Original Research Article

Research on minimally invasive pipeline repair method based on expansion technique and its effect evaluation

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Abstract: With the continuous advancement of urban renewal, the problem of aging and deteriorating underground pipeline infrastructure has become increasingly prominent. The traditional excavation repair method causes significant disturbance, has a long construction period, and incurs high social costs. The existing minimally invasive repair techniques such as the inner lining method and spraying method have defects such as large material loss, severe reduction in inner diameter after repair, and insufficient sealing performance when dealing with local damage, irregular pipe sections, and narrow space conditions. To address these engineering challenges, this paper proposes an expansion method for minimally invasive pipeline repair: prefabricated expandable repair units are transported to the damaged location of the pipeline, and through an electric heating coupling chemical triggering method, the units expand fully in the pipe and closely adhere to the pipe wall, forming a continuous and dense reinforcement layer, achieving the sealing of local defects such as cracks and holes and the reinforcement of the structure. A multi-diameter indoor model test platform was established in this paper, and repair performance tests were systematically conducted under different pipe diameters, damage types, and expansion material formulations. Multi-dimensional effect evaluations were carried out around the adhesion degree of the repair layer, inner diameter loss, compressive strength, water resistance performance, interface bonding force, long-term durability, and construction efficiency. The test results show that this process is suitable for municipal pipelines with diameters ranging from DN200 to DN600, with an inner diameter loss of less than 5% after repair; the anti-seepage pressure of the repair layer is ≥ 0.8 MPa, and the interface bonding strength meets the design standards for municipal pipeline engineering; compared with the traditional CIPP inner lining method, the overall construction period is shortened by approximately 40%. The research results can provide a low-cost, high-efficiency, and highly adaptable technical solution for the precise non-digging maintenance of urban underground pipelines, and have important engineering application value and theoretical reference significance.

Keywords: expansion repair; minimally invasive repair of pipelines; non-digging; effect evaluation; polyurethane expansion material

1. Introduction

1.1. Research background and significance

Over the past several years, urbanization construction in China has been ongoing. The early laid municipal water supply and drainage pipelines have gradually entered the aging and failure period. Longitudinal cracks, circumferential cracks, local holes, misalignment of pipe sections, etc. occur frequently, which not only reduce the water and drainage capacity of the pipelines but also easily trigger secondary disasters such as pavement collapse, groundwater leakage, and soil pollution. Traditional excavation repair requires large-scale removal of the pavement, interruption of traffic, and relocation of underground pipelines, which cause intense interference to the lives of urban residents and the urban appearance and environment, and are difficult to meet the demand for pipeline renewal in high-density built-up areas. Non-excavation minimally invasive repair technology, with advantages such as small surface disturbance, short construction period, and low overall social cost, has become the mainstream technical route for pipeline renovation at present. The current mainstream minimally invasive techniques include

ultraviolet light-cured lining (CIPP), spraying repair, and local point patch repair, etc. However, there are still obvious shortcomings: CIPP lining is suitable for the repair of entire pipelines, but material waste is serious when repairing local damages, and the reduction in pipe diameter after repair is large; the spraying method has a thin forming thickness and insufficient structural reinforcement ability, and has poor anti-seepage and durability; conventional local patching equipment has a complex structure and poor positioning and fitting effect in narrow pipe sections and irregular elbows. The minimally invasive expansion repair belongs to a new type of local non-excavation repair technology, relying on the in-situ expansion and solidification of prefabricated expansion repair units, specifically sealing local defects, which can complement the limitations of existing minimally invasive techniques. Developing a complete set of expansion repair process design and quantitative evaluation of repair effects can improve the theoretical system of local minimally invasive pipeline repair, provide new technologies for the fine management of old pipelines, and have significant engineering and theoretical value.

1.2. Research objectives and main research contents

1.2.1. Research objectives

Develop a set of minimally invasive repair technology for DN200 to DN600 pipelines using the expansion method. Complete the optimization of the expansion base material formula, the design of the repair unit structural parameters, and the development of the transportation positioning and electrothermal curing control system; Establish an indoor multi-condition model test platform, and establish an integrated evaluation system for the repair effect that considers the adhesion degree, inner diameter loss, mechanical properties, impermeability durability, and construction efficiency; Quantitatively analyze the influence laws of pipe diameter, damage form, and material formula on the repair quality, and verify the comprehensive performance advantages of the expansion method repair technology[1-2].

1.2.2. Core research contents

Design of expansion repair unit materials and structures: Compare the mechanical and expansion properties of polyurethane and rubber as expansion substrates, and select the PU-based modified expansion material; optimize the wall thickness, initial outer diameter, and sectional structure dimensions of the repair unit through finite element simulation;

Design of complete construction processes and equipment configuration: Design a micro-tube conveying positioning system, and develop an electric heating coupled chemical expansion triggering and constant temperature curing control module;

Design of indoor model tests: Set up multiple pipe diameters (DN200/300/400/500/600) under various conditions, distinguish between circumferential cracks, longitudinal cracks, holes, and composite damage, and formulate standardized mechanical, anti-seepage, and durability test plans;

Quantitative evaluation of repair effects: Calculate the gap fitting rate of the repair layer and the inner diameter loss rate, test the compressive strength, adhesion, and anti-seepage indicators, compare the construction efficiency of the traditional lining method, and summarize the technical application boundaries.

Table 1. Research modules and core indicators list.

Research Module	Concrete Content	Key Index
Repair method design	Selection of expansion material formulations and design of repair unit structure	Expansion volume, curing time, initial setting strength
Construction process configuration	Transportation positioning system, expansion triggering and curing control	Expansion positioning accuracy, trigger pressure, curing temperature
Effect evaluation system	Mechanical properties, sealing performance, fit degree and inner diameter loss	Permeation resistance pressure, bonding strength, adhesion coefficient

2. Expansion-based minimally invasive repair system design

2.1. Design of repair unit materials and structural parameters

The repair unit is the core carrier of the expansion repair technology. The materials determine the expansion, mechanical, and sealing durability properties, and the structural parameters directly affect the uniformity of the pipe fit and the retention rate of the inner diameter[3]. This paper uses modified HDPE as the basic framework and composites a foaming expansion substrate, simultaneously optimizing the material formula and the geometric dimensions of the unit.

2.1.1. Selection of foaming base material formula

Select two foaming systems, polyurethane (PU) and rubber-based[4], for comparative tests. Control the variables of foaming agent and crosslinking agent dosage, and test the three core indicators of free expansion rate, curing time, and tensile strength. The test results (see **Figure 1**) show that the maximum expansion rate of the rubber-based material is only 120%, with a curing time of 25 minutes at room temperature and a tensile strength of 1.9 MPa; after adding 5% azobisisobutyronitrile (AIBN) foaming agent to the PU-based material, the free expansion rate can reach 180%, the curing time is reduced to 15 minutes, and the tensile strength is 2.8 MPa. Further adjusting the ratio of crosslinking agent and stabilizer, the stable expansion range of the PU composite base material is 150% to 200%, the initial setting curing time is shortened to 12 minutes, balancing rapid molding and high structural strength. Finally, PU modified material is determined as the expansion base material of the repair unit. The decomposition temperature of the AIBN chemical foaming agent is 65℃, suitable for the electrical heating temperature triggering mechanism. When the temperature is raised to 80℃, the foaming reaction is fully sufficient, and the cured structure forms a dense cross-linked waterproof structure.

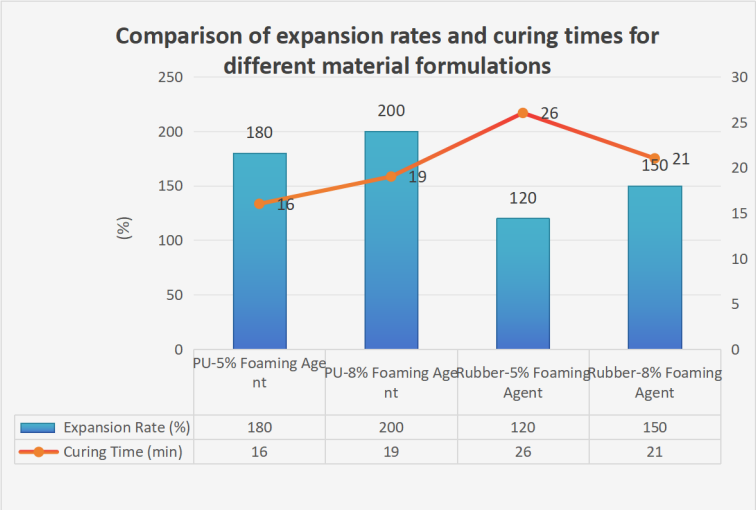


Figure 1. Comparison of expansion rates and curing times for different material formulations.

2.1.2. Optimization of unit structure parameters based on PU expansion material

By using finite element radial stress simulation, three parameters of the unit thickness[5], initial outer diameter, and segment length were optimized:

Unit thickness: Four groups of comparisons were set with thicknesses of 4 mm, 6 mm, and 8 mm. When the thickness was 6 mm, the contact pressure of the pipe wall after expansion was 0.35 MPa, and the uniformity of the circumferential adhesion was the best; too small a thickness resulted in insufficient contact pressure, while too large a thickness could cause a significant reduction in the pipe diameter;

Initial outer diameter matching degree: The factory-outside diameter of the repaired unit was set at 85% to 95% of the original inner diameter of the pipeline. Under the condition of 90% matching degree, the inner diameter loss was stable at less than 5%, and the thickness of the expansion layer was uniform, with no local stress concentration;

Segment length and sealing end: For DN200 small pipe diameter units, the length of the moduleized advancing conduit was 300 mm, and the axial sealing length of the conical sealing end was 20 mm; for DN400 and above large pipe diameters, the length of the unit was 500 mm, and the matching degree of the initial outer diameter was reduced to 88%. The actual measured fitting degree of the DN400 pipeline was 92%, and the inner diameter loss rate was only 4.2%. The segmented ring structure can adapt to local circumferential and longitudinal damage of the pipeline, and the conical end head can block the leakage of foaming liquid, meeting the different pipe diameter differential repair requirements.

2.2. Construction process and modular equipment system

The entire set of construction equipment is based on micro non-digging pipe top drive equipment, divided into three major parts: the conveying and precise positioning system, the electric heating expansion triggering system, and the PLC automatic control system. The entire process is fully automated, reducing

manual intervention.

2.2.1. Conveying and precise positioning system

The repaired unit is pre-installed at the front end of the modular advancing conduit. The gap between the conduit and the unit is strictly controlled within 2 mm to prevent deviation in the pipeline movement; the directional navigation module, end high-definition visual probe, and pressure sensing module work collaboratively for positioning, and the positioning accuracy of the damaged point can reach ±5 mm. The conduit adopts a segmented modular design, and by replacing different outer diameter conduits, it can adapt to all specifications of DN200 to DN600 pipelines. The probe resolution is 0.1 mm, and for large-diameter pipelines, dual probes are used for coordinated coordinate verification.

2.2.2. Electric heating expansion trigger and constant temperature solidification control

The internal pre-installed resistance wire electric heating components of the repaired unit are controlled by the control console after being placed in position. Within 60 seconds, the substrate temperature rises to 80°C, and the AIBN foaming agent is heated and decomposed to release nitrogen gas, driving the unit to expand radially to fill the gaps and hole defects in the pipe wall; after the temperature rise, it is continuously maintained at 80°C for 5 minutes to complete the high-molecular cross-linking and solidification reaction. The total duration of the triggering and solidification process is controlled within 90 seconds, with high heating efficiency and small space occupation, suitable for the construction environment inside narrow pipelines. Compared with the external heating process using hot air, the built-in heating of the electric heating is uniform, and the material tensile strength increases by 12% after the curing process. The temperature fluctuation has a weak impact on the uniformity of expansion, and it can stably form a continuous and dense repair inner lining[6].

3. Indoor model test plan and implementation

3.1. Test platform construction and operating conditions design

Build an integrated indoor pipeline repair test platform covering five types of commonly used municipal drainage pipes with diameters of DN200, DN300, DN400, DN500, and DN600, simulating the entire scenarios of city branch pipes, secondary main pipes, and main main pipes; set four types of pipe damage conditions: circumferential cracks, longitudinal cracks, local holes, and combined damage of cracks and holes, covering both single and complex aging diseases. The test adopts orthogonal variable control, respectively studying the influence of pipe diameter size, damage type, and expansion material formula on the repair effect. All specimens are uniformly standard-cured to eliminate the interference of environment and material batch.

3.1.1. Pipe diameter and damage condition settings

The basic pipe diameter is DN200/300/400, and the expanded DN500/600 is adapted to large main pipes; the damage forms are single cracks, holes, and combined defects, simulating various structural damages caused by corrosion and settlement of the pipes during long-term service, fully covering typical diseases of municipal pipelines.

3.1.2. Standardized control of test variables

To ensure the repeatability and comparability of test data, the materials, temperature and humidity, and curing conditions are uniformly controlled, as shown in **Table 1**.

3.2. Standardized testing methods for key performance tests

All performance tests adopt current national standards and specifications, with uniform loading rates, stable pressure duration, and sample quantities to ensure the standardization of test results[7-8]. 1) Compressive Strength: Refer to GB/T 50081-2019, using a universal testing machine for circumferential compression loading, with a loading rate of 0.5 mm/min, and taking the average value of 6 specimens per group; 2) Interface Bonding Strength: According to GB/T 16777-2008 standard, 90° pull-out test with a stretching rate of 1 mm/min; 3) Impermeability Performance: Following GB 50108-2008water pressure loading, each level of water pressure is stabilized for 30 minutes, and the critical leakage pressure is recorded; 4) Durability: Dry-wet cycle accelerated aging test, with a single cycle of 12 hours immersion in water + 12 hours drying, and detecting the attenuation rate of bonding strength after 60 cycles.

3.2.1. Test results of mechanical performance

Settings Two sets of PU base material formulas are compared: Formula A has a foaming agent content

of 8%, and Formula B has a content of 12%. The circumferential compressive test shows that the average compressive strength of Formula A is 12.3 MPa, 14% higher than that of Formula B (10.8 MPa); the average 90° peel force of Formula A is 2.1 N/mm, 23.5% higher than that of Formula B (1.7 N/mm). Excessive foaming agent content will increase the internal micropores of the material, reducing the density and interface bonding force. 8% is the optimal ratio.

3.2.2. Testing of impermeability and durability performance

Sequential water pressure impermeability test: The average critical leakage pressure of the repaired pipe with Formula A is 0.85 MPa, while Formula B is only 0.62 MPa, an increase of 37.1%. After 60 dry-wet cycle durability tests, the attenuation rate of interface peel force of Formula A is 8.3%, while Formula B is 15.6%; an appropriate foaming agent content forms a dense cross-linked structure, with fewer water leakage channels, and stronger interface bonding stability in alternating wet and dry environments.

4. Evaluation of repair effect and analysis of test results

4.1. Evaluation of fit degree and inner diameter loss of the repair layer

The fit degree reflects the degree of tightness between the repair layer and the original pipe wall. The inner diameter loss directly determines the water delivery capacity of the repaired pipeline and is two core flow evaluation indicators for minimally invasive repair.

4.1.1. Quantitative analysis of fit degree

The gap thickness between the repair layer and the pipe wall is measured using an ultrasonic thickness gauge[9]. The gap rate is defined as the percentage of the gap thickness to the designed thickness of the repair layer. The test data for DN200/300/400 pipe diameters are shown in **Figure 2**.

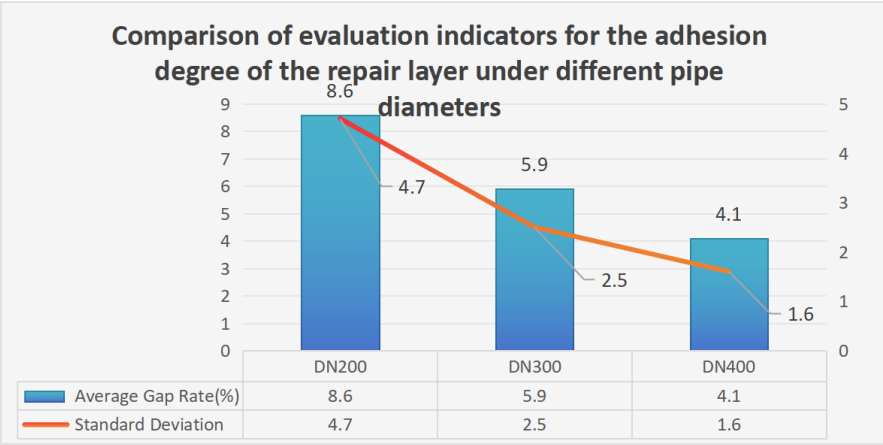


Figure 2. Comparison of evaluation indicators for the adhesion degree of the repair layer under different pipe diameters.

The internal space of the small diameter DN200 is narrow, the radial restraint of the expansion material is strong, the uniformity of the circumferential adhesion is poor, and local wrinkles cause a higher gap rate; the expansion flow space of the large diameter DN400 is sufficient, the expansion pressure distribution is uniform, and the standard deviation of the gap rate is only 1.5%, with the best adhesion effect. Under the overall working conditions, the maximum gap thickness is controllable and can completely fill the pipeline cracks and hole defects.

4.1.2. Calculation and analysis of inner diameter loss rate

By using a three-dimensional laser scanner to scan the cross-sectional contours of the pipeline before and after repair, the inner diameter loss rate = (original inner diameter - equivalent diameter after repair) / original inner diameter × 100%, and the average value is taken for each group of 5 sections. The average inner diameter loss rates of DN200, DN300, and DN400 are 4.2%, 3.5%, and 2.8% respectively, all of which are below the 5% design control threshold. The pipe wall stiffness of the small diameter pipeline is low, and the solidification and contraction of the expansion layer are prone to cause radial compression, resulting in a greater inner diameter loss; the self-structural stiffness of the large diameter is high, which can counteract the material shrinkage deformation, and the retention effect of the diameter is better. The overall inner diameter loss amplitude is extremely small, and it has almost no negative impact on the water supply and drainage capacity of the pipeline.

4.2. Comparison and analysis of sealing mechanical performance and construction efficiency

4.2.1. Anti-seepage pressure and interface bonding strength

The test results (in **Figure 3**) of anti-seepage and bonding strength of the three pipe diameter repair specimens are:

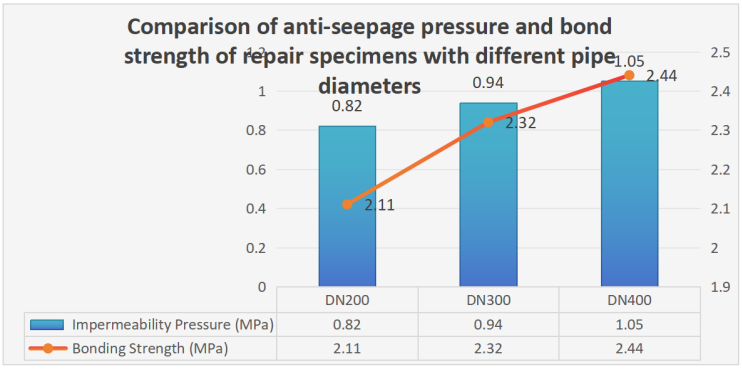


Figure 3. Comparison of anti-seepage pressure and bond strength of repair specimens with different pipe diameters.

The wall of the large-diameter pipe is evenly supported, and there are fewer micro-pores inside the repair layer, resulting in better sealing and interface bonding performance. The PU expansion material, after curing, forms a mechanical interlock + chemical bonding composite interface with the HDPE pipe wall, making it less likely to peel off and leak under long-term water pressure.

4.2.2. Comparison of construction time with traditional CIPP lining method

In the construction time comparison test, the expansion method minimally invasive repair process competed with the traditional CIPP lining method under the same working conditions. For a damaged pipeline with a diameter of DN300 and a length of 10m, the expansion method took only 4.2 hours from equipment entry to curing completion, while the traditional lining method took 7.1 hours, with an efficiency increase of 40.8%.

The advantage of the expansion method in the curing stage is most significant. The chemical-triggered expansion mechanism it adopts can complete the main curing within 30 minutes at room temperature[10], while traditional CIPP relies on hot water circulation heating for 90 to 120 minutes. This efficiency advantage stems from the optimization of the self-heating reaction design of the expansion material, significantly reducing the waiting time for energy.

5. Conclusions and research prospects

5.1. Main research findings

The PU-based expansion repair unit developed in this study is suitable for municipal water supply and drainage pipelines with diameters ranging from DN200 to DN600. The optimal formulation consists of 8% foaming agent content, with an expansion range of 150% to 200%, and it has a fast curing speed and excellent mechanical and anti-seepage properties. When the unit wall thickness is 6 mm and the initial outer diameter matches 90% of the pipeline inner diameter, the fitting effect and diameter retention reach the optimal balance.

Indoor model tests verified that the expansion repair process resulted in an internal diameter loss of the pipeline that was all below 5%, without significantly weakening the pipeline's flow capacity. The anti-seepage pressure of the repair layer exceeded 0.8 MPa, and the interface bonding strength was higher than the 1.8 MPa design threshold, enabling long-term sealing and structural reinforcement of cracks and holes as local defects.

The entire automated conveying and electric heating-triggered curing process has a positioning accuracy of ±5 mm. The total construction time is shortened by 40.8% compared to the traditional CIPP lining method, with minimal surface disturbance and low material loss, making it suitable for rapid emergency repairs of local pipeline damage in urban built-up areas.

The pipe diameter has a significant impact on the repair effect: larger pipe diameters (DN400 and above) have better uniformity of fitting, anti-seepage, and bonding performance compared to smaller pipe diameters (DN200). The construction of smaller pipe diameters can be further improved in terms of fitting

quality by shortening the unit length and optimizing the conical sealing end.

5.2. Future research directions

Durability in complex service environments: Conduct long-term aging tests under multiple coupled conditions such as high groundwater pressure, corrosive wastewater[11], and traffic dynamic loads, and establish a prediction model for the repair lifespan under multi-factor coupling;

Intelligent integration and upgrade: Integrate micro-sensing components into the repair unit to achieve real-time data collection during expansion molding and curing, and build a long-term digital monitoring system for the repaired pipeline network[12-13];

Expansion method application expansion: Conduct repair tests for pressure water supply pipelines and industrial corrosion pipelines to expand the applicable boundaries of the expansion repair technology and improve the quality acceptance standards for the entire construction process.

Acknowledgements

This paper was supported by the "Zhejiang College of Construction Undergraduate Innovation Training Program" project.It is an outcome of Construction Engineering Innovation Center of Department of Housing and Rural-Urban Development of Zhejiang Province-Smart Testing.

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