Original Research Article

Research and application of a new technology for tunnel disease treatment

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Abstract: In view of the problems of poor maintenance effect and repeated occurrence of diseases in the existing tunnel disease treatment technologies, this paper analyzes the current situation of tunnel construction in China. By adhering high-mechanical-performance and high-durability high-performance concrete to the existing concrete secondary lining, a complete and brand-new lining structure is formed. This structure closely adheres to the existing lining to form a composite lining structure that can bear loads together, which can significantly improve the mechanical characteristics of the lining structure and enhance the stability of the surrounding rock. The results of engineering application show that the compressive strength of specimens cured under the same conditions at the construction site reaches 110.4 MPa at 7 days, and the flexural strength reaches 16.9 MPa, far exceeding the design strength. This method has simple construction procedures, low cost, and strong applicability for the treatment of various tunnel diseases.

Keywords: Tunnel diseases; Special concrete; New technology; Maintenance and reinforcement

1. Introduction

In the contemporary epoch,the swift expansion of infrastructure within the People's Republic of China has been a pivotal component of its economic growth and modernization endeavors. A critical aspect of this development has been the accelerated construction of highway and railway tunnels, which have emerged as indispensable conduits for the transportation network. According to the statistical data on railway tunnels, by the conclusion of the year 2020, the operational mileage of railways in China had achieved a remarkable 145,000 kilometers[1].Within this extensive network, there were 16,798 railway tunnels in operation, spanning a total length of approximately 19,630 kilometers. The developmental scale of railway tunnels across various periods in China is delineated in Table 1.

Table 1. Development scale of railway tunnels in China at different periods.

Period	Number of tunnels	Total length of tunnels/ km
By the end of 1949	429	112
By the end of 1979	4386	2009
By the end of 1999	6877	3667
By the end of 2005	7538	4314
By the end of 2010	9800	7000
By the end of 2015	13411	13038
By the end of 2020	16798	19630

It can be seen from Table 1 that most of the existing tunnels in China have been in service for more than 10 years. These tunnels are perpetually subjected to environmental exposure and are influenced by a multitude of factors, including geological conditions, extreme meteorological events, and various challenges that arise during the construction process. Such conditions predispose these tunnels to a spectrum of structural ailments, such as cracking, falling blocks, and water seepage[2,3].These maladies not only compromise the safety and stability of the tunnel structure itself but also pose significant safety hazards for traffic within the tunnels, potentially leading to catastrophic consequences.

In response to these challenges, existing tunnel disease treatment technologies have been developed to address the specific geological conditions, service environments, and disease conditions of each tunnel[4–6]which can be regarded as typical in centives for tunnel diseases such as cracks, water leakage, and spalling, seriously threatening the durability and safety of lining structures. In this paper, the health inspection and reinforcement design for typical quality defects were systematically reviewed. Firstly, the inspection techniques of typical tunnel quality defects were reviewed. Subsequently, the formation causes of typical quality defects were reviewed and summarized based on the hi erarchical structure model. Then, the research status of reinforcement techniques of tunnel structures with typical quality defects, especially the fiber-reinforced plastic (FRP. For tunnels with less severe disease levels, cost-effective methods such as grouting and sealing, as well as localized repairs, are commonly employed. While these methods are relatively inexpensive and involve straightforward engineering, they are not without their shortcomings, often failing to achieve the desired maintenance outcomes. The method of injecting mortar into corrugated plates, although an improvement over traditional methods, still faces issues such as non-compact grouting, loose bonding, susceptibility to rusting of accessories in coastal regions, and high costs. These limitations underscore the necessity for innovation in material and technology research to enhance the effectiveness of tunnel maintenance and reinforcement.

The development of tunnel maintenance technology has been a dynamic field, with a growing focus on the integration of advanced technologies to improve the efficiency and effectiveness of treatment methods. For instance, the use of ground penetrating radar and other non-destructive testing methods has become increasingly prevalent for detecting water infiltration and structural defects within tunnels[7]infrastructure maintenance is becoming increasingly important. This paper aims to develop a maintenance strategy for tunnels, which determines when, where and what to maintain, to ensure the safe and serviceable operation of tunnel structure with the intention to minimise the total risk. Application of the proposal is presented in a numerical example of a practical case study. It was found that an optimum solution, which can predict when, where and what to maintain for tunnel structure to ensure its safe and serviceable operation during its lifespan, exists. The paper concludes that the proposed framework can equip tunnel operators and asset managers with a tool in developing a risk cost optimised maintenance strategy for tunnels under their management.”,”container-title”:”Tunnelling and Underground Space Technology”,”DOI”:”10.1016/j.tust.2017.06.008”,”ISSN”:”08867798”,”journalAbbreviation”:”Tunnelling and Underground Space Technology”,”language”:”en”,”page”:”72-84”,”source”:”DOI.org (Crossref.These technologies provide a more accurate assessment of the tunnel’s condition, allowing for targeted interventions that can extend the lifespan of the tunnel and reduce long-term maintenance costs.

Furthermore, the advent of artificial intelligence and machine learning in tunnel construction has opened new avenues for the prediction and prevention of tunnel diseases. By analyzing data from various sources, including geological surveys, construction records, and real-time monitoring systems, AI algorithms can identify patterns and anomalies that may indicate potential issues before they become critical[1,8].This proactive approach to tunnel maintenance not only enhances the safety and stability of the tunnels but also optimizes resource allocation and planning for maintenance activities.

In addition to technological advancements, the field of tunnel maintenance has also seen significant developments in the area of materials science. The use of advanced materials, such as high-performance concrete and fiber-reinforced composite materials, has shown promise in improving the durability and resilience of tunnel linings against the various stressors they face[9,10].These materials can be tailored to specific conditions, providing a more robust defense against environmental degradation and structural fatigue.

As the railway network continues to expand, the importance of maintaining the integrity and safety of railway tunnels cannot be overstated. The research presented in this paper contributes to the ongoing efforts to develop innovative solutions to the complex challenges posed by tunnel diseases. By combining cutting-edge materials technology with advanced diagnostic and predictive tools, the maintenance and reinforcement of tunnel linings can be significantly improved, ensuring the continued reliability and safety of this critical transportation infrastructure.

In light of these challenges, this paper presents the results of innovative practical research on materials and technologies, proposing a novel technology for the maintenance and reinforcement of tunnel lining diseases. The urgency of addressing these issues is underscored by the critical role that tunnels play in the transportation infrastructure, and the potential risks to public safety and economic activity if these structures are not properly maintained and reinforced.

2. Technical characteristics

In recent years, with the continuous development and expansion of tunnel engineering, the issue of tunnel diseases has become increasingly prominent. Tunnel diseases not only affect the normal operation and service life of tunnels but also pose potential safety hazards. Against this background, the tunnel disease treatment technology proposed in this paper presents a novel and effective solution. This technology involves adhering high-mechanical-performance and high-durability high-performance concrete to the existing concrete secondary lining, thereby creating a complete and brand-new lining structure. The new structure closely adheres to the existing lining, forming a composite lining structure that can jointly bear loads. This composite structure can remarkably enhance the mechanical characteristics of the lining structure and improve the stability of the surrounding rock. The following are the outstanding advantages of this technology.

2.1. Safe structural design

In the realm of tunnel construction and maintenance, the assurance of tunnel structural safety stands as an uncompromising priority. The continuous augmentation in the complexity and scale of tunnel projects, compounded by the diverse geological and environmental adversities they encounter, has rendered the pursuit of more dependable and proficient tunnel disease treatment technologies an exigency of the highest order. Amidst this context, the novel tunnel disease treatment technology proffered herein represents a momentous and consequential breakthrough.

This technology is characterized by a composite lining structure that amalgamates a steel arch frame with a bespoke special concrete. The genesis of this special concrete lies in an exhaustive and profound research and design endeavor predicated on the density packing theory. This theory, which is centered around the optimization of the packing configuration of particles within the concrete matrix, endows the special concrete with an exceptionally elevated level of density and homogeneity. As a corollary, it attains ultra-high mechanical attributes and durability that eclipse those of conventional concrete by a substantial margin.

The steel fibers embedded within the special concrete constitute a pivotal constituent underpinning its outstanding performance. These steel fibers, possessing high tensile strength and manifesting favorable adhesion to the adjacent cementitious materials and aggregates, fulfill a crucial function in forging intimate connections among the disparate components of the concrete. They engender a sophisticated three-dimensional network-like holistic structure, which can be conceptually envisaged as a fortified skeletal framework within the concrete mass. This network proficiently disperses and conveys the stresses instigated by external loads, thereby precluding the origination and proliferation of cracks and augmenting the overall integrity of the concrete.

When the tunnel lining fabricated with this composite structure is exposed to the pressure of the surrounding rock, which represents a predominant and incessant external load, in conjunction with other potential loads such as seismic forces or dynamic perturbations emanating from traffic, this idiosyncratic structure exhibits a remarkably enhanced stability and resilience against damage. The steel arch frame, conversely, imparts supplementary support and rigidity to the overarching structure. It functions as a principal load-bearing entity, efficaciously apportioning and transmitting the loads from the surrounding rock to the tunnel foundation.

To guarantee the seamless integration and synergistic operation of the steel arch frame and the special concrete, threaded steel is astutely deployed to interconnect them. The threaded steel affords a reliable mechanical coupling that can proficiently transmit shear and tensile forces between the two constituents. Concurrently, chemical bolts are harnessed to permanently affix the steel arch frame to the extant secondary lining. These chemical bolts, endowed with robust bonding strength and durability, penetrate deeply into the existing lining and establish a steadfast connection. This confluence of connection modalities not only bolsters the load-bearing capacity of the structure but also renders the entire structure more robust and secure. It effectively mitigates the potential quandaries of relative displacement and detachment among the disparate segments of the lining, thereby ensuring the long-term stability and dependability of the tunnel lining under a gamut of service conditions. This inventive structural design, therefore, proffers a comprehensive and efficacious panacea to the conundrums associated with tunnel disease treatment and structural reinforcement.

2.2. Safe construction process, fewer processes, and high efficiency

In the current tunnel engineering field, tunnel construction and maintenance require effective disease treatment along with a high focus on safety and operational efficiency. The new tunnel disease treatment technology is a crucial response to these needs, indicating a significant transformation in tunnel rehabilitation.

The construction process of this innovative technology is inherently safe and controllable. Traditional lining replacement methods involve complex and dangerous procedures. For example, concrete cutting needs heavy equipment, generating noise and dust that endanger workers and structures. Blasting vibration can undermine tunnel and geological stability, leading to collapses or subsidence. Grooving and bolt drilling are labor-intensive and introduce stress, worsening existing diseases. Steel bar welding demands high skill, and errors can damage the lining's integrity.

In contrast, the new technology eliminates these hazardous tasks, reducing risks related to traditional methods. This benefits worker safety and tunnel durability. Moreover, it removes the need for large, cumbersome equipment and a large amount of manpower. Skilled workers for such tasks are no longer required in large numbers, optimizing workforce allocation.

To enhance construction safety and quality, the on-site construction adopts standardized and modular management. Standardized procedures ensure consistent and reliable construction. Modular management organizes the process into discrete modules, each with specific tasks and quality control. For instance, the lining surface treatment module focuses on preparing the lining surface for adhesion, following predefined standards.

The main processes of this technology work in harmony. Lining surface treatment is the initial step, involving inspecting and preparing the surface. Then, the steel arch frame is installed precisely with advanced tools. After that, steel formwork is erected between adjacent arch frames. The formwork is light yet strong for easy installation and removal while maintaining integrity during concrete pouring.

The special concrete pouring is a key phase. The 8 - 15 cm thick special concrete, with specific properties like high compressive strength and durability, is carefully poured and compacted, eliminating voids. After curing, the steel formwork is removed and cleaned in a controlled manner for reuse or storage.

Compared with traditional technologies, the new process is more streamlined. Traditional methods are time-consuming and error-prone, with complex procedures and safety precautions slowing down construction. The new technology simplifies the process, saving construction time. The elimination of complex steps and efficient task organization through standardized and modular management enable faster completion of each phase, shortening the overall construction period. This reduces disruptions to traffic and other activities, and improves efficiency and cost-effectiveness. Fewer man-hours and reduced equipment and material needs lower the project cost. Thus, the new tunnel disease treatment technology is an appealing option for tunnel rehabilitation in terms of safety and economic viability.

2.3. High cost-effectiveness

In the domain of tunnel engineering, cost-effectiveness constitutes a critical parameter that demands meticulous consideration. The nascent tunnel disease treatment technology has achieved substantial advancements in this respect. Through a significant curtailment of the subsequent maintenance cost, it proffers a highly appealing alternative for tunnel proprietors and infrastructure custodians. This reduction in maintenance expenditure is not a trifling enhancement but rather a profound one, effectively accomplishing the long-cherished objective of a one-time comprehensive remediation.

The construction schema of this technology exhibits a remarkable degree of adaptability and can be meticulously calibrated in accordance with a diverse array of factors. The grade of the tunnel's surrounding rock is a cardinal determinant as it governs the magnitude of stress and the potential for instability that the lining will encounter. Distinct grades of surrounding rock, notably grade IV and grade V, which are characteristically more demanding owing to their relatively inferior properties, necessitate bespoke solutions. Concurrently, the disease classification of the tunnel, encompassing a gamut of manifestations such as secondary lining fissures, seepage, voids, spalling, and deformation, also assumes a preponderant role in dictating the appropriate remedial measures. The tunnel clearance height and construction clearance are equally salient as they impinge upon the design and installation of the treatment constituents.

For illustrative purposes, in the context of grade IV and grade V surrounding rock tunnels beset by the aforementioned maladies, the technology can furnish lining structure maintenance and reinforcement blueprints with thicknesses spanning from 5 - 15 cm. This adaptability permits a customized approach that caters to the idiosyncratic requisites of each tunnel. In scenarios where severe leakage is a preponderant concern, a meticulously engineered drainage and diversion configuration can be incorporated posterior to the newly fabricated lining. This not only alleviates the immediate quandary of water infiltration but also contributes to the long-term preservation of the lining structure's integrity by attenuating the hydrostatic pressure and precluding the accumulation of water that could precipitate further degradation.

The special concrete deployed in the new tunnel lining reinforcement and maintenance technology represents a technological tour de force. It manifests preeminent anti-seepage attributes, which are indispensable for impeding water percolation through the lining and averting internal damage. Its anti-cracking characteristics are equally remarkable, as it can efficaciously resist the origination and dissemination of cracks even under substantial stress. The tensile and shear resistance of this special concrete further fortify its structural robustness, endowing it with the capacity to withstand the intricate loading regimens that tunnels are subjected to. Moreover, its seismic and impact resistance properties render it suitable for tunnels situated in seismically active zones or those that may be exposed to external perturbations such as those emanating from adjacent construction undertakings or vehicular collisions.

The lining structure fabricated from this special concrete is engineered to perdure. With a projected service life of 50 years and the capacity to uphold its integrity, typified by the absence of cracking, detachment, and spalling, it proffers a dependable and sustainable panacea. This durability not only diminishes the frequency and cost of maintenance and repair interventions but also mitigates the disruptions to tunnel operations and the attendant economic ramifications. It is, incontrovertibly, a secure, reliable, and highly applicable comprehensive treatment technology for tunnel diseases. It efficaciously addresses the multifarious challenges engendered by tunnel deterioration, proffering a long-term and cost-efficient solution that can augment the overall performance and longevity of tunnel infrastructure.

3. Process overview

In the domain of tunnel engineering, where the integrity and durability of tunnels are of paramount importance, the emergence of tunnel diseases has necessitated the development of advanced treatment technologies. The new tunnel disease treatment technology, which has been the focus of this study, presents a comprehensive and systematic approach to address the complex issues associated with tunnel lining deterioration.

The main construction process of this innovative technology commences with a meticulous assessment of the tunnel lining disease location. This initial step is crucial as it allows for a precise determination of the areas that require intervention. Once identified, the steel arch frame is installed on the existing secondary lining. The installation process demands a high level of precision and expertise to ensure that the arch frame is properly aligned and securely attached. This is achieved through the use of advanced measurement techniques and specialized installation equipment.

Following the installation of the steel arch frame, reinforcement bars are permanently implanted. These bars serve not only to enhance the connection between the arch frame and the existing lining but also to provide additional structural support. The implantation process is carefully executed to ensure that the bars are inserted at the correct depth and orientation, thereby maximizing their effectiveness in reinforcing the structure.

Between every two adjacent arch frames, steel formwork is erected. The formwork is designed to withstand the pressure exerted by the subsequent pouring of the special concrete and to maintain the desired shape and dimensions of the new lining. It is constructed using high-quality steel materials that possess sufficient strength and rigidity. The erection process involves careful assembly and alignment of the formwork panels to ensure a seamless and leak-free structure.

Subsequently, 8 - 15 cm thick special concrete is poured behind the steel formwork. The special concrete is a key component of this technology, possessing unique properties that enable it to effectively address the various issues associated with tunnel diseases. It is formulated with a combination of high-performance additives and aggregates that confer excellent strength, durability, and resistance to environmental factors. The pouring process is carried out under strict quality control measures to ensure that the concrete is evenly distributed and compacted, thereby minimizing the occurrence of voids and defects.

After the concrete has set and cured, which typically requires a specific period of time depending on the environmental conditions and the properties of the concrete, the steel formwork is removed. The removal process is carried out with caution to avoid any damage to the newly formed composite lining structure. The composite lining structure formed by the special concrete and the steel arch frame is thus able to completely replace the bearing capacity of the secondary lining. This replacement is not only essential for restoring the structural integrity of the tunnel but also for meeting the construction clearance requirements.

This process not only addresses the existing diseases of the tunnel lining, such as cracks, leaks, and deformations, but also restores and enhances the structural integrity and load-bearing capacity of the tunnel. By effectively treating the diseases and strengthening the lining, the safety and service life of the tunnel are significantly improved. This ensures its safe and efficient operation for an extended period, reducing the need for frequent maintenance and repair works and minimizing the disruption to traffic and other tunnel-related activities. Overall, the new tunnel disease treatment technology offers a promising solution for the sustainable management of tunnel infrastructure.

4. Special concrete

4.1. Main raw materials

The cement adopts Conch P·O 52.5 ordinary Portland cement; the fly ash adopts grade I fly ash; the ultra-fine slag powder is S140; the silica fume adopts silicon dioxide with a content of not less than 85%; the natural river sand with a continuous grading of 40 - 100 mesh is used; the early strength agent adopts HM - C type early strength agent; the retarder adopts HM - D type retarder; the polyether defoamer is used; the admixture is polycarboxylate high-performance water reducer; the diameter of the steel fiber is 0.2 - 0.25 mm, the length is 13 mm, and the tensile strength is not less than 2850 MPa; and the water is tap water.

4.2. Sample preparation method

Accurately weigh the dry mix of the special concrete and place it in the mixing pot. Add water according to the water consumption in the formula. First, add 2/3 of the water and mix for 3 minutes. Then add the remaining water and mix for 1 minute. Slowly and evenly add the steel fibers and mix for 2 minutes until it is uniform. Then prepare the test specimens according to the testing standards.

4.3. Main performance indicators

The performance index requirements of the special concrete are shown in Table 2.

Table 2. The performance index requirements of special concrete.

Performance Index	Requirements
Compressive strength/ MPa	≥50 (1d) ≥80 (7d) ≥100 (28d)
Flexural strength / MPa	≥8 (1d) ≥12 (7d) ≥16 (28d)
Bleeding Rate / %	0
Splitting Tensile Strength / MPa	≥9
Elastic Modulus / GPa	≥35
Bond Strength / MPa	≥1.5
Impermeability	≥P15
Chloride Ion Content / %	＜ 0.02
Shrinkage Rate / %	≤0.06

4.4. Comparison of the properties of special concrete and secondary lining concrete

The comparison of the main properties of the special concrete and the tunnel secondary lining concrete is shown in Table 3.

Table 3. Comparison of main performance of special concrete and tunnel secondary lining concrete.

Materials	Compressive strength/MPa	Flexural strength/ MPa	Elastic modulus /GPa	Splitting tensile strength/MPa	Anti-seepage performance
Special concrete	≥50 (1d) ≥80 (7d) ≥100 (28d)	≥8 (1d) ≥12 (7d) ≥16 (28d)	≥35	≥9	≥P15
Secondary lining concrete	≥30	≥4.5	≥30	≥2	≥P9

It can be seen from Tables 2 and 3 that the special concrete has performance advantages and also has the construction properties of self-leveling, self-compacting, and micro-expansion that are difficult to achieve with ordinary concrete. After being processed in a professional factory, the special concrete is made into small packaged dry materials and transported to the site. Only the specified proportion of water needs to be added and mixed with special equipment before pouring. During the pouring construction, vibration is not required. In this way, the construction of the special concrete has the characteristics of accurate mix proportion and controllable quality.

4.5. Force calculation of the replacement lining structure of the special concrete

Taking the composite lining section (ballastless track) of a single-track tunnel with a speed of 160 km/h in a passenger and freight mixed railway in grade V surrounding rock as an example for checking calculation.

4.5.1. Load calculation

Calculate the surrounding rock pressure borne by the tunnel according to the “Code for Design of Railway

Tunnels" (TB 1003 - 2016).

The calculation formula of the load height is shown in formula (1).

$$h = 0.45 \times 2^{5-1} \times 1.334 = 9.605 \tag{1}$$

In formula (1), is the load height, and the unit is m. The result is 9.605 m. The vertical and horizontal loads are shown in formula (2).

$$\begin{aligned} q_a &= 18.5 \times h = 177.6 \\ q_b &= q_a \times 0.4 = 71.04 \end{aligned} \tag{2}$$

In formula (2), is the vertical load, and the calculation result is 177.6 kN/m²; is the horizontal load, and the calculation result is 71.04 kN/m². The lining structure of the tunnel in grade V surrounding rock bears 70% of the total surrounding rock pressure load. When the tunnel lining is severely damaged, considering the most unfavorable situation, the surrounding rock pressure shared by the lining is borne by the special high-strength concrete material.

4.5.2. Calculation results

For the safety calculation of the defective structure of the secondary lining, first, it is necessary to select the tunnel surrounding rock grade according to the existing design data and specifications and determine the surrounding rock parameters. Then, the load calculations are carried out according to the allowable stress method and the limit state method respectively. The specific values of the loads have been obtained through the previous calculations, and the safety calculations can be carried out using these values. Since the thickness of the tunnel secondary lining is uneven, in order to obtain the minimum lining thickness that meets the specification requirements, special high-strength concrete materials with different thicknesses are taken for lining until the minimum lining thickness that meets the specification requirements is found. After comparative analysis, the optimal results are obtained. The force calculation results of the replacement secondary lining structures with thicknesses of 100 mm and 80 mm are shown in Tables 4 and 5 respectively.

Table 4. Calculation results of structural stress for replacing a 2-inch structure with a 100mm-thick special high-strength concrete material.

Axial Force / kN	Bending Moment / (kN·m)	Calculation Length / mm	Cross-Sectional Thickness / mm	Ultimate Compressive Strength of Material / MPa	Ultimate Tensile Strength of Material / MPa	Safety Factor
352.90	-8.41	1000	100	100.00	9.00	10.38

Table 5. Calculation results of structural stress for replacing a 2-inch structure with a 80mm-thick special high-strength concrete material.

Axial Force / kN	Bending Moment / (kN·m)	Calculation Length / mm	Cross-Sectional Thickness / mm	Ultimate Compressive Strength of Material / MPa	Ultimate Tensile Strength of Material / MPa	Safety Factor
352.90	-8.41	1000	80	100.00	9.00	4.53

5. Engineering application

The new tunnel disease treatment technology has been tested in a 2.4 m test section on-site in the Beiji Tunnel of the Fangchenggang - Dongxing Railway constructed by the 16th Bureau of China Railway. During the test, the construction experience of the new technology has been accumulated, and good test results have been achieved, winning the praise of the construction unit.

The construction site diagram of the new tunnel disease treatment technology is shown in **Figure 1.**

Figure 1. Special concrete lining.

The mechanical property test results of the specimens cured under the same conditions at the test section of the Beiji Tunnel of the Fangchenggang - Dongxing Railway are shown in **Table 6.**

Table 6. Mechanical properties test results of specimens under the same conditions for maintenance in the test section of Beiji tunnel.

Project	Compressive strength/ MPa	Flexural strength/ MPa	Bleeding rate/%	Splitting tensile strength/MPa	Elastic modulus /GPa
Result	≥53.2 (1d) ≥110.4 (7d) ≥124.2 (28d)	≥10.6 (1d) ≥16.9 (7d) ≥20.1 (28d)	0	≥9	≥P15

It can be seen from Table 6 that the compressive strength of the specimens cured under the same conditions at the construction site reaches 110.4 MPa at 7 days, and the flexural strength reaches 16.9 MPa, far exceeding the design strength. In addition, according to Figure 1, after the compressive and flexural destructive tests, the specimen state remains very intact, with only slight cracks on the specimen surface, and the overall structure remains intact. Therefore, it can be inferred that the lining structure formed by the special concrete material has the technical advantages of no cracking, no falling off, and no falling blocks.

According to the on-site test data, the material strength still has a large surplus compared with the structural design strength. Moreover, during the on-site construction, the special concrete and the steel arch frame work together to form a 12 cm thick composite lining structure. Therefore, this technology can fully ensure the stability of the lining structure and the operation safety after the tunnel disease treatment.

6. Conclusion

The new tunnel lining reinforcement technology proposed by our research group perfectly solves the defects such as void, no adhesion with the original lining, and high cost in the corrugated plate reinforcement technology. The new concrete lining can form a good adhesion with the contact surface of the original lining. With the progress of cement hydration and the penetration and self-healing ability of active materials, it can even form an integrated structure with the original lining. The on-site test work has been successfully completed and good results have been achieved. In the next step, our research group will refine the process flow, formulate the construction quality acceptance standards and the performance standards of the special concrete to standardize the construction technology and widely apply this new technology in the tunnel disease treatment projects.

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