%)	Polymer (%)	Accelerator (%)	Salt-fixing material (%)	Liquid plasticizer (%)
263	601	1293	44	C×1.6	C×12	C×10	C×10	1.1



Fig.4 Casting of the second layer by shotcrete method

2.2 Method of bond strength test

Pull-out test was conducted to evaluate the effect of pre-treatment of the construction joint and the effect of bonding chemical agent.

The pull-out test was conducted using the specimens shown in Fig.1 and Fig.2.

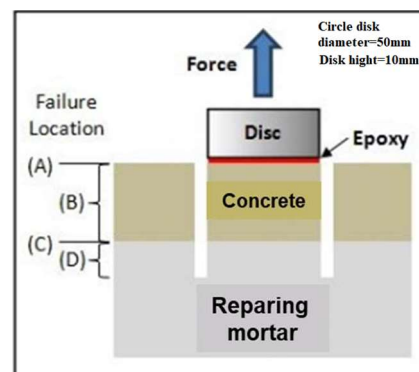


Fig.5 Schematic figure for pull-out test

The pull-out tests were conducted at 28 days after placing repairing mortar. Originally, it was planned that the pull-out tests were conducted at 7 and 15 days also, however, the appropriate test methods to obtain reliable data could not be established at 7 and 15 days. Thus, in this paper, the test results only at 28 days are reported. In practice, early age bond strength development is very important to enable the train operation just after the repairing. Long-term bond strength is also important to prevent spalling of repairing mortar. The pull-out test method established in this study will be utilized in future study.

In order to obtain reliable bond strength, the following enhancements were made for pull-out test procedures.

1. After using core driller which made specimens wet, the specimens were kept dried for one day.
2. Using appropriate amount of epoxy glue (Fig.5) and leave the specimens for 5-6 hours after applying the glue.
3. Keeping the axis of pull-out test vertical to the surface of the specimen.

2.3 Experimental results and discussion

Fig.6 shows the results of the bond strength test at 28 days. 6 specimens showed variable bond strength results.

Two specimens in which no chemical agent was used for surface treatment at the interface (Water-L and Water-R) showed very low bond strength. Just wetting the surface of the original concrete may not be enough for this repairing mortar to obtain sufficient bond strength.

Two specimens in which Silicate-based Surface Penetrants (Ever Prolong) was used for surface treatment at the interface (EP-L and EP-R) showed much higher bond strength than Water-L and Water-R. The bond strength was higher than 2MPa and the effect of the mechanical roughness on the bond strength was not significant.

The specimens in which primer of EVA based adhesive was used (EVA-L and EVA-R) showed relatively high bond strength. EVA-R showed the highest bond strength of more than 3 MPa. The mechanical roughness of the surface at the interface had a remarkable effect on bond strength in these two specimens.

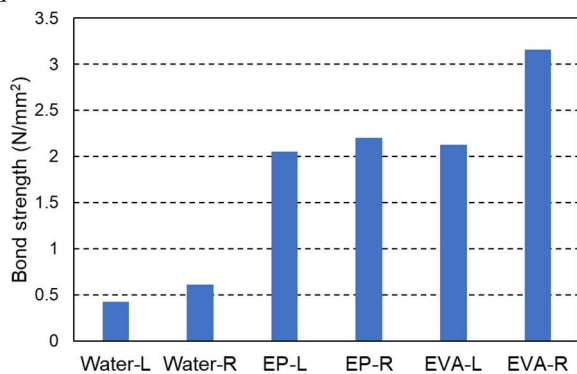


Fig.6 Results of bond strength test at 28 days

After the bond strength test, failure mode was observed for each specimen. Here six specimens were subjected to testing, with two testing points designated for each specimen. The resultant values were derived by averaging the bond strength results obtained from these two testing points. The failure modes can be classified into three distinct categories. If the failure occurred at the interface (location C in Fig.5), it is interface failure. If the failure occurred at location B, it is concrete failure. If the failure occurred at location D, it is mortar failure. The failure at location A (the interface between the steel plate and mortar) must be avoided. In this study bond strength test at 28 days, we observed 2 kinds of failures. The interface failure was identified as the dominant mode of failure, constituting approximately 66.7% of the observed failures (Fig.7). The subsequent most frequent failure mode was concrete failure (33.3%).

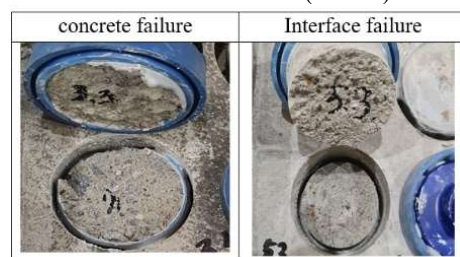


Fig.7 Failure patterns

3. WATERTIGHTNESS OF CONSTRUCTION JOINT UNDER HYDRAULIC PRESSURE

3.1 Experiment overview

This experimental study investigates the effects of joint treatment methods on improving the watertightness of the joint at repairing mortar and original concrete.

A special apparatus developed by the authors was employed to subject the specimens with construction joint to incremental water pressure ranging from 0.25 MPa to 2.0 MPa. Fig.8 shows the dimensions of the specimen with construction joint. For this investigation, 6 hollow cube specimens of 300 mm long with a construction joint and with an 80 mm diameter cylindrical hole were prepared.

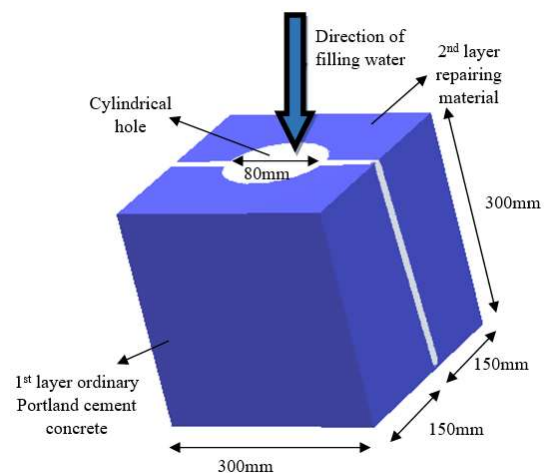


Fig.8 Shape of specimen for watertightness test

The specimens used in this investigation also had two layers. The first layer simulating the original tunnel

lining concrete (by ordinary Portland cement-OPC) was placed in the laboratory condition using the material described in Table 4.

Table 4 Mixture of concrete (1st layer of specimen)

Slump (cm)	Air volume (%)	W/C (%)	Maximum size of coarse aggregate (mm)	Absorption ratio of sand (%)	Absorption ratio of aggregate (%)	Sand to aggregate ratio (%)
12±2.5	4.5±1.5	55	20	1.95	0.9	45

The first layer was processed in the same way as in chapter 2 using an electric chisel for coarser surface and a wire brush grinder for smoother surface as shown in Fig. 3. The finished top surface was roughened at the



Fig.9 Water pressure test system

age of 5 days. The concrete surface, prior to casting the second layer of repairing mortar, was subjected to three

kinds of treatments. 6 kinds of surface treatments at the interface shown in Table 2 were provided.

The second layer, made of the repairing mortar of 150mm thickness whose mix proportion was described in Table 3, was applied by shotcrete method at 14 days after casting 1st layer.

In the process of making the specimens, a cardboard cylinder was installed to generate a cylindrical hole in the center of the specimens. After casting the second layer, the cardboard cylinder was removed by applying hot water at 14 days after the casting of the second layer.

3.2 Method of testing by Hydro pressure device for watertightness

The watertightness test was conducted at around 60 days after the placement of the second layer. The set up of watertightness test is exhibited in Fig. 9.

The specimen with a construction joint and with a cylindrical hole in the center in vertical direction was sandwiched by two perforated stainless-steel plates, fixed securely using bar screws. Water leakage from the joint between the steel plate and the specimen was carefully avoided by deliberate sealing. Subsequently, water was introduced into the cylindrical hole of the specimen through a specified injection orifice, and the application of water pressure was carried out manually, utilizing a pump-driven apparatus for pressurization.

The onset of leakage and the quantity of water leakage from the joints were carefully observed and recorded as key parameters for evaluating the watertightness performance of the joint.

After starting the watertightness test, the water pressure given to the inside of the cylindrical hole was incrementally raised to specific levels of 0.25 MPa, 0.5 MPa, 1 MPa, 1.5 MPa, and 2 MPa, with each pressure level being sustained for a duration of 30 minutes.

When water leakage was observed from the joint,

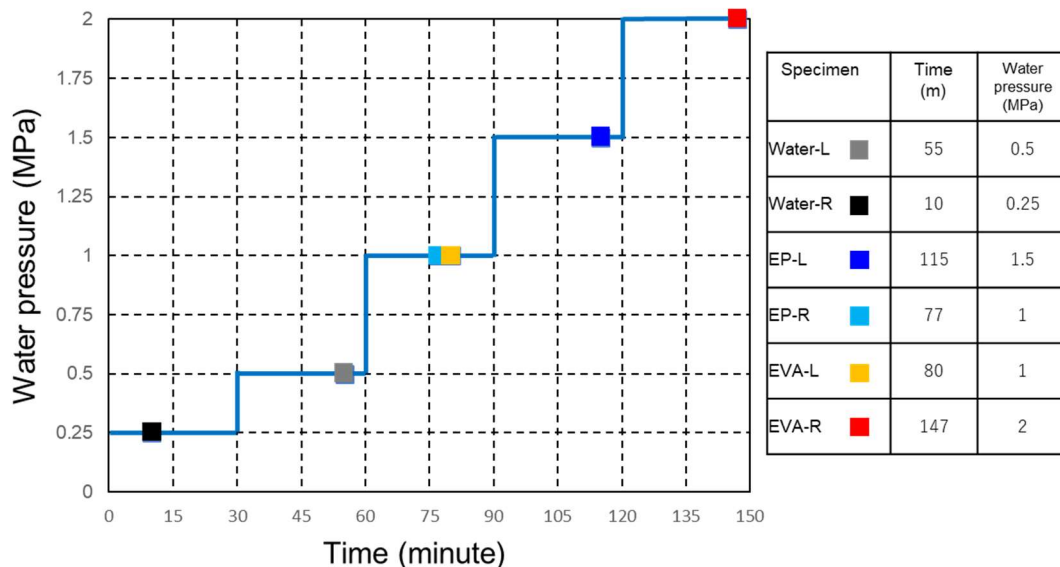


Fig. 10 Water pressure change over time and start point of water leakage

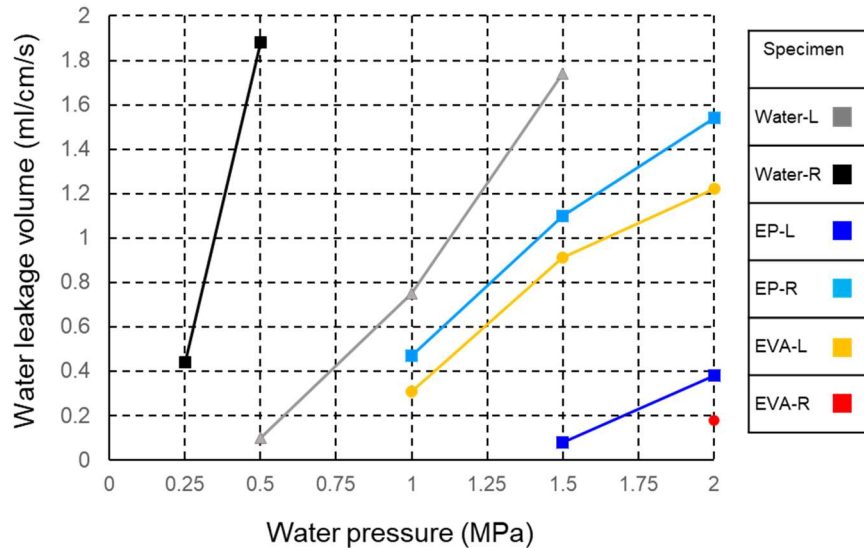


Fig. 11 Results of measurement of water leakage

precise records were made for the timing of leakage and the corresponding water pressure. Additionally, the quantity of water absorbed by the paper attached to the leakage point was measured, from which the water leakage amount per unit length of the joint (ml/cm/s) was obtained.

The amount of the leakage water from the joint was measured as follows:

- (1) The weight of dry paper was measured on a scale before attaching the paper to the joint.
- (2) All the papers were collected at the end of each 30 minutes under a predetermined water pressure.
- (3) The total weight of the papers was measured using the scale.
- (4) To determine the amount of water leakage, the weight of the dry paper was subtracted from the total weight.

3.3 Experimental results and discussion

Fig. 10 and 11 show the experimental results of watertightness test.

Fig. 10 shows the change of water pressure over time and the colored square dots in the figure show the starting points of water leakage of the specimens. 6 specimens showed different watertightness and water leakage was observed in different time in each specimen.

The specimen **Water-R** exhibited the weakest resistance against water pressure. In this specimen, water leakage was observed at 10 minutes after the water pressure reached 0.25 MPa. The specimen **Water-L** showed second lowest resistance, in which water leakage was observed at 25 minutes after the water pressure reached 0.5MPa. The two specimens which showed very low bond strength in Fig.6 showed low resistance against water pressure.

Two specimens in which silicate-based surface penetrants (Ever Prolong) was used for surface treatment at the interface (**EP-L** and **EP-R**) showed much higher watertightness than **Water-L** and **Water-R**. Especially, **EP-L** showed relatively high resistance, in which water leakage was observed at 25 minutes after the water pressure reached 1.5MPa. In **EP-R**, water leakage was

observed at 17 minutes after the water pressure reached 1.0MPa.

The specimens in which primer of EVA based adhesive was used (**EVA-L** and **EVA-R**) also showed relatively high-water tightness. Especially, **EVA-R** showed the best resistance, in which water leakage was observed at 27 minutes after the water pressure reached 2.0MPa. In **EVA-L**, water leakage was observed at 20 minutes after the water pressure reached 1.0MPa.

The watertightness at the interface was much improved by applying two chemical bonding agents applied in this study.

Fig.11 shows the results of measurement of water leakage volume over time in each specimen.

The specimen **Water-R** whose resistance of watertightness was the lowest showed water leakage of 0.44 ml/cm/s at water pressure of 0.25 MPa, which increased to 1.88 ml/cm/s at 0.5 MPa, and then finally this specimen was broken due to water pressure.

The specimen **Water-L** started to show water leakage of 0.1 ml/cm/s at water pressure of 0.5 MPa, which increased to 1.74 ml/cm/s at 1.5 MPa, and then finally this specimen was also broken due to water pressure.

4 specimens with treatment by two kinds of chemical bonding agent showed higher resistance against water pressure than the two specimens above.

The specimens in which primer of EVA based adhesive was used (**EVA-L** and **EVA-R**) showed relatively high-water tightness. Especially, **EVA-R** showed the best performance, in which water leakage was only 0.18ml/cm/s at 2.0MPa. **EVA-L**, in which the surface of the interface was less roughened, showed lower resistance than **EVA-R**. **EVA-L** started to show water leakage of 0.31 ml/cm/s at water pressure of 1.0 MPa, which increased to 1.22 ml/cm/s at 2.0 MPa. The specimen was not broken at 2.0 MPa.

The specimens in which silicate-based surface penetrants (Ever Prolong) was used for surface treatment at the interface (**EP-L** and **EP-R**) also showed relatively high-water tightness. Especially, **EP-L**, in which the surface of the interface was less roughened showed the

second-best performance. EP-L showed water leakage of 0.08ml/cm/s at 1.5 MPa, which increased to 0.38 ml/cm/s at water pressure of 2.0 MPa. EP-R started to show water leakage of 0.47 ml/cm/s at water pressure of 1.0 MPa, which increased to 1.54 ml/cm/s at 2.0 MPa. This specimen was not broken at 2.0 MPa.

4. CONCLUSIONS

In this study, the effects of treatment methods for the interface between the repairing mortar for RC tunnel structures and the original concrete on bond strength and on watertightness were investigated. The following results were obtained.

- (1) The methods for surface treatment of concrete before applying sprayed repairing mortar remarkably affected bond strength by pull-out test. The specimens in which primer of EVA based adhesive was used showed relatively high bond strength. The specimen with EVA primer and with rougher surface showed the highest bond strength. Two specimens in which a silicate-based surface penetrant was used for surface treatment at the interface showed much higher bond strength than the specimens just treated by wetting with water.
- (2) The watertightness at the interface was much improved by applying two kinds of chemical bonding agents applied in this study.

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