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Mechanical and Impermeability Properties of Polymer Grouting Materials for Hydraulic Expansion Joints

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Abstract

Among the water leakage issues in hydraulic tunnels, the issue of water leakage through expansion joints accounts for nearly 90%, making it the primary defect of hydraulic tunnels and posing serious safety hazards to hydraulic structures. To address the issue of water leakage through hydraulic expansion joints, this study investigated a polyurethane polymer grouting sealing material. Traditional sealing and leaking stoppage materials used for hydraulic expansion joints had drawbacks, such as high viscosity, excessive rigidity resulting in the failure to adapt to the deformation of expansion joints, and poor adhesion to concrete. The mechanical properties and impermeability of grouting materials prepared by blending polyurethane with epoxy resin were analyzed through orthogonal and single-factor tests. The excellent sealing and leaking stoppage effects of polyurethane polymer were demonstrated and the optimal mix ratio of the polymer grouting material was determined. Results show that, (1) the gel formed by the reaction of polyurethane and epoxy resin has good mechanical properties. (2) The compressive strength of the grouting material continuously increases with the increase in the dosage of the curing agent and reaches the maximum of 0.98 MPa. The tensile strength of the grouting material initially increases then decreases, and the maximum value is 0.7 MPa. The elongation at break is negatively correlated with the dosage of the curing agent, and the minimum value is 54%. (3) Magnesium oxide can improve the mechanical properties and setting time of the grouting material. The setting time of the grouting material initially increases then decreases with the increase in the dosage of magnesium oxide. Moreover, the compressive strength increases with the increase in the dosage of magnesium oxide, and the swelling rate upon contact with water decreases with the increase in the dosage of magnesium oxide. The comprehensive property is optimal when the dosage of magnesium oxide is 1%. (4) With the increase in the dosage of magnesium oxide, the water pressure at which the grouting material permeates the specimen increases then decreases, and the maximum water permeation pressure is 0.5 MPa. This study provides a good reference and basis for assessing the impermeability of polyurethane polymer grouting materials.

Keywords: Grouting material, Polyurethane, Epoxy resin, Impermeability and leaking stopping, Expansion joint

1. Introduction

Hydraulic structures are often equipped with a series of expansion joints along their length to accommodate temperature variations and internal stress changes [1]. Expansion joints in hydraulic structures are prone to water leakage, with leakage in the expansion joints of tunnels being a common issue in construction projects. Study data indicate that leakage in expansion joints accounts for over 90% of leakage in hydraulic structures [2]. Traditional sealing and leaking stopping methods for expansion joints mainly include asphalt grease, polyvinyl chloride mastic, rubber strip sealing, sealants, elastic concrete, and other fillers. These methods are characterized by complex construction operations, relatively high requirements for construction conditions, and low bonding strength with concrete [3].

As the issue of leakage in the expansion joints of tunnels becomes increasingly severe, traditional lea

king stoppage materials for expansion joints are often likely to fail because of weak bonding strength with concrete at the joint interfaces [4]. This study addresses leaking stoppage in expansion joints by employing a grouting method that uses polyurethane polymer grouting to enhance the integrity and impermeability of expansion joints. Research on leaking stoppage materials for expansion joints has practical value and economic benefits. Although scholars have conducted extensive research on the sealing and leaking stoppage of expansion joints [5,6], studies on bonding strength with concrete and impermeability are limited(Fig. 1). Thus, enhancing the bonding strength with concrete interfaces and the impermeability of leaking stoppage materials for expansion joints is an urgent issue to be addressed.

Polyurethane polymer grouting materials are prepared in this study by mixing polyurethane with epoxy resin by means of combined experimental research and theoretical analysis to address the limitations of traditional leaking stoppage materials for expansion joints. In consideration of the construction and property characteristics of expansion joints in hydraulic structures, indoor impermeability, leaking stoppage, and bonding strength tests are conducted on the polyurethane polymer grouting materials to verify their

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bonding strength, compressive strength, water swelling rate, impermeability, and leaking stoppage.

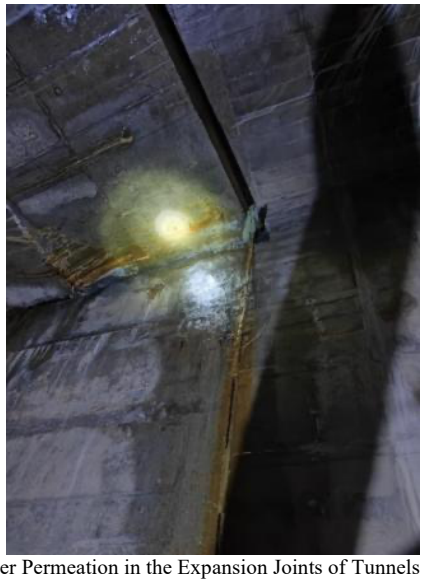

Fig. 1. Water Permeation in the Expansion Joints of Tunnels

2. State of the art

Scholars have conducted extensive research on materials for repairing expansion joints. Haufe [7] studied a novel acrylic resin gel that could be injected into concrete cracks to repair honeycomb-like areas and fill voids in concrete structures. However, this study did not address the repair of expansion joints. Izmaylov [8] investigated a polymer compound and added high-strength mineral aggregates to polyurethane resin. This work provided a reference for research on the wear resistance and durability of polyurethane composites. Wang [9] analyzed the effects of ambient temperature and increasing the roughness of the interface of expansion joints on the bonding strength of polyurethane concrete to establish a reference for enhancing the bonding strength of repair materials. However, the impermeability of the materials was not investigated. Mei [10] analyzed the addition of sodium silicate and epoxy resin to polyurethane grouting materials and concluded that sodium silicate and epoxy resin considerably improved the compression properties, swelling rate, and internal pore structure of polyurethane grouting materials; however, bonding was not considered. Yahye [11] enhanced the strength and toughness of polyurethane elastic concrete by adding steel fibers. Zhuang and Wang [12,13] introduced epoxy resin E-44 into waterborne polyurethane and studied its effect on the properties of polyurethane by changing the dosage of epoxy resin. Their results served as a reference for the study of waterborne polyurethane and epoxy resin composite grouting materials. Zhang [14] physically blended waterborne polyurethane with polyacrylate and demonstrated that the mixed material was characterized by good water resistance and moisture sensitivity. These results could be used as a reference for studying the water resistance of polyurethane composites. Meanwhile, Yang [15] discovered that epoxy resin acted as a crosslinker in mixtures of waterborne polyurethane, epoxy resin, and emulsified asphalt. This finding provided a reference for studying the improvement of the bonding and tensile strengths of waterborne polyurethane composites.

Jia [16] added epoxy resins with different contents to synthesized waterborne polyurethane to study the effects of epoxy resins with different contents on the property of the composite. The composite exhibited an optimal property when the content of the epoxy resin was 7%–9% primarily because of the increased crosslinking effect and the formation of a dense spatial network. However, the study did not investigate the mechanical properties at high dosages of epoxy resins. Wang and Zhao [17,18] blended epoxy resin E-51 and epoxy resin E-44 into waterborne polyurethane and demonstrated that the addition of epoxy resin could increase the solid content and viscosity of the composite and enhance its mechanical properties. This work provided a reference for improving the solid content and mechanical properties of materials. Meanwhile, Yang [19] prepared a composite grouting material by mixing waterborne polyurethane, epoxy resin, and cement; the results of this study offer a reference for studying the mechanical properties of polyurethane polymer grouting materials. Liu [20] studied a mixture of epoxy resins with different epoxy values (E-21, E-44, and E-51) and their addition amounts with waterborne polyurethane to provide a reference for investigating the effects of epoxy resins with different epoxy values and addition amounts on the property of the composite. Long [21] incorporated nanosilica into a waterborne polyurethane coating and conducted impermeability tests to provide a reference for studying the impermeability of polyurethane grouting materials. Zuo [22] prepared a composite polyurethane coating by combining epoxy resin, silicone, and waterborne polyurethane and concluded that the addition of inorganic fillers considerably improved the comprehensive property of waterborne polyurethane coating. This work served as a reference for studying polyurethane polymer grouting materials.

The studies above focused on the multi-functionality and physical and mechanical properties of polyurethane composite films, and only a few studies have been conducted on the bonding, impermeability, and other mechanical properties of polyurethane polymer grouting materials, especially those associated with the correlation between grouting and leaking stoppage of expansion joints. This study establishes an expansion joint grouting impermeability and leaking stoppage model with polyurethane polymer grouting impermeability mortar specimens. Starting from the impermeability and leaking stoppage characteristics of the grouting material, it discusses the bonding strength, compressive strength, water swelling rate, impermeability, and leaking stoppage characteristics of the polyurethane polymer grouting material and establishes a coupling relationship between the polyurethane polymer grouting material and the expansion joint. This work can serve as a basis for the optimization and testing of polyurethane polymer grouting materials.

The remaining part of this study is organized into sections. Section 3 determines the initial mix ratio of the polyurethane polymer grouting material through a three-factor, four-level orthogonal test on the mechanical properties. Section 4 presents the effect of magnesium oxide on the property of the grouting material and the influence of the curing agent on the compressive strength, tensile strength, and elongation at break of the grouting material. The optimal dosages of the curing agent and magnesium oxide for the property of the grouting material are also presented. The subsequent sections involve the study of impermeability and leaking stoppage tests on mortar. The final section summarizes the entire study and presents the main conclusions.

3. Methodology

3.1 Test scheme

Orthogonal Test Scheme: The initial mix ratio of the grout was determined through a three-factor, four-level orthogonal test (Table 1). The mass ratios of waterborne polyurethane and epoxy resin in Component A and the mass ratio of silicate in Component B were the three factors in the orthogonal test for examining the bonding strength, compressive strength, and water swelling rate of each mix ratio. The percentages of the silane coupling agent, solvent oil, plasticizer, and acrylic acid in Component A and the percentage of the surfactant in Component B were fixed at 0.5%, 8%, 18%, 10%, 15%, and 0.5%, respectively. The dosage of the curing agent was 10%. In this phase, the mass ratio of Component A to Component B was 9.45:1.55.

Table 1. Orthogonal Test Table

Formula No.	A: Polyurethane (%)	B: Epoxy Resin (%)	C: Silicate (%)
1	21	3	8
2	21	6	11.5
3	21	10	15
4	21	13.5	18.5
5	24.5	3	11.5
6	24.5	6.5	8
7	24.5	10	18.5
8	24.5	13.5	15
9	28	3	8
10	28	6.5	18.5
11	28	10	15
12	28	13.5	11.5
13	31.5	3	15
14	31.5	6.5	18.5
15	31.5	10	8
16	31.5	13.5	11.5

Inorganic Filler Modification Test: The formulas for Groups 10 and 11, which performed well in the orthogonal test, were used to study the effects of magnesium oxide with mass ratios of 0.5%, 1%, 1.5%, 2%, and 2.5% on the volume shrinkage rate, compressive strength, bonding strength, and water swelling rate of the grouting material.

Grouting Impermeability and Leaking Stoppage Test. The formulas for Groups 10 and 11, which performed well in the orthogonal test, were utilized to conduct a grouting impermeability test on a 10 mm × 30 mm mortar specimen.

3.2 Test Materials and Instruments

Component A included waterborne polyurethane, epoxy resin E51, chlorinated paraffin-52, solvent oil, acrylic acid, silane coupling agent, and deionized water. Component B contained sodium silicate and dodecylbenzenesulfonic acid sodium, and the inorganic fillers were heavy calcium carbonate, talc powder, and magnesium oxide.

The primary instruments used in the study included a digital display universal testing machine, a fully automatic compression testing machine, an impermeability tester, a rotary viscometer, a standard curing chamber, and a constant temperature drying oven.

3.3 Test Method for Bonding Strength

A bonding strength test was conducted with reference to the bonding strength test method specified in JG/T316-2011. In the test, each group consisted of five specimens. The prepared material (2-3 mm) was taken and evenly applied on the surface of the upper clamp (40 mm × 40 mm); then, the upper clamp was placed in the middle of the mortar specimen, and light pressure was applied to ensure that the grout was evenly filled between the clamp and the mortar block. After 1 day of placement, the excess cured material around the upper clamp was cut off using scissors (Fig. 2). Then, the stone was placed in a standard curing chamber for 6 days and tested within 10 min after removal (Fig. 3). The bonding strength was calculated as follows:

$$\sigma=\frac{P}{1600} \tag{1}$$

where σ is the bonding strength in MPa and P is the maximum tensile force in N.

Fig. 2. Bonding Strength Specimen

Fig. 3. Digital Display Universal Testing Machine

3.4 Test Method for Compressive Strength

A cubic mold with dimensions of 20 mm × 20 mm × 20 mm was utilized for the compressive strength test, and each group had three specimens. The prepared grouting material was poured into the 20 mm × 20 mm × 20 mm cubic mold and cured in a temperature-controlled box at an ambient environment of 23 °C and relative humidity of 50% for 24–48 h before demolding (Fig. 4). After demolding, the specimens were allowed to stand at room temperature for

168 h before the compressive strength test (Fig. 5). Compressive strength was calculated using the formula:

$$\sigma_c = \frac{P}{F} \tag{2}$$

where σ_c is the compressive strength in MPa, P is the maximum load at failure in N, and F is the cross-sectional area of the specimen in mm².

Fig. 4. Specimen for Compressive Strength

Fig. 5. Fully Automatic Compression Testing Machine

3.5 Test Method for Water Swelling Rate

The prepared grouting material was placed in a mold with an inner diameter of 50 mm and a height of 50 mm. After the grouting material had gelled and cured in the mold, the cured material was removed after a three-day curing period, with three specimens per group. The specimens were immersed in distilled water for seven days and calculated (Fig. 6). The water swelling rate was computed using the formula:

$$\Delta V = \frac{(V_1 - V) - (V_0 - V)}{V_0 - V} \tag{3}$$

where ΔV is the water swelling rate, V is the volume of water in the measuring cylinder in mL, V_0 is the volume of the gel and water before the test in mL, and V_1 is the total volume of the gel and water after the test in mL.

Fig. 6. Specimen for Water Swelling Rate

3.6 Test Method for Impermeability and Leaking Stoppage of Grouting Materials

Impermeability Test on Grouting Materials: First, in line with the standard for polymer waterproof mortar, a batch of mortar impermeability specimens with 10 mm × 30 mm cracks was prepared with a mass ratio of water, cement, and sand of 1:1.27:5.19. Second, a random group of specimens was selected for the impermeability tests. The specimens were cured under standard conditions for 14 days and dried for standby application. The specimens were then sealed along the crack edges using tape. Third, the prepared polyurethane polymer grouting material was uniformly mixed and injected along the crack in the specimen (Fig. 7) while ensuring that the grouting material was slightly above the specimen surface. Last, an impermeability test was conducted after curing under standard conditions. Specifically, the repaired specimen was sealed with a sealing material and placed in the impermeability mold. The air was exhausted from the impermeability tester (Fig. 8), and the specimen was placed in it (Fig. 9). The pressure was increased from 0.1 MPa after starting the tester and increased by 0.1 MPa every 30 min until the specimen exhibited water permeation. The water pressure at which the fourth specimen permeated was recorded as the water pressure at the time of water permeation (hereinafter referred to as the water permeation pressure).

Fig. 7. Impermeability Specimen after Grouting

Fig. 8. Impermeability Tester

Fig. 9. Placement of the Impermeability Specimen

3.7 Test Method for Tensile Strength and Elongation at Break

The prepared grouting material was poured into a smooth glass or steel plate with a pouring thickness of 3.5–4.5 mm, and a release agent or glass paper was applied to the plate. The mold was removed after 24–48 h of curing at room temperature, and the specimen was cut into a dumbbell shape by using a cut-off knife and a sheet-punching machine after reaching the curing period at room temperature or standard ambient temperature. Each group had at least five specimens (Fig. 10). Then, the tensile strength and elongation at break were measured using a digital display universal testing machine (Fig. 11). Tensile strength was calculated using the formula:

$$\sigma_t = \frac{P}{b \times h} \tag{4}$$

where σ_t is the tensile strength in MPa, P is the maximum load in N, b is the width of the specimen in mm, and h is the thickness of the specimen in mm. Elongation at break was calculated using the formula:

$$\varepsilon_t = \frac{\Delta L_b}{L_0} \times 100 \tag{5}$$

where ε_t is the elongation at break, ΔL_b is the elongation value within measured distance L_0 at the time of specimen fracture in mm, and L_0 is the measurement gauge in mm.

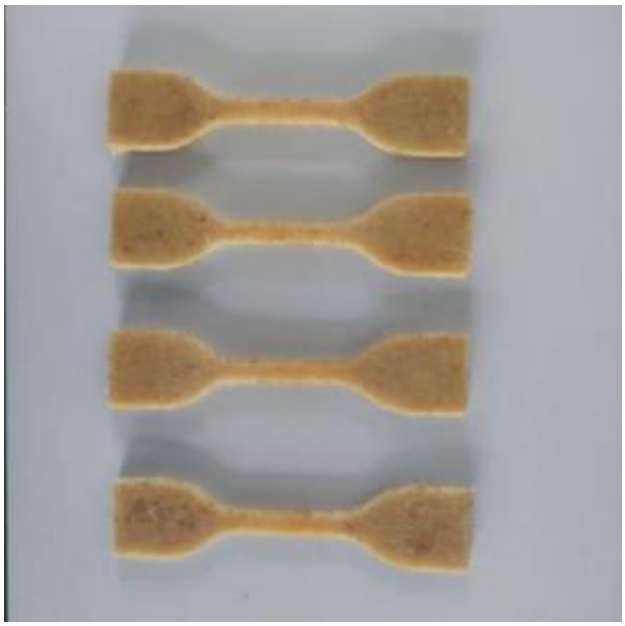

Fig. 10. Dumbbell Specimen

Fig. 11. Digital Display Universal Testing Machine

4. Result Analysis and Discussion

4.1 Analysis of Orthogonal Test Results

The orthogonal test results (Table 2) were examined based on the test scheme in Section 3.1.

Table 2. Orthogonal Test Results Table

Formula No.	Bonding Strength (MPa)	Compressive Strength (MPa)	Water Swelling Rate (%)
1	0.51	0.45	65
2	0.7	0.55	58
3	0.85	0.63	44
4	0.8	0.82	23
5	0.6	0.48	62

6	0.75	0.51	64
7	1.01	0.64	30
8	0.93	0.7	24
9	0.65	0.49	68
10	0.92	0.75	38
11	1.12	0.77	45
12	1.04	0.68	27
13	0.73	0.58	50
14	0.94	0.78	35
15	1.11	0.67	32
16	1.08	0.8	18

The range analysis of the orthogonal test results (Tables 3, 4, and 5) indicated that the primary and secondary order of factors affecting the bonding strength of the grouting material was B (percentage of epoxy resin in total mass) > A (percentage of polyurethane emulsion in total mass) > C (percentage of silicate in total mass). The primary and secondary order of factors affecting the compressive strength of the grouting material was B (percentage of epoxy resin in total mass) > C (percentage of silicate in total mass) > A (percentage of polyurethane emulsion in total mass). Meanwhile, the primary and secondary order of factors affecting the water swelling rate of the grouting material was B (percentage of epoxy resin in total mass) > C (percentage of silicate in total mass) > A (percentage of polyurethane emulsion in total mass).

The analysis of Tables 3, 4, and 5 revealed that epoxy resin exerted the largest effect on the mechanical properties of the grouting material primarily because epoxy resin and polyurethane exhibit good compatibility. The epoxy resin in this study, which contained a high concentration of hydroxys, underwent physical blending and chemical crosslinking reactions with the active groups in polyurethane, resulting in the formation of a crosslinked structure. Moreover, the epoxy resin readily underwent ring-opening reactions and further interacted with polyurethane to generate a reticulated structure. The crosslinked structure of the two components contributed to the increased compactness of the grouting material, thereby enhancing its compressive strength [23]. As the dosage of the epoxy resin increased, the bonding properties were enhanced, resulting in a compact crosslinked structure with polyurethane and improving the bonding strength of the grouting material. The increased compactness of the internal structure of the grouting material reduced its water retention capacity, leading to a decrease in the water swelling rate to some extent.

Table 3. Range Analysis of the Bonding Strength Test

Category	Factor A	Factor B	Factor C	Factor D
K_1	2.860	2.490	3.020	3.500
K_2	3.290	3.310	3.420	3.480
K_3	3.730	4.090	3.630	3.450
K_4	3.860	3.850	3.670	3.310
$\overline{K_1}$	0.715	0.623	0.755	0.875
$\overline{K_2}$	0.823	0.828	0.855	0.870
$\overline{K_3}$	0.933	1.023	0.908	0.863
$\overline{K_4}$	0.965	0.963	0.918	0.828
Range R	0.250	0.400	0.163	0.048
Primary and Secondary Order	B>A>C			

Table 4. Range Analysis of the Compressive Strength Test

Category	Factor A	Factor B	Factor C	Factor D
K_1	2.450	2.000	2.120	2.550
K_2	2.330	2.590	2.510	2.600
K_3	2.690	2.710	2.680	2.660
K_4	2.830	3.000	2.990	2.490
$\overline{K_1}$	0.613	0.500	0.530	0.638
$\overline{K_2}$	0.583	0.648	0.628	0.650
$\overline{K_3}$	0.673	0.678	0.670	0.665
$\overline{K_4}$	0.708	0.750	0.748	0.623
Range R	0.125	0.250	0.218	0.043
Primary and Secondary Order	B>C>A			

Table 5. Range Analysis of the Water Swelling Rate Test

Category	Factor A	Factor B	Factor C	Factor D
K_1	190	245	229	150
K_2	180	195	158	177
K_3	171	151	163	162
K_4	135	85	126	187
$\overline{K_1}$	47.5	61.25	57.25	37.5
$\overline{K_2}$	45	48.75	41.25	44.25
$\overline{K_3}$	42.75	37.75	40.75	40.5
$\overline{K_4}$	33.75	21.25	31.5	46.75
Range R	13.75	40	25.75	9.25
Primary and Secondary Order	B>C>A			

The analysis results in Tables 3, 4, and 5 reveal that the proportion of epoxy resin considerably affected the mechanical properties of the grouting material. As indicated in Table 2, the water swelling rate gradually decreased with the increase in the dosage of epoxy resin because the addition of epoxy resin enhanced the full compatibility with polyurethane, leading to an increase in the number of crosslinking points and improving the crosslinking density and dense network-like internal structure of the grouting material. The internal structure and crosslinking density of the grouting material were the primary factors that affected its mechanical properties. The increase in the dosage of epoxy resin led to increased crosslinking density and a stable internal structure, which enhanced the compressive and bonding strengths of the material. However, the increase in epoxy resin also resulted in a decrease in the water swelling rate of the grouting material.

The analysis results in Tables 3, 4, and 5 also indicate that silicate exerted a considerable effect on the compressive strength and water swelling rate of the grouting material, and its effect was second only to that of epoxy resin. Silicate underwent hydrolysis reactions in the emulsion and generated silanols that effectively reduced the curing speed of the polyurethane polymer grouting material. The silanols further underwent condensation reactions to form a stable 3D crosslinked structure. These reactions increased the crosslinking density of the polymer grouting material. Moreover, the silanol structures produced by silicate hydrolysis formed covalent bonds, which exhibited strong bonding forces and stable properties, making the internal structure of the grouting material increasingly compact and thereby enhancing its compressive strength. The compactness of the internal network space reduced the water swelling rate. Polyurethane exerted less influence on the compressive strength and water swelling rate of the grouting material compared with epoxy resin and silicate. As a highly molecular polymer emulsion, polyurethane has excellent compatibility and aging resistance. It also has good compatibility with epoxy resin, and in this study, the two formed a crosslinked structure. However, with the increase in the amount of polyurethane, some of it mixed with epoxy resin to form a crosslinked structure, and the rest was

dispersed in the grouting material, thus reducing the solid content and affecting the mechanical properties of the grouting material.

In consideration of the comprehensive property of the polyurethane polymer grouting material, the formulas for Groups 10 and 11 from the orthogonal test exhibited an excellent mechanical property.

4.2 Effect of Inorganic Fillers on the Property of Polymer Grouting Materials

Fillers can enhance the physical and chemical properties of grouting materials and lower the volume shrinkage rate of polyurethane polymer grouting materials. This study also investigated the effects of fillers on polyurethane polymer grouting materials. Heavy calcium carbonate, talc powder, and magnesium oxide were used to examine the effects of 0.5%, 1%, 1.5%, 2%, and 2.5% contents on the volume shrinkage rate of the grouting material.

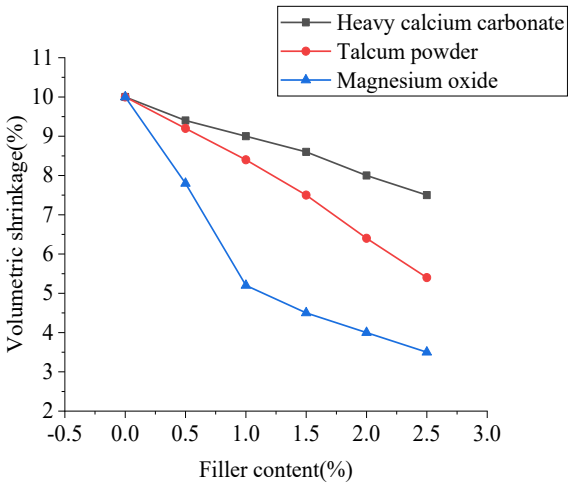

Fig. 12. Effects of Inorganic Fillers on the Volume Shrinkage Rate

As depicted in Fig. 12, the three inorganic fillers, when added to the polyurethane polymer grouting material, exhibited varying effects on the volume shrinkage rate, with magnesium oxide outperforming talc powder, which in turn outperformed heavy calcium carbonate. Heavy calcium carbonate and talc powder simply filled the internal pores of the grouting material, reducing their size and consequently diminishing the volume shrinkage rate. Talc powder, with its layered structure, exhibited better dimensional stability than heavy calcium carbonate, which is granular, leading to the more favorable effect of the former on the volume shrinkage rate of the grouting material compared with the effect of the latter. Magnesium oxide exerted a more favorable influence on the volume shrinkage rate than talc powder because magnesium oxide undergoes hydration reactions in water, causing its volume to increase and thus exerting a slight swelling effect on the grouting material. Moreover, magnesium oxide fills the internal pores of the grouting material and makes them highly compact, resulting in a reduced volume shrinkage rate. Thus, the effect of magnesium oxide on the volume shrinkage rate of grouting materials is superior to that of talc powder and heavy calcium carbonate. In this study, when the dosage of the fillers increased, the volume shrinkage rate of the grouting material gradually decreased; the effect of magnesium oxide on the volume shrinkage rate diminished when its dosage exceeded 1%.

Given the favorable performance of magnesium oxide in reducing the volume shrinkage rate of the grouting material, its dosage was considered a variable factor and added to the formulas of Groups 10 and 11 to examine its effect on the setting time, compressive strength, and water swelling rate of the grouting material.

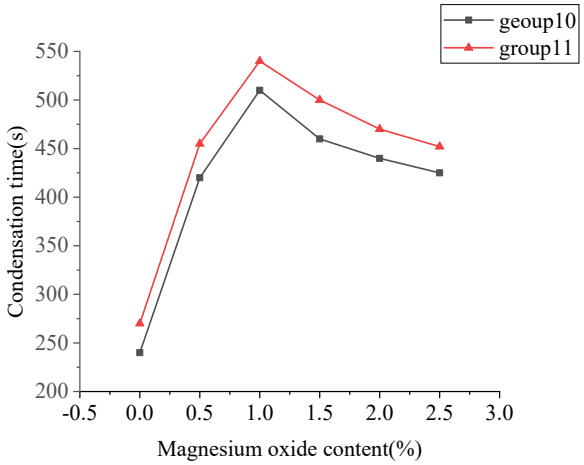

Fig. 13. Effect of Magnesium Oxide on Setting Time

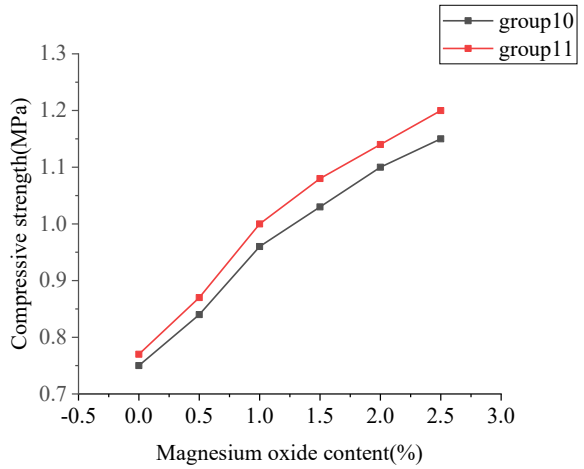

Fig. 14. Effect of Magnesium Oxide on Compressive Strength

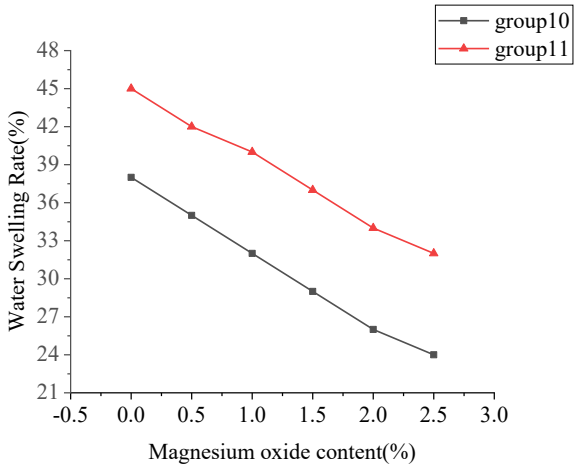

Fig. 15. Effect of Magnesium Oxide on Water Swelling Rate

As observed in Figs 13, 14, and 15, the water swelling rate of the formulas of Groups 10 and 11 gradually decreased with the increase in the dosage of magnesium oxide. Magnesium oxide entered the interior of the grouting material, making the internal structure increasingly compact and reducing the water molecules it contained, thereby decreasing the water swelling rate. The higher the dosage of

magnesium oxide, the more compact the interior of the grouting material and the higher the compressive strength. This phenomenon was due to the easy dispersibility of magnesium oxide and the increase in volume upon hydration, which allowed it to effectively fill the internal pores of the polyurethane polymer grouting material, thus enhancing its compressive strength and stability. Magnesium oxide, as inorganic filler, produced some hydroxyls upon hydration with water, and a few hydroxyls could delay the hydrolysis of silicates and reduce the setting rate of the grouting material, consequently extending the setting time. However, with the increase in the content of magnesium oxide, its hydration released heat, which increased the temperature as a result. The increased temperature promoted the hydrolysis of silicates, accelerated the setting rate, and shortened the setting time. Thus, the effect of magnesium oxide on the setting time of the grouting material initially increased then decreased. Magnesium oxide could improve the physical and mechanical properties of the grouting material and reduce the volume shrinkage rate, but its setting time increased initially then decreased with the increase in the content of magnesium oxide. A dosage of 1% magnesium oxide was used in consideration of the comprehensive effect of magnesium oxide on the volume shrinkage rate, setting time, water swelling rate, and compressive strength of the grouting material.

4.3 Effect of Curing Agent on the Property of Polymer Grouting Materials

The results of the test scheme in Section 3.1 revealed that the curing agent exerted a considerable effect on the mechanical properties of the grouting material. After examining the influences of different contents of the curing agent on the compressive strength, tensile strength, and elongation at break of the grouting material, the effect of the curing agent on tensile strength and elongation at break was determined and is given in Fig. 16. Meanwhile, the effect on compressive strength is shown in Fig. 17.

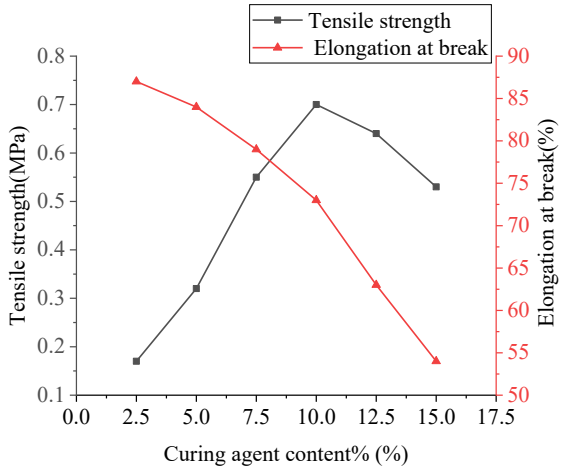

Fig. 16. Effect of the Curing Agent on Tensile Strength and Elongation at Break

According to Fig. 16, with the increase in the content of the curing agent, the tensile strength initially increased then decreased, and the elongation at break gradually decreased. This result was obtained because the curing agent contained a large number of hydroxyl, amino, and benzene rings, with the hydroxyl and benzene rings forming crosslinking structures with polyurethane. As the content of the curing agent increased, the crosslinking density of the grouting material rose, and the intermolecular forces gradually increased, hindering the movement of the molecular chains. Consequently, the tensile strength initially increased then decreased. The increase in crosslinking density reduced the elongation at break.

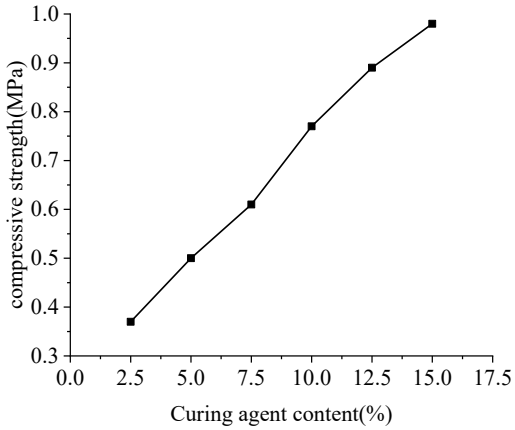

Fig. 17. Effect of the Curing Agent on Compressive Strength

Fig. 17 indicates that the compressive strength of the grouting material gradually increased with the addition of the curing agent because the hydroxyl and amino in the curing agent formed crosslinking structures with polyurethane and epoxy resin, respectively. As the content of the curing agent increases, the internal crosslinking structure of the grouting material became increasingly compact, and the addition of benzene rings in the curing agent enhanced the rigidity of the grouting material. Thus, the compressive strength of the grouting material gradually increased. In full consideration of all the factors, the content of the curing agent was set to 10% of the total mass, at which the compressive strength was 0.77 MPa, the tensile strength was 0.7 MPa, and the elongation at break was 73%.

4.4 Impermeability and Leaking Stoppage Test on Polymer Grouting Materials

On the basis of the test scheme in Section 3.1, the inorganic filler magnesium oxide was added to the formulas of Groups 10 and 11 to examine the properties of impermeability and leaking stoppage. The test conditions showed that under the action of water pressure, the mortar specimen after grouting and leaking stoppage developed a bulge at the location of the grouted material in the reserved crack (Fig. 18), and continued pressure resulted in water permeation at the bulge (Fig. 19). The grouting material filled the pores of the mortar specimen well and had good bonding with the interface of the specimen because the polyurethane polymer grouting material had good water resistance and maintained excellent bonding strength even after contact with water.

As shown in Fig. 20, the water permeation pressure of the grouting material initially increased then decreased with the increase in the content of magnesium oxide because after hydration, magnesium oxide expanded in volume, filling the internal network structure of the grouting material and making it increasingly compact, thereby increasing its compressive strength. As the content of magnesium oxide increased, the internal network structure of the grouting material became highly compact, leading to an increase in the water permeation pressure. Meanwhile, with the increase in the content of magnesium oxide, the water swelling and bonding strength of the grouting material decreased,

resulting in a decrease in leaking stoppage and bonding with the interface of the specimen and causing a gradual decrease in water permeation pressure.

Fig. 18. Bulging of Grouting Materials

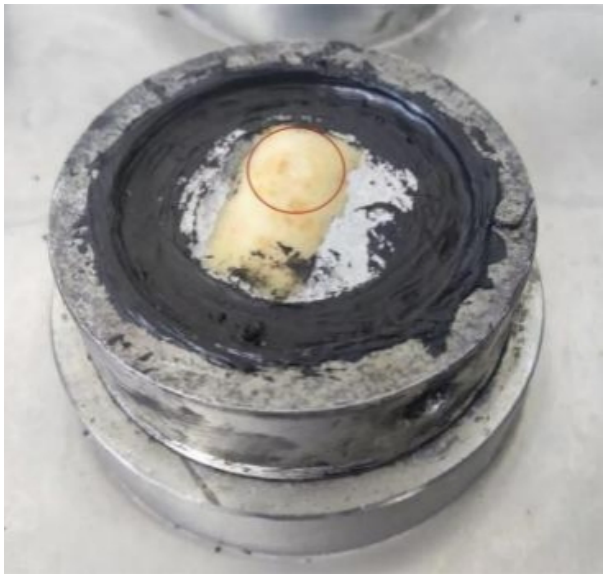

Fig. 19. Water Permeation of Grouting Materials after Bulging

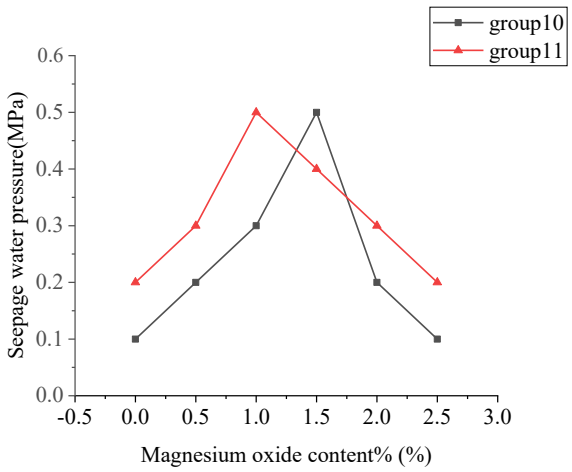

Fig. 20. Effect of Magnesium Oxide on Impermeability and Leaking Stoppage

5. Conclusions

To enhance the mechanical properties of polyurethane polymer grouting materials, address the volume shrinkage of cured grouting material, and elucidate the impermeability repair characteristics of polyurethane polymer grouting materials, this study focused on polyurethane, epoxy resin, and sodium silicate and applied a combined approach of orthogonal and single-factor testing to analyze the mix ratio of the polyurethane polymer grouting material. The contents of magnesium oxide and the curing agent and their effects on the material property and impermeability repair characteristics were determined. The following conclusions could be drawn.

(1) When the polyurethane in Component A was 28%, the epoxy resin was 10%, and the sodium silicate in Component B was 15%, the prepared polyurethane polymer grouting material exhibited a bonding strength of 1.12 MPa, a compressive strength of 0.77 MPa, and a 7-day water swelling rate of 45%, indicating good physical and mechanical properties.

(2) When the dosage of magnesium oxide increased, the volume shrinkage rate of the cured grouting material considerably decreased. With the increase in the dosage of magnesium oxide, the compressive strength of the grouting material increased and reached the maximum of 1.15 MPa. Meanwhile, a marked decrease in the water swelling rate, which was as low as 24%, was observed. The increase in the dosage of magnesium oxide retarded the setting time of the grouting material, with the maximum setting time being 540 s. The content of magnesium oxide was fixed at 1% in consideration of all factors.

(3) When the content of the other components remained constant, an increase in the content of the curing agent led to a gradual increase in compressive strength, which reached the maximum of 0.98 MPa. Tensile strength initially increased then decreased, and elongation at break gradually decreased. The dosage of the curing agent remarkably improved the mechanical properties of the grouting material but notably reduced the elongation at break of the material. The dosage of the curing agent was fixed at 10% in consideration of compressive strength, tensile strength, and elongation at break.

(4) The polyurethane polymer grouting material demonstrated surface bulging under water pressure during the impermeability and leaking stoppage tests. Continued pressure caused water permeation at the bulges. As the content of magnesium oxide increased, the water permeation pressure initially increased then decreased, with the maximum water permeation pressure being 0.5 MPa.

By integrating indoor testing with theory, this study proposed a method for impermeability and leaking stoppage testing of polyurethane polymer grouting materials and grouting leaking stoppage mortar specimens mixed with polyurethanes and epoxy resins. The impermeability tests performed are simplified and close to actual field conditions, thus offering a certain reference for subsequent research on and development of polyurethane polymer grouting materials. However, the considerations for field testing and construction techniques are limited because of the lack of actual field data and supporting equipment. In future research, the developed polyurethane polymer grouting materials could undergo actual engineering tests with supporting equipment design and optimized construction techniques to enhance the comprehensive properties of polyurethane polymer grouting materials.

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