Minireview Article

Prestressedsteel cylinder concrete pipe development status: A mini review

ABSTRACT

Pre stressed steel cylinder concrete pipe (PCCP) is a composite pipe composed of thin steel plates, high-strength steel wires, and concrete. It fully and comprehensively utilizes the tensile and easy sealing properties of steel, as well as the compressive and corrosion resistance properties of concrete. It has the characteristics of high sealing, high strength, and high impermeability. Due to its excellent characteristics, it has been widely used worldwide. This article mainly introduces the structure and components of prestressed steel cylinder concrete pipes, the development history and research status at home and abroad, as well as the PCCP design standards and development prospects.

Keywords**:** ;pipeline structure;development status; research status;design standards

1.Introduction to PCCP

PCCP is a high-strength concrete pipe core with a steel cylinder wrapped with prestressed steel wire, sprayed with a cement mortar protective layer, and welded with a steel socket. The socket has grooves and rubber rings, forming a flexible joint with sliding rubber rings. It is a composite structure composed of steel plate, concrete, high-strength steel wire, and cement mortar, with the characteristics of steel and concrete. Suitable for large-scale water transmission projects across regional water sources, water supply and distribution networks for tap water, industrial and agricultural irrigation systems, circulating water pipelines for power plants, various municipal pressure discharge main pipelines and inverted siphon pipes, etc., widely used worldwide.

2.Classification and structural composition of PCCP pipelines

2.1PCCP pipeline classification

PCCP pipes can be divided into two types in terms of structural form: one is the lined prestressed steel cylinder concrete pipe (PCCP-L), which is made by first forming concrete on the inner wall of the steel cylinder, winding circumferential prestressed steel wire outside the steel cylinder, and then spraying a mortar protective layer to make the pipe; Another type is the embedded prestressed steel cylinder concrete pipe (PCCP-E), which is made by first burying the steel cylinder in the concrete core of the pipe, then wrapping the circumferential prestressed steel wire on the concrete core of the pipe, and spraying a mortar protective layer to make the steel cylinder concrete pipe; According to the different number of winding layers of prestressed steel wire, it can be divided into single-layer wrapped prestressed steel cylinder concrete pipes and multi-layer wrapped prestressed steel cylinder concrete pipes [1]

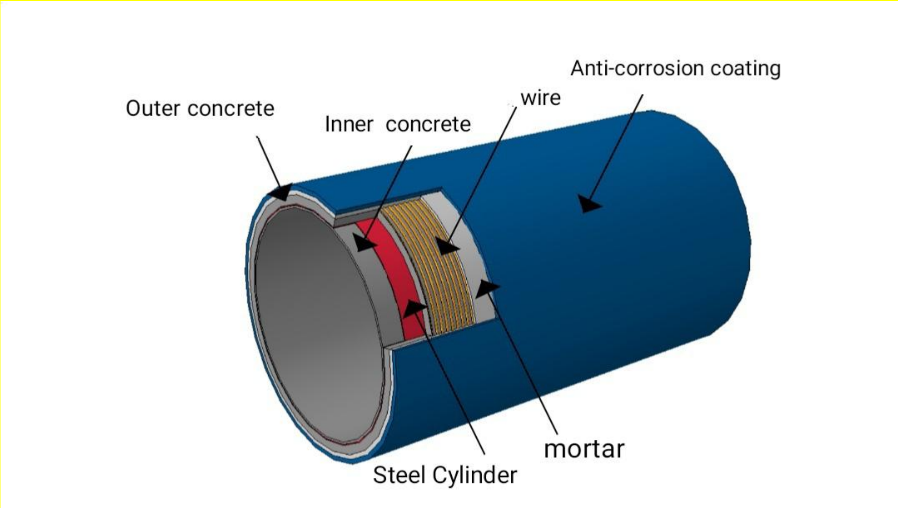

Figure 1.PCCP structure diagram

2.2 PCCP Structure Composition

PCCP pipeline [2] is composed of high-strength concrete core, cold drawn prestressed steel wire, mortar protective layer, steel support, and socket joint. Its functions are as follows:

(1) High strength concrete pipe core: It is the main structural part of the pipeline and can provide a smooth inner surface to facilitate water flow. The steel cylinder inside the core of the pipe serves as an anti-seepage and provides longitudinal tensile stiffness, while also increasing circumferential strength. In PCCP-E type pipelines, the steel cylinder is embedded in the concrete core, while in PCCP-L type pipelines, the steel cylinder is wrapped outside the concrete core. The two ends of the steel cylinder are connected with steel bearings, socket rings, and elastic "0" - shaped rubber rings, which can provide water stop for the connection between pipes and align the centers of adjacent pipes. PCCP - The concrete of E-type pipelines is poured vertically in steel molds, and is often used for large-diameter PCCPs. PCCP - The concrete of L-shaped pipes is poured by centrifugal pumps or compacted in the inner diameter of steel cylinders, and is often used for small diameter PCCP [3].

(2) Cold drawn prestressed steel wire: The steel wire is spirally wound around the pipe core with a certain tensile stress, generating uniform prestressing on the pipe core to compensate for the tensile stress generated by internal pressure and external load. The steel wire diameter, pre compression stress, and winding density can be designed according to specific operating conditions to provide the desired optimal pre stress [4].When producing pipelines, the strength grade of the steel wire used is generally 1570MPa or 1470MPa, and the diameter of the steel wire is generally two types: 5mm and 7mm.

(3) Mortar protective layer: protects high-strength steel wires and pipe cores from physical

damage and external corrosion [5].

(4) Steel socket and spigot joints: welded to both ends of the steel cylinder, they are PCCP connectors and seals [6]

Figure 2. PCCP Physical image

2.3Characteristics of PCCP

There are currently two types of concrete pipes used for pressurized water transportation in China: prestressed concrete pipes and PCCP. Pre stressed concrete pipes have been used in domestic water supply projects for many years. The presence of hollowing or cracks in the pipe body can cause leakage problems, and there have also been cases where the interface is not tight due to irregular circular sockets. Explosion accidents and water leaks are common in existing pipelines. In recent years, PCCP produced with foreign technology has the following characteristics in response to the shortcomings of prestressed concrete pipes:

(1) There are 1 to 2 millimeters of steel plates sandwiched in the pipe body, which are rolled into a tube shape. After pressure testing, it can be ensured that there is no leakage. Compared with previous pipes, PCCP has the advantages of wide applicability, long economic life, good seismic performance, convenient installation, low operating cost, and basically no water leakage.

(2) Its interface adopts a steel ring socket, and the steel ring is welded to the pipe body steel pipe. The machining accuracy of the steel ring socket is relatively high[7].

3. Current Application Status at Home and Abroad

3.1 Current Application Status of PCCP Tube in China

At present, PCCP pipes are widely used in national infrastructure projects such as water conservancy, electricity, and municipal water supply and drainage in China due to their combination advantages of pipes.

In 1984, Suzhou Concrete and Cement Products Research Institute collaborated with the Water Supply Company Pipe Factory in Yingkou City, Liaoning Province to produce PCCP with a diameter of 0.6 meters using a simple method and applied it in water transportation projects. In 1985, Nanjing Cement Pipe Factory in Jiangsu Province collaborated with Beijing Municipal Engineering Research Institute to develop PCCP with a diameter of 0.6m and 1.2m using self stressing concrete, which was installed on the Fujian Jianyang Hydropower Station project and Nanjing water supply pipeline. Subsequently, under the guidance of the reform and opening up policy, advanced foreign technologies and concepts entered the Chinese market through various channels, and PCCP also entered the perspective of domestic people. Domestic enterprises developed PCCP, a new type of pipe, on the basis of introducing and digesting advanced foreign technologies and key equipment[8].

In 1989, Shandong Power Pipeline Company imported PCCP process technology and key equipment from Amelon Company in the United States, established a PCCP production line, and produced the first batch of 2600mm diameter PCCP-E pipes in June 1990, thus opening the prelude to the production of PCCP pipes in China[9].

Shenzhen Sun Pipeline Co., Ltd. introduced a complete set of equipment from Price Brothers in 1992, which can produce PCCPs with diameters ranging from 900 to 2600 mm. Wuxi Huayi Pipeline Co., Ltd., a joint venture with foreign investors, completed the PCCP production line in April 1995. The company has also introduced Amaron's steel tube coil welding machine and socket equipment from the United States. The Hangzhou Mechanical Design and Research Institute of State Power Corporation has improved the design of vertical differential wire winding machines and other equipment, and built a very well-equipped production line. By the end of 2000, these three companies had produced PCCPs with diameters ranging from 600 to 3000mm for over 600 km, which had been applied to over 80 engineering projects of various sizes [10].

Since 2000, there has been a wave of PCCP factory construction in China. At present, in addition to the first three companies to build factories, there is also Chengdu Jinhao Group Co., Ltd., a joint venture between Sichuan Chengdu Jinhao Group Co., Ltd., Chengdu Water Supply Company, and Chengdu Jinhao Pipe Manufacturing Co., Ltd. established in April 2000. The company has two production lines with an annual production capacity of over 100 km; There is Guotong Pipeline Co., Ltd. in Xinjiang, a joint-stock company jointly established by Xinjiang Tianshan Building Materials Co., Ltd. and Taiwan, China Guotong International Co., Ltd., a PCCP manufacturer in Taiwan, China, in 2001, with 9 PCCP production lines and an annual design production capacity of 224 km; Jilin Power Pipeline Co., Ltd. has 12 production lines with an annual designed production capacity of 100km; Beijing Heshan Pipe Industry Co., Ltd. has 2 PCCP production lines with an annual designed production capacity of 15km. According to incomplete statistics, there are currently more than 40 domestic PCCP production enterprises, with up to 50 PCCP production lines. The maximum diameter of the produced PCCP pipes reaches 4.8m, with effective lengths of 5m and 6m. The applicable working pressure range is 0.2-2 MPa, and the annual designed production capacity is over 1000km[11].

3.2 Current Application Status of PCCP Pipes Abroad

In 1893, Bonna, a Frenchman, designed and manufactured a new type of pipe called PCCP, which was composed of reinforced concrete and steel pipes. The pipe had a diameter of 1800mm and an internal water pressure of 0.35MPa, and was laid in the Cologne Bay water diversion network in Paris. Using the principle of prestressed concrete, the Bonnet Pipeline Company manufactured prestressed concrete pipes in 1939 and laid them in the suburbs of Paris. In 1942, the United States also developed prestressed steel tube concrete pipes, and Rockwell Company successfully manufactured lined PCCP. Subsequently, 10 pipe manufacturing companies were established in North America. By 1994, more than 30000 km of PCCP pipes had been produced and used in over 28000 engineering projects. Over 90 out of 100 large and medium-sized cities in the United States used PCCP pipes in infrastructure construction such as hydropower and municipal engineering. At present, PCCP is the preferred pipe material for long-distance large-diameter pressurized water pipelines in North America. The maximum diameter of PCCP produced and used reaches 7.6 meters, the maximum internal pressure used reaches 2.75 MPa, and the maximum soil cover depth reaches 30.5 meters. There were only four American manufacturers that evolved from two to eight: Ameron, Pricr Brothers, Gifford Hill Ameccan, and Gretex, with Ameron and Price Brothers being the largest. Amaron Corporation has produced a large pipeline with a diameter of 6.4m for the Central Arizona Project in California, USA, with an internal pressure of 0.98 MPa, a depth of 10.5 meters of soil covering the top of the pipeline, and a construction length of 10.5 km. In the Kastek project, the pipe diameter is 5.1m, the internal pressure is 0.95 MPa, the length is 9.5km, and the top of the pipe is covered with soil at a depth of 13.5m. The construction of the Libyan "Dagong River" water transmission project in Africa is currently the world's largest PCCP usage project. The total water diversion capacity of the "Dagong River" project is 2.5 billion cubic meters per year, with a water transmission trunk line length of 4500km and a planned total investment of over 30 billion US dollars. The first phase of the project is 1900 km long, and the second phase is 1700 km long. The diameter of the pipes is mostly 4 m, with small parts ranging from 2.8 m, 2 m, and 1.6 m. The internal pressure is mostly 1.0 to 1.2 MPa, with small parts ranging from 0.6 MPa, 0.8 MPa, 1.6 MPa, and 1.8 MPa. They have now been put into water operation [12].

4 Current research status of PCCP tubes at home and abroad

4.1Current research status of PCCP tubes abroad

American scholar[13] Zarghamee et al. established a two-dimensional finite element numerical model of mortar protective layer and analyzed five working conditions, including mortar shrinkage strain, radial tension, radial expansion of steel wire, combination of mortar shrinkage and radial pressure, and combination of mortar shrinkage and radial expansion of steel wire. The protective layer mortar and prestressed steel wire were fully bonded, partially bonded, and unbonded under three different conditions, The stress condition of the protective layer and the separation of the protective layer mortar from the pipe core. The dry shrinkage strain and radial expansion deformation of the steel wire are applied through equivalent temperature deformation. The conclusion drawn from the comparative analysis of experimental results and numerical calculations is that there is no significant softening between the mortar and the steel wire in the early stage of mortar hardening, and the detachment of the protective layer is mainly determined by the average tensile strength of the mortar between adjacent steel wires in the later stage of mortar hardening.

Gomez established three finite element models for PCCP tubes, including two two-dimensional models and one three-dimensional model. The first two-dimensional model simulated and analyzed the stress state of a steel cylinder under internal pressure. The second two-dimensional model simulated and analyzed the stress conditions of the inner and outer layers of concrete and steel cylinder under three working conditions: internal pressure, the self weight of backfill soil within the range of internal pressure+pipe top diameter, and the self weight of backfill soil around the pipe under internal pressure. The three-dimensional model analyzed the stress situation of the pipe under internal pressure after the occurrence of pre-stressed loss zone [14].

Diab et al. established two-dimensional plane strain finite element models and three-dimensional finite element models respectively. The models assume that the protective layer mortar has no effect on the external resistance of the pipe body, and the pipe body is in complete contact with the foundation soil. Analyzed the stress distribution of the pipe structure under internal pressure [15]. Lotfi R. established a finite element model based on D1ANA software, including the inner and outer layers of the pipe core, steel cylinder, and foundation. The interaction between the pipe and soil was simulated throughout the entire process from excavation to pipe laying. The ability of the pipe core to continue to withstand internal pressure, external soil loads, and live loads was analyzed when the loss of prestress in the pipe core was caused by the fracture or corrosion of prestressed steel wires [16].

The numerical analysis of PCCP pipes in foreign countries mainly focuses on studying the impact of prestress loss on the load-bearing capacity of PCCP structures, thereby providing reference for the safety evaluation and risk assessment of PCCP.

The cement mortar protective layer is an important component of PCCP pipe structure. Its main function is to protect the prestressed steel wire from external environmental corrosion, while providing sufficient bonding force to ensure the overall stress of the steel wire. Ejbouh et al. [17] conducted tensile strength tests on mortar specimens to evaluate the influence of mortar shrinkage and humidity, prestressed steel wire diameter and spacing on mortar strength. The results showed that as mortar hydration progressed, its tensile strength increased, while mortar shrinkage and steel wire diameter (steel wire spacing exceeding 2 times the steel wire diameter) had little effect on the radial tensile strength of mortar. Li HZ et al. [18] conducted a study on the length of the prestressed loss zone after the fracture of prestressed steel wire and the stress transfer mechanism between the broken wire and mortar. They derived analytical solutions for interface slip, interface shear stress, and axial stress at the broken wire, and verified them through finite element analysis. Sara Hassi et al. [19] established three mortar coating mixtures to study the resistance of mortar protective layers to chemical corrosion. They found that the compressive strength and flexural strength of mortar increased with the addition of fly ash and silica fume. Sunil Sinha [20]et al. analyzed the effect of bonding quality of mortar protective layer on the structural integrity of PCCP. A theoretical method was proposed to determine the length of prestressed break line considering the bonding quality of mortar protective layer.

Zhang Haifeng [21] believes that unlike concrete materials, there is currently no unified standard for mortar materials in China. Therefore, there are significant differences in the values of strength representative values, strength testing methods, and constitutive models of mortar materials used in different structures. Jana D et al. studied the acid erosion of PCCP mortar and found that acid erosion can increase the porosity and permeability of the protective layer, resulting in loss of coating quality and strength. Gu Xiaobo[22] proposed methods to improve the effectiveness of PCCP protective layer, including increasing the density of the protective layer, adding aggregates, and protecting the outer layer of the protective layer. Gu Xiaobo [23] found that under the condition of medium to high speed, the overall operating speed of the roller shooting system can achieve the optimal strength, water absorption rate, and protective layer thickness of the formed mortar; When the outer edge of the roller is tangent and the rolling distance is 40 centimeters, the mortar strength, water absorption rate, and rebound rate are optimal; The compressive strength of mortar gradually increases with the decrease of sand cement ratio, but the water absorption rate shows a phenomenon of first decreasing and then increasing with the decrease of sand cement ratio. Dong Xiaonong[24] analyzed the effects of PCCP structural material properties, pipeline structure design, manufacturing process, and pipeline usage environment on the safety of PCCP structures. Reference [25] found through the evaluation and analysis of cement mortar protective layer that the loss of mortar alkalinity leads to corrosion of prestressed steel wires. The influence of chloride ion penetration on the corrosion rate of buried steel was also discussed. Reference [26] found cracks between the mortar coating and concrete in the failed PCCP pipeline through non-destructive testing [27].

4.2 Current research status of PCCP tubes in China

Sun Shaoping[28] et al. used ANSYS three-dimensional finite element model and pointed out through research that visible cracks in the cement mortar protective layer are only a necessary condition for the peeling of the protective layer. The excessive tensile stress between the inner surface of the cement mortar and the outer surface of the pipe core is a sufficient condition for the cracking and peeling failure of the protective layer; The shrinkage of cement mortar is beneficial for the bonding between the protective layer and the pipe core, and the stress relaxation of prestressed steel wire and the temperature difference inside and outside the pipe body are important factors that cause the detachment of the protective layer . [29]Zhang Shirong et al. conducted finite element simulation on PCCP pipes designed according to the AWWAC304 specification, established a finite element overall calculation model for PCCP pipes, calculated and analyzed the stress, strain, and cracking of the pipe body under load conditions, and compared the strain values obtained from finite element calculations with structural calculations, verifying that the design of the specification meets the limit state design criteria . Zhang Caixiu[30] established a finite element model of PCCP pipes based on the ANASYS finite element software, simulating the entire process from manufacturing, construction to operation. She applied load prestress, pipe self weight, backfill soil pressure, fluid self weight, and internal water pressure in sequence, and analyzed the variation of pipe deformation with increasing load, as well as the stress distribution and variation characteristics of each component .

In the early days, Interspace Company in the United States [31] used grade IV prestressed steel wire, but later many pipe explosions occurred, causing huge losses. One of the reasons was the occurrence of stress corrosion. After research, it was found that the tensile strength of grade IV prestressed steel wire is too high and the toughness is reduced. The likelihood of stress corrosion on grade IV high-strength steel wire is 20-40 times higher than that of grade III steel wire, and the use of grade IV high-strength steel wire on PCCP is now prohibited.

Jiangsu Academy of Building Science [32]conducted stress corrosion tests on steel bars, and the results showed that with the increase of loading stress, the corrosion of HRB400 steel bars worsened. However, amino alcohol organic rust inhibitors can act on the surface of stress loaded HRB400 steel bars, increase their attachment thickness, suppress the damage of chloride ions to the HRB400 steel bar matrix in the simulated pore fluid of concrete, and have an anti rust effect.

Nanjing Institute of Water Resources Research, in conjunction with marine engineering environment, has conducted research on φ Five high-strength steel wires were subjected to stress corrosion tests in simulated solution and mortar, respectively. The test results showed that high-strength steel wires generally do not undergo stress corrosion in saturated calcium hydroxide solution; In a 3.5% sodium chloride solution, high-strength steel wires may undergo stress corrosion cracking, but the probability of stress corrosion cracking is very low when the stress level is below 65% of the tensile strength and the incision depth is less than 1.6mm; In mortar, when the chloride ion concentration is less than 0.1%, the steel wire does not undergo stress corrosion cracking. As the chloride ion concentration increases, the steel wire will undergo stress corrosion cracking; When the water cement ratio of the mortar is not greater than 0.32, the steel wire does not experience stress corrosion cracking. As the water cement ratio increases, the compactness of the mortar decreases and the sensitivity of the steel wire to stress corrosion increases [33] [34].

Evans and Stark studied the corrosion of prestressed steel wires under different stress levels in pre tensioned concrete components subjected to chloride ion erosion. In Evans's experiment, a single prestressed steel wire was used as the research object, and the maximum tensile control stress taken did not exceed the elastic limit. In Stark's experiment, steel strands were used as the research object, and a total of 19 pre tensioned prestressed concrete beams were tested. The value of the maximum tensile control stress was also not high, The maximum value is 60% of the ultimate strength of the steel strand (if considering the loss of prestress, the effective prestress value in the steel strand is even lower). Their experimental results indicate that within the tension controlled stress range they took, the stress level in prestressed steel wires (or steel strands) has little or no effect on their corrosion performance [35] [36].

Toribio derived the stress assisted diffusion equation for hydrogen in steel under axial tension, and obtained the relationship between hydrogen concentration and static water stress, thus clearly understanding the role of static water stress in hydrogen embrittlement fracture of prestressed steel wires [37]. Toribio also conducted a systematic study on the stress corrosion behavior of prestressed steel bars from the perspective of materials science, mainly including two achievements. The first is about the role of residual stress at the crack tip in stress corrosion of prestressed steel (high-strength pearlite steel). It is believed that whether in anodic dissolution cracking or hydrogen induced cracking, residual compressive stress at the crack tip will improve the stress corrosion fracture resistance of steel, The residual tensile stress at the crack tip will reduce the stress corrosion (hydrogen embrittlement) fracture performance of steel. Therefore, in the design of stress corrosion resistance, the "effective stress" containing residual stress should be considered instead of just considering external stress; The second is to establish microstructure models for the fracture morphology of anodic dissolution type stress corrosion and hydrogen induced cracking type stress corrosion corresponding to different degrees of cold drawing [38] [39].

5 Design standards for PCCP pipes at home and abroad

5.1Design standards for foreign PCCP pipes

The widely recognized and adopted PCCP design and manufacturing specifications in the world are the ANSI/AWWA C304[40] and ANSI/AWWA C301[41] specifications jointly developed by the National Bureau of Standards (ANSI) and the American Water Works Association (AWWA).

The first edition of the ANSI/AWWA C301 specification was introduced in 1949, which included the production standards and design methods of PCCP. After several revisions, the structural design methods section of PCCP was removed, forming the widely used 1999 version of the AWWA C304-99 specification. This specification mainly provides detailed provisions for the production and manufacturing standards of PCCP. The structural design calculation of PCCP is separately stipulated by the design code ANSI/AWWA C304-92 for prestressed steel tube concrete jointly issued by the National Institute of Standards and the Water Supply Association in 1992. AWWA C304-92 has been revised and currently uses the 1999 version of AWWA C304-99.

5.2Design standards for domestic PCCP pipes

Since the introduction of PCCP for more than 10 years, there has been no corresponding standard established in China, and the design and manufacturing of pipelines mainly refer to American standards. In 1996, the National Bureau of Building Materials Industry officially issued the production and manufacturing standard for PCCP pipes, "Pre stressed Steel Tube Concrete Pipes" (JC 625-1996), which provides detailed regulations on the classification, technical requirements, test methods, inspection rules, labeling, packaging, transportation, storage, and other aspects of PCCP pipes. This standard is mainly applicable to PCCP pipes with a nominal inner diameter of 600 to 3000 mm and a static water pressure of 0.4 to 2.0 MPa, But it is not applicable to PCCP used in corrosive water and soil environments [42].

With the continuous development of PCCP research and development technology in China, the National Standardization Administration of China has issued the national standard "Pre stressed Steel Tube Concrete Pipe" (GB/19685-2005) based on the JC 625 standard. This standard specifies the terminology and main symbols of prestressed steel cylinder concrete pipes, their classification, testing methods, inspection rules, marking, transportation, storage, and usage regulations. Suitable for manufacturing PCCP pipes with a nominal inner diameter of 400 to 4000 mm, a working internal pressure not exceeding 2 MPa, and a soil cover depth not exceeding 10 meters [43]. In terms of structural design calculation of PCCP, the China Engineering Construction Standardization Association issued the association standard "Design Specification for Buried Pipe Core Wrapped Pre stressed Concrete Pipe and Pre stressed Steel Tube Concrete Pipe Structure in Water Supply and Drainage Engineering" (CECSl40:2002) in 2002. This specification adopts a probability based limit state design method, using reliability indicators to measure the reliability of pipeline structures. Structural calculation and analysis are carried out for five different load combinations according to the normal use limit state and the bearing capacity limit state. The specific design calculation steps are as follows:

(1) Determine the geometric dimensions such as pipeline diameter and wall thickness, as well as the characteristic parameters of each component material.

(2) Calculate the standard and design values for various permanent and variable loads.

(3) Design and calculate the stability of the pipeline according to the five load combinations of the bearing limit state and normal limit state specified in the specifications. [44]

The production and application time of prestressed steel cylinder concrete pipes in China is relatively short, and the accumulated engineering practice experience is limited. There is still a significant gap between the research work in various aspects and the international level. At present, most engineering design and manufacturing of PCCP still follow American standards, and American standards are formulated based on factors such as the quality level of raw materials, testing level, design concept, and production level in China. Considering the actual engineering level and national conditions of our country, it is unlikely to fully refer to the standards of the United States for engineering design and application. Therefore, it is necessary for us to conduct in-depth research on the structure of PCCP and explore the development of more advanced production design standards that are in line with China's national conditions, in order to guide China's PCCP design practice.

6Conclusion

PCCP pipes are increasingly being used in water conservancy and other engineering projects due to their characteristics such as good structural rigidity, long service life, low maintenance and transportation costs that other pipes do not have.Now it is a product with great market potential, with great prospects and future.

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