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The durability and rehabilitation technologies of concrete sewerage pipes: A state-of-the-art review

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Abstract: This paper reviews the literature available on the subject of the durability of concrete sewer pipes and the corresponding rehabilitation technologies. An introduction related to the importance of the sewer system in urban life and its durability issues was first discussed as most people did not recognise the scale and complexity of the underground sewer system. Then the recent development of alternative binder materials or filler materials to improve the acid resistance of concrete was specified. For instance, the effects of alternative binders on the hydration products and the mechanism of biogenic corrosion were discussed in detail. The paper ends with the current rehabilitation technologies and the structural performance of rehabilitated sewer pipes. Also, some suggestions associated with future research were made.

Keywords: Concrete Sewer Pipe**;** Microbially-Induced Acid Corrosion; Review; Concrete Mix Design; Rehabilitation Technologies.

1. Introduction

The sewer system is a critical urban infrastructure, which comprises a collection system and treatment system to transfer wastewater from households to the wastewater treatment plant [1,2]. A simplified schematic view of the underground sewerage piping system is shown in Fig.1. In some countries, the total length of the sewer system can far exceed the circumference of the earth by ten times and more. For instance, the US has the most extended length of sewer networks in the world, exceeding 1,300,000 kilometres, followed by the UK and China, which owns pipelines approaching 624,200 kilometres and 519,000 kilometres, respectively. Due to a relatively low population, the total length of sewer pipes in Australia is around 117,000 kilometres [3].

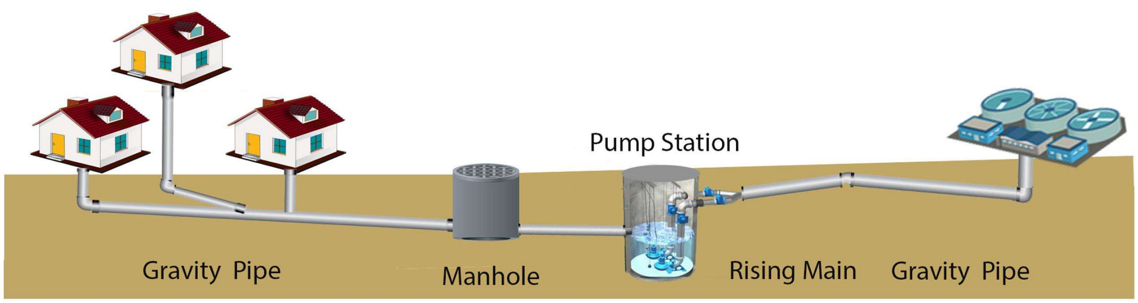

Fig. 1 – Schematic view of sewerage network infrastructure [4]

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Concrete is the most used material for manufacturing sewer pipelines [5,6]. However, the concrete sewer pipes are susceptible to failure prematurely far before reaching their asset life due to microbially-induced acid corrosion (MIC). Specifically, MIC is the process in which the acid generated by microbial activities keeps dissolving the cement-matrix. Leaking or even collapse of the concrete sewage pipes can be caused by MIC; therefore, regular maintenance is required. Fig. 2 shows the health and safety concerns derived from damage to roads and pavements during and after a catastrophic pipe failure.

Fig. 2 – Pavement collapse and pipe burst caused by concrete pipes failure [7,8]

In most developed countries, the sewer system is more than 40–50 years old, and the corresponding maintenance fee is significant. As an example, about 100 billion US dollars is spent on repairs and maintenance of private and public sewer pipes in Germany alone, and 40% of this cost can be attributed to the failure induced by MIC [9]. In addition, it is reported that the financial cost associated with the modernisation and replacement of buried sewage lines is in a range between $660 billion and $1.1 trillion dollars in the US over the next 20 years [10]. Moreover, in the state of South Australia alone, about 48 million Australian dollars each year is projected to be spent on maintaining the existing underground wastewater constructions [4]. To make matters worse, the concerns related to the deterioration of sewer pipes are not limited to the economic cost but extends to public health and environmental costs.

Concrete pipes are available either in plain or reinforced with steel reinforcement classifications in various strength categories [11–16] Meanwhile, reinforced and nonreinforced concrete pipes are both used for sewerage pipelines with a gravity flow system. This paper specifically reviews the linkage with MIC mechanism, concrete mix design, externally rehabilitation technologies, and structural performance of rehabilitated concrete sewer pipes. The first part presents the MIC deterioration mechanism. Then strategies for improving MIC resistance with the development of concrete mix design are discussed. Finally, the current technologies for concrete pipe rehabilitation are summarised, e.g., carbon fibre reinforced polymer (CFRP), slip liner and epoxy lining; the corresponding structural behaviour was also analysed.

2. Fundamentals of microbially induced corrosion

2.1 MIC mechanism

The MIC mechanism is first reviewed to help better understand the issues of concrete sewerage pipe. After MIC, the sound concrete would be transformed into a mushy material with no adhesive properties and easily washed out by flowing water. The photos show typical sewage facilities that suffered from MIC (Fig. 3). To repair such deteriorations, a cost of around £85 million in the UK and $390 billion in the USA is needed in the next 20 years [17].

MIC involves both chemical and microbiological processes. The hydrogen sulfide (H_2S) and sulfuric acid (H_2SO_4) were first identified as the corrosion media [18]. Later studies then confirmed the participation of the microorganism in producing the corrosion acid [19]. Fig. 4 shows a schematic diagram of the MIC process in concrete sewage pipes, and the MIC process can be summarised as three stages: (i) Generation of H_2S, (ii) Generation of H_2SO_4 and (iii) Corrosion on concrete [20–24]

Fig. 3 – Photos of MIC in sewage facilities [17], Photos (A), (B), (D) are taken from the manhole of sewage pipes; Photos (C) and (E) are taken from wastewater catchment basins.

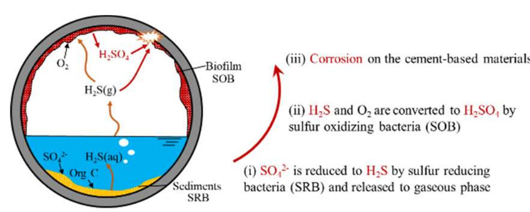


Fig. 4 – Schematic diagram of the MIC process in concrete sewage pipes

2.1.1 Generation of hydrogen sulfide (H_2S)

The MIC process starts with the generation of H_2S in sewage water [25]. The sulfate-reducing bacteria (SRB) in the sediments, where an anaerobic condition is ensured, utilizes the sulfate (SO_4^{2-}) as electron acceptor and organic compounds as electron donors to produce aqueous H_2S. The reaction can be described with Eq (1):

$SO_4^{2-} + 2C$ (Organic matter) $+ 2H_2O \rightarrow 2HCO_3^- + H_2S$ (aq) (1)

The aqueous H_2S will transform into gaseous H_2S above the waterline in pipes with satisfying conditions such as a low pH value, a high temperature or strong turbulence. The pH value in the sewage is considered to have the most significant impact on transforming aqueous to gaseous H_2S [3,26]. In the municipal sewage pipeline, the pH range of the wastewater is usually between 6 and 8. In this condition, approximately 30% to 50% of aqueous H_2S can be radiated in the air phase [3,27]. Due to the alkaline and porous nature of the cement-based material, the diffused gaseous H_2S can be dissolved in the moist pores in the cement-matrix, reacting with the alkaline contents and reducing the surface pH of the concrete pipe walls. In this stage, the chemical-induced corrosion is dominant as it is difficult for acid-generating bacteria to colonize on the newly cast cement surface where the pH value is around 13 [28,29]. However, once the pH value is reduced below 9 by the gaseous H_2S, the sulfur-oxidizing bacteria (SOB) will grow in the form of biofilm on the concrete surface [29]. The colonization of the SOB initializes the generation of the sulfuric acid process.

2.1.2 Sulfuric acid (H_2SO_4) generation

In this process, the SOB utilizes the H_2S and produces H_2SO_4, further decreasing the pH happens on the concrete pipe wall. The reaction formula can be described as Eq. (2).

$$H_2S + 2O_2 \rightarrow H_2SO_4 \quad (2)$$

Fig. 5 shows the relationship between SOB activity and pH values. The neutrophilic SOB (NSOB) first colonizes at the surface when the pH is between 4 and 9. Then, the surface pH can be further reduced below 4 with the continuing growth of bacteria communities. The acidophilic SOB (ASOB) will start to grow within this pH range and reach its highest activity at pH values between 1 and 2 [17,30].

Due to the aerobic nature of the SOB, the bacteria community tends to appear above the waterline where sufficient oxygen exists. In addition, the pipe crown is usually cooler than the sewage water; the temperature difference could cause the dew condensation in this zone, providing the moisture that favours the bacterial growth. As a result, more severe MIC damages are found in the manhole, the crown, and the sections near the water level in concrete pipes [28,31].

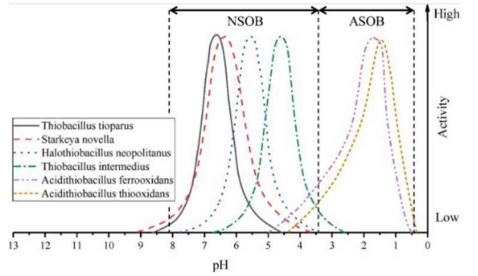


Fig. 5 – The SOB activity of different bacterial communities related to the pH value (modified from [30]); NSOB: Neutrophilic SOB; ASOB: Acidophilic SOB

2.1.3 Corrosion on the cement-based materials

The Portland cement-based materials are vulnerable to acid corrosion due to their alkaline nature. Moreover, corrosion due to sulfuric acid can result in a more severe deterioration effect because it combines both the acid and sulfate attacks [32–34]. The corrosion reaction between the cement-matrix and sulfuric acid can be described as the following equations:

$$H_2SO_4 + CH \rightarrow CaSO_4 + 2H_2O \quad (3)$$
$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2CO_3 \quad (4)$$
$$H_2SO_4 + C\text{-}S\text{-}H \rightarrow CaSO_4 + Si(OH)_4 + H_2O \quad (5)$$
$$3CaSO_4 + C_3AH_6 + 26H_2O \rightarrow AFt \quad (6)$$

The sulfuric acid generated by the SOB reacted with the Portlandite (CH) from the cement hydration (Eq. 3) and the calcite from the cement carbonation (Eq. 4). The dissolution of these hydration products will open the pores of the cement-matrix, increasing the permeability and promoting corrosion media transportation. The calcium silicate hydrate (C-S-H) is then dissolved under the sulfuric acid attack (Eq. 5). Fig. 6 shows the schematic image of the corrosion layers distributed in the pipe wall. The reactant of these reactions, i.e., gypsum ($CaSO_4 \cdot 2H_2O$), formed on the pipe wall surface, is a non-cohesive material, which is easy to wash out, creating new un-reacted textures for the SOB to colonize and corrode. In addition, the formed gypsum may diffuse inside the concrete and react with calcium aluminates (C_3AH_6), producing the ettringite (Eq. 6). The ettringite precipitation can lead to 227-700% volume expansion, causing cracking of the corroded concrete [35].

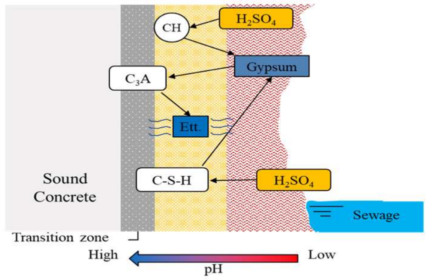


Fig. 6 – Schematic image of corrosion layers distributed in concrete (modified from [36])

2.2 Evaluation methods

In addition to placing samples in the actual sewer system, many lab-scale evaluation methods have been developed to determine the cementitious materials' performance under MIC attack [37,38]. They can be divided into two categories: mineral acid corrosion test and microbiological simulation corrosion test. The mineral acid corrosion test utilizes chemical sulfuric acid directly as the corrosion media to simulate the final stage of MIC. An example of a mineral acid corrosion test is shown in Fig. 7. In the test, samples are immersed in the sulfuric acid solution. The acid concentration is maintained by regularly replacing the sulfuric acid solution [39,40] or using automated titration [41,42]. Mineral acid corrosion test provides a simple method to evaluate MIC resistance. It can accelerate the reaction rate and, therefore, shorten the experimental time. However, the limitation of this method is that it neglects the material's effect on microorganism activities. For instance, if the materials could prevent the growth of the corrosion-induced bacteria at an earlier stage, the material is not necessary to have strong resistance to sulfuric acid corrosion.

Fig. 7 – Sulfuric acid corrosion test for mortar samples (modified from [39])

The other lab-scale evaluation method is to simulate the microbiological corrosion activities that occurred in sewage pipes. As the MIC phenomena in sewage pipes may take years or decades to be observed, an accelerated MIC test environment in the laboratory-controlled condition is usually developed. The strategies to expedite the MIC in cement materials include simplifying the reaction chain and increasing the bacteria activity level [25,43–46]. In sewage pipes, H_2S is generated by the SRB and then transformed into H_2SO_4 by SOB. This process can be simplified by maintaining the concentration of artificial H_2S at a high level instead of utilizing the biogenic H_2S for SOB. Fig. 8 shows an example of schematic test equipment with this principle. The microbiological simulation corrosion test can evaluate both the chemical and microbial processes in the sewage environment. Thus, it may provide a more reliable service life estimation of concrete sewage pipes.

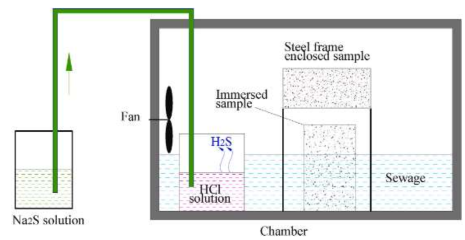


Fig. 8 – Schematic diagram of microbiological simulated acid corrosion test equipment (modified from [30,45])

3. Improving concrete mix design

3.1 Alternative binders

3.1.1 Calcium aluminate cement

When exposed to sulfuric acid conditions, the performance of concrete prepared by calcium aluminate cement (CAC) is generally better than ordinary Portland cement (OPC) [47]. Scrivener et al. [47] and Goyns [48] mentioned that the difference between CAC and OPC was the nature of active phases that led to hardening. The CAC contains Al_2O_3 and CaO as principle oxides with almost no SiO_2, which results in the hydration products mainly consisting of calcium aluminate hydrates. Also, some quantities of alumina gel ($Al(OH)_3$) precipitate out of the solution at the time of hydration or reaction between calcium aluminate hydrates and acid. As known, alumina gel ($Al(OH)_3$) is rather inert to moderate acid attack. Even though it is unstable when exposed to severe acid attack, but the released aluminium ions can accumulate in the thin biofilm. Therefore, preventing the bacteria from oxidizing sulfur and resulting in an improved acid resistance [49].

Saucier and Kaitano [50] suggested using CAC-based mortar as a lining material to resist MIC. Compared with the traditional coating resin method, the CAC-based mortar can provide a durable rehabilitation and a low cost. The reasons for the improvement can be attributed to (i) without drying the substrate and by-pass the effluent in most cases, (ii) exceptional acid resistance. Berndt [51] also confirmed that CAC-based mortar exhibited excellent resistance to acid attack. Furthermore, the biodeterioration of mortar made with CAC and Portlandite cement was investigated in bioleaching tests, which provided a new insight to explain the acid resistance improvement of CAC-based mortar [52]. For instance, the different reactive phases of CAC lead to a weaker acid-neutralizing capacity, resulting in a quicker drop of pH from 6.5 to 3, decreasing the amount of bio generated sulfuric acid. Recently, Grengg et al. [53] investigated the long-term MIC resistance of mortar samples using CAC, OPC, and geopolymer. Compared with the other two binders, CAC-based mortar exhibited a stable low corrosion rate, and the corrosion depth of OPC and CAC samples was characterized by back-scattered electron image combined with element mapping (Fig. 9). Such an explanation was also supported by the study of Herisson et al. [54,55], which demonstrated the excellent long-term acid resistance of CAC-based mortar. In addition to lab-scaled sulfuric acid tests, Khan et al. [56] and Kiliswa et al. [57] conducted a study on MIC resistance of CAC mortar and OPC mortar under actual sewer. After tests, the obtained results further evidenced the superior acid resistance of CAC-based mortar, and crystallization of gypsum was the main factor for the deterioration.

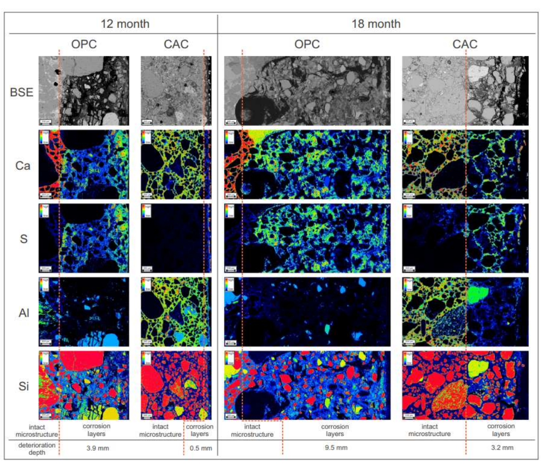


Fig. 9 – Acid corrosion depth characterized by chemical mapping and back-scattered electron image in OPC and CAC mortar after 12 months and 18 months of testing [53]

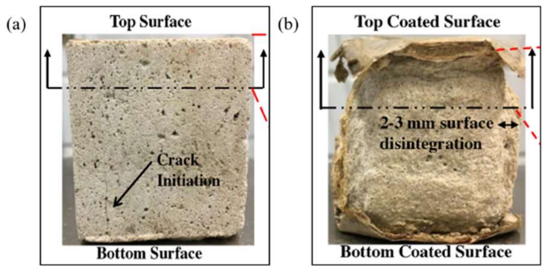
Dashti and Nematzadeh [58] studied the compressive and direct tensile behaviour of concrete containing CAC and fibre under sulfuric acid attack. The obtained results indicated that CAC could contribute to a higher strength than that of Portlandite cement ones either in acidic or non-acidic conditions; the CAC improved the concrete tensile strain in the acid environment. Also, Fourie [33] found that CAC concrete products outperformed ordinary concrete in the acid resistance test due to the ability of CAC hydration products to stifle the metabolism of the bacteria, thereby mitigating the formation of sulfuric acid. However, the main limitation of the CAC to be used as a structural material is the conversion issue [59]. The initial CAC hydration products such as CAH_{10} and C_2AH_8 generated at ambient temperatures could be converted to the more stable phase C_3AH_6 later during the long period reaction [60]. This conversion increases the material's porosity and permeability, leading to a significant strength loss. Moreover, the moisture environment in sewage pipes may accelerate this conversion [61]. Although the MIC resistance can be improved using CAC, the risk of structural failure still exists at a later age if an improper CAC amount is used.

3.1.2 Geopolymer

Geopolymer is an alternative binder for OPC, and the main binding phases of geopolymer are derived from the reaction between an aluminosilicate precursor and an alkaline activator. Such a reaction mechanism avoids the formation of Ca-rich acid-soluble hydration products. In addition, the alkaline solution accelerates the reaction rate, resulting in properties of hardened binder comparable to those of OPC, thereby improving the acid resistance [62,63]. The study conducted by Gu et al. [64] confirmed the excellent acid resistance of geopolymer. The obtained results indicated that after an acid corrosion test, the dissolution of Portlandite and C-S-H gel and the formation of expansive gypsum in the OPC matrix resulted in severe concrete deterioration. In comparison, the chemical change due to acid attack in the geopolymer matrix was the dissolution of N-A-S-H gel, which only slightly coarsens the pores. Furthermore, Xie [65] checked the gypsum amount (the main corrosion product) produced on the surface of the corrosion layer and found that the gypsum amount of OPC was more significant than that of geopolymer, indicating a higher corrosion degree.

William et al. [66] assessed the acid resistance of geopolymer concrete using low-quality fly ash (FA) as a precursor. The samples were placed in the solution with a sulfuric acid concentration of 1 M for 360 days. The experimental results showed that geopolymer concrete exhibited better resistance to acid attack than that of OPC concrete.

For instance, the maximum mass loss of geopolymer concrete was 6%, much lower than the 19% mass loss of OPC concrete. Khan et al. [67] investigated the sulfuric acid resistance of OPC mortar and FA-based geopolymer mortar in a natural sewer environment. After two years of exposure, the images of samples are shown in Fig. 10, in which the geopolymer sample exhibited less deterioration than OPC one. These results were consistent with the study of Xie [65].



(a) geopolymer mortar (b) OPC mortar
Fig. 10 – Mortar samples after exposure to a natural sewer environment for two years [67]

Apart from FA, ground blast furnace slag was another popular precursor to produce geopolymer. Some studies investigated the effects of FA/slag mixture on resistance to MIC. Aiken et al. [68] reported that an increase in slag content decreased the porosity of FA-based geopolymer but made the binding phase more susceptible to sulfuric acid attack. The mechanism of sulfuric attack on mortar samples with different binder systems is shown in Fig. 11. When the hydrogen protons (H^+ and H_3O^+) attacked the binding phases (e.g., Si-O-Al bonds), the ejection of Al^{3+}, Ca^{2+}, Na^+, K^+, and some other ions into the acid solution happened, leaving behind a siliceous framework. When the diffused SO_4^{2-} anions met with Ca^{2+}, the gypsum crystals precipitated inside the penetrated layer. The increase of slag content promoted the formation of expansive gypsum, leading to more cracks. Such explanation was supported by the study of Sturm et al. [69].

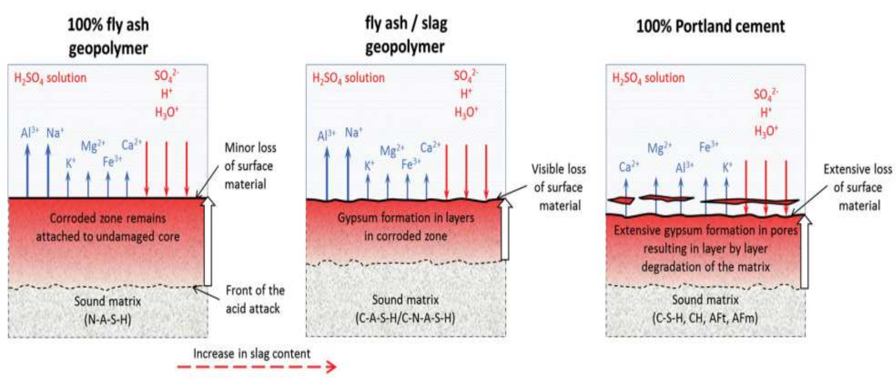


Fig. 11 – Mechanism of sulfuric acid attack in different binder systems [68]

The limitation of using geopolymer as a binder material for sewage pipe is that the product is more difficult to manufacture than OPC or CAC. Rather than simply mixing with water for typical cement products, high molar concentrations of alkaline solution, for example, 6~12 M sodium hydroxide, are usually used in geopolymer to ensure a satisfactory mechanical performance [70]. In addition, the expensive activator has also constrained the commercialization of the geopolymer to replace OPC [71].

3.2 Siliceous or aluminosilicates materials and crumb rubber

In recent years, some studies found that the addition of siliceous materials, such as hollow glass microsphere [72], glass powder, and waste glass aggregates, in concrete might contribute to improving acid resistance. Zhang et al. [73] reported that the geopolymer samples with 5% hollow glass microsphere and 5% quartz powder exhibited higher resistance to acid attack if the curing temperature was controlled at 80 °C. Also, Siad et al. [74] determined the superior acid resistance of mortar samples containing glass powder as supplementary cementitious material. After the acid immersion test, the mortar samples containing 45% glass powder showed remarkably lower strength and mass loss than neat OPC samples (Fig.12). These results were attributed to the fact that the crystalline C-S-H gel derived from the pozzolanic reaction may contain high aluminium content and a low Ca/Si ratio. Such Si and Al-rich gel might act as a barrio to stop further corrosion. Furthermore, Bisht [75] found that the reaction between waste glass and sulfuric acid could form sodium sulfate, which prevented the decomposition of cementitious materials. Meanwhile, 21 % of sand replaced with waste glass achieved the optimized performance to acid attack. However, utilization of the silicious materials, especially as aggregate, has the potential to cause Alkali-silica reaction (ASR) [76,77]. The amorphous silicious aggregate could react with the alkaline from cement pore solution and generate expansive ASR gels, resulting in cracks in cement-matrix and structural failure [78].

Bisht [79] incorporated crumb rubber into OPC concrete as aggregates replacement and showed that the sulfuric acid resistance was significantly improved. These results are due to the fact that the inclusion of crumb rubber reduced the concrete separation and quickly reacted with acid to generate adhesiveness, mitigating the crack formation. However, the compressive strength of crumb rubber concrete decreased; thus, the rubber content was limited to 4% by volume.

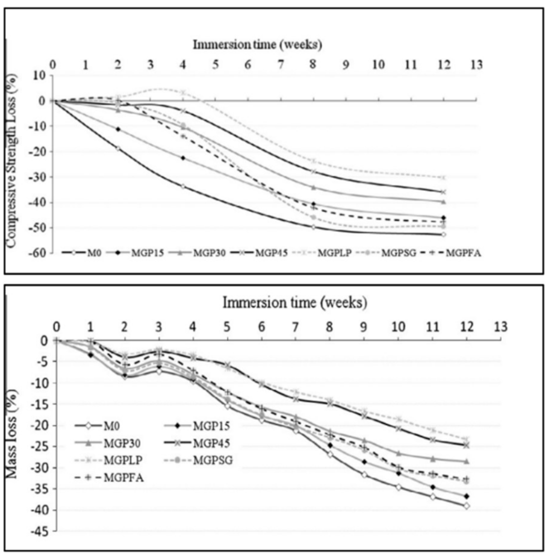


Fig. 12 – Compressive strength loss and mass loss of mortar samples after sulfuric acid test [74]

Alum sludge, derived from drinking water purification processes, is a recent addition to the list of pozzolanic materials. Based on the testing results of recent studies [80–83], the blended sludge-cement binder system transferred the original 'Al-minor' C-(A)-S-H gel to 'Al-rich' C-(A)-S-H gel [80]. Also, the formation of aluminium-bearing phases was promoted, such as calcium aluminate hydrates (C-A-H) and $Al(OH)_3$ gel, which exhibited excellent acid resistance [81,82]. Therefore, alum sludge may contribute to improving the acid resistance of concrete products when used as supplementary cementitious material or a solid precursor of geopolymer binder. However, only limited research has been done, a comprehensive study on acid resistance of sludge-derived composites is required.

4. External rehabilitation technologies

4.1 CFRP

Improving concrete mix design using alternative binders or some filler materials can reduce the corrosion risk. However, external rehabilitation technologies also need to be applied to prolong the longevity of existing sewerage pipes. The current rehabilitation methodologies, such as CFRP liners, HDPE (High-Density Polyethylene) liners, epoxy liners, and cement-based liners, are reviewed in this section.

CFRP is the most used rehabilitation material for deteriorated concrete pipes [84]. It has favourable long-term durability as well as high strength. CFRP can be easily bonded to the surface of the damaged area with epoxy adhesive to enhance the load-carrying capacity. Moreover, CFRP can also hinder sulfuric acid ingress, therefore effectively protecting the integrity of concrete pipes. Hu et al. [85] used CFRP as an inner liner to repair a prestressed concrete cylinder pipe (PCCP) under combined loads (Fig.13). The rehabilitation effect of CFRP-lined PCCP was evaluated by 3D finite element analysis (FEA) models. The results showed that CFRP-lined PCCP had an excellent rehabilitation effect on the inner concrete core, and CFRP worked even more effective with the increasing number of broken wires. Another case of using CFRP-lined PCCP under internal pressure was also reported in the study of Ozbay et al. [86]. To prevent a catastrophic failure of PCCP by broken pre-stressing wires, CFRP adhered at the inner concrete core as an internal repairing method. A full-scale experimental, as well as FEA model (see Fig. 14), was conducted to evaluate the structural performance of the CFRP-lined PCCP. Results showed that the watertightness could be improved by using CFRP laminate under internal pressure. Simulation results also showed that, for each additional CFRP layer, the design pressure threshold value increased by seven broken wires under the damage limit state and by 20 broken wires for the working pressure. Similar results were also reported in Zhai et.al. [87]. Prestressed concrete cylinder pipe operation was improved after repairing with CFRP; strains and stresses both decreased at the spring line. The strengthening effect of CFRP-lined PCCP was enhanced as the number of repair layers increased [88].

Fig. 13 – The image of CFRP-lined PCCP [85]

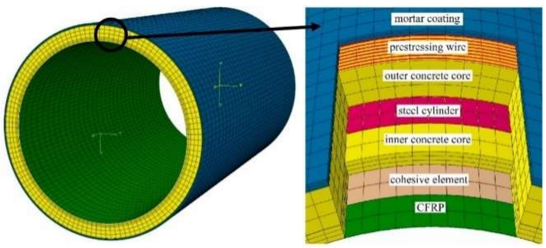


Fig. 14 – FEA model of CFRP-lined PCCP [86]

Other than PCCP, the use of CFRP to repair RCP has also been investigated [89]. A 610mm diameter pipe with 0.52% volume polypropylene fibre reinforcement was tested under a three-edged bearing load. The pipe was pre-cracked and repaired with CFRP then exposed to 3% saline solution for up to 3000 hours. Results showed that triple layers of CFRP were required for complete recovery of ultimate strength. However, debonding issue of CFRP due to buckling is a major drawback of this retrofitting technology as can be seen in Fig. 15. The epoxy bonding material is susceptible to acid attack, which leads to a delamination issue inside the pipe. The CFRP retrofitting system also requires a careful preparation of degraded pipe surface, the corrosion layer generated on concrete surface needs to be removed before applying epoxy bonding agent. The best solution to install CFRP is by hand lay-up, thus, this application limits its use to man-entry sewer only.

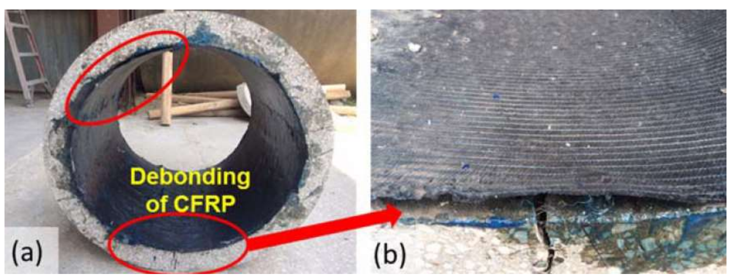


Fig. 15 – The images of CFRP-lined RCP [89]

4.2 Slip lining

Slip lining rehabilitation for sewer pipes has been developed for decades, which is the oldest pipeline renew technology that uses a corrosion-resistance liner material to cover the deteriorated concrete pipe. The liner material includes high-density polyethylene (HDPE) line and corrugated steel pipe liner depending on different applications. Simpson et al. [90] used slip lining to rehabilitate an RCP under surface loading. Before and after slip lining, two damaged RCP samples were buried and tested under surface load. Reported rehabilitation results showed that the stiffness of the pipes was significantly increased by 87%, and the vertical diameter deformation was decreased by 93%. Li et al. [91] investigated the load-sharing theory of slip-lined RCP with HDPE liner; the obtained results showed that the load-carrying capacity was 1.51 times higher than the original RCP. The cracking distribution and pipe after HDPE lining is shown in Fig.16.

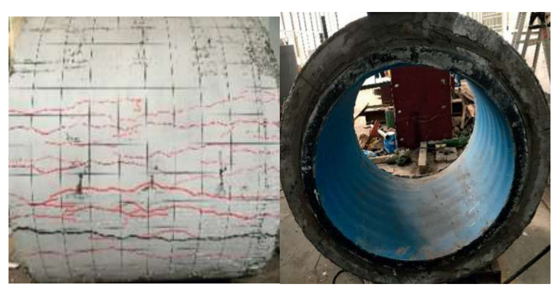


Fig. 16 – Crack distribution and RCP repaired with HDPE liner [91]

Grouted corrugated steel pipe liner has also been widely used in slip lining. Li et al. [92] investigated the performance of an RCP rehabilitated with a grouted corrugated steel pipe (CSP). The CSP rehabilitated RCP showed an increase in both stiffness and load-carrying capacity. A grout was poured between the CSP and existing RCP, which played a critical role in this circumstance by distributing the loads (load mechanism is shown in Fig. 17). The CSP-lined RCP acted as a pipe-in-pipe system and provided a promise solution for deteriorated concrete sewer rehabilitation. Also, the structural performance of CSP-lined RCP was investigated by the study of Hu et al. [93]. The results showed that the RCP could undergo a large residual deformation after rehabilitating with a CSP liner. A calculation method was proposed, and the estimated value of the test loading capacity of post-rehab RCPs is provided within 30%.

A significant limitation of slip lining with grouted CSP is the reduction of pipe section area. According to Smith et.al. [94], 10% to 30% of the pipe cross-section area was reduced. This drawback of slipliner may result in a non-compliance of hydraulic capacity for the sewerage pipe.

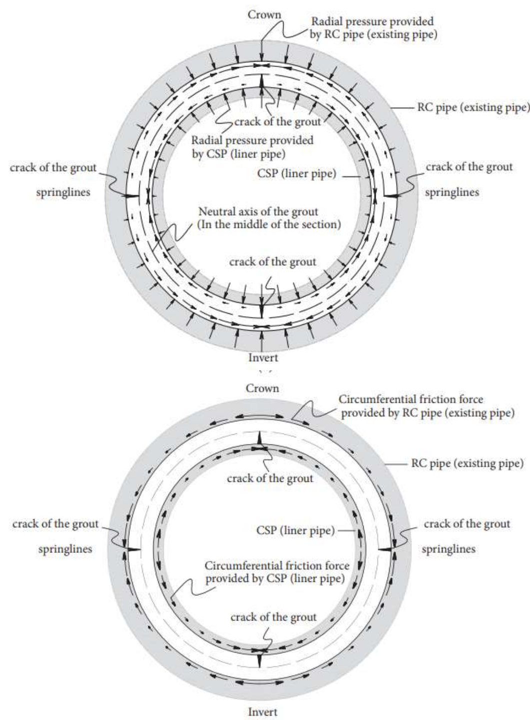


Fig.17 – Stress distribution of CSP-lined RCP [92]

4.3 Epoxy and mortar lining

Epoxy lining material has been used in the actual crown and tidal zone due to its superior resistance to biogenic acid attack [95]. Also, the D-load of epoxy-lined concrete pipes has been improved [96]. As shown in Fig. 18, the three-edged bearing test was conducted on epoxy-lined concrete pipe with strain gauges attached to pipe crown, invert and spring lines. Results showed that by adding a 3-mm layer of epoxy lining inside the concrete pipe, the peak load increased by 6%, while 6 and 12 mm-thick liners resulted in 27% and 40% increase in the peak load, respectively (see Fig. 18).

The infiltration resistance of epoxy-lined concrete pipe was tested by Zhai et al. [97], in which a hydrostatic pressure test was conducted to investigate the effect of concrete flaw size, epoxy thickness and concrete surface preparation. The performance spray-applied epoxy lining is primarily governed by its shear capacity and the concrete tensile strength, and this promising lining system provided a feasible solution to repair large diameter concrete pipe subject to large hydrostatic infiltration forces.

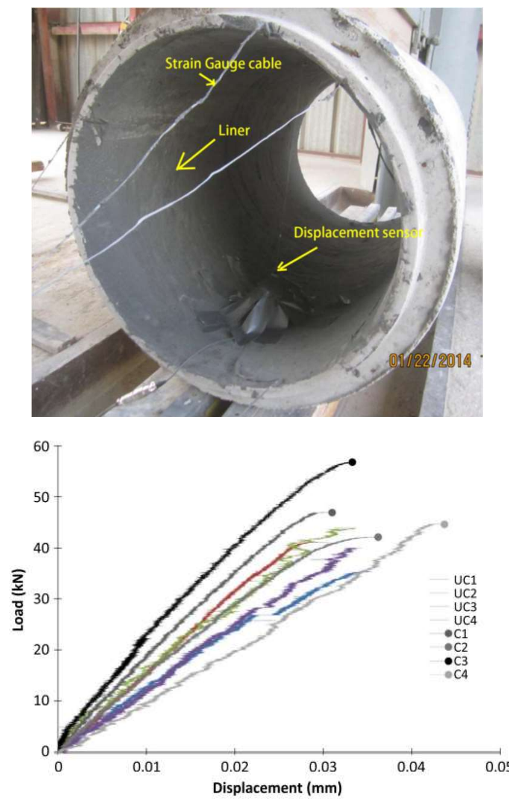


Fig.18 – Epoxy-lined concrete pipes and their peak load [96]

For cement-based liners, Zhao et al. [98] studied the structural performance of a rigid concrete pipe by spray-applied cement mortar liner. The pipe was pre-damaged to 14.7% with vertical deformation and then spray with 50 mm thickness lining. The experimental results showed that the D-load strength increased by 2% compared with the residual strength of the original pipe. However, the solely use of epoxy to retrofit pipeline is relatively expensive compared with other solutions, especially for structural application, the required thickness can lead to a high cost. Except for the uneconomical reason, epoxy is also a toxic material which is difficult for manual worker to handle it.

5. Conclusion and suggestions for future research

This paper carries out a state-of-the-art review on the fundamental of MIC mechanisms in sewage pipes and MIC mitigation strategies. The mitigation methods focus on enhancing the durability of cement-based materials, including mix design improvement for new-made concrete pipes and rehabilitation technologies for existing pipes. The conclusions can be summarised as follow:

- The sulfuric acid generated in the MIC process plays a critical role in cement deterioration. It can dissolve hydration products, transform the sound concrete matrix into non-cohesive materials and generate expansive gels.
- Optimising the concrete mix design aims to improve the acid resistance of hydration products and release agents to interfere with microbial activities. It is an effective method to ensure the service life and reduce the maintenance cost for the concrete pipes.
- CAC has an excellent corrosion resistant to MIC due to its special hydration products. However, the conversion issue limits its application in structural retrofitting.
- The application of geopolymer under sewerage environment has been widely discovered, the excellent resistance to acid attack makes it an alternative option to OPC. A major limitation of geopolymer is the manufacturing difficulty as well as the high cost.
- Filler materials includes siliceous, or aluminosilicates materials or crumb rubber can improve the acid resistance of concrete due to the generation of Si and Al-rich gel, which acts as a barrio to resist acid attack. But the associated drawbacks such as ASR issue, reducing compressive strength and lack of comprehensive study leave a big gap to be further investigated.
- External rehabilitation technologies provide promising solutions to prolong the service life of concrete pipes by applying lining materials on the inner surface of deteriorated concrete pipes. The rehabilitation materials can not only resist corrosion media penetration but also retrofit damaged pipes. However due to the debonding issue of CFRP, cross-section reduction of slipling and relatively high cost of epoxy, to find out an optimum solution that can balance the benefits and drawback of sewer rehabilitation is still challenging.
- Based on the current literature, most laboratory studies were conducted on concrete coupons taken from corroded sewerage channels, and limited research focused on the effect of MIC on retrofitted concrete structures. Therefore, the need for future studies is to advance understanding of the actual corrosion-resistance of rehabilitated concrete sewerage pipes. Monitoring and condition assessment of sewerage pipes have attracted many interests recently, the future research should also focus on the development of multi-functional concrete pipes, where the advanced carbon fibre could be combined with concrete to produce high strength, lightweight and durable composite structure, and the sensors could be installed to monitor the condition of the structure.

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