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PCCP Mortar Protection Layer Research Progress

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Prestressed steel cylinder concrete pipe (PCCP) has the characteristics of high strength, excellent impermeability, strong sealing and easy installation, and has become an irreplaceable first choice pipe in China's long-distance water diversion project. However, in the process of using PCCP, there will be pipe bursts and other phenomena, most of which are caused by the broken wire of the prestressed steel wire, and the most important function of the protective layer of PCCP mortar is to protect the prestressed steel wire. In this paper, the research progress of PCCP by scholars at home and abroad is reviewed from five aspects: PCCP working environment, mortar mechanical properties, mortar durability, mortar thickness and mortar curing. as well as testing the durability of the mortar through different solution environments; The research prospect of the production of PCCP mortar protective layer, the detection of PCCP mortar protective layer, and the monitoring of PCCP mortar protective layer were carried out, which provided reference enlightenment for the development of PCCP mortar protective layer.

Keywords: Prestressed steel cylindrical concrete pipe; mortar protective layer; protective layer optimization.

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1. INTRODUCTION

Prestressed steel tube concrete pipe is a kind of high quality composite pipe composed of thin steel plate, high strength prestressed steel wire, high strength concrete and protective layer mortar. This kind of pipe integrates the advantages of concrete pipe and steel pipe, so it is widely used in various water transmission and diversion projects [1]. PCCP not only has good interface sealing performance, high pipe strength and stiffness, but also has high permeability resistance. It has the advantages and properties of steel pipe and prestressed concrete pipe, lower cost than steel pipe, more than twice as long service life than steel pipe, and generally designed service life of more than 50 years (the corrosion resistance committee of the American Water Supply Association believes that 100 years can be used) [2]. Since all the steel used to make PCCP is wrapped in good dense concrete, the exposed parts of the anti-corrosion treated spout after installation are filled with mortar to seal the concrete or the high-alkaline environment provided by the mortar to passivate the steel inside PCCP, thereby preventing its corrosion and avoiding secondary pollution of water quality [3].

In addition to the extensive use of PCCP pipelines in China, some problems have also occurred, such as cracks in the mortar of the pipeline protective layer, longitudinal cracks in the concrete inside the pipeline, corrosion and wire breakage of the circumferential prestressed steel wire, and pipe explosion accidents in some pipelines [4]. The damage of PCCP can be classified into two categories: circumferential and longitudinal damage. The failure process of the circumferential failure mode consists of initial corrosion and subsequent wire breakage, or wire breakage caused by hydrogen brittleness, followed by cracking and delamination of the protective mortar. Corrosion and wire breakage will cause prestress loss, resulting in cracking of the concrete tube core, exposing the steel cylinder buried in the tube core concrete to the environment, which will further cause corrosion and rupture of the steel cylinder, and finally lead to partial or complete failure of the working state of PCCP. Longitudinal failure patterns are usually caused by inadequate resistance to thrust, uneven foundation settlement, dynamic ground movement caused by explosions or earthquakes at pipe bends or fork junctions [5].

In order to improve the anti-erosion ability of PCCP, some scholars analyzed the design and test of PCCP to optimize the overall structure of PCCP. Qu Fulai et al. [6] used a comparative test method to test the application of made sand concrete to PCCP, and the results showed that the working performance of made sand met the requirements for the casting and forming of tube-core concrete, and the resistance to water penetration and chloride ion penetration of made sand concrete was higher than that of natural sand concrete, which could be used to prepare PCCP tube-core concrete. Shang Pengran et al. [7] showed that the quality of PCCP concrete core mainly depended on the concrete strength, external quality of pipe wall and pipe wall cracking at 28 days. The 28-day strength of concrete is the main criterion of pipeline quality, and the crack of pipe wall is the secondary criterion. The overall appearance of the pipeline has little effect on it. [8] Through the simplified limit design and verification of prestressed concrete pipe under the action of internal water pressure, it is proposed that attention should be paid to the crack resistance and impermeability of protective layer mortar to improve the tensile strength of concrete. Wang Zilong [9] et al. developed a grouting mortar with great fluidity, good cohesiveness, micro-expansion, high crack resistance and durability, and carried out mortar tests. The test results show that compared with ordinary cement mortar, the initial mortar expansion is increased, the initial and final setting time is delayed, and the dry shrinkage deformation is reduced. The working performance, mechanical properties, crack resistance and durability of the developed grouting mortar have obvious advantages [10,11,12].

Although relevant research plays a role in improving the mechanical performance and corrosion resistance of PCCP, there are still deficiencies in the research of protective coating mortar. For this reason, this paper collects relevant research data at home and abroad, and combines the research results of PCCP working environment, mortar mechanical properties, mortar durability, mortar thickness and mortar maintenance at home and abroad. The relevant researches of PCCP are summarized to provide reference for the development and research direction of PCCP industry.

2. RESEARCH AND DEVELOPMENT OF PCCP PROTECTIVE LAYER MORTAR

2.1 PCCP Working Environment

PCCP protective layer mortar is at the outermost end of PCCP pipe, which can prevent the external corrosive medium from contacting with the steel wire inside the structure and cause structural damage. A dense hydrated iron oxide film is formed on the surface of the prestressed steel wire. Water and oxygen cannot penetrate, so that the surface of the steel wire is transformed into a state that is not easy to oxidize. Li Jin [13] pointed out that in most natural soil and water environments, there is no damage to hydrated iron oxide films, and the key factor of corrosion is the presence of oxygen. Keeping steel in an alkaline environment to ensure that there is no free oxygen is the key to steel corrosion resistance. Yu Hongfang [14] pointed out that PCCP pipe is not suitable for open-air operation, which is easy to reduce the service life of pipeline and even cause pipeline quality accidents. The specific reason is that the PCCP pipe experiences the sun and rain, freeze and thaw cycle, which easily leads to the spalling of the protective layer mortar, cracks, corrosive media contact with the steel wire, and the corrosion of the steel bar. Bian Zhiyuan [15] proposed anti-corrosion measures for PCCP pipes in view of the fact that prestressed steel wires could not resist corrosion only by self-passivation under some special circumstances: increase the thickness of protective layer, increase the amount of cement, improve the water absorption rate of protective layer mortar, and improve the compressive strength of protective layer mortar. Li Jinrui [16] pointed out that when using PCCP pipe in cold areas, attention should be paid to the following aspects: the raw material should be cement with good frost resistance, the influence of raw material on water absorption should be reduced, the roller shooting equipment should work normally, the finished pipe should be maintained well, and the pipe top should be placed below the limit frozen soil layer.

The operating environment of PCCP pipeline is an important aspect to ensure the service life of PCCP. In the design of PCCP pipeline, it is necessary to fully understand the local soil condition, and take corresponding anti-corrosion measures according to different soil conditions to ensure the healthy operation of PCCP pipeline.

2.2 Mortar Maintenance

GB/T 19685-2017 "Prestressed steel Tube concrete pipe" stipulates that [17] the completed protective layer mortar should be maintained by appropriate methods. When using natural curing, after the protective layer mortar is fully solidified, water should be sprayed at least twice a day to keep the protective layer mortar wet, and the natural curing environment temperature should not be less than 5°. When using heating curing, the heating rate and maximum temperature in the curing cover (kiln and pit) should be controlled in accordance with AWWA C301 standard [18] for a minimum of 12 hours of curing. Yang Bokai et al. [19] made a comparative study on the Cl^-penetration rule of epoxy coal asphalt anticorrosive coating thickness on PCCP steamed and standard cultured mortar under the conditions of single chloride and sulfate-chloride coupled erosion. The influence of coating thickness and curing method on the coupled sulfate and chloride erosion resistance of mortar was evaluated by the coefficient of compressive and corrosion resistance. The results show that compared with the steam curing mortar, the standard curing mortar has stronger corrosion resistance. With the increase of coating thickness of epoxy coal asphalt paint, the erosion resistance of mortar is obviously enhanced. Under the co-erosion of $SO4_2^-$ and Cl^-, the compressive and corrosion resistance coefficient increases first and then decreases. $SO4_2^-$ can inhibit the diffusion of Cl^- to a certain extent in the early stage of erosion. With the increase of erosion time, a large amount of ettringite is generated, the internal porosity of the mortar gradually increases, and the diffusion rate of Cl^- gradually increases.

In order to obtain high-quality concrete products, in addition to the need for reasonable mix ratio, mixing and vibration, the establishment of maintenance system is very important. Reasonable curing system can effectively improve the compressive strength of concrete products and prevent the appearance of dry shrinkage cracks on the outside of PCCP pipe wall.

2.3 Mechanical Properties of Mortar

The structural strength standard of the material is the most basic requirement to meet the safety performance of PCCP. The strength test of protective layer mortar should be carried out at least once every 3 months or when the source of raw materials used to make protective layer mortar changes. The 28-day compressive strength of the 25mm×25mm×25mm protective layer mortar specimen made by cutting method shall not be less than 45 Mpa [17]. Qu Fulai et al. [20] conducted a test on a full-size PCCP with a diameter of 3.2m. Under the internal water pressure environment, the strain of concrete, prestressed steel wire and protective layer mortar was tested to evaluate the ultimate state of bearing capacity under internal water pressure. The results show that under the internal water pressure, when the external coagulation of PCCP is in the service limit state, the prestressed steel wire is in the elastic state, and some protective layer mortar exceeds the service limit state due to visible cracks. It is proved that the protective layer mortar is prone to crack, and the current specification may overestimate the tensile control strain of protective layer mortar. Shang Pengran et al. [21] found that when cracks occur in the concrete at the top of PCCP, due to the influence of bending moment redistribution, PCCP will receive additional tensile stress, resulting in easy cracking of the protective layer mortar, and proposed that the tensile properties of PCCP protective layer mortar should be improved. Chen Bochi et al. [22] analyzed some provisions on mortar strength values and cracking control conditions in Chinese and American PCCP design standards. Based on ABAQUS finite element analysis software, they simulated and studied the mechanical response mechanism of protective layer mortar during installation and operation of PCCP, and discussed the problems existing in the design standards according to the calculation results. He [23] believes that different from concrete materials, there is no unified standard for mortar materials in China at present, so the mortar materials used in different structures have great differences in the value of strength representative value, strength test method and constitutive model. In the design of PCCP structure, CECS 140:2011 regulation simply stipulates that the standard value of compressive strength of mortar is not less than 45MPa, and gives the empirical formula for calculating the standard value of tensile strength and elastic modulus of mortar. The results show that the current design uses the compressive strength of mortar as the design value of mortar strength, overestimating the bearing capacity of PCCP mortar. At the same time, the strain limit in the design standard to control the cracking of mortar layer is too high, which leads to the phenomenon that the protective layer mortar is prone to crack, which is easily caused by the design defects of PCCP structure failure and damage. Wang Hao et al. [24] believe that the tighter the meshing of the two roller firing wheels in the parameters of the roller firing system, the greater the potential energy stored between the two wheels, the greater the kinetic energy converted from the potential energy, the greater the instantaneous velocity of slurry centrifuge, the denser the protective layer formed by the roller firing on the surface of the tube, the higher the compressive strength of the protective layer mortar, the lower the water absorption rate, and the more resilient material generated. In addition, the roll shooting distance also affects the densification of the mortar. The greater the distance, the greater the accumulated kinetic energy loss of mortar flow in the air, the lower the incident velocity of mortar and the lower the density.

Protective layer mortar is the first line of defense of PCCP pipeline, and its strength determines the protective effect of protective layer mortar. Low strength of mortar leads to low protective effect. Therefore, the strength of the protective mortar has become the index of the quality control of the mortar.

2.4 Durability of Mortar

The durability of PCCP protective layer mortar has become an index difficult to control in PCCP production due to cumbersome test and inspection means, time-consuming and impossible to detect in real time. The durability of PCCP protective layer mortar also determines the quality and working life of PCCP tubes, playing a crucial role. Sarah Hasey et al. [25] artificially studied the resistance of mortar protective layer to chemical corrosion and established three mortar mixtures: a control mortar, a 10% FA (fly ash) and 10% SF (silica fume) mortar. The samples were immersed in 9.5wt % NaCl solution and 9.5wt % NaCl and 34wt % Na2SO42 in order to simulate the chloride ion and complex chlorine-sulfate ion erosion environment of PCCP protective layer mortar. Electrochemical impedance spectroscopy (EIS) was used to characterize the corrosion process, and it was found that the compressive strength and bending strength of the mortar mixed with fly ash and silica fume were improved. In addition, the addition of 10%FA and 10% improved the porosity of PCCP protective layer mortar under chloride ion and complex chlorine-sulfate ion erosion. Que Xiaoping et al.

[26] conducted relevant experimental studies on the process quality control of water absorption index of PCCP protective layer mortar, collected a series of test data on technical means such as equipment process parameters, mortar mix ratio and the use of special water repellent, and analyzed the reasons for the influence of the above factors on the water absorption of mortar, and concluded: Under certain conditions, the water absorption rate of mortar can be improved and the production efficiency can be increased by adding appropriate amount of special waterproofing agent in mortar. Wang Dong et al. [27] studied the effect of mortar densifier on the durability of PCCP protective layer mortar, and designed experiments to test the effects of DSF on the density, compressive strength, water absorption rate, chloride ion diffusion coefficient, permeability grade (seepage height), dry shrinkage rate, ring method cracking resistance and bond strength of protective layer mortar at 0, 15%, 20% and 25% contents. The results showed that: DSF has no adverse effect on the fluidity and mechanical properties of protective mortar. The durability of the protective layer mortar, such as impermeability, crack resistance, erosion resistance and bond strength, is obviously improved. Jana D[28] et al. studied the acid erosion of PCCP mortar and found that acid erosion would increase the porosity and permeability of the protective layer, resulting in loss of quality and strength of the protective layer. The severity of corrosion depends on the type and concentration of acid (pH of the solution) and the amount and flow rate of the solution over the surface of the protective layer and along the surface of the coating. The durability of PCCP depends on the resistance of the mortar protective layer to potentially aggressive chemicals in the exposed environment. The PCCP was subjected to severe acid attack, resulting in a reduction in the thickness of the mortar protective layer by more than 25% and subsequently a loss of structural integrity.

The durability of the protective layer mortar must be qualified through the implementation of strict and serious quality control to achieve, if the enterprise only pay attention to the other indicators of the protective layer mortar and ignore the durability, the final will only make the life of PCCP pipe greatly reduced.

2.5 Mortar Thickness

In 2005, China promulgated GB/T 19685-2005 "Prestressed steel tube concrete pipe", enterprises began to use domestic standards for production, installation of PCCP, 2005 version of the protection layer thickness ≥20mm, in 2017 updated to GB/T 19685-2017 "prestressed steel tube concrete pipe", Some indexes of the protective layer mortar [17] are adjusted, and the thickness of the protective layer is ≥25mm. Yang Huiqin [29] pointed out that the thickness of the protective layer of mortar is too thin, which is easy to cause damage during transportation and installation. According to the research, increasing the mortar thickness can significantly improve the pipeline life. Zhang Hongyu [30] studied the stress distribution of PCCP pipe wall section under the action of working load and internal water pressure when the thickness of the mortar layer varies between 20mm and 100mm, and concluded that the stress of PCCP pipe wall section changes linearly with the thickness of the protective layer mortar, except for the inner stress of the pipe top/bottom section, which all decreases with the increase of the thickness. Therefore, from this point of view, the greater the thickness of the protective layer mortar, the more beneficial it is to improve the bearing capacity of PCCP. When the thickness of the protective layer mortar increases appropriately, the tensile stress of the tube core will decrease. The thickness of the mortar layer should be about 30mm, which should not be too thick, but should not be less than 20mm or twice the diameter of the steel wire.

The increase of the thickness of the protective layer mortar is closely related to the rolling process of the protective layer mortar and the control of the production requirements of PCCP tube mortar. The final thickness should be tested by the manufacturer and can be put into production after passing the test.

3. RESEARCH PROSPECTS

In actual engineering, PCCP pipe to make the protective layer to achieve high quality and durability, still need to take effective measures in the production stage, the operation stage, there are still some technical bottlenecks to be broken.

3.1 PCCP Protective Layer Mortar Production

PCCP pipe protective layer mortar thickness is thin, easy to crack, resulting in a gradual decline in durability, can not effectively protect the prestressed steel wire from erosion in the daily work of PCCP pipe, affecting the safety of PCCP pipeline operation. As a PCCP manufacturer, we should pay attention to the design of PCCP mortar protective layer according to local conditions in combination with the working environment of PCCP, improve the density of protective layer, prevent the diffusion and penetration of $Cl^{-}SO_4^{2-}$ ions, and delay and prevent steel wire rust. In the selection of raw materials, it is one of the measures to improve the durability of the mortar protective layer to change the ordinary cement into chlorine-resistant and sulfate-resistant cement. In the process of mortar production, adding effective mixtures can also improve its durability. Studies have shown that [31,32] when polypropylene fiber is added to cement mortar, the dry shrinkage of mortar is reduced, the toughness is increased, the crack resistance is enhanced, and the strength of mortar is increased, which can significantly improve the permeability resistance of the material. At the same time, the production should pay attention to reduce the rebound caused by roller mortar, reduce the economic cost; In the selection of protective layer thickness, reasonable selection of protective layer thickness can effectively increase the time of steel wire losing passivation; In the maintenance stage of PCCP pipe, attention should be paid to ensuring the demoulding time as far as possible, controlling the temperature difference between the finished pipe and the environment, wetting the surface of the product in time after demoulding, reducing the shrinkage of the mortar of the protective layer of the pipe wall and preventing cracks.

3.2 PCCP Protective Layer Mortar Inspection

During the production period, the method of testing the protective layer of mortar should be the cutting method mentioned in GBT 15345-2017 "Test Method for Concrete Water Transmission Pipe" [33]. The method of testing the strength of protective layer mortar is to use diamond cutting equipment to cut the protective layer mortar specimen into a cube test block. However, the operation of this method is complicated and the workload is large, it is difficult to ensure that the compression surface of the roller-fired mortar test block is flat and parallel after cutting, and the shape of the roller-fired mortar test block is cube, which is easy to damage the cube corners and the mortar falls off during cutting, and the test block is difficult to meet the requirements of the code. Depending on the on-site situation, enterprises can consider adding other detection methods to detect the compressive strength of mortar. For example, by adding cylinder specimens, this method has low requirements on the sampling process of core specimens, which can ensure that the cylinder core specimens are not easily damaged, simplify the operation process, shorten the preparation period of mortar specimens, and promote the research and application of PCCP roller mortar strength detection. During operation, the protective layer mortar will crack and continue to develop, causing wire breakage and pipe explosion accidents. Therefore, monitoring the mortar cracking of the protective layer of PCCP pipeline in operation is helpful to clarify the structural health of the protective layer of mortar, and adopt reinforcement maintenance for the cracked section to effectively delay the time of steel wire erosion by the outside world and improve the working life of PCCP.

4. CONCLUSION

This paper introduces the research progress of PCCP protective layer mortar from many aspects, and puts forward the technical problems to be solved in the research prospect part, and puts forward the prospect of the future development of PCCP protective layer mortar. The production of PCCP in China started late, and there are still many problems during the current PCCP operation. It is hoped that the scientific research and technical personnel in this industry can overcome the difficulties, so that PCCP can better serve the development of China's water conservancy industry and promote China's economic development.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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