Experimental Investigations of a Tunnel Lining Segment Strengthened by In Situ Spraying Mortar

Fuzhi Wang¹, Cong Zeng¹*, Baosong Ma², Chenkun Gong¹, Baoyong Liao³, Yahong Zhao¹, Chong Ma⁴ and Yaozu Kong⁵

¹ Faculty of Engineering, China University of Geosciences, Wuhan 430074, China; wangfuzhi0328@163.com (F.W.); 18086486825@163.com (C.G.); yhchaos@163.com (Y.Z.)
² School of Civil Engineering, Sun Yat-sen University, Guangzhou 510275, China; mabaosong@163.com
³ Anyue Environmental Technology Co., Ltd., Xiamen 361000, China; lby@xmanyue.com
⁴ Liangshan Engineering Technology (Wuhan) Co., Ltd., Wuhan 430074, China; machong666666@163.com
⁵ Wuhan CUG Trenchless Technology Research Institute Co., Ltd., Wuhan 430074, China; info@cug-tti.com
* Correspondence: zengcong@126.com

Abstract: After long-term operation, tunnel lining segments encounter various problems. Aiming at these problems, in this paper, we present a method of strengthening tunnel lining segments by in situ spraying mortar. An experimental study of the in situ spraying mortar was carried out to determine the compressive strength, flexural strength and interface properties (splitting tensile strength and shear strength) between concrete and H-70 mortar. The experimental results show that the mechanical properties of H-70 mortar are less dependent on the curing humidity than ordinary concrete under standard curing conditions, the 7-day compressive strength of H-70 is 55 MPa, which is 61% of the 28-day compressive strength. This shows that H-70 has high early strength and is very suitable for rapid reinforcement. The interface roughness has a significant effect on the splitting tensile strength, and it can be increased by chiseling to improve the bearing capacity of the strengthened structure. A full-scale loading experiment was carried out on the segment strengthened by in situ spraying mortar. The loading process, failure mode and ultimate bearing capacity of the strengthened structure were analyzed by full-scale loading experiment. The research shows that the ultimate bearing capacity of the tunnel segment strengthened by in situ spraying mortar increased significantly. The ultimate bearing capacity of the strengthened structure is 10% higher than that of the unstrengthened structure. The advantages and disadvantages of in situ spraying-mortar strengthening method are analyzed in comparison with the internal-tension steel-ring strengthening method.

Keywords: tunnel lining; segment strengthening; in situ spraying; full-scale loading experiment

1. Introduction

In recent years, with the rapid development of China’s economy, the population has gradually concentrated in large- and medium-sized cities, and the problem of population density has gradually become the primary problem that needs to be solved in major cities, which has further promoted the development and utilization of underground space. In particular, the construction of subways has become the focus of the development of major cities. With the continuous development of underground space technology, there are more and more urban subways. Considering the particularity of urban subway construction, it is necessary to minimize the impact on the surrounding environment, so shield tunneling is often used. At present, China has become the fastest-developing country in the world in terms of urban rail transit.

During the construction or operation of subway shield tunnels, considerable deformation of tunnel lining structure is caused by surcharge on the top of the tunnel [1]. Considerable deformation of the tunnel causes many structural issues, such as concrete spalling, cracks, leakage and so on, which seriously endanger the safe operation of the...
subway shield tunnel. For shield tunnels with serious issues, there are two methods to improve the stress condition of the tunnel. One is to strengthen the stratum externally, and the other is to strengthen the lining structure internally, including enhancing the structural bearing capacity, controlling the structural deformation, controlling the development of cracks and preventing seepage and plugging [2].

The external strengthening method involves strengthening the tunnel lining structure by grouting outside the tunnel. This method effectively reduces the lateral deformation of the tunnel and solves the problem of water leakage of tunnel segments and has been applied in Shenzhen and Shanghai subway tunnels [3,4]. However, the process of this method is complex, and there are many uncertainties in construction.

Internal strengthening methods mainly refer to improving the performance of the lining structure by adding reinforcement layers on the inner surface of the lining structure to form a composite structural system. This strategy an easy method to form a standardized reinforcement technology, and the influencing factors are relatively few, mainly affected by reinforcement materials. Internal tunnel-strengthening methods include strengthening by bonding fiber cloth, internal steel tension rings, and composite cavities. The advantages of strengthening by bonding fiber cloth include lightweight reinforcement materials and convenient construction. However, its fire resistance is very poor, and the control of structural deformation and an anti-seepage plugging effect are not obvious [5–7]. Strengthening with internal steel tension rings effectively improves the stiffness of the structure, which is conducive to controlling structural deformation. However, the installation of steel plates requires special lifting equipment, with many welds and large fluctuation of welding quality [8]. The composite cavity strengthening method makes up for the deficiency of steel-ring reinforcement in construction, but the structure shows brittle failure, poor fire resistance, and does not have the effect of anti-seepage and plugging after reinforcement [9,10].

The in situ spraying method is a repair method by which high-performance composite mortar material is uniformly coated on the surface of the structure to form a lining by pressure spraying. An American sewer operator found that this method can structurally repair concrete pipes and has the advantage of fast construction speed [11]. The in situ spraying method has been widely used to renew riveted steel pipes since the early 1900s [12]. With the continuous progress and development of materials and technology, “in situ cement mortar spraying” technology has become a mature method of sewer pipeline repair. High-performance cement mortar has strong antideformation ability, which can repair even the slightest leakage in the pipe and increase the anticorrosion ability [13,14]. The in situ spraying method does not have pipe diameter or section length limitations. It can be used to renovate cement pipe, clay pipe, steel pipe, cast iron pipe, asbestos pipe, brick pipe and other materials.

In this paper, a new strengthening method is proposed that uses in situ spraying mortar combined with steel mesh to strengthen damaged tunnel lining segments. With the strengthened tunnel lining segment taken as the research object, an ultimate bearing capacity experiment was carried out, and the loading process, failure mode and strengthening performance of the strengthened segment were analyzed and studied. The advantages and disadvantages of in situ spraying mortar-strengthening method were analyzed by comparison with the internal-tension steel-ring strengthening method, and supporting examples are provided for subsequent theoretical research.

2. Experimental Overview

2.1. In Situ Spraying Mortar Material Performance Experiment

Zhang found that when the interface shear strength is greater than the shear stress and the interface tensile strength exceeds the radial tensile stress, a superimposed structure is formed. Otherwise, a composite structure is formed [15]. Therefore, in addition to testing the compressive strength and flexural strength of mortar materials, it is also necessary to study the splitting tensile strength and shear strength of the interface between mortar and concrete. Considering the difference between the curing conditions of the tunnel
reinforcement construction site and standard curing conditions, in order to explore the influence of this difference on the strength of the mortar material, the curing conditions of the test specimens were divided into two types: standard curing condition and construction site curing condition. The material test specimens were divided into four types for use in the compressive strength test, flexural strength test, interface-splitting tensile strength test and interface shear strength test.

2.1.1. Raw Material

The raw materials used included tap water and H-70 trenchless rehabilitation mortar produced by Wuhan CUG Trenchless Technology Research Institute Co., Ltd. H-70 is a kind of high-strength special mortar with the characteristics of ultra-high strength, wear resistance and corrosion resistance. H-70 is mainly composed of high-grade cement, refined quartz sand with strict gradation, microsilica powder, water-reducing agent, accelerator and polypropylene fiber. The water/material ratio by mass of H-70 is 1:6.

2.1.2. Compressive Strength

1. Test block preparation

The test block size was 70.7 × 70.7 × 70.7 mm. A total of six groups of test blocks were made, with three blocks in each group. The three groups of test blocks were cured for 7 days, 14 days and 28 days under standard curing conditions of 20 ± 2 ºC and humidity above 90%. The other three groups of test blocks were cured for 7 days, 14 days and 28 days in the same environment as the strengthened structure.

2. Testing method

Compressive strength was tested by the method recommended in JGJ/T 70, 2009 [16]. The test block was placed on the lower pressure plate of the testing machine. The bearing surface of the test block should be perpendicular to the top surface during molding, and the center of the test block should be aligned with the center of the lower pressure plate of the testing machine. The test machine and loading were started. The pressure test should be loaded continuously and evenly, and the loading speed should be 0.25~1.5 kN/s. When the test block was close to failure and began to deform rapidly, adjustment of the throttle of the test machine was ceased until the test block was destroyed, and the failure load was recorded. The calculation formula of compressive strength is as follows:

\[ f_{m,cu} = K \frac{N_u}{A} \]  

where \( f_{m,cu} \) is compressive strength (MPa), \( N_u \) is failure load (N), \( A \) is pressure area of test block (mm²), \( K \) is reduction coefficient (\( K = 1.35 \)).

2.1.3. Flexural Strength

The flexural strength was tested by the method recommended in GB/T 17671, 1999 (ISO679) [17]. The test block size was 40 × 40 × 160 mm. A total of six groups of test blocks were made, with three blocks in each group. The three groups of test blocks were cured for 7 days, 14 days and 28 days under standard curing conditions of 20 ± 2 ºC and humidity above 90%. The other three groups of test blocks were cured for 7 days, 14 days and 28 days in the same environment as the strengthened structure.

2.1.4. Interface Splitting Tensile Strength

1. Test block preparation

The mold size of the test block was 100 × 100× 100 mm. First, C55 and C65 concrete were poured into the test mold as the base, with a pouring height of 50 mm. C65 and C55 concrete base blocks were separated into four groups, with three blocks in each group. The surface was smoothed. After the concrete was finally solidified, a tool was used to hack the concrete surface in one-way and orthogonal directions to simulate different surface
roughnesses. The concrete was cured for 7 days, and then H-70 mortar was poured in the first half of the test mold. The two groups of test blocks were cured for 28 days under standard curing conditions of 20 ± 2 °C and humidity above 90%. The other two groups of test blocks were cured for 28 days in the same environment as the strengthened structure. The production scheme of the test blocks is shown in Table 1.

Table 1. The production scheme of test blocks for interface splitting tensile strength.

| Block | Mortar | Strength Grade of Base Concrete | Hacking Method | Curing Condition |
|-------|--------|---------------------------------|----------------|------------------|
| P11   | H-70   | C55                             | One-way        | Standard curing  |
| P12   |        |                                 | Orthogonal     |                  |
| P13   |        |                                 | One-way        | Construction environment |
| P14   |        |                                 | Orthogonal     |                  |
| P21   | H-70   | C65                             | One-way        | Standard curing  |
| P22   |        |                                 | Orthogonal     |                  |
| P23   |        |                                 | One-way        | Construction environment |
| P24   |        |                                 | Orthogonal     |                  |

(2) Testing method

Interface-splitting tensile strength was tested by the method recommended in GB/T 50081, 2002 [18]. Parallel straight lines were drawn in the middle of the top and bottom surfaces of the test block so as to determine the position of the splitting surface. The test block was placed in the center of the pressure plate. Circular pads and bars were placed between the upper plate and the test block and between the test block and the lower plate. The pads and bars should be aligned with the center lines above and below the test block and perpendicular to the top surface of the test block. The testing machine was started, continuously and uniformly loaded, with a loading speed of 0.05 MPa/s~0.08 MPa/s. Block failure was tested, and the failure load was recorded. The experiment is shown in Figure 1. The calculation formula of compressive strength is as follows:

\[
f_{ts} = 0.637 \frac{F}{A}
\]

where \( f_{ts} \) is interface splitting tensile strength (MPa), \( F \) is failure load (N), \( A \) is area of the split surface of the test block (mm\(^2\)).

Figure 1. Interface-splitting tensile test.
2.1.5. Interface Shear Strength

(1) Test block preparation

C55 concrete specimens were made with a size of 100 × 100 × 100 mm. The specimens were cured for 28 days under standard curing conditions of 20 ± 2 °C and humidity above 90%. Then, a core-drilling machine was used to drill the specimen surface to the other surface perpendicular to the surface, and the diameter of the drilling hole was 30 mm. H-70 mortar was poured into the drilling hole with a height of 30 mm, as shown in Figure 2. The test blocks were divided into two groups. One group of test blocks was cured for 28 days under standard curing conditions of 20 ± 2 °C and humidity above 90%. The other group of test blocks was cured for 28 days in the same environment as the strengthened structure.

![Figure 2. Interface shear strength test block; (a) boring a hole; (b) front of block; (c) bare face of block.](image)

(2) Testing method

A hydraulic servo pressure testing machine was used to test interface shear strength. A loading block was placed on the surface of the mortar cylinder, and the hydraulic servo pressure testing machine pressurized the mortar cylinder in the hole through the loading block. Under the action of pressure, slippage occurred between the mortar cylinder and the concrete block, and the failure load was recorded. The experiment is shown in Figure 3. The calculation formula of interface shear strength is as follows:

$$
\tau_s = \frac{F_s}{\pi hd}
$$

(3)

where $F_s$ is shear destructive force (N), $d$ is diameter of the drilling hole (mm), $h$ is height of mortar (mm).

![Figure 3. Interface shear test; (a) test equipment; (b) broken test block.](image)
2.2. Experiment of Lining Segment Structure Strengthened by In Situ Spraying Mortar

2.2.1. Test Structure

The strengthened tunnel lining segment structure adopted a Wuhan subway lining ring, as shown in Figure 4. The lining ring had an outer diameter of 6200 mm, an inner diameter of 5500 mm, a segment thickness of 350 mm and a ring width of 600 mm. The ring was divided into six blocks, including one cap block (F), two adjacent blocks (L1 and L2), two standard blocks (B1 and B2) and one base block (B3). Starting from the center of the F block in a clockwise direction, the six seam positions are located at 10.75°, 78.75°, 146.25°, 213.75°, 281.25° and 349.25°. Each longitudinal joint is connected by one M30 bending bolt. The segment concrete grade is C55, and the reinforcing bar is an HRB335 rib bar.

Zhao found that after the interior of the concrete pipe is repaired by cement mortar, if the shear strength of the old and new interfaces is low, the old and new interfaces of the composite structure will strip under the external loads, which will affect the bearing capacity of the structure [19]. Therefore, in order to improve the shear strength of the interface, when the segment is strengthened, the first step should be to plant reinforcement for the segment. The planting bar is an HRB400 ribbed steel bar with a diameter of 12 mm; the depth of the original concrete is 100 mm, and the length of the embedded spray mortar layer is 30 mm. The mortar layer adopts circumferential Φ10 @ 100; longitudinal Φ10 @ 200 steel mesh reinforcement; the inner lining ring width is 80 cm, the steel mesh is HRB400 threaded steel with a welding method and the lap length is not less than 10 D (100 mm). The strengthened ring is made of in situ spraying mortar, and the overall strengthened thickness is controlled at about 50 mm. The layout of the reinforcement cage is shown in Figure 5. After the spraying was completed, it was cured to the test age. The strengthened structure is shown in Figure 6.
2.2.2. Loading Equipment and Scheme

The loading system is mainly composed of a horizontal loading device, a reaction balance device and rolling bearings. The horizontal loading device is mainly composed of jacks and a loading beam. A total of 24 horizontal loading points were arranged in the experiment, and the jack was placed at the loading point. The maximum horizontal load provided by each jack was 100 t, and the maximum stroke of the jack was 300 mm. The 24 jacks were evenly distributed outside the test ring; the spacing between the jacks was 15°, symmetrically arranged about the center of the circle. The loads of all loading points were applied through the ring reaction frame to form a self-balancing loading system, as shown in Figure 7.

In related research, a steel-plate-, composite-cavity- and steel–concrete-composite-reinforced whole ring were used to simulate the overload condition of the top of a 15 m buried tunnel in the Wuhan area. Therefore, the loading scheme was also adopted in this study to simulate the top overload condition of a 15 m buried tunnel in the Wuhan area. A total of 24 jacks were divided into three groups; the load values of each point in a group were the same, and the load was completely synchronized. $P_1$ contains six loading points, $P_2$ contains 10 loading points and $P_3$ contains eight loading points. The loading point arrangement is shown in Figure 8. All loads are collected in the central steel ring through the loading beam to form a self-balancing loading system.

Figure 5. Layout of reinforcement cages.

Figure 6. Structure strengthened by in situ spraying.
Each loading point is composed of a load distribution beam, a load bearing beam and two steel tie rods. In the first stage, $P_1$ is loaded from 0 kN to 150 kN, maintaining $P_2 = 0.65 \times P_1$, $P_3 = (P_1 + P_2)/2 = 0.825 \times P_1$. This loading stage simulates the design condition of a 15 m deep tunnel in Wuhan. $P_1 = 150$ kN is equivalent to the force of a 15 m buried stratum on the top of the tunnel, and the coefficient 0.65 represents the common earth pressure coefficient in Wuhan soft soil area. In the second stage, $P_1$ is loaded from 150 kN to 215 kN. At this time, $P_2$ reaches a passive earth pressure of 137.5 kN. In this stage, $P_2 = 0.65 \times P_1$ and $P_3 = (P_1 + P_2)/2 = 0.825 \times P_1$ are still cured. This loading stage simulates top overload until lateral earth pressure reaches passive earth pressure. Finally, $P_1$ is loaded from 215 kN to the limit state. During this process, $P_2 = 137.5$ kN and $P_3 = (P_1 + P_2)/2 = 0.825 \times P_1$ are cured. This loading stage simulates a process in which the top continues to be overloaded, but the lateral earth pressure does not continue to increase.
2.2.3. Measuring System

The test contents include overall deformation, segment concrete strain, interface slipping and stripping between the sprayed mortar layer and the concrete segment, mortar layer strain and oil pressure connected with jack. A summary of measuring points is shown in Table 2.

Table 2. Summary of measuring points.

| Test Item                  | Sensor                      | Range              | Precision        | Number of Measuring Points |
|----------------------------|-----------------------------|--------------------|------------------|----------------------------|
| Overall deformation        | Guyed displacement sensor   | 500 mm             | 0.01 mm          | 32                         |
| Segment concrete strain    | Foil strain gauge           | $20 \times 10^{-3}$ mm | $1 \times 10^{-6}$ mm | 48                         |
|                            | Electronic displacement sensor | 100 mm       | 0.01 mm          | 12                         |
| Slipping                   | Electronic displacement sensor | 100 mm       | 0.01 mm          | 12                         |
| Stripping                  | Electronic displacement sensor | 100 mm       | 0.01 mm          | 12                         |
| Mortar layer strain        | Foil strain gauge           | $20 \times 10^{-3}$ mm | $1 \times 10^{-6}$ mm | 48                         |
| Oil pressure               | Oil pressure sensor         | 700 kN             | 0.1 kN           | 3                          |

(1) Overall deformation

A guyed displacement sensor was used to measure the displacement of the measuring point, and the sensor is fixed on the inner arc surface of the segment. Two sections were selected in the lining structure, and sixteen positions were selected for each section to arrange sensors to monitor the overall deformation. A total of 32 guyed displacement sensors were arranged in the experiment. The sensor arrangement scheme of each section is shown in Figure 9.

Figure 9. Sensor arrangement scheme of each section.
(2) Segment concrete strain and mortar layer strain

Circumferential concrete strain and mortar strain were measured using foil strain gauges (model DX50AA-120) with a gauge length of 50 mm. A total of twelve sections were selected to arrange strain gauges, and each section was arranged with four strain measuring points. Forty-eight strain gauges were arranged on the concrete outer arc surface, and forty-eight strain gauges were arranged on the mortar layer. The strain-gauge arrangement scheme is shown in Figure 10.

![Figure 10. Strain-gauge arrangement scheme.](image)

(3) Interface slipping and stripping

The slipping and stripping between the mortar layer and the concrete lining were measured with electronic displacement sensors, and monitoring points were arranged at the joints of the original segment and the middle of the segment, with a total of 48 monitoring points. The monitoring-point arrangement scheme is shown in Figure 11.

![Figure 11. Monitoring-point arrangement scheme.](image)

3. Experimental Results

3.1. Properties of Spraying Mortar Materials

3.1.1. Compressive and Flexural Strength

The experiment results of H-70 compressive and flexural strength are shown in Figure 12. Under standard curing conditions, 7- and 14-day compressive strengths of...
H-70 reached 61% and 90% of the 28-day compressive strength, respectively. The 7- and 14-day flexural strengths of H-70 reached 65% and 86% of the 28-day flexural strength, respectively. This indicates that H-70 has high early strength, which is beneficial for rapid repair. Comparing the compressive and flexural strength of the two curing conditions at 28 days, it can be seen that the curing conditions (mainly the difference in humidity) have no obvious effect on the strength of H-70. The reason for this phenomenon is that H-70 has sand with a special particle size as the main aggregate, and the gaps between the sand particles are filled with finer powder particles, such as cement and silica fume, so that the mortar test block can reach the maximum compact state. The microstructure of the H-70 test block is denser than that of the ordinary concrete test block, so the external humidity environment has no obvious effect on the internal hydration process of H-70.

3. Experimental Results

3.1. Properties of Spraying Mortar Materials

3.1.1. Compressive and Flexural Strength

The experiment results of H-70 compressive and flexural strength are shown in Figure 12. Under standard curing conditions, 7- and 14-day compressive strengths of H-70 reached 61% and 90% of the 28-day compressive strength, respectively. The 7- and 14-day flexural strengths of H-70 reached 65% and 86% of the 28-day flexural strength, respectively. This indicates that H-70 has high early strength, which is beneficial for rapid repair. Comparing the compressive and flexural strength of the two curing conditions at 28 days, it can be seen that the curing conditions (mainly the difference in humidity) have no obvious effect on the strength of H-70. The reason for this phenomenon is that H-70 has sand with a special particle size as the main aggregate, and the gaps between the sand particles are filled with finer powder particles, such as cement and silica fume, so that the mortar test block can reach the maximum compact state. The microstructure of the H-70 test block is denser than that of the ordinary concrete test block, so the external humidity environment has no obvious effect on the internal hydration process of H-70.

3.1.2. Interface-Splitting Tensile Strength

The experiment results of interface-splitting tensile strength are shown in Table 3. Table 3 shows that:

1. The splitting tensile strength between H-70 and concrete is not affected by the curing condition.
2. The strength of the matrix concrete has a certain influence on the interface-splitting tensile strength. The higher the strength of the matrix, the greater the interface-splitting tensile strength.
3. Surface roughness has a significant effect on the split tensile strength. For the C55 concrete-splitting test block cured under standard curing conditions, the splitting tensile strength of the test block treated with orthogonal brushing is 55% higher than that of the test block treated with one-way brushing. Therefore, when using mortar to strengthen the tunnel lining segment, the interface roughness can be increased by chiseling, thereby improving the bearing capacity of the strengthened structure.

3.1.3. Interface Shear Strength

Interface shear strength test results are shown in Figure 13. According to the test results, under standard curing conditions, the 28-day shear strength of the interface between...
Table 3. Interface-splitting tensile strength.

| Block | Mortar | Strength Grade of Base Concrete | Hacking Method | Curing Condition | Splitting Tensile Strength (MPa) |
|-------|--------|---------------------------------|----------------|-----------------|----------------------------------|
| P11   | H-70   | C55                             | One-way        | Standard curing  | 1.52                             |
| P12   | H-70   | C55                             | Orthogonal     | Standard curing  | 2.36                             |
| P13   | H-70   | C55                             | One-way        | Construction     | 1.43                             |
| P14   | H-70   | C55                             | Orthogonal     | Construction     | 2.26                             |
| P21   | H-70   | C65                             | One-way        | Standard curing  | 1.73                             |
| P22   | H-70   | C65                             | Orthogonal     | Standard curing  | 2.51                             |
| P23   | H-70   | C65                             | One-way        | Construction     | 1.62                             |
| P24   | H-70   | C65                             | Orthogonal     | Construction     | 2.37                             |

Table 3 shows that:

1. The splitting tensile strength between H-70 and concrete is not affected by the curing condition.
2. The strength of the matrix concrete has a certain influence on the interface-splitting tensile strength. The higher the strength of the matrix, the greater the interface-splitting tensile strength.
3. Surface roughness has a significant effect on the split tensile strength. For the C55 concrete-splitting test block cured under standard curing conditions, the splitting tensile strength of the test block treated with orthogonal brushing is 55% higher than that of the test block treated with one-way brushing. Therefore, when using mortar to strengthen the tunnel lining segment, the interface roughness can be increased by chiseling, thereby improving the bearing capacity of the strengthened structure.

3.1.3. Interface Shear Strength

Interface shear strength test results are shown in Figure 13. According to the test results, under standard curing conditions, the 28-day shear strength of the interface between H-70 and concrete is 6.9 MPa, indicating that H-70 and C55 have high bond strength. The curing conditions have little effect on the shear strength of the interface.

Figure 13. Shear strength of interface between H-70 and concrete.
3.2. Structural Performance of Shield Tunnel Strengthened by In Situ Spraying Mortar

3.2.1. Failure Process

(1) Before $P_1$ reached 210 kN, the structure did not change significantly, but cracks appeared on the mortar surface; the maximum crack reached 0.65 mm, as shown in Figure 14a,b.

(2) When $P_1$ reached 235 kN, the concrete segment and mortar layer began to strip at the bottom, the mortar layer at 314° began to strip from the concrete segment and the surface cracks of the mortar layer at the top and bottom of the segment were large.

(3) When $P_1$ reached 254 kN, the concrete segment and mortar layer began to strip at 270°, as shown in Figure 14c. When $P_1$ reached 281 kN, the structure appeared to be continuous and sound, the reinforcement cage was separated and the mortar layer was stripped from the concrete segment from 120° to 360°.

(4) When $P_1$ reached 320 kN, the stripping of the mortar and concrete segment suddenly increased at 314°.

(5) When $P_1$ reached 368 kN, we observed the continued sound of the reinforcement cage stripping in the structure, and then a loud noise occurred. The joint at 54° opened outside, and the inner mortar layer was broken, as shown in Figure 14d. The structure reached the ultimate bearing capacity, and the experiment was completed.

![Image 1](image1.jpg)

![Image 2](image2.jpg)

![Image 3](image3.jpg)

![Image 4](image4.jpg)

Figure 14. Failure of strengthened segment under load; (a) cracks near 342° inner arc surface; (b) cracks near 126° inner arc surface; (c) interface stripping at 277.5°; (d) mortar layer broken.
3.2.2. Load–Convergence Deformation

The load–convergence deformation curve of the strengthened segment structure is shown in Figure 15. The stress mechanism of the tunnel lining segment structure strengthened by the in situ spraying mortar method is roughly as follows: (1) When the mortar layer and the concrete segment are not stripped, segment displacement increases linearly with an increase in the load. (2) When $P_1$ reaches 254 kN, the top and bottom of the strengthened structure begin to strip. The stiffness of the strengthened structure begins to decrease, and then the stripping position begins to expand until the mortar layer and concrete segment between 120° and 360° are all stripped. (3) Finally, the mortar layer at the 50° joint is crushed, and the structure reaches the ultimate bearing state.

![Figure 15. Load–convergence deformation of the strengthened segment.](image)

3.2.3. Interface Stripping and Slipping

A total of 12 interface stripping and slipping measurement points were set up in this experiment. Stripping and slipping measurement points were set at the seam. The measured values of interface slipping were divided into positive and negative. Positive values indicate that the mortar layer slips counterclockwise relative to the concrete segment, and negative values indicate that the mortar layer slips clockwise relative to the concrete segment. The measured value of interface stripping is positive. Before the experiment, the slipping value and stripping value were both 0 mm. After the experiment, the slipping value of each measuring point was 0 mm. The final stripping values of each point at the crown and bottom of the segment are shown in Figure 16. The maximum stripping value at the crown of the segment is 15.22 mm, and the maximum stripping value at the top of the segment is 17.12 mm.
The strengthening effect of the shield tunnel lining structure is mainly reflected in the ultimate bearing capacity. The load–convergence deformations of the strengthened and unstrengthened segment are shown in Figure 17. A is defined as the elastic limit point of the unstrengthened segment, and B is defined as the ultimate bearing capacity point of the unstrengthened segment. D is defined as the elastic limit point of the strengthened segment, and the E is defined as the ultimate bearing capacity point of the strengthened segment. The slope, \( k_0 \), of OA is the elastic-stage stiffness of the unstrengthened segment, and the slope, \( k_1 \), of CD is the elastic-stage stiffness of the strengthened segment. A performance comparison between the strengthened and unstrengthened segments is shown in Table 4.

![Figure 16. Stripping values of each point at the crown and bottom of the segment.](image1)

![Figure 17. Load–convergence deformation of the strengthened and unstrengthened segments.](image2)
Table 4. Performance comparison between the strengthened and unstrengthened segments.

| Type of Segment      | Elastic Limit Load (kN) | Ultimate Bearing Capacity (kN) | Maximum Elastic Displacement (mm) | Structural Stiffness in Elastic Stage (kN/mm) |
|----------------------|-------------------------|--------------------------------|-----------------------------------|-----------------------------------------------|
| Unstrengthened segment | 316                    | 335                            | 35.34                             | 10.15                                         |
| Strengthened segment  | 214                    | 368                            | 11.55                             | 8.53                                          |

From Table 4, it can be seen that the ultimate bearing capacity of the segment strengthened by in situ spraying mortar is 10% higher than that of the unstrengthened segment.

4. Comparison of In Situ Spraying Mortar Method and Internally Tensioned Steel Ring Method

At present, the internally tensioned steel-ring strengthening method is commonly used in engineering to strengthen the shield tunnel lining segment. Engineering economy is an important factor that determines the promotion of engineering technology. Therefore, in this paper, we compared the economy of the two strengthening methods, as shown in Table 5. The material cost of in situ spraying mortar is low, and the construction speed is fast, which reduces the construction period. In the situ spraying-mortar method controls the operation and maintenance costs and provides good durability and fire resistance.

Table 5. Comparison of engineering economics of the two strengthening methods.

| Strengthening Method       | Material                          | Construction Period                                   | Durability                                      | Fire Resistance                        |
|----------------------------|-----------------------------------|------------------------------------------------------|-------------------------------------------------|----------------------------------------|
| In situ spraying mortar    | Mortar, steel reinforcement,      | It takes time to reinforce grillage                   | High density and durability of mortar            | Mortar has excellent fire             |
|                            | reinforced grillage                | Chemical anchor construction takes time and requires large lifting equipment, and it is difficult to weld steel plates on site [9] | Epoxy resin adhesive has aging risk             | resistance                              |
| Internal-tension steel ring| Steel plate, epoxy resin, chemical anchor | The use of in situ spraying mortar saves cost         | In situ spraying mortar is faster in construction | In situ spraying mortar has better durability | Poor fire resistance                   |

Comparison of results

5. Summary and Conclusions

After long-term operation, tunnel lining segments encounter various problems. The currently used shield tunnel lining strengthening method has various shortcomings. Therefore, in this paper, we proposed a new shield tunnel lining strengthening method by in situ spraying of cement mortar. Based on the material properties test of H-70 for in situ spraying mortar and a full-scale experimental study on the strengthening of tunnel lining segment structure, and compared with internal tensioned steel ring strengthening method, the main conclusions are as follows:

1. The mechanical properties of H-70 mortar are not dependent on curing conditions. Under standard curing conditions, the 7- and 14-day compressive strengths of H-70 reached 61% and 90% of the 28-day compressive strength, respectively, indicating that H-70 has high early strength and is convenient for rapid repair.
(2) The strength and surface roughness of the strengthened segment have a certain influence on the interface-splitting tensile strength. When strengthening the shield tunnel lining segment structure, the roughness of the interface between the segment and the mortar can be increased by chiseling, thereby improving the bearing capacity of the reinforced structure.

(3) The ultimate bearing capacity of the tunnel lining segment structure strengthened by in situ spraying mortar was significantly increased; the ultimate bearing capacity of the lining segment structure is increased by 10% compared with the unstrengthened lining segment structure. Compared with the internal steel-ring strengthening method, the in situ spraying mortar method has obvious advantages in terms of economy, workability and durability.

(4) The full-scale loading experiment clarified the effectiveness of the new strengthening method. The next step will be to carry out ongoing research on construction technology, combined with the actual project, and to provide comprehensive technical support for the practical application of the new strengthening method.

Author Contributions: Conceptualization, F.W. and C.Z.; methodology, F.W.; validation, C.Z. and B.M.; formal analysis, F.W.; investigation, F.W., C.G. and Y.Z.; resources, B.M. and B.L.; data curation, F.W., C.Z. and Y.K.; writing—original draft preparation, F.W.; writing—review and editing, F.W., Y.Z., C.G. and B.L.; supervision, C.Z. funding acquisition, C.Z. All authors have read and agreed to the published version of the manuscript.

Funding: Engineering Research Center of Rock-soil Drilling & Excavation and Protection 20210501.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors are very grateful for the technical support provided by Wuhan CUG Trenchless Technology Research Institute Co., Ltd., Wuhan, China.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Chang, C.T.; Sun, C.W.; Duann, S.W.; Hwang, R.N. Response of a Taipei Rapid Transit System (TRTS) tunnel to adjacent excavation. Tunn. Undergr. Space Technol. 2001, 16, 151–158. [CrossRef]
2. Yuan, Y.; Jiang, X.; Liu, X. Predictive Maintenance of Shield Tunnels. Tunn. Undergr. Space Technol. 2013, 38, 69–86. [CrossRef]
3. Jin, D.; Yuan, D.; Li, X.; Zheng, H. An in-tunnel grouting protection method for excavating twin tunnels beneath an existing tunnel. Tunn. Undergr. Space Technol. 2018, 71, 27–35. [CrossRef]
4. Zhang, D.; Liu, Z.; Wang, R.; Zhang, D. Influence of grouting on rehabilitation of an over-deformed operating shield tunnel lining in soft clay. Acta Geotech. 2019, 14, 1227–1247. [CrossRef]
5. Kiriyama, K.; Kakizaki, M.; Takabayashi, T. Structure and Construction Examples of Tunnel Reinforcement Method Using Thin Steel Panels. Nippon Steel Tech. 2005, 92, 45–50.
6. Liu, X.; Jiang, Z.; Yuan, Y.; Mang, H.A. Experimental investigation of the ultimate bearing capacity of deformed segmental tunnel linings strengthened by epoxy-bonded filament wound profiles. Struct. Infrastruct. Eng. 2017, 13, 1268–1283.
7. Li, Y.J.; Wang, M.S.; Xu, H.J.; Zhang, Y. Numerical analysis of metro tunnel structure reinforced by fiber cloth material. China Civ. Eng. J. 2014, 47, 138–144.
8. Bi, X.L.; Liu, X.; Wang, X.Z.; Lu, L.; Zhu, Y.F. Experimental study of ultimate load-bearing capacity of deformed segmental tunnel linings strengthened by steel plates. China Civ. Eng. J. 2014, 47, 128–135.
9. Liu, X.; Jiang, Z.; Yuan, Y.; Mang, H.A. Experimental investigation of the ultimate bearing capacity of deformed segmental tunnel linings strengthened by epoxy-bonded steel plates. Struct. Infrastruct. Eng. 2018, 14, 685–700. [CrossRef]
10. Xian, L.; Min, T.; Liang, L. Experimental study of ultimate bearing capacity of shield tunnel reinforced by full-ring steel plate. Chin. J. Rock Mech. & Eng. 2013, 32, 2300–2306.
11. Najafi, M.; Sever, F. Structural Capabilities of No-Dig Manhole Rehabilitation Products; WERF Report INFR1R12; Water Environment Research Foundation: Denver, CO, USA, 2015.
12. Weber, J.; Gadermayr, N.; Bayer, K.; Hughes, D.; Kozlowski, R. Roman cement mortars in Europe’s architectural heritage of the 19th century. *Binders 2007*, *4*, 100667–100681. [CrossRef]

13. Grengg, C.; Mittermayr, F.; Ukrainczyk, N.; Koraimann, G.; Kienesberger, S.; Dietzel, M. Advances in concrete materials for sewer systems affected by microbial induced concrete corrosion: A review. *Water Res.* *2018*, *134*, 341–352. [CrossRef] [PubMed]

14. Valix, M.; Zamri, D.; Mineyama, H.; Cheung, W.H.; Shi, J.; Bustamante, H. Microbiologically induced corrosion of concrete and protective coatings in gravity sewers. *Chin. J. Chem. Eng.* *2012*, *20*, 433–438. [CrossRef]

15. Zhang, H. Theoretical and Experimental Study on Structural Performance of the Sprayed-on Cement Mortor Liners Rehabilitating Precast Concrete Drainage Pipe. Ph.D. Thesis, China University of Geosciences, Wuhan, China, 2019.

16. *JG/T 70*; Standard for Test Method of Performance on Building Mortar. Standard Press: Beijing, China, 2009.

17. *GB/T17671*; Method of Testing Cements-Determination of Strength. Standard Press: Beijing, China, 1999.

18. *GB/T50081*; Standard for Test Method of Mechanical Properties on Ordinary Concrete. Standard Press: Beijing, China, 2003.

19. Zhao, Y.; Ma, B.; Ariaratnam, S.T.; Zeng, C.; Yan, X.; Wang, F.; Wang, T.; Zhu, Z.; He, C.; Shi, G. Structural Performance of Damaged Rigid Pipe Rehabilitated by Centrifugal Spray on Mortar Liner. *Tunn. Undergr. Space Technol.* *2021*, *116*, 104117. [CrossRef]