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Review of influencing factors of prestressed concrete cylinder pipe durability

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Professional paper

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A prestressed concrete cylinder pipe (PCCP) is a composite conduit comprising a concrete core, an anti-seepage steel cylinder, prestressed steel wires, and a mortar protective layer. Accidents involving PCCPs can have adverse effects on water supply and industrial production. Therefore, exploring and analysing the factors influencing the durability of PCCPs has significant scientific and practical value. This provides researchers with a more comprehensive perspective on the lifespan and durability of PCCP. This paper systematically summarises and categorises the factors affecting PCCP durability, including chemical erosion, manufacturing defects, improper installation, and poor operational conditions. The main factors and processes influencing PCCP durability are delineated from these four aspects. This paper concludes with recommendations for enhancing PCCP durability. This suggests the need for more suitable concrete additives, improving the composition of the surface coatings on pipelines, researching the longitudinal stress of PCCPs, and conducting non-destructive testing on PCCPs.

Key words:
prestressed concrete cylinder pipe, chemical erosion, manufacturing defects, improper installation, poor operational conditions

Stručni rad

Yuan Li, Hao Feng, Zhou Sha

Pregled utjecajnih čimbenika na trajnost prednapete betonske kružne cijevi

Prednapeta betonska kružna cijev (PCCP) kompozitna je cijev koja se sastoji od betonske jezgre, čeličnog cilindra protiv istjecanja, prednapetih čeličnih žica i zaštitnog sloja od morta. Nesreće koje uključuju PCCP mogu imati negativne posljedice na opskrbu vodom i industrijsku proizvodnju. Zato istraživanje i analiza čimbenika koji utječu na trajnost PCCP-a imaju veliku znanstvenu i praktičnu vrijednost. Ono istraživačima pružaju sveobuhvatniju perspektivu o vijeku trajanja i trajnosti PCCP-a. Ovaj rad sustavno sažima i klasificira čimbenike koji utječu na trajnost PCCP-a poput kemijske erozije, proizvodnih pogrešaka, nepravilne ugradnje i loših radnih uvjeta. Ključni čimbenici i procesi koji određuju trajnost PCCP-a analizirani su u sklopu tih četiriju aspekata. Ovaj rad završava preporukama za povećanje trajnosti PCCP-a. To upućuje na potrebu za prikladnijim dodatcima za beton, poboljšanjem sastava površinskih premaza na cjevovodima, istraživanjem uzdužnih naprezanja u PCCP-ovima te provođenjem nerazornih ispitivanja PCCP-ova.

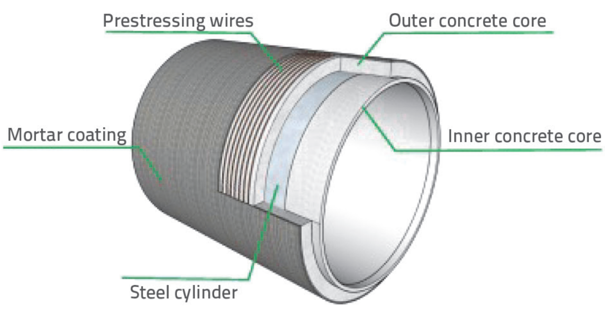
Ključne riječi:
prednapeta betonska kružna cijev, kemijska erozija, pogreške u proizvodnji, nepravilna ugradnja, loši radni uvjet

1. Introduction

The prestressed concrete cylinder pipe (PCCP) originated in 1894 when Aime Bonna, the founder of the French company Bonna, invented concrete pipes with steel cylinders without prestressed wires [1]. In 1939, Bonna Pipelines enhanced its design by incorporating prestressed steel wires to create a PCCP. Over the years, the PCCP has evolved, resulting in interior lining-type prestressed concrete cylinder pipes (PCCPLs), primarily for medium-sized pipes, and buried-type prestressed concrete cylinder pipes (PCCPEs) for larger diameters. Currently, PCCPs are important and excellent pressure water transmission materials that are widely utilised in water diversion projects.

A PCCP is a composite pipe material comprising a leak-proof steel cylinder, core concrete, prestressed steel wires, and a mortar protective layer, as shown in Figure 1. Depending on the type of PCCP joint, it can be categorised into PCCPL and PCCPE.

Figure 1. Structure of the PCCP



As a pressure water transmission material, the PCCP boasts numerous advantages [1], including its rational structure, high compressive strength, strong corrosion resistance, excellent sealing properties, and adaptability to various soil conditions. Thus, the PCCP is often critical in providing water to urban populations. However, if a PCCP pipe bursts, adverse effects on normal production and the daily lives of people may occur. Therefore, the factors that influence PCCP durability are important to investigate. A more comprehensive perspective on the durability of PCCP can be provided by systematically and comprehensively summarising these factors. This is beneficial for reducing or avoiding the probability of a PCCP bursting in an all-encompassing manner and is significant to public welfare.

The factors influencing the durability of the PCCP are listed in Table 1, based on a summary and classification of the collected research data. This table includes information regarding chemical corrosion, manufacturing defects, improper installation, and poor operational conditions.

Reference [1] primarily discussed the developmental history of the PCCP. references [2-40] investigated the impact of chemical corrosion on the durability of PCCPs, with sulfuric acid degradation, carbonation corrosion, and chloride ion corrosion being the three main types of chemical corrosion. Sulfuric acid degradation and carbonation corrosion can result in concrete expansion, softening, and acidification, resulting in cracking, reduced strength, and inhibition of passivation film formation. Chloride ion corrosion can cause the rusting of steel wires and pipes, resulting in wire breakage and mortar detachment from the steel pipe.

Table 1. Factors affecting PCCP durability

Factors	Types
Chemical corrosion	Sulfate degradation
	Carbonation corrosion
	Chloride ion corrosion
Manufacturing defects	Substandard steel wires
	Substandard steel pipes
	Incorrect pipe types
	Insufficient thrust restraint
Improper installation	Bedding, support installation
	Substandard mortar quality
	Failure to follow requirements
Poor operational conditions	Third-party damage
	Internal pressure issues
	Air pockets

References [41-55] investigated the effects of manufacturing defects on the durability of PCCPs. Four main manufacturing defects were identified: substandard prestressed steel wires, substandard steel pipes, incorrect pipe type selection, and insufficient thrust restraints. Substandard prestressing steel wires exhibit problems such as harmful tension aging and hydrogen embrittlement, resulting in wire breakage and potential pipe-bursting accidents. Substandard steel pipes exhibit poor pressure-bearing capacity and concrete tearing. An incorrect selection of pipe types can result in pressures exceeding the design limits, causing accidents. An insufficient thrust restraint can result in circumferential cracks, steel pipe tearing, and joint opening.

Reference [56-64] investigated the impact of improper installation on the durability of PCCPs. Inadequate bedding, poor support installation, lack of mortar or substandard mortar quality, and failure to follow design requirements are the primary types of improper installations. Inadequate bedding and poor support installation can cause excessive stress in concrete, resulting in mortar cracking and the exposure of steel wires to passivation and corrosion threats. The lack of mortar or substandard mortar quality prevents PCCPs from obtaining proper protection, resulting in reduced durability. Failure to follow the design requirements can result in the deterioration of the surrounding environment of a PCCP.

Reference [65-79] investigated the effect of poor operational conditions on the durability of PCCPs. Third-party damage, internal pressure issues, and air pockets were the main adverse operational conditions. Hasty excavation results in unintended leakage, excessive external loads, and drilling or puncturing of the pipe wall under third-party damage, directly resulting in PCCP damage. Internal pressure problems primarily refer to frequent fluctuations in the internal and external pressures in PCCP pipes, resulting in pipe-bursting accidents. Air pockets refer to the inability of exhaust gas to be released; they accumulate at the top of the pipe, condense, and adhere to the pipe wall, thereby causing corrosion and reducing the lifespan of the PCCP.

This article compiles research data from international sources. By integrating research findings from various aspects, including PCCP structural design, manufacturing and installation, operational maintenance, and materials, we summarise the factors affecting PCCP durability. This article concludes with recommendations for enhancing the durability of PCCP, primarily focusing on improving concrete additives and pipeline surface coating materials. Additionally, it suggests researching the longitudinal stress of the PCCP and conducting non-destructive testing. These recommendations aim to provide other scholars with ideas for researching the durability of PCCPs.

2. Chemical corrosion

Chemical corrosion constitutes a significant aspect of research on the factors affecting PCCP durability. According to statistics, from 1943 to 1990, 82.1 % of PCCP damage incidents were attributed to corrosion [2]. Ferkous et al. [3] and Ma et al. [4] investigated the corrosion of carbon and X80 steels under different soil extracts and coatings and observed that the chemical properties of the soil and the local environment under the coating had a significant impact on corrosion. Wang [5] studied the performance degradation of organic coatings caused by UV degradation by simulating environmental conditions. These studies show that chemical erosion is not only related to the properties of the material itself but is also significantly influenced by external environmental factors. During operation, a PCCP is susceptible to three types of corrosion: sulfate degradation, carbonation corrosion, and chloride ion corrosion [6]. Figure 2 [7] illustrates the corrosion of the PCCP and its prestressed steel wire. Table 2 summarises the main research content of the papers related to chemical erosion.

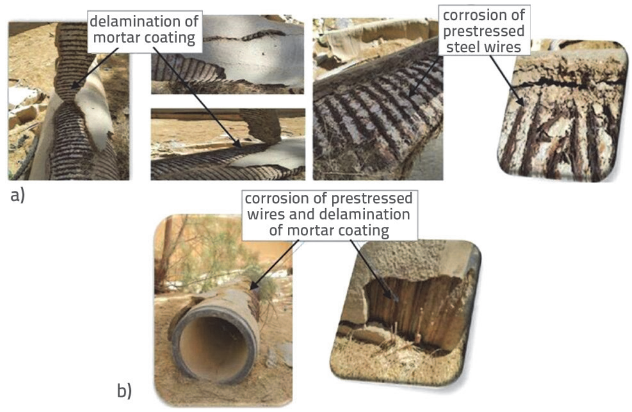


Figure 2. Corrosion of PCCP and prestressed steel wires [7]

Table 2. References for chemical corrosion

Reference	Analyzed factors affecting on durability
Zhang, Q.J. (2015) [2]	From 1943 to 1990, 82.1% of PCCP failures were due to corrosion. Six forms of corrosion exist: carbonization reaction, chloride ion attack, sulfate deterioration, acid rain corrosion, dissolution corrosion, freeze–thaw damage.
Ferkous et al. (2022) [3] Ma et al. (2020) [4]	The corrosion of carbon and X80 steels under different soil extracts and coatings was investigated. The chemical properties of soil and the local environment under coatings were observed to have significant effects on the corrosion.
Ma et al. (2022) [5]	The degradation of organic coatings due to UV degradation was investigated by simulating environmental conditions. This study showed that chemical erosion is not only related to the properties of the material itself but is also significantly influenced by external environmental factors.
Hassi, S. (2021) [6]	The causes of severe corrosion and damage of PCCP in the Agadir water transmission pipeline project were investigated. The study observed that chloride-induced steel wire corrosion was the main cause, in addition to manufacturing defects and the water hammer effect, which also exacerbated the damage.
Hassi, S. (2021) [7]	The performance of PCCPs used in northeastern Morocco was analysed. The main causes of damage were observed to be wire corrosion caused by chloride, water hammer effect, and manufacturing defects. The study suggested that cement resistant to chloride and sulfate should be used to improve the durability of pipes in this chemical environment.
Hassi, S. (2020) [8]	Samples were soaked in a 9.5 wt% NaCl solution and a composite solution of 9.5 wt% NaCl and 34 wt% Na2SO4 to simulate the most aggressive environment on the right side of the Moroccan pipeline. The microstructure of mortar coating and rebar was characterized using electrochemical impedance spectroscopy (EIS). The electrochemical equivalent model of Dong was achieved and fitted with the experimental results.

Table 2. References for chemical corrosion - continuation

Reference	Analyzed factors affecting on durability
Cui et al. (2020) [9]	Microbial influenced corrosion (MIC) of 2205 duplex stainless steel (DSS) caused by sulfate-reducing bacteria (SRB) was investigated using high-resolution characterization. SRB caused severe local corrosion of 2205 DSS.
Liu et al. (2019) [10]	In the presence of SRB, the corrosion mechanism of carbon steel in sediments was investigated by surface analysis, weight loss, and electrochemical measurements. The results showed that SRB significantly promoted both general and local corrosion in sediments.
Jana, D., Lewis, R.A. (2004) [11]	The corrosion resistance of mortar under different acidic conditions was analysed using experiments, and the results showed that acidic substances could significantly reduce the strength and durability of mortar.
Thiebaut, Y. (2018) [12]	Delayed ettringite formation (DEF) is a sulfate deterioration that affects civil engineering structures. This chemical reaction occurs within the concrete matrix of the structure, destroying the concrete and the stretching of rebars.
Nixon, R.A. (2022) [13]	Groundwater with high sulfate content will also cause the expansion and degradation of cement mortar coating, exposing the prestressed steel wire to corrosive conditions. Low-pH soil and groundwater promote the corrosion of prestressed steel wire.
Leach, D.G. (2022) [14]	A case study on microbiological-influenced corrosion (MIC) failure analysis of produced water pipelines is introduced in detail.
Kiliswa, M.W. (2019) [15]	The corrosion rates of Portland cement and calcium aluminate cement (CAC)-based concrete mixtures were compared. The higher the content of amorphous AHx in the CAC concrete matrix, the stronger the neutralization ability to attack acid.
Qiu et al. (2022) [16]	The permeability and microscopic scanning of coarse porous concrete with different cement contents in sulfuric acid solution were tested. The effect of sulfuric acid on the permeability of coarse porous concrete was studied. Information was provided on the possible effects of sulfate attack on concrete properties. With the decrease in pH of sulfuric acid solution and increase in cement content, the permeability of coarse porous concrete decreases, which promotes the hydration and corrosion process of cement.
Fu et al. (2022) [17]	The influence of concrete composition on the drying shrinkage behaviour of ultra-high performance concrete (UHPC) was studied. The influence degree of water-binder ratio, steel fibre, superplasticant, silica fume, and fly ash content on the drying shrinkage behaviour of UHPC was evaluated by grey correlation entropy analysis, and it was observed that low water-binder ratio and high fly ash content helped reduce the drying shrinkage of UHPC. The addition of superplasticizer and silica fume aggravated the drying shrinkage.
Wang et al. (2023) [18]	The effects of different mixed design parameters on the properties of compression cast concrete (CCC) were investigated. Concrete placement methods, such as compression placement, can improve the density of concrete.
Zhang et al. (2019) [19]	With the increase in sodium sulfate solution concentration, the deterioration of the physical and mechanical properties of concrete becomes more severe. At low concentration sodium sulfate solution, the concrete is chemically eroded, while at high concentration, the concrete is physically eroded.
Zhang et al. (2023) [20]	The concentration of sulfate affects the transport process of sulfate in concrete. The higher the concentration, the higher the sulfate transport rate and the stronger the erosion.
Liang, Y.S. (2013) [21]	The main corrosion factors of the inner wall of PCCPs are CO_2 (producing $CaCO_3$ carbonization), magnesium salt (Mg(OH)2 has no cementing ability), sulfate (inverting with cement hydrate to produce expansive ettringite and gypsum causing cracking), and chlorine salt (increasing the solubility of $Ca(OH)_2$, forming corrosion batteries, reducing pH, and destroying passivation film).
He, Q.K. (2015) [22]	Concrete has a multi-pore structure, and other substances flow into the concrete through the pores and react with $Ca(OH)_2$ to destroy the concrete structure. The reaction of water and CO_2 produces a larger volume of $CaCO_3$, which causes expansion and cracks. Mg2+ in saline-alkali soil reacts with $Ca(OH)_2$ to form $Mg(OH)_2$ without gel ability, which can also cause concrete damage.
Zhao, M.Y. (2011) [23]	A low concentration of chloride ions inhibits the dissolution of silicate and aluminate and thus inhibits hydration. In contrast, a high concentration accelerates the dissolution effect of calcium ions and promotes hydration. External chloride ions can destroy the passivation film on the steel bar surface without being consumed.
Wang, X.D. (2014) [24]	The specific indicators of soil corrosion are soil water content, soil resistivity, soil total salt content, and pH value.
Chu, X.Y. (2012) [25]	of the study analysed corrosion conditions of water conservancy and water conveyance projects: concrete corrosion, steel structure corrosion. Concrete corrosion: Carbonization: $Ca(OH)_2$ $CO_2 \rightarrow CaCO_3$ H_2O; Sulfate attacks the tricalcium aluminate in concrete and destroys concrete and mortar. Acid soil. Corrosion of steel structure: carbonization reduces pH and destroys passivation film; Chloride ion contact with steel surface promotes the corrosion reaction Fe → Fe_2+ + 2e-, O2 + $2H_2O$+4e- → 4OH-, corrosion reduces the tensile strength of steel wire, and corrosion products further result in cracking and damage of concrete.

Table 2. References for chemical corrosion - continuation

Reference	Analyzed factors affecting on durability
Podhajecky, A.L. (2023) [26]	The effects of initial humidity on the creep and shrinkage behaviour of concrete under different humidity conditions were studied. The results showed that the initial humidity has a significant effect on the deformation behaviour of concrete, particularly under cyclic humidity.
Wang et al. (2021) [27]	Increasing the temperature can accelerate the carbonization process of concrete. Particularly in the presence of liquid water, the carbonization rate can be significantly improved in a short time (such as 1 h).
Xu et al. (2022) [28]	Increasing the temperature can accelerate the carbonization process of concrete. Relative humidity and CO_2 concentration are also important factors affecting the rate of carbonization. The relationship between relative humidity and carbonization depth is a power function, whereas the relationship between CO_2 concentration and carbonization depth is a polynomial function.
Liu et al. (2020) [29]	A prediction model of carbonation depth including environmental factors and concrete components is proposed. The results revealed an exponential function relationship between temperature and carbonation depth, and relative humidity and CO_2 concentration are also important factors affecting the carbonation rate.
Lee, H.M. (2018) [30]	Atmospheric CO_2 penetration in concrete reduces the basicity of the concrete, destroying the protective film around the steel bar, which causes corrosion.
Fang et al. (2022) [31]	The accelerated corrosion test method was used to compare the macroscopic mechanical properties and appearance degradation of different concrete in three types of composite salt solutions. The results showed that the high concentration of composite salt aggravates the deterioration of concrete properties, and the cement material directly affects the strength and durability of concrete.
Yuan et al. (2022) [32]	UHPC mixed with silica fume and fly ash exhibited better water stability.
Li et al. (2022) [33]	UHPC prepared with polycarboxylic acid superplasticizer had a high compressive strength and excellent corrosion resistance.
Cui et al. (2023) [34]	The erosion process of chloride ions in cold regions is particularly complicated and affected by many factors. The erosion of chloride ions will accelerate the corrosion of steel bars, which is an important reason for the decline in durability.
Liu et al. (2022) [35]	Chloride ions will reduce the enrichment of Cr and Ni, weaken the electronegativity of the inner film, and aggravate the penetration of chloride ions, thus destroying the passivation film. This suggests that chloride ions can reduce the protective properties of passivation films by changing their composition and structure.
Wang et al. (2022) [36]	Although the pH value in magnesium potassium phosphate cement (MKPC) is much lower than that in ordinary phosphate cement (PC), the corrosion resistance of carbon steel is significantly improved, and the critical chlorine value in MKPC is several orders of magnitude higher than that in PC. This shows that although chloride ions have a destructive effect on the passivation film, other factors in the environment (such as pH) can also affect the corrosion effect of chloride ions.
Liu et al. (2022) [37]	Owing to the synergic degradation of chloride and phosphate ions, pre-passivated carbon steel will exhibit more apparent pitting corrosion.
Zhang et al. (2021) [38]	In the process of soaking lithium-ion batteries, corrosion intensifies with the increase in the potential, NaCl concentration, and soaking time.
Du et al. (2023) [39]	After forming a "corrosion battery," corrosion often involves an interface reaction between the electrode material and electrolyte. The corrosion of the battery is related to the dissolution/passivation of the electrode material and dissolution/oxidation/passivation of the collector fluid.
Hu, Y. (2023) [40]	Chloride penetration is considered to be the main cause of corrosion of steel during the use of PCCPs. A time-varying model of instantaneous chloride ion diffusion coefficient and surface chloride ion concentration of steam-cured concrete was established considering the effect of curing age and exposure time. Based on this, a chloride ion diffusion model was established considering the effects of curing age, exposure time, time-varying chloride ion diffusion coefficient, and time-varying surface chloride ion concentration, which is significant to the durability evaluation of PCCPs.

2.1. Sulfate degradation

Sulfate degradation is a significant aspect of PCCP durability research and represents a complex and highly damaging form of environmental water-induced degradation. Sulfate ions are present in soil and can decompose organic matter, groundwater, seawater, and industrial wastewater [7, 8]. They react with cement hydration products, causing the concrete to expand, crack, and deteriorate, resulting in a reduction in concrete strength and cohesion. In some cases, these properties are completely lost.

Sulfate degradation in concrete involves complex physical and chemical processes [5]. The overall process can be summarised as follows:

- Sulfate ions from the environment infiltrate the concrete and undergo a chemical reaction with certain solid-phase

components of the cement, resulting in the formation of insoluble salt minerals [9, 10]. These salt minerals absorb water molecules, which results in volume expansion and concrete cracking.
- The reaction of sulfate ions with cement also results in the leaching or decomposition of components such as calcium hydroxide (CH) and calcium silicate hydrate (C-S-H) within the hardened cement paste, which causes a reduction or loss of concrete strength and cohesion [11].

During the degradation process, when the concentration of sulfate ions in the solution exceeds 1000 mg/L and the capillary pores of the cement paste are saturated with a calcium hydroxide solution, ettringite is formed, and gypsum crystals precipitate [12]. Ettringite has a needle-like crystalline structure and grows radially on solid surfaces, thereby increasing the solid-phase volume. This radial growth generates significant internal stresses through mutual compression, ultimately resulting in the deterioration of the concrete structure [12, 13]. The precipitated gypsum crystals within the cement paste further transform into dihydrate gypsum, expanding in volume by 1.24 times. This expansion results in significant stress, destroying the cement [13].
Microbially induced corrosion (MIC) caused by sulfate-reducing bacteria (SRB) on pipelines was studied [14]. The case study involved severe corrosion of a production water pipeline in an oil field, which caused it to fail within seven months. The inspection team observed that heavy white deposits (suspected microbial biofilms) were directly related to corrosion failure, and iron carbonates and iron sulfides were observed beneath the black scales. These findings suggested that sulfate-reducing bacteria and other anaerobic microorganisms play important roles in pipeline corrosion.

2.1.1. Internal causes of sulfate degradation

The resistance of concrete to sulfate degradation is largely determined by the mineral composition and relative content of cement clinker, where the content of $3CaO{\cdot}Al_2O_3$ and $3CaO{\cdot}SiO_2$ has the most significant impact on its resistance to sulfate degradation [15]. $3CaO{\cdot}Al_2O_3$ undergoes a chemical reaction, resulting in the production of calcium hydroxide and the precipitation of gypsum crystals, which ultimately result in the deterioration of the concrete. $3CaO{\cdot}SiO_2$ also undergoes a chemical reaction, producing calcium sulfoaluminate crystals, and destroying the concrete.
The density of the concrete also affects its resistance to degradation. High-density concrete has a low porosity, making it difficult for eroding solutions to penetrate, which generally results in increased concrete strength [16]. Factors influencing the concrete density include the mix proportion, method of concrete mixing, and compaction of concrete. A well-balanced mix proportion of the primary materials [17] (cement, sand, aggregate, and water) enhances the density of concrete. Employing physical mixing methods and ensuring an adequate mixing time [18] can improve the robustness and stability of concrete. When compacting concrete through vibrations, selecting the appropriate frequency and amplitude [18] can effectively consolidate the concrete and achieve a higher level of density.

2.1.2. External causes of sulfate degradation

The concentration of sulfate ions in the environment can significantly affect the resistance of concrete to sulfate degradation [19, 20]. When the sulfate ion concentration is less than 400 ppm, it does not cause significant damage to the concrete. Mild damage occurs in the range of 400–1200 ppm. Moderate damage occurs at concentrations of 1200–2000 ppm. Severe damage can occur beyond 2000 ppm and up to 5000 ppm.
The coexistence of sulfate and magnesium ions in eroding solutions accelerates degradation [21, 22]. When the solution contains only magnesium ions without sulfate ions, magnesium salt degradation occurs, resulting in the formation of $Mg(OH)_2$. $Mg(OH)_2$ has a low solubility and is a weakly bonded loose material. This can clog capillary pores, prevent the diffusion of solutions, and halt the magnesium salt degradation process. If sulfate and magnesium ions are present together, this results in $MgSO_4$ leaching-crystallisation-type damage, resulting in the continued diffusion of solutions and ongoing degradation of the concrete.
The coexistence of sulfate and chloride ions in solution can slow the degradation. When sulfate and chloride ions coexist in the solution, the penetration rate of chloride ions is higher than that of sulfate ions. For surface concrete, the formation of ettringite in cement paste occurs before the reaction with sulfate ions [9-12], and the reaction with chloride ions occurs only after the sulfate ions are depleted [23]. In the internal concrete, chloride ions first infiltrate and then undergo ion exchange with hydroxide ions. When the chloride concentration is relatively high, chloride can also react with calcium aluminate hydrates to form calcium chloroaluminate, reducing the quantity of ettringite crystals and thereby slowing degradation.
The pH of a solution [24] affects the rate of degradation. As shown in Figure 3, when the pH is between 12 and

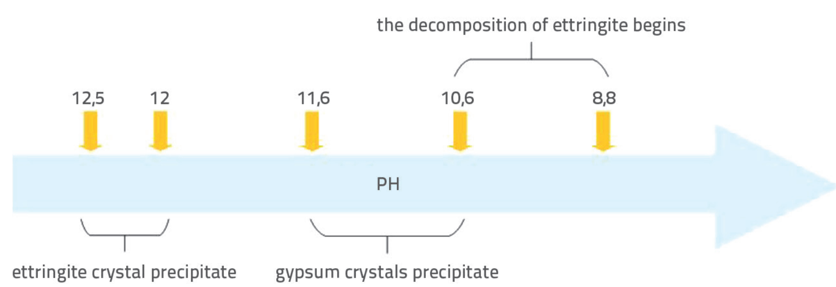


Figure 3. PH values have different effects on sulfate degradation

12.5, the precipitation of ettringite crystals intensifies, exacerbating the degradation. When the pH is between 10.6 and 11.6, gypsum crystals precipitate, exacerbating degradation. When the pH is between 8.8 and 10.6, the decomposition of ettringite begins, slowing the degradation rate.

2.2. Carbonation corrosion

The process by which carbon dioxide enters concrete and undergoes acid-base neutralisation reactions with alkaline substances in concrete, such as calcium hydroxide, is known as concrete carbonation. In underground buried pipelines, the carbonation process primarily involves a carbonation reaction in concrete, where carbon dioxide (CO_2) reacts with alkaline substances in the concrete, such as $Ca(OH)_2$ and cement hydration products (e.g. C-S-H), to form $CaCO_3$. This reaction lowers the pH of the concrete, weakening its protective effect on the internal steel reinforcement, thereby resulting in steel corrosion. Concrete is alkaline and carbonation lowers its pH to approximately 10. Consequently, concrete loses its ability to protect the reinforcement steel, and the passivation film on the steel surface is compromised [21]. After the depassivation of steel, if the environment is mildly alkaline or acidic and is exposed to moisture and oxygen, the steel begins to corrode. In PCCP structures, both the core concrete and mortar layer provide an alkaline environment for the protection of prestressed steel wires and cylinders. Therefore, if the core concrete and mortar layer undergo carbonation [25], resulting in the loss of the alkaline protection environment for the steel wires and steel cylinders, this can result in the loss of prestress in the steel wires, potentially resulting in wire breakage and pipe bursting incidents, posing significant risks.

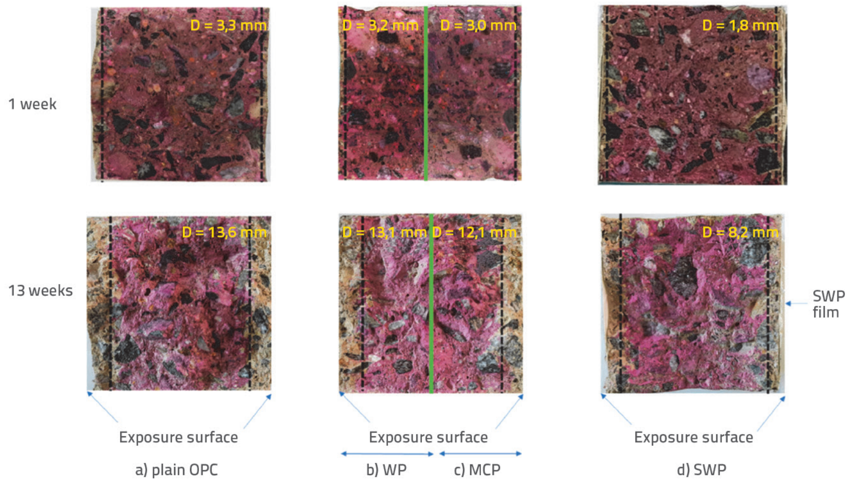


Figure 4. Carbonation depth measurement for: a) plain ordinary Portland cement (OPC); b) WP; c) MCP; d) SWP [30] (Note: Images are not on scale bar)

Concrete exhibits a capillary pore structure comprising several components [22]. These components comprise air voids retained during concrete formation, capillary pores within the cement paste, gel pores, and tiny pores at the interface between the cement paste and aggregate. Additionally, small cracks may be induced by the drying shrinkage of the cement paste and temperature variations. In the natural environment, carbon dioxide initially penetrates the interior of concrete [21], filling the air-filled voids and capillaries. It then dissolves in the liquid within the capillaries and interacts with the hydration products of cement, such as calcium hydroxide, tricalcium silicate, and dicalcium silicate. This interaction results in the formation of calcium carbonate.

The rate and extent of concrete carbonation are primarily influenced by the diffusion rate of carbon dioxide [27-29] and its reactivity with concrete components. The diffusion rate of carbon dioxide is influenced by the density of concrete, the concentration of carbon dioxide in the environment, environmental temperature, humidity, and other conditions [28, 29]. These influencing factors can be categorised as internal and external factors. Notably, the continuous variation in environmental humidity [26], transitioning from wet to dry and then from dry to wet, is a necessary condition for carbonation reactions to occur. If the concrete is submerged in water for an extended period, carbonation reactions will not occur.

Regarding the research related to carbonisation erosion, Lee et al. [30] discussed the influence of carbonation-induced corrosion on steel bars in concrete. They conducted accelerated carbonisation experiments in the laboratory, used different finishing materials (water paint (WP), multicolour paint (MCP), and silk wallpaper (SWP)) to treat concrete samples, and measured the carbonisation depth and coefficient. Figure 4 shows the physical appearance of the concrete after the carbonation test at different time intervals for different finishing materials using 1 % phenolphthalein. The study observed that the infiltration of atmospheric carbon dioxide into concrete reduces its basicity, resulting in the breakdown of the protective film around the steel bars, which causes corrosion. The study used different finishing materials to reduce the impact of carbonisation, and through field investigation and accelerated experimental comparison, they observed that the use of SWP as a finishing material can effectively reduce CO_2 penetration. Even after 100 years, carbonisation would not reach the position of rebar.

2.2.1. Internal causes of carbonation corrosion

The higher the water–cement ratio, the greater the degree of carbonation erosion [16]. To some extent, the water–cement ratio determines the density of the concrete. When the water–cement ratio was higher, the cured concrete will have more pores, which increases the contact surface between the concrete and the carbon dioxide in the air. Additionally, the ability of carbon dioxide to diffuse into the concrete becomes stronger, resulting in a larger extent of carbonation erosion.

The greater the cement content, the smaller the extent of carbonation erosion [31]. The amount of cement used affects the density of concrete. When more cement is used, the concrete becomes denser with fewer internal pores. Thus, the surface area of contact between the concrete and carbon dioxide decreases, resulting in less carbonation. Moreover, a higher cement content implies greater alkalinity in the pore solution owing to the higher alkaline content in the cement. This higher pH value [16] in the pore solution reduces the concentration of calcium carbonate precipitation resulting from partial carbonation, which enhances the density of the concrete, thus reducing carbonation erosion.

The addition of blending materials can impact the resistance of concrete to carbonation erosion [8, 32]. The blending materials include fly ash, slag, and silica fume. Blending materials contain significant amounts of active substances that can partially replace cement during hydration. These substances react with the carbon dioxide present in the cement hydration products. This not only reduces the cement content but also enhances the alkalinity of the concrete, effectively resisting carbonation erosion. Blending materials also participate in the secondary hydration reaction of cement, generating hydration products that can fill the internal pores of the concrete, thereby improving its overall integrity.

Admixtures can affect the resistance of concrete to carbonation erosion [33]. When high-quality admixtures are used in combination with compatible cement, they can reduce the amount of water required for concrete while enhancing its overall density. This reduces the extent of the carbonation reactions.

2.2.2. External causes of carbonation corrosion

Humidity significantly affects the rate of carbonation erosion. The relative humidity of air [28, 29] plays a crucial role in determining the diffusion rate of carbon dioxide within concrete. When the humidity within the concrete is relatively high, it hinders the diffusion of carbon dioxide from the air, thereby reducing the contact surface area between carbon dioxide and concrete. Consequently, the carbonation rate slows.

Temperature variations also have a significant impact on concrete carbonation [27-29]. According to physical principles, higher temperatures increase the migration speed of ions, which accelerates the spread of carbon dioxide within the concrete. Generally, for every 10 °C increase, the reaction rate doubles. Additionally, some theories suggest that higher temperatures decrease the solubility of carbon dioxide.

The concrete production process significantly affects its carbonation resistance. Construction factors, such as thorough and uniform mixing [18], effective compaction [18], and appropriate curing conditions [26] can enhance the density of concrete, thereby improving its resistance to carbonation. These measures can reduce the likelihood of cracks, holes, and porosity in concrete, consequently lowering the carbonation risk. The curing conditions also affect the generation of hydration products and the size of the internal pores within the concrete. Generally, concrete subjected to steam curing may have a carbonation rate 1.5 times higher than that of naturally cured concrete.

2.3. Chloride ion corrosion

Chloride ions have an erosive effect on concrete [6], manifested as follows: Chloride ions can damage the passivation film, participate in the formation of a "corrosion cell," exhibit an anodic depolarisation effect, and possess electrical conductivity that accelerates erosion.

Chloride ions damage the passivation film [34-37]. In a cement slurry with a pH value of 12–13, a tightly packed passivation film primarily composed of Fe_3O_4 oxide forms on the surface of the enclosed steel reinforcement in a highly alkaline environment. This film can exist stably in a highly alkaline environment; however, when the pH drops below 10, it destroys the existing passivation film and prevents the formation of a new one. When a large number of chloride ions enter the concrete and come into contact with the steel reinforcement surface, they are adsorbed onto the passivation film, causing the pH around the passivation film to rapidly decrease below 4. This destroys the passivation film on the surface of the steel reinforcement and generates a significant amount of corrosive rust ($Fe_2O_3 \cdot nH_2O$ crystals) under the influence of water and oxygen.

Chloride ions participate in the formation of a "corrosion cell" [38, 39]. Owing to the presence of chloride ions, parts of the passivation film on the steel reinforcement surface are damaged. The damaged areas expose the iron base, creating an electric potential difference between these areas and the undamaged passivation film region. Chloride ions are electrically conductive and contribute to the formation of ionic pathways. Simultaneously, the iron base serves as the anode and undergoes corrosion, whereas the passivation film acts as the cathode. This ultimately results in the formation of a "corrosion cell." During the initial corrosion stages, the area covered by the undamaged passivation film is significantly larger than that covered by the exposed iron base. Consequently, a battery configuration is formed with a smaller anode and a larger cathode, resulting in a rapid corrosion rate of the anode.

Chloride ions exhibit anodic depolarisation effect [34, 39]: Chloride ions not only promote the formation of the "corrosion cell" on the surface of steel reinforcement but also accelerate the process of the electrochemical cell. When the iron matrix is eroded as an anode [25], iron atoms undergo chemical reactions to generate divalent iron ions. Divalent iron ions combine with chloride ions to form $FeCl_2$, preventing the accumulation of divalent iron ions at the anode and thereby accelerating the anodic corrosion process. This process is referred to as the anodic depolarisation effect, in which chloride ions play a role in transporting divalent iron ions and are not consumed, enabling free chloride ions to participate repeatedly in the corrosion process.

One case of chloride ion erosion [6] was reported in 2016 when the authorities in Agadir discovered multiple failure events of a PCCP owing to the extensive corrosion of prestressed steel wires and water hammer action, particularly in the P3 water pipeline, as shown in Figure 5. The main reason for the failure of the PCCP was corrosion of the prestressed steel wire caused by chloride ions. The chloride content in the mortar coating exceeded the corrosion threshold (0.04 % by weight of concrete or 0.2 % by weight of cement); therefore, it caused the corrosion of prestressed steel wires. The study also observed that the erosiveness of the soil and high chloride ion content of the new PCCP mortar coating indicated that the mortar was contaminated during the mixing process.

Figure 5. Failed PCCP pipe [6]

2.3.1. Internal causes of chloride ion corrosion

The corrosion of reinforced concrete structures by chloride ions refers to the penetration and diffusion of chloride ions into the interior of concrete through various pathways. When the concentration of chloride ions on the surface of the reinforcement reaches a critical value, it can disrupt the passivation film on the reinforcement surface, resulting in corrosion of the reinforcement. This results in early damage to the structure and impairs its durability.

Chloride ions exhibit a strong depassivation effect [34-37]. When chloride ions penetrate the concrete and reach the surface of the prestressed steel wires and steel cylinders, they adsorb onto the local passive film, causing a rapid decrease in the pH value to below 4 in that area, thereby disrupting the passivation film on the steel surface. Additionally, owing to the non-uniformity of concrete, damage to the passivation film caused by chloride ions typically occurs in localised areas, exposing the iron matrix in these regions. This creates a potential difference from the intact passivation film areas, where the iron matrix acts as the anode in the corrosion cell and the larger passivation film areas act as the cathode. Consequently, the action of the corrosion cells results in the formation of corrosion pits on the steel surface. Because the large cathodic area corresponds to the small anodic area, the corrosion area and pits expand rapidly.

Chloride ions not only initiate corrosion cells on the steel surface but also accelerate the progress of electrochemical reactions [39]. This is because chloride ions can continuously transport anodic products, maintaining or even increasing the potential difference, thereby promoting anodic processes. Chloride ions are not depleted in this process [25]; therefore, each time chloride ions enter the concrete, they repeatedly trigger a corrosive effect, which is also a characteristic of the harm caused by chloride ions.

One of the key elements of corrosive cells is the presence of ionic pathways [38, 39]. Chloride ions in concrete enhance these ionic pathways, reducing the ohmic resistance between the anode and cathode, thereby increasing the efficiency of the corrosion cells and accelerating the electrochemical corrosion process.

In summary, chloride ions not only disrupt the passivation film on the metal surface but also accelerate the electrochemical corrosion of steel, indicating that chloride ions pose a significant threat to the durability of structures.

2.3.2. External causes of chloride ion corrosion

Chloride salts are widely distributed in various environments, particularly in coastal, saline-alkali regions, and winter regions, which require the use of de-icing salts. In these regions, the chloride ion content is abundant and the soil tends to be acidic [23, 24], which exacerbates the corrosion of reinforced concrete and steel structures in buildings and infrastructure [40]. Furthermore, modern water treatment and purification methods often use chlorine-based agents such as bleach, chlorine gas, or chlorine dioxide for the disinfection and purification of water resources. This results in a high chloride ion concentration in the purified water, posing a severe threat to the structural durability

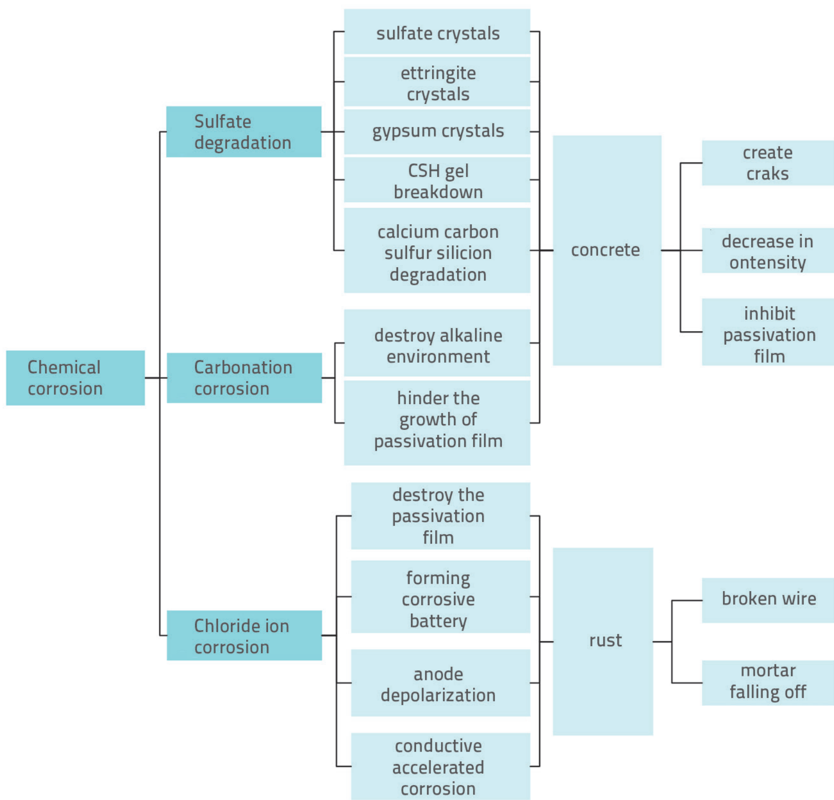


Figure 6. Chemical erosion process of PCCPs

of PCCPs, which are widely used in urban domestic water supply systems and industrial water supply systems. Figure 6 summarises the aforementioned chemical erosion processes.

3. Manufacturing defects

PCCP durability is affected not only by the surrounding environment but also by the manufacturing process. Improper material selection, inappropriate material quality or proportions, and improper drawing of prestressed steel wires during the manufacturing process can affect PCCP durability. Based on a review and summary of the literature, the factors affecting PCCP durability during manufacturing include the substandard quality of prestressing wires, non-compliant steel cylinders, incorrect selection of pipe types, and insufficient thrust restraint. Among these factors, the substandard quality of prestressing wires is the most significant contributing factor to manufacturing defects. Table 3 summarizes the main research contents of manufacturing defect-related papers. Among them, references [41-49] studied the content of prestressed steel wire quality, [50-52] studied the content of steel cylinder quality, [53] studied the content of pipeline type selection, and [54, 55] studied the content of thrust constraints.

3.1. Substandard quality of prestressing wires

According to statistical data from the American Water Works Association Research Foundation's official "Prestressed Concrete Cylinder Pipe Failure Report" [41], out of 317 confirmed pipe burst incidents, 230 were cases of Grade IV prestressing wire engineering failures, accounting for 70.7 % of the total pipe burst incidents. This indicates that the quality of the prestressed wires

Table 3. References on manufacturing defects

Reference	Factors affecting on durability
Li, J. (2018) [41]	The main cause of pipe explosion is the use of IV pre-stressed steel wire (drawing stress age hardening, hydrogen embrittlement), other reasons are: grooves cushion unreasonable, water hammer, man-made damage, and car loads.
Berrami, K. (2021) [42]	Through electrochemical analysis, the incorporation of fly ash can significantly improve the corrosion resistance of concrete, slow wire breaking, and prolong the service life of the pipeline.
Li, Y. (2022) [43]	The ability of structural health monitoring of pipelines can be improved by laying fibre optic sensors in PCCP to detect and locate the broken wires in pipelines in real time.
Zarghamee, M. S. (2019) [44]	The combination of BIM and GIS technology can significantly improve construction quality and efficiency, improve the quality of prestressed steel wire, reduce construction errors, and reduce costs.
Driscoll, M.R. (2015) [45]	Combining BIM and GIS technology can improve the efficiency of data integration and real-time monitoring, improve the quality of prestressed steel wire, and effectively predict and solve problems in construction.
Goldstein, W. (2009) [46]	The main problem of PCCPs is the increased brittleness of the prestressed steel wire, which is mainly due to the phenomenon of hydrogen embrittlement and the erosion of acidic groundwater.
Acosta, P. (2019) [47]	Combining BIM and GIS technologies offers advantages in data integration, real-time monitoring, and problem prediction.
Brzozowski, C. (2011) [48]	The use of high-density polyethylene (HDPE) pipes for the trenchless repair of PCCPs for sudden rupture due to hydrogen embrittlement has proven to be the most cost-effective method, saving significant amounts of money.
Tantaean, D. (2022) [49]	The study highlighted the use of advanced inspection techniques, such as electromagnetic inspection, to identify and prioritize the repair of pipeline segments that have problems due to the fracture of prestressed steel wires, thereby avoiding catastrophic failures.
Zhai, K. (2021) [50]	The mechanical properties of PCCPs reinforced with carbon fibre-reinforced polymer (CFRP) were analysed. The results showed that the CFRP technology can effectively improve the bearing capacity of a PCCP and prolong its service life.
Eskridge, F. (2001) [51]	A unified design method is proposed to evaluate and optimize the performance of different types of trenchless repair linings.
Nardini, P. (2016) [52]	The research used advanced detection techniques, such as electromagnetic detection and acoustic emission monitoring, to identify problem areas in the pipeline and make timely repairs.
Donaldson, F. H. (2006) [53]	Using case studies, the study considered various factors, including topography, soil conditions, existing infrastructure, and environmental protection requirements. A systematic method for evaluating and optimizing water pipe routing is presented.
Engindeniz, M. (2015) [54]	A unique condition assessment and maintenance program.
Brzozowski, C. (2014) [55]	Through the use of advanced leak detection technology and management system, the water loss was successfully reduced and the efficiency and reliability of the pipeline system improved.

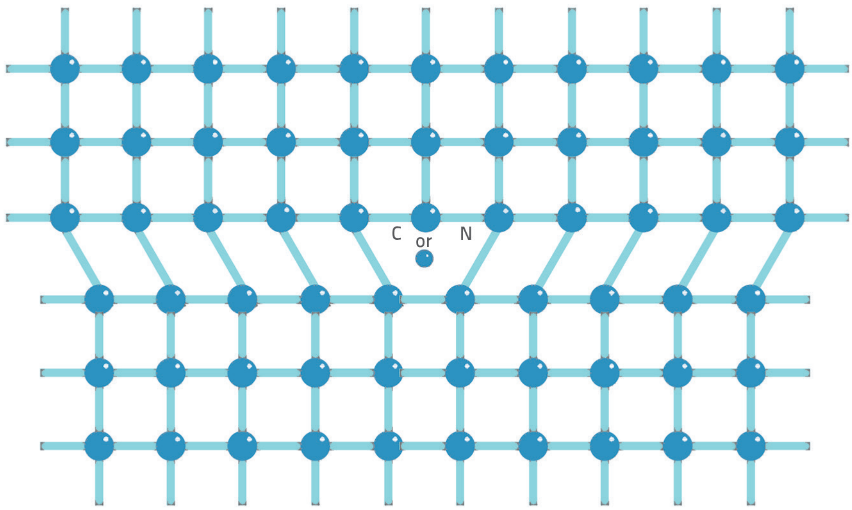


Figure 7. Harmful tension aging lattice of a prestressed steel wire

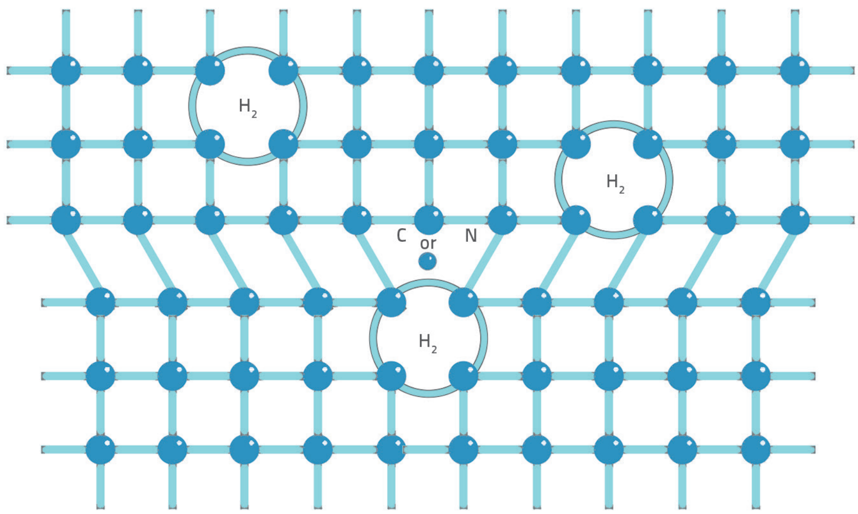


Figure 8. Hydrogen atoms infiltrating a prestressed wire lattice

is a crucial factor in determining PCCP durability.

Prestressing wires are wrapped around the concrete core of the PCCP, enabling the core concrete to withstand pressure and the PCCP to bear significant internal and external loads. During the pressurisation of the PCCP, prestressing wires play a role in bearing the internal water pressure; thus, the quality of the wires directly affects the service life of the PCCP. The quality of the wires is reflected in the manufacturing process. By rationally selecting aggregates and controlling alkali-aggregate reactions, wire quality can be ensured [42,43], effectively enhancing the durability of the PCCP.

3.1.1. Analysis of reasons

The direct causes of substandard prestressing wires are harmful stress aging and hydrogen embrittlement [44-49]. Harmful stress aging: During the manufacturing process of prestressing wires, if nitrogen (N) or carbon (C) monatomic atoms migrate into the iron plane structure and become fixed on dislocation lattices, it results in the phenomenon known as "harmful strain aging." When the planar structure of iron is distorted, the slip of the distorted lattice provides the iron or steel with good toughness, high strength, and fracture resistance. However, during the production of prestressing wires, if the wire is drawn too quickly, increasing the temperature to 316–371 °C and insufficient cooling, C and N atoms may migrate into the iron plane lattice and lock dislocations, as shown in Figure 7. This dislocation locking hinders the dislocation slip, resulting in reduced material ductility, elongation, and shrinkage, making the wire brittle and prone to fracture. Additionally, this structure often exhibits excellent tensile strength; however, during the drawing process, it is more susceptible to hydrogen atom embrittlement because of the occurrence of embrittlement at high temperatures and speeds.

Hydrogen embrittlement: Hydrogen embrittlement in prestressing wires is primarily attributed to the ingress and binding of hydrogen atoms, which exert pressure on their microstructures, as depicted in Figure 8. This pressure results from the formation of hydrogen molecules owing to the binding of hydrogen atoms, causing an expansion pressure on the microstructure of the wire, ultimately resulting in its embrittlement. This theory has been validated by multiple research institutions, including the Battelle Memorial Institute of Columbus in Ohio, USA, and Atomic Energy in Canada. Three main sources of hydrogen atoms are responsible for hydrogen embrittlement in cathodic corrosion-prevention systems: general corrosion-produced rust, electrochemical corrosion, and voltage release. Therefore, to prevent hydrogen embrittlement during PCCP production, stringent control measures must be implemented, including high-quality wire production processes and temperature control during wire drawing. In addition, measures must be taken to reduce or block the source of hydrogen atoms. Furthermore, strict adherence to the regulations outlined in AWWA301-99 and ASTMA648 is essential, along with the necessary testing and inspections, to ensure that the wire quality meets the standards, and is only used when it meets the required criteria.

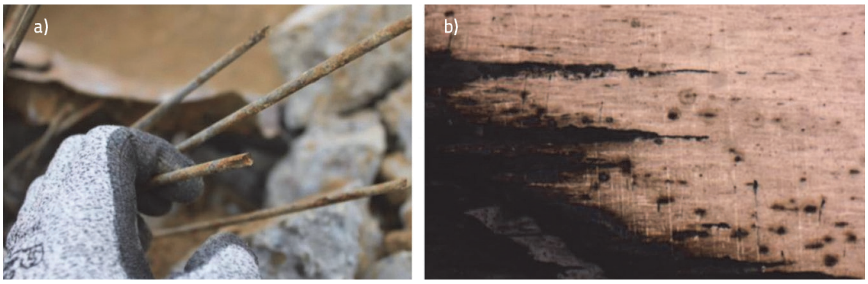


Figure 9. Prestressed wires in field and laboratory [52]: a) Britte wire fracture surface observed on corroded wires; b) Longitudinal splits and corrosion oriented along the wire axis

3.2. Non-compliant steel cylinders

The use of non-compliant steel cylinders can also affect PCCP durability, including uneven steel cylinder radii and inappropriate cylinder specifications.

After the welding of steel cylinders for a PCCP, if specialised equipment for correcting the steel cylinder arc at the lap joint is not used [50] and only a manual internal hydraulic pressure test is conducted, it can result in pipe burst incidents. The principle is as follows: After the pipeline starts operating, owing to the radial hydraulic pressure acting on the inner wall of the steel cylinder, the circumferential forces in all directions are evenly distributed. However, owing to the non-circular nature of the steel cylinder, under the combined action of the internal hydraulic and circumferential forces, the steel cylinder readjusts its curvature, causing displacement and deformation at the non-circular points. This deformation results in a concentration of tensile stress in the outer concrete of the steel cylinder, resulting in tensile cracking of the concrete. As cracks appear, moisture from the soil gradually penetrates the concrete, further promoting the rusting of the wires within the steel cylinder. These factors eventually result in concrete cracking, wire corrosion, and breakage.

The use of inappropriate steel cylinder specifications [51], particularly when the steel cylinder thickness does not satisfy the requirements, can potentially subject the PCCP to actual internal and external pressures that exceed its safety threshold, ultimately resulting in pipe burst incidents. A classic case is the 2015 incident when the Santa Clara Valley Water District (SCVWD) discovered a rupture in Section 2 of the Santa Clara pipeline at Station 12+17 (Pipeline 126), partly because of the incorrect use of an 18-inch steel cylinder instead of the specified 16-inch cylinder [52], which resulted in pipe burst incidents in some PCCP segments. Figure 9 [52] shows the status of the prestressed steel wire of a broken pipe.

3.3. Incorrect selection of pipe types

The selection of an incorrect pipeline type can also result in pipe bursts in a PCCP. This is because different pipeline types have different quantities of prestressing wires, and choosing a pipeline type that does not conform to the regulations can result in pressures exceeding the specified limits, resulting in accidents. In 2006, in Baltimore County, Maryland [53], an assessment was conducted on a 48-inch PCCP pipeline located on Kenilworth Avenue. This pipeline experienced two leakage incidents before inspection, and the main range of the 48-inch water transmission system suffered two significant ruptures, causing severe damage to the road and surrounding houses, resulting in the closure of the Kenilworth Drive main road and the shutdown of local schools.

Figure 10. Damaged PCCP [53]

Figure 10 [53] shows a damaged PCCP, the appearance of which shows obvious cracks in the coating with staining owing to corrosion, and all the prestressed tendons were destroyed.

One of the contributing factors was the use of a Class A pipeline design for pipelines 51 and 63, instead of the specified Class C design.

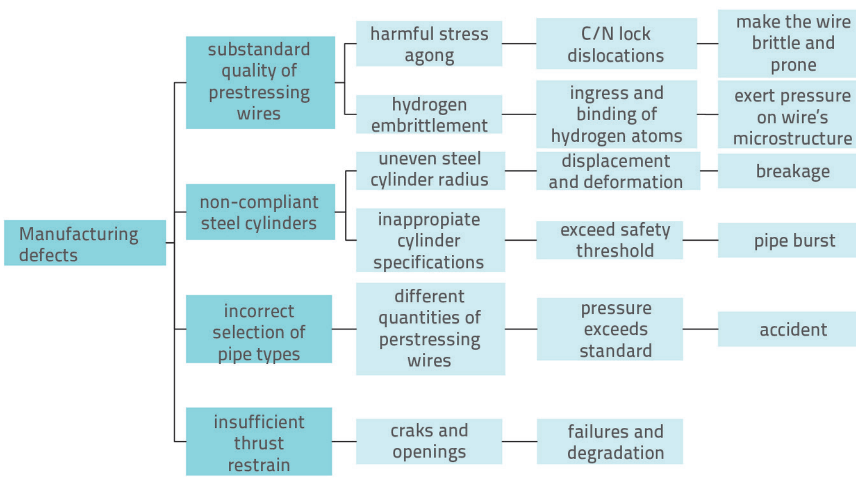


Figure 11. Manufacturing defects in PCCPs

Table 4. References on improper installation

Reference	Causes of pipe damage
Hassi, S. (2022) [56]	The main causes of pipe damage include installation defects, wire corrosion caused by chloride, and water hammer effect.
Shenkiryk, M. (2014) [57]	Cushion and support challenges are encountered in the construction and implementation of large diameter pipeline condition assessment projects.
Marshall, J. (2014) [58]	Through field experiments and numerical simulations, the effects of basic conditions on pipeline performance are demonstrated, and corresponding improvement measures are proposed to ensure the long-term reliability and safety of the pipeline.
Gossett, M. D. (2012) [59]	The influence of crack length on the burst strength of PCCPs is analysed experimentally and theoretically. It is observed that the burst strength of the pipeline decreases significantly with the increase of crack length.
WSSC Water (2009) [60]	The reason for the water pipe rupture is due to improper installation. The study observed that water pipes failed to comply with standard specifications during installation, resulting in structural instability and eventual rupture.
Crook, J. (2009) [61]	This paper introduces application examples of horizontal directional drilling (HDD) for pipeline installation under complex geological conditions, which can reduce the impact on environment and improve the efficiency of construction.
Hassi, S. (2022) [62]	The main causes of pipe damage include installation defects, wire corrosion caused by chloride, and water hammer effects such as uneven coating thickness.
Crook, J.M. (2010) [63]	The application examples of HDD technology under complex geological conditions are discussed in detail, particularly in the construction of large-scale infrastructure such as airports.
Chen, J. (2007) [64]	The construction quality is poor and the foundation is not treated as required, resulting in uneven settlement.

According to the electromagnetic testing and analysis conducted at the accident site, under a working pressure of 118 psi, each pipe section with only six consecutive wire breaks causes the concrete core of a Class A pipeline to crack.

3.4. Insufficient thrust restraint

Today's pipelines, particularly those installed in soft soil, may be susceptible to damage related to thrust, such as circumferential cracks, steel cylinder tearing, and joint opening [54, 55]. These problems can result in failures and accelerated degradation. According to structural assessments using concrete thrust blocks to provide thrust restraints, the pipelines near the bends exhibited circumferential cracks with corrosion traces. This suggests that if the thrust block at the bend moves, the thickness of the steel cylinder is insufficient to resist the longitudinal stress. Therefore, the repair of this pipeline should address not only circumferential effects but also thrust. In the future, more attention should be given to similar pipelines near bends during power outages. Figure 11 summarises the aforementioned manufacturing defects.

4. Improper installation

The installation of PCCPs is significantly influenced by the construction process, during which problems such as improper construction procedures, inadequately compacted backfill, neglect of flood control considerations, and poor mortar quality often occur [56]. All these factors have an adverse impact on the safety and PCCP durability. Based on the summary and compilation of the literature, the primary factors affecting PCCP durability during installation include inadequate bedding and poor support installation, lack of mortar or substandard mortar quality, and failure to follow the design requirements. Table 4 summarizes the primary research content of papers related to improper installation. Specifically, references [57-60] focused on topics related to bedding and support installation, references [61-63] addressed challenges related to mortar, and reference [64] explored construction according to design requirements.

4.1. Inadequate bedding and poor support installation

Non-compliant bedding conditions subject concrete to superimposed stresses, resulting in mortar cracking [57] and exposing the wires to passivation and corrosion threats. Under extreme conditions, such as placing the pipeline directly on rocks [58], point loading can occur on the pipeline, which significantly exacerbates pipeline failure. Conversely, high-quality bedding can significantly reduce the design strength requirements for pipelines. A classic case occurred on 5 February 1999 when a 24-foot-long segment of a 96-inch main waterline in Tucson's water supply system experienced a severe leak [57], flooding residential areas with 38 million gallons of water. Figure 12 [57] is a photograph of the damaged PCCP. Analysis indicated that the cause of the accident was the installation of clay dams around the pipeline to divert water from the trench to the exterior, resulting in poor bedding conditions.

Figure 12. Incipient failure of a 96-inch diameter pipe [57]

Figure 13. Failed pipe section i [63]

Poor support installation can also result in PCCP accidents, and the reasons for inadequate support [59] include 1. Excessive cover depth beyond the design; 2. Wide trenches resulting in a lower design cover depth; 3. Insufficient soil density and compaction; 4. Neglect of heavy snow loads; 5. Use of inappropriate bedding materials (large organic particles). A classic case occurred on 23 December 2008 when a 66-inch PCCP burst in the 8500 block of River Road, Bethesda, Maryland [60]. The analysis revealed that the cause was an improper load-bearing installation dating back to 1965. The installation contractor failed to remove the rocks as required and provided uniform and continuous load-bearing support for the pipeline by filling the trench bottom with the selected materials. Instead, the pipeline was directly installed on rocks, resulting in inadequate load-bearing support, cracks, and corrosion.

4.2. Lack of mortar or substandard mortar quality

If no mortar coating protection is provided at the joint of the pipe segments [61] or mortar decalcification occurs owing to improper mixing of mortar before installation at the joint of the pipe segments [62], the durability of the PCCP can be reduced. For example, a 48-inch PCCP under a major state highway in the southern part of Houston, Texas, failed [63]. Figure 13 [63] shows that a section of the pipe ruptured at the top, and the resulting water flow washed away the soil beneath the pavement of the southbound lane of Almeda Road, causing severe damage to the pavement. According to the analysis, in addition to mechanical damage to the pipeline and non-compliant bedding material and installation, another significant reason is the lack of mortar protection at the external pipe joints and poor or no mortar protection at the internal pipe joints.

4.3. Failure to follow the design requirements

A PCCP has clear construction steps and requirements during installation, and improper construction procedures can result in deterioration of the surrounding environment. For example, after exhaust wells are excavated and steel pipes installed, if subsequent procedures such as reinforcing concrete valve well base treatment, reinforcement arrangement, formwork installation, and pouring well wall concrete are not promptly conducted, water can inundate the floating pipes. Improper construction can also result in mechanical damage to the mortar and structural damage to pipelines. For example, in the leakage incidents in the Linyi City, Dezhou City, and Tai'an City Dawenkou Water Diversion Project [64] in China, the causes of these incidents were related to low construction quality. The specific reasons are as follows: 1. Foundation: In sections with rocks and clay in Linyi and Tai'an, it was necessary to deepen the trench excavation depth and backfill with sand to the design elevation; however, the construction team did not follow the requirements, resulting in uneven settlement; 2. Floating pipes: Common in conditions with groundwater and large-diameter pipes due to inadequate backfill quantity or compaction, resulting in the combined weight of the soil and the pipe being less than the buoyancy of the groundwater, causing the pipe to float. This often occurs because of uneven compaction on both sides, resulting in a large angular displacement at the interface and causing the

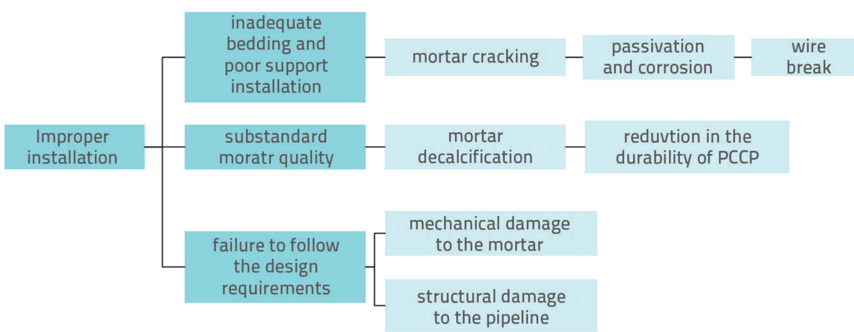


Figure 14. Improper installation of the PCCP

Table 5. References on poor operating conditions

Reference	Factors affecting on durability
Vidal, E. (2022) [65]	The prediction of pipeline rupture events using machine learning is discussed. This approach uses historical data to estimate the likelihood of pipeline failure and is designed to enhance maintenance strategies and reduce infrastructure downtime.
Yao, Y. (2009) [66]	During geological exploration, the geotechnical company drilled through the pipe wall 1.7 m from the end of the pipe socket, resulting in severe damage and water leakage.
Chen, Q.F. (2010) [67]	
Bass, B.J. (2012) [68]	The degree of corrosion and fracture significantly affects the strength and durability of the pipe. Enhanced monitoring and maintenance measures such as regular inspections and appropriate protective treatment are recommended to reduce the risk of failure.
Ojdrovic, R. (2022) [69]	The importance of pipeline material selection, structural integrity and long-term durability is emphasized. Examples are given to illustrate how to optimize pipeline design to improve its load-bearing capacity and durability and reduce the risk of failure.
Henry, G. (2021) [70]	In this study, 124 dry stack prism tests were performed to investigate the effects of compressive strength and interface treatment methods on the structural properties of concrete blocks. The results show that the optimized interface treatment method can significantly improve the compressive properties of dry-stacked concrete blocks.
Zarghamee, M.S. (2006) [71]	The methods and challenges of implementing HDD technology in the Biscayne Bay Marine Reserve are discussed.
Donnally, S. (2019) [72]	The research focused on the use of advanced microscopic techniques and computational simulations to characterize and predict the behaviour and properties of materials under different conditions. With this comprehensive approach, a deeper understanding of the microscopic mechanisms of materials can be obtained, thereby optimizing their design and application.
Stroebele, A. (2010) [73]	The pipeline infrastructure planning and innovative technologies adopted in the project, such as the application of prestressed concrete pipes, are discussed to improve the durability and efficiency of the system.
Henderson, M.C. (2010) [74]	The data obtained from the inspection process is described and methods for translating this data into an effective design are proposed. The study highlighted key parameters including structural integrity, environmental impact and maintenance needs.
Sauer, J. (2009) [75]	The use of air sacs and leak detection techniques to assess the status of in-service pressure arterial roads is discussed. The results show that these technologies can significantly improve the efficiency and safety of pipeline maintenance.
Mak, G. (2011) [76]	This paper introduces the process of constructing a spillway siphon under Santa Clara River using microtunnel technology.
Santana, M.B. (2009) [77]	Install underground pipes in busy airport environments to avoid surface interference using advanced directional drilling technology.
Yurcich, R. (2021) [78]	The research focused on the effectiveness of different reinforcement techniques, including the use of a combination of foundation columns and geosynthetics, through numerical simulation and experimental analysis. These techniques can significantly reduce the settlement of the embankment and improve the stability of the structure.
Pozos-Estrada, O. (2016) [79]	Studies have shown that PCCP bursts due to the presence of air sacs after a power failure of the pump system. A hydraulic transient simulation of different scenarios confirmed that the small volume air sac is the direct cause of PCCP rupture. The hydraulic model was also used to analyse the behaviour of the air sac at the high point of the pipeline, showing that the small volume of the air sac will significantly increase the pressure peak, resulting in pipeline rupture.

gasket to come off; 3. Mechanical backfill: The construction unit did not follow the required backfill operation, resulting in damage. Figure 14 summarises improper installation.

5. Poor operational conditions

Poor operational conditions can reduce the durability of PCCPs. According to the literature, the main factors contributing to poor operational conditions of PCCPs include third-party damage, internal pressure issues, and airbags. Table 5 summarizes the primary research content of papers related to poor operating conditions. Specifically, references [65-70] focused on topics related to third-party damage, references [71-75] addressed problems related to internal pressure, and references [76-79] explored challenges concerning air pockets.

5.1. Third-party damage

Third-party damage refers to damage caused by individuals or entities unrelated to PCCPs and often has a random and uncertain nature. This can include factors such as hasty excavation resulting in accidental leakage, excessive external loads [65], and drilling or puncturing of the pipe wall [66-69]. For example, in 2007, a PCCP water pipeline in Houston, Texas, was observed to have cracked in the MK#242 pipe section during inspection [70]. An investigation revealed that the primary cause of the damage was third-party damage: this pipe section was installed just 2 feet below a stormwater pipe, and the construction of the stormwater pipe caused cracks in the PCCP section.

5.2. Internal pressure issues

Sudden internal and external pressure changes can result in PCCP pipe failure. Many factors can cause significant pressure fluctuations, including

- Automatic control of pipeline valves through a timer [71], with the timer mistakenly set to the default of 1 min and not correctly modified during operation, resulting in rapid valve closure, causing severe pressure fluctuations within the pipeline and ultimately resulting in pipe failure.
- Sudden power interruptions from external sources cause pump shutdowns [72], resulting in pressure loss within the pipeline. When the power is restored, the pipeline experiences transient pressure, resulting in accidents.
- During the refilling process after water maintenance, a high rate of pressure change occurs within the pipeline owing to water hammer effects [73].
- Restriction on the use of a sprinkler system causing pressure fluctuations within the water supply system [74], exerting additional pressure on the aging pipelines.
- High flow rates in power plant cooling water systems with frequent valve opening and closing operations can result in severe pressure fluctuations within the pipeline, thereby causing pipeline damage [75].

5.3. Air pockets

In addition to water supply pipelines, PCCPs are often used as sewage pipelines. When sewage flows, it can release corrosive gases, such as hydrogen sulfide, owing to factors such as temperature and liquid flow. Under normal circumstances, these gases are vented through the air-release valves of a PCCP. However, if the air release valves of a PCCP are damaged, preventing gases from being released, waste gases may accumulate in the air pockets of the pipe at the top. After condensation, they can adhere to the pipe wall and corrode it [76-79], which can affect the service life and durability of the PCCP.

For example, in 1999, a segment of a 1350 mm diameter sewage pipeline in Regina, Saskatchewan, Canada, experienced failure [76]. Internal inspection results in 2008 indicated that the cause of the accident was an improper internal flow design of the pipeline. The disruption in water flow conditions within the pipeline transitioned from supercritical to subcritical, causing turbulence. The pipeline conveyed sewage with a high hydrogen sulfide content, and under turbulent conditions, the process of hydrogen sulfide changing from liquid to gas was accelerated. This caused a significant accumulation of hydrogen sulfide at the top of the pipe, corroding the inner surface of the concrete, and ultimately resulting in pipeline failure. Figure 15 [76] shows the surface corrosion and exposed aggregates. Figure 16 summarises the aforementioned poor operating conditions.

Figure 15. Surface corrosion and exposed aggregates [76]

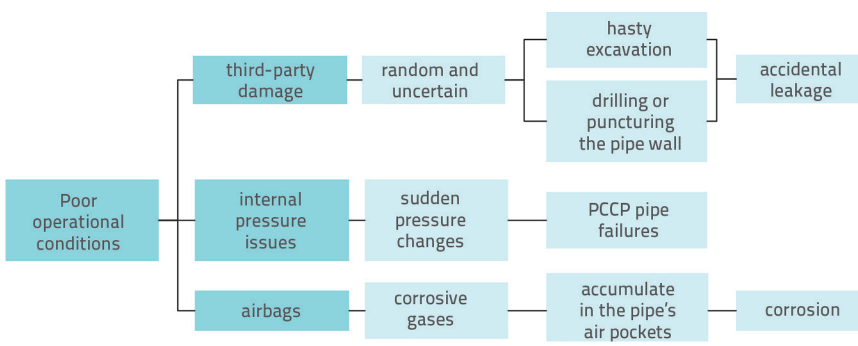


Figure 16. Poor operational conditions of PCCPs

6. Conclusion

A PCCP is a fundamental and crucial component of water supply systems, and its durability is closely linked to the quality and stability of the water supply. Several factors affect PCCP durability: chemical erosion, including sulfate attack, carbonation, and chloride ion penetration; manufacturing defects, including substandard prestressing steel wires, unsuitable steel cylinders, incorrect pipe-type selection, and insufficient thrust restraint; improper installation, which includes poor bedding and support, lack of mortar or subpar mortar quality, and non-compliance with design specifications; and operational issues, such as third-party damage, air pockets, and internal pressure problems.

In-depth research on the factors affecting the durability of the PCCP shows that the PCCP is a highly effective large-diameter water transmission pipeline. Improvements should be made to materials, installation, and maintenance to enhance PCCP durability.

In terms of materials, the composition of cement clinker can be modified, such as reducing the content of $3CaO{\cdot}Al_2O_3$ and $3CaO{\cdot}SiO_2$ while increasing the density of concrete to more effectively resist cracking caused by sulfate degradation. Controlling the water–cement ratio and using appropriate admixtures can improve the carbonation resistance and slow the carbonation process. Additionally, the use of high-quality anti-corrosion coatings and the incorporation of anti-chloride penetration additives into concrete can effectively protect the reinforcement and prestressed steel wires. The production of prestressed steel wires should be strictly controlled to prevent hydrogen embrittlement and harmful stress aging, thereby ensuring the quality of the wires. For steel cylinder production, appropriate specifications and uniform arc radii should be used to avoid early failures owing to improper specifications or welding quality problems.

In terms of installation, the quality of bedding and support during the installation process should be ensured to prevent structural damage caused by poor installation.

In terms of maintenance, monitoring and protection measures for PCCPs should be strengthened to prevent damage from external factors, such as construction excavation and heavy vehicles. Properly controlling the internal and external pressure fluctuations in a pipeline can prevent burst incidents caused by sudden pressure changes. Regular inspection and maintenance of air valves are necessary to prevent the accumulation of corrosive gases at the top of the pipeline, ensuring smooth gas discharge.

In practical applications, the factors affecting the durability of PCCPs are comprehensive and complex, and some urgent technical areas still require further research.

PCCPs often experience durability reduction in acidic environments. More suitable additives should be incorporated into the concrete to block or delay the infiltration of acidic substances, thereby enhancing PCCP resistance to acid erosion. Additionally, it alloys should be studied to determine optimised methods for prestressed steel wire structures to improve their corrosion resistance and resistance to hydrogen embrittlement.

Based on the operating environment of the pipeline, the composition of surface coatings applied both inside and outside the pipeline should be improved. Owing to the highly alkaline nature of concrete, alkali resistance should be ensured. Based on the alkali resistance, materials with better adhesion and corrosion resistance, such as epoxy coatings, can be sought. This renders the pipeline surface less susceptible to corrosion, thereby enhancing its durability.

The bends in PCCPs are subjected to significant longitudinal stress. More detailed research should be conducted on the maximum longitudinal stress at bends under different pipeline specifications, bending angles, and fluids and to establish corresponding models. This provides theoretical support for subsequent research on new PCCP structures.

During practical operation, PCCPs may encounter problems such as prestressed steel wire breakage, internal pressure fluctuations, and pipe wall leakage. Non-destructive testing of a PCCP is recommended. A distributed optical fibre should be wound onto the PCCP to establish the corresponding models, and feedback from the optical fibre should be used to determine the operational status of the PCCP.

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