Review on the Development Status of Tunnel Refractory Technology Research

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Abstract: With the economic development and technological innovation, the number of domestic tunnels has increased year by year. Because the tunnel structure is a closed and narrow structure, the loss of life and property caused by the fire is very serious. The manuscript summarizes the current status of the development of tunnel structure fire prevention technology. It introduced the development of fire protection technology for tunnel structures, fire protection technology for concrete composite structures, and fire resistance of fireproof coatings for fireproof panels, and summarized and prospected the current fire protection technology.

1. Introduction
With the rapid increase in scale, fire accidents in tunnels have increased year by year, causing major socio-economic impacts. Fires cause damage to the tunnel lining structure, reducing its bearing capacity and safety performance, and affecting emergency rescue and long-term safety operations after the disaster. At the same time, there are many technical gaps in China in the rapid detection, assessment and repair of fire damage to tunnel lining structures. There are no special technical specifications for fire protection design, reinforcement and repair of highway tunnel lining structures in China. Norms and specifications available for fire resistance design of tunnel lining structures. The standards are still insufficient, and highway management departments face great difficulties in emergency rescue and protection, structural health diagnosis, repair and reinforcement, and safe operation after a tunnel fire. In 1996, a train that entered a tunnel in the British-French Channel spontaneously ignited a serious fire. No casualties were caused, but the fire caused the reinforced concrete lining of the tunnel to be hundreds of meters long and could only be replaced. The tunnel was not put into use for about half a year after the fire, causing huge financial losses [1]. 1999, Europe The Mont Blanc Tunnel spontaneously ignited due to the spontaneous combustion [2] of a train carrying 40t heavy cargo. Within a short time after burning, the temperature soared to above 1000 °C, and three-quarters of the tunnel lining was completely destroyed. As urban traffic became more developed, the number of tunnels also increased year by year. Under the warning of various tunnel fire accidents, the tunnels Many fire prevention technologies have been valued. Scholars from all walks of life have conducted a lot of research on the performance of various structures in the tunnel after fire, the transmission of smoke and temperature after the fire, the methods of evacuation, the monitoring of the tunnel and the temperature control. Development and urbanization construction, various submarine immersed tube tunnels have also begun to be constructed and operated. These new tunnel structures also bring difficulties in the direction of fire prevention, such as fire prevention measures for joints of immersed tube tunnels and new steel shell concrete. Technical requirements for fire prevention of immersed tube tunnels with combined structures, etc.
2. Research and development status of refractory technology

2.1. Reinforced concrete tunnel structure

Generally, the tunnels are mostly reinforced concrete structures. As of the end of 2016, there were 15,181 highway tunnels in China with a total of 14039.7km [3]. In tunnel fire accidents, the consequences are often severe in long or extra long tunnels, which are long or extra long. When a tunnel fire occurs, due to poor ventilation, closed and narrow spaces, the temperature rises rapidly after the fire, and smoke accumulation is likely to cause death and damage to the tunnel structure. To master the fire behavior in highway tunnels, Yan Zhiguo He et al. Carried out a fire model test for a long highway tunnel, and based on the test results, made recommendations for the fire prevention measures in the tunnel, the control of the ventilation wind speed and the driving distance when the tunnel fire occurred, and concluded that: 1) the ventilation wind speed is less than 2m/s In the tunnel, the horizontal distribution of temperature in the tunnel is the rule of the highest vault, the second is the arch waist and the side wall, and the lowest is the bottom. When the wind speed is 2m / s or more, the lateral distribution of the temperature in the fire zone is high at the bottom and the lowest is the vault. The lower part of the fire zone is the highest vault, the second is the arch waist and the side wall, and the lowest is the bottom. As it moves away from the fire zone, the temperature distribution on the cross section becomes more uniform; 2) The longitudinal temperature distribution in the tunnel is that the fire zone. The temperature is the highest, and the temperature gradually decreases with the distance from the fire zone. Under the same conditions, as the wind speed increases, the temperature of the fire zone decreases, while the temperature along the way increases, and the vertical temperature distribution curve becomes smooth; 3) The wind speed increases with the same scale. The smaller the temperature, the shorter the temperature diffusion length, the larger the temperature gradient; the larger the wind speed, the longer the temperature diffusion length, but the smaller the temperature gradient. At the same wind speed, the larger the fire scale, the longer the temperature diffusion length, and the fire The smaller the scale, the shorter the temperature diffusion length [4]. Yan Zhiguo also conducted a large-scale model fire test on the super-long highway tunnel, and studied the change of the temperature in the tunnel with time during a fire. The maximum temperature was related to the ventilation speed and the scale of the fire. Zhou Xiangchuan carried out a full-scale test on the extra-long highway tunnel and analyzed the stress conditions of the lining structure in the tunnel under fire conditions. Based on the temperature distribution and smoke spread law after the fire, a fire prevention scheme [6] for the lining structure was proposed. Shi Jianmei analyzed the mechanical behavior of the lining after the tunnel fire, and analyzed its behavior under the high temperature of the fire, lining bursting, etc. have been studied. It is believed that when the ground overload is small, the lining master vault becomes closer and closer to the surrounding rock as the
temperature increases; when the ground overload is large, it is far away from the surrounding rock, and the larger the load, the more deformation. The larger the arch waist, the displacement increases with the increase of the ground overload. The larger the lateral pressure coefficient, the more the arch moves outward, and the arch waist moves inward. The higher the peak temperature, the more the arch The farther away from the surrounding rock, the arch waist moves more towards the surrounding rock side. The heating rate has a greater impact on the deformation of the lining in the early stage of heating, and the later period is not significant. The greater the reinforcement ratio, the closer the arch top is to the surrounding rock, and the farther the arch waist is away from the surrounding rock. The strength level of the reinforcement has little effect on the lining and deformation. The higher the concrete strength level, the greater the deformation of the vault to the surrounding rock side and the less deformation of the arch waist to the surrounding rock side [7]. For the railway tunnel Zhang Nian et al. A full-scale model fire test was performed on a high-altitude railway tunnel. The temperature and smoke distribution laws were measured and a proposal for assistance was proposed. The vertical distribution law of the fire temperature field in a high-altitude tunnel was: The temperature near the center line; the temperature is highest near the fire source. The setting temperature decreases as the distance from the source of the fire increases; the magnitude of the longitudinal wind speed has an important effect on the smoke distribution in the tunnel, and the temperature downstream of the source of the fire is higher than the upstream temperature. It can be seen that the tunnel fire temperature is normal at normal altitude. Compared with the distribution law, the overall trend of the distribution is basically the same, but the temperature change in the tunnel is not the same under the same scale fire conditions [8]. The fire protection measures for tunnel linings are mostly surface insulation methods as a change in form. The German Society for Research on Underground Transport Facilities (STUVA) has developed a new method of heat insulation: laying a trapezoidal corrugated steel plate (fastened with anchor rods) on the surface of the lining, and filling an inorganic mineral insulation layer between the steel plate and the lining. It was confirmed by fire experiments. This method works well.

In addition to mountains and urban tunnels, the development of underwater tunnels is also becoming more and more vigorous. The first underwater tunnel in China-Dapu Road Underwater Tunnel was completed, completed in 1970, Liuyang River Tunnel in 2009, and Xiang’an Tunnel in 2010. Both are underwater tunnels [9]. The Hong Kong-Zhuhai-Macao Immersed Tube Tunnel and the Deep-Medium Channel Immersed Tube Tunnel currently in use signify the rapid development of underwater tunnels. The splicing is shown in Figure 3. Due to the special structure of the underwater immersed tube tunnel, the impact on the immersed tube structure under consideration of fire has a different direction from that of ordinary mountains and urban tunnels. Jiang Shuping et al. Research, by simulating the temperature rise curve of the fire, adopting different protection and fire protection measures for the joint members to propose a recommended scheme for joint fire protection technology [10]. Guo Jun et al. Used the submarine tunnel of the Hong Kong-Zhuhai-Macao Bridge project as the basis for the project, and compared and tested the results. The calculation and analysis of the temperature distribution law of the tube joint structure of the subsea tunnel and the fire prevention technical scheme [11]. Chen Daifei et al. conducted a fire test on the Hong Kong-Zhuhai-Macao Bridge 1: Fire protection technology provided support [12]. Zhang Mengxi et al. Based on Shanghai's crossover river immersed tube tunnel in Shanghai, based on comparative experiments and numerical calculations, obtained the temperature distribution of the immersed tube tunnel during a fire and the effect of temperature on the stress field [13]. Using the Hong Kong-Zhuhai-Macao Bridge immersed tube tunnel as the engineering background, Xu Yan analyzed the smoke distribution and spreading rules after the fire. The test data can provide the basis for the fire prevention technology of Hong Kong-Zhuhai-Macao Bridge immersed tube tunnel and the post-fire evacuation strategy [14]. Zhang Zhuyong researched the temperature distribution and stress of the immersed tube tunnel under fire conditions, and gave the structural design method and expression of the high temperature of the fire [15]. The fire lining commonly used in immersed tube tunnels at present. There are fire-resistant panels and fire-resistant coatings, both of which can meet the requirements of fire-resistant grades, but each has its own advantages and disadvantages. The advantages of fire-resistant panels are that they are easy to install and have little impact on other related processes during
construction. The advantages of fire-resistant coatings are that they can play a certain role. Sound absorption effect, but it will cause some impact on other processes, and the fireproof coating on the top of the pipe must be reinforced with a reinforced mesh. Regardless of the structure of the submerged pipe tunnel, it is expected that due to its narrow internal space, the number of entrances and exits is relatively single, and the airtightness is strong, once a fire occurs, the evacuation of people, the dilution and discharge of toxic gases, and the suppression of fires will face great challenges. In the case of fire, how to ensure the coordination and waterproof characteristics of the overall structure is also one of its key technical issues.

![Figure 3 Joints of Immersed Tunnels of Hong Kong-Zhuhai-Macao Bridge](image)

2.2. Refractory technology of concrete composite structure
Relying on the immersed tube tunnel of the Hong Kong-Zhuhai-Macao Bridge, domestic scholars have done a lot of research on the fire prevention technology of the immersed tube tunnel. However, the Hong Kong-Zhuhai-Macao Bridge is still an immersed tube tunnel using a reinforced concrete structure, and the immersed tube tunnel in the Zhongshan channel is in the form of a steel shell concrete composite structure, as shown in Figure 4.

![Figure 4 Pipe joint structure of deep and middle channel immersed tube tunnel](image)

The research on the fire protection technology of concrete composite structures is mostly in the building construction and bridge engineering. Han Yulai researches the reinforced concrete and rigid frame structure, its deformation and stress state under fire high temperature, and discusses two structures under high temperature Calculation analysis method [16]. Liu Guirong performed fire analysis on ordinary concrete shear wall and reinforced concrete shear wall, and studied its stress-strain, crack, temperature distribution and seismic performance after fire [17]. Min et al. Conducted a fire resistance
test on steel structures, studied their fire resistance limits, protective technical measures, and pointed out the problems of existing fire protection technologies [18]. In the temperature field study of steel-concrete composite structures, Liao Qianjian made corrugated steel webs. The temperature effect of the plate box girder bridge is studied, and the simulation of the temperature field distribution and change law at different positions of the structure is simulated by wired software [19]. Chen Chunmiao studied the temperature effect of the steel-concrete suspension bridge. Combined with finite element software and experimental data to analyze the temperature effect of steel-concrete composite structures of long-span suspension bridges under different working conditions [20]. In 2006, Yao Weifa studied the performance of a rigid-concrete composite beam bridge under fire, and analyzed its residual flexural bearing capacity after the fire [21]. Deng Libin used numerical simulation and fire resistance tests to study the mechanical behavior of precast concrete laminated floors. The study of fire prevention technology and temperature distribution provides effective suggestions for the structure's treatment measures after a fire [22]. Concrete composite structures are used more in building construction and bridge engineering, and their research is weak in tunnel engineering.

2.3. Status of R & D of fireproof coatings and fireproof panels for tunnels
Fire-resistant coating refers to a kind of fire-resistant coating that covers the surface of the material to block heat and prevent fire from spreading. It can be divided into organic fire-resistant coatings and inorganic fire-resistant coatings according to the composition of the base material. Additives, refractory fillers, foaming materials and additives.

The first domestic fire-resistant coatings were used in building structures. In 2001, some fire-resistant coatings for building structures were used in tunnel engineering. Before 2005, fire-resistant coatings for tunnels were carried out in accordance with the "General Technical Conditions for Fire-resistant Coatings for Prestressed Concrete Floors". Inspection, after the promulgation of the industry standard "Fireproof Coatings for Concrete Structures" in 2005, tunnel fireproof coatings have also entered the professional supervision and implementation stage (composite tunnel fireproof coatings and performance research). In the same year, Lanbin compared different coating formulations. The research found that Formula 11 has the strongest comprehensive performance, and analyzed the fire resistance mechanism of Formula 11 tunnel coating from both physical and chemical aspects [23]. In 2009, He Shijia developed a tunnel fire-resistant coating that can adapt to humid environments and is environmentally friendly. Compared with traditional coatings, it has the advantages of good fire resistance and thin coating [24]. After improving the shortcomings of the current tunnel fireproof coatings, Zhang Siqing prepared an intumescent concrete fireproof coating at the preparation site, which has better fireproof performance. [25]. In 2017, Wang Tong targeted long and large tunnels with nanometer fire-resistant coatings, which has the functions of degrading automobile exhaust and self-cleaning [26]. After repeated tests, an environmentally friendly material that is lightweight, easy to construct and does not emit harmful gases has been developed and used as a tunnel fire board [27].

Today's fire-resistant coatings still have defects: ① the coating is too thick; The knot strength is low and it is easy to fall off; ② It is harmful to the environment; ④ The water resistance is poor, and compared with the fire board, its advantages are: easy construction; temperature and humidity resistance; small deformation.

3. Conclusion
With the rapid increase in the size of tunnels, fire accidents in tunnels have increased year by year, causing significant socio-economic impacts. Fires cause damage to the tunnel lining structure, reducing its bearing capacity and safety performance, affecting emergency rescue and long-term safe operation after the disaster. Particularity, during the operation of the tunnel, it is difficult to control the fire in time. The following is a summary of the current research on fire resistance technology:

(1) The tunnel fire prevention technology of reinforced concrete structures has been relatively mature, and there have been more studies on the mechanical behavior and temperature distribution of its internal structures after a fire. However, for new tunnel structures such as steel shell concrete composite
structures of immersed tube tunnels, Fire protection technology research is weak.

(2) The research on the fire resistance of concrete composite structures is concentrated in construction engineering and bridge engineering. The fire resistance of concrete composite structures in tunnel engineering is weak.

(3) Today's fire-resistant coatings still have defects: ① the coating is too thick; ② the bonding strength is low, and it is easy to fall off; ③ the environmental hazard is large; ④ the water resistance is poor, and its performance is superior to the fire-proof board. For: ① easy construction; ② temperature and humidity resistance; ③ small deformation.

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References
[1] Dai Guoping. An Analysis of the Fire Accident in the British-French Channel Tunnel and Its Enlightenment [J]. Railway Construction, 2001 (03): 6-9.
[2] Lu Yi. Mont Blanc Tunnel Fire [J]. Labor Protection, 2006 (10): 66-69.
[3] Jiang Shuping. Statistics of highway tunnels in China [J]. Tunnel Construction, 2017, 37 (05): 643-644.
[4] Yan Zhiguo, Yang Qixin, Zhu Hehua. Experimental study of temperature distribution in long-sized road tunnel [J]. Journal of Southeast University (Natural Science Edition), 2005 (s1): 84-88.
[5] Yan Zhiguo, Yang Qixin, Zhu Hehua. An experimental study of fire hazard at the QingLing highway tunnel[J]. Journal of Civil Engineering, 2005 (11): 96-101.
[6] Zhou Xiangchuan. Field fire test of extra-long highway tunnel and research on fire resistance performance of lining structure [D]. Central South University, 2011.
[7] Shi Jianmei. Research on Fire Performance of Tunnel Lining Structure [D]. Suzhou University of Science and Technology, 2013.
[8] Zhang Nian, Tan Zhongsheng, Mao Jun, Yan Fei, Guo Feng. Experimental Study on Fire Combustion Characteristics in High-altitude Railway Tunnels [J]. China Safety Science Journal, 2011, 21 (12): 52-57.
[9] Editorial Department of China Journal of Highways and Transport. Review on China’s Tunnel Engineering Research: 2015 [J]. China Journal of Highways and Transport, 2015, 28 (05): 1-65.
[10] Jiang Shuping, Zhang Enqing, Guo Jun, Liu Shuai. Experimental Research on Fire Protection for Immersed Tunnel Joint [J]. Chinese Journal of Underground Space and Engineering, 2016, 12 (03): 607-612.
[11] Guo Jun, Liu Shuai, Jiang Shuping. Fire-proof Test and Numerical Simulation on Tube Structure of Subsea Tunnel [J]. China Journal of Highway and Transport, 2016, 29 (01): 96-104 + 114.
[12] Chen Dafei, Zhou Jian, Xie Yaohua. Fire test of 1: 1 full-scale immersed tube tunnel of Hong Kong-Zhuhai-Macao Bridge [J]. China Highway, 2015 (09): 93-97.
[13] Zhang Mengxi, Huang Jin, He Xiaochong. Coupling analysis of thermal field and stress field for immersed tunnels under fire load [J]. China Civil Engineering Journal, 2007 (03): 83-87.
[14] Xu Pai. Research on Fire Smoke Movement Characteristic in Submarine Immersed Tunnel [D]. Chongqing Jiaotong University, 2014.
[15] Zhang Zhuyong. Research of mechanics immersed tunnel under fire load [D]. Chongqing Jiaotong University, 2013.
[16] Han Yulai. Resistance Capability Investigation of Building Structure in Fire [D]. Harbin Engineering University, 2008.
[17] Liu Guirong. Experimental Study on Fire-resistance and Post-fire Seismic Behavior of Concrete Shear Walls [D]. Dalian University of Technology, 2010.
[18] Qian Jianmin, Wang Liangwei. Study on the Steel Fire Resistance Rating Test [J]. Fire Science and Technology, 2002 (01): 12-14.

[19] Liao Qianjian. Study on Thermal Response and Fatigue Performance of Box Girder with Corrugated Steel Webs[D]. Zhejiang University, 2015.

[20] Chen Chunmiao. Temperature Effect Analysis on the Steel-concrete Composite Bridge Deck of Long-span Suspension Bridge[D]. Changsha University of Science and Technology, 2014.

[21] Yao Weifa. Study on Response of Fire Process and Post-Fire Residual Capacity of Steel-concrete Composite Girder Bridge [D]. Southeast University, 2016.

[22] Deng Libin. Experimental research and theoretical analysis on fire-resistance behaviors of precast concrete composite slabs [J]. Hunan University, 2015.

[23] Lan Bin. Research on Novel Fireproofing Coating for Tunnel [D]. Chongqing University, 2005.

[24] He Shijia. Study on Environment Friendly Fireproofing Coatings for Tunnel Linings [J]. Paint & Coating Industry, 2009, 39 (01): 52-54.

[25] Zhang Siqing. Preparation and Study of Fire-Resistant Performance of a Novel Intumescent Fire Retardant Coating for Concrete [D]. Southwest Jiaotong University, 2011.

[26] Wang Tong. Study on preparation and properties of multifunctional nano coatings for long tunnel [D]. Nanjing Forestry University, 2017.

[27] Wan Shiyin. The study of an environment protective fire plate for tunnel linings [D]. Chongqing University, 2005.