

Review

The Sustainability of Concrete in Sewer Tunnel—A Narrative Review of Acid Corrosion in the City of Edmonton, Canada

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Abstract: This paper is intended to conduct a narrative review on the acid corrosion of sewer tunnel concrete in the City of Edmonton—an investigation on the MIC (microbially induced corrosion) mechanism and the potential control methods to improve the sustainability of concrete. Firstly, three categories of main influencing factors were identified for the rate of MIC: hydraulic parameters, environmental factors, and concrete mixture design. Secondly, it is found that the sewer tunnel design plays an essential role in the control of the MIC. Building on that, a review was conducted on eight municipal drainage design standards in consideration of the MIC, indicating a lack of design standards of the flow velocity and pipe material. Finally, an investigation was done for cement-based rehabilitating techniques and materials.

Keywords: sustainability; microbially induced corrosion; Edmonton; control methods; rehabilitation; drainage design standards

1. Introduction

In sewer systems, when hydrogen sulfide gas (H₂S) emitted from sewage meets condensing moisture, the process can form sulfuric acid (H₂SO₄) that corrodes the concrete in sewer tunnel rapidly [1,2]. This is known as the microbially induced corrosion (MIC), which poses a severe threat to the sustainability of concrete in sewer tunnel. Acid corrosion causes a gradual loss of concrete, which significantly reduces the service life of concrete structures in sewer systems and may lead to structural failures such as collapse, threatening public safety. Costs to rehabilitate corroded sanitary sewer tunnels can be extremely high. In the United States (US) alone, it was estimated to cost around \$14 billion USD per year to rehabilitate and replace the deteriorated sewers [3]. When sanitary structures corrode, several processes coincide as a consequence of excessive chemical content (i.e., sulfate, acids, and chloride) in wastewater. Sulfate and acids react mainly with the cement hydration products, while chloride facilitates the corrosion of reinforcing steels by destroying the protective layer on steel surface [4]. Among these chemicals, sulfuric acid is particularly aggressive because of the highly expansive corrosion products [5].

Currently, concrete MIC issues have emerged throughout the sewer system in the City of Edmonton (COE), Canada. Many sewer tunnels are significantly deteriorated. For example, in Figure 1, the chamber and tunnel segment (located under the 127 street and 153 Avenue in Edmonton; constructed in 2001), was found severely deteriorated, showing peeled-off zone and exposed rebar in a walk-through inspection conducted in 2016. As a result, the lifetime of this chamber has been significantly reduced from 75–100 years to less than 20 years. In general, the lifetime of many sewer tunnels built in the 1960s and 1970s has been greatly reduced from 75–100 years to less than 50 years.

Severe corrosion (up to 100 mm in depth) was even observed in sewer tunnels built in the late 1990s (e.g., Clareview Sanitary Trunk). As shown in Figure 2, up to 20% of the sanitary infrastructure was reported to present poor conditions [6]. To repair the deteriorated sewer infrastructure, the COE has been spending a significant portion of its budget on rehabilitation. In 2009, the emergency repair cost was \$6.5 million CAD. By 2015, this number had jumped to \$16.8 million CAD [7].



Figure 1. Corrosion conditions in a chamber located under 127 Street and 153 Avenue in Edmonton.

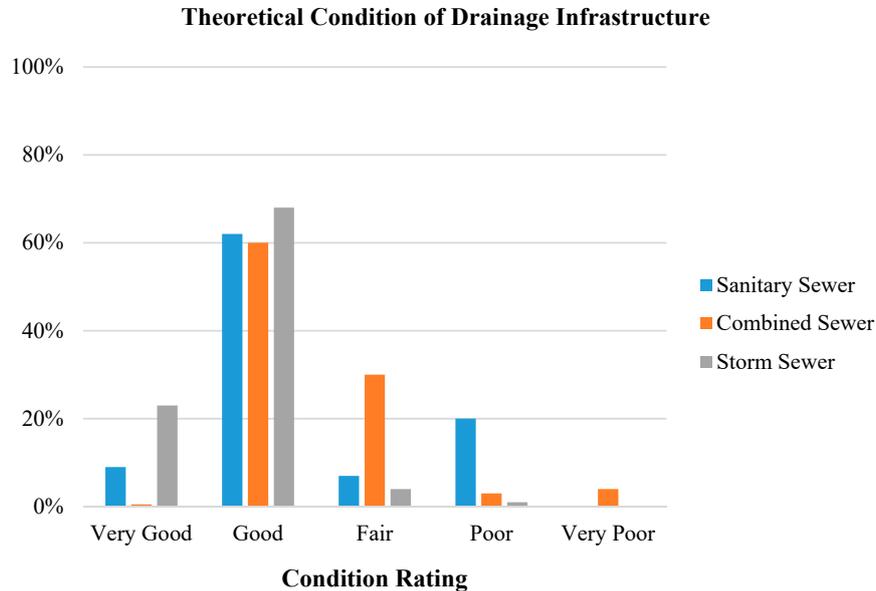


Figure 2. The estimated condition of Edmonton’s drainage infrastructure [6]. Modified from “Major Edmonton sewer trunk line hanging on by ‘ribs and lagging’” by E Stolte. (2015) *Edmonton Journal*.

However, there is a lack of understanding of how MIC occurs and what the options are to control it. To that end, this paper is intended to conduct a narrative review on the acid corrosion of sewer tunnel concrete in the COE. It aims to provide a preliminary investigation of the MIC mechanism and recommendations on how to mitigate MIC issues in Edmonton concerning drainage design, corrosion control methods, rehabilitation techniques, and materials.

2. Fundamentals for Microbially Induced Corrosion of Sewer Concrete

In the sanitary sewer systems, the progress of microbially induced corrosion (MIC) often determines the service life of concrete structure [8]. Under the MIC process, aqueous H_2S is firstly converted from sulfate by bacteria activities in a slime layer. After that, the gaseous H_2S is released from sewage to the tunnel crown. This gaseous H_2S then dissolves in the moisture film formed at the tunnel crown. Finally, the dissolved H_2S is converted to sulfuric acid (H_2SO_4) under the reactions of sulfur-oxidizing bacteria (SOB) (i.e., *Thiobacillus*) [9]. The sulfuric acid is the end product that reduces the pH value of the concrete surface down to 1–2 [10]. In such acidic environments, cement hydration products can be easily decomposed. That is, hydration products (i.e., portlandite, calcium aluminate hydrate, ettringite and calcium silica hydrate) dissolve sequentially when the pH of the solution gradually decreases from 12.5 to 8.8 or below [11]. In addition, the MIC is an active deterioration process in which bacteria provide sustained sulfuric acid in the reaction [10]; as a result, the MIC rate can be as high as 12 mm/year in many sewer systems [12] and even 14 mm/year in laboratory setups [13]. The following section provides more detail regarding the MIC process.

As shown in Figure 3, there are five sub-processes in MIC: carbonation, H_2S generation in sewage, H_2S buildup at the crown, sulfuric acid generation, and corrosion reaction. These sub-processes are explained in detail below.

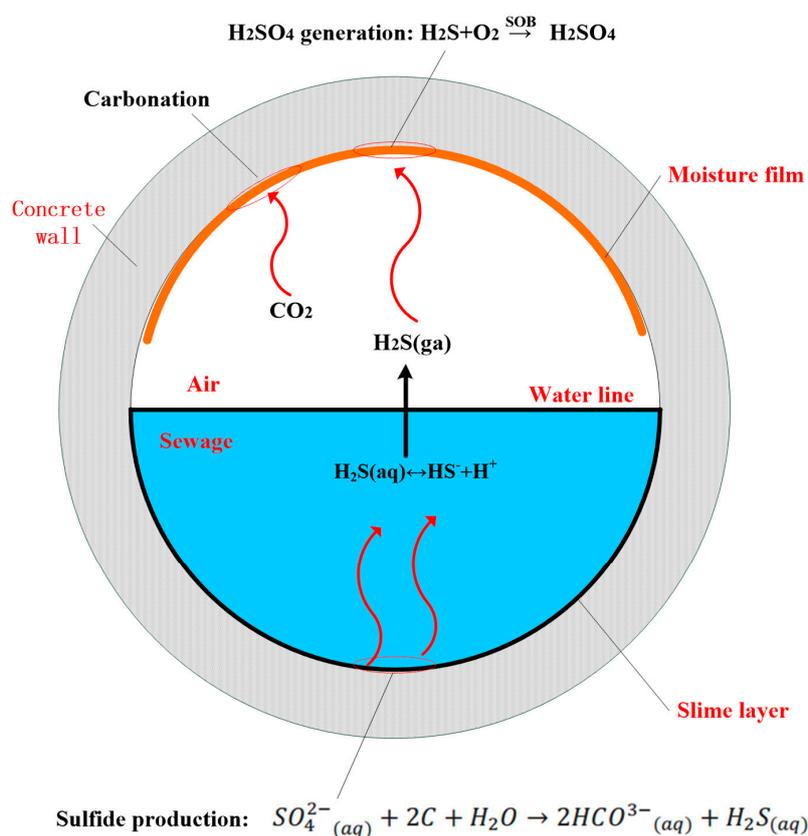


Figure 3. Schematic of the microbially induced corrosion (MIC) process within a sewer.

2.1. Hydrogen Sulfide Generation

The root cause of MIC is the formation of aqueous hydrogen sulfide— H_2S (aq). It is produced from sulfate in wastewater under a reaction with sulfate-reducing bacteria (SRB) located in a slime layer. The slime layer is a layer of bacteria and inert solids at the interface between the concrete wall and the sewage—the submerged portion [14]. The slime layer is typically between 0.3 and 1.0 mm thick, depending on the flow velocity and solids abrasion in the sewage [15].

The slime layer often consists of three laminated zones (counting from the sewage toward the concrete wall): an aerobic zone, an anaerobic sulfate-reducing zone, and an inert layer. These zones are presented in Figure 4. The aerobic zone has aerobic SOB that consumes the dissolved oxygen (DO) in sewage. The other two zones consist of SRB that requires an anaerobic environment (e.g., DO level < 0.1 mg/L). As it penetrates through the slime layer, oxygen in sewage is firstly consumed in the aerobic zone, leading to the second zone—an anaerobic sulfate-reducing zone [10]. The second zone is suitable for the growth of anaerobic SRB. In addition, as shown in Equation (1), these anaerobic SRB generate H₂S from the nutrients—sulfate and organic matters (org). The nutrients in sewage are gradually consumed by SRB while they diffuse through the slime layer, and nutrients concentration approaches zero near the surface of the concrete wall. At this location, the third zone, the inert layer, is formed. This portion of the slime layer is called the inert layer because it cannot receive enough sulfate and organic matter, and therefore the bacteria become inactive [15].

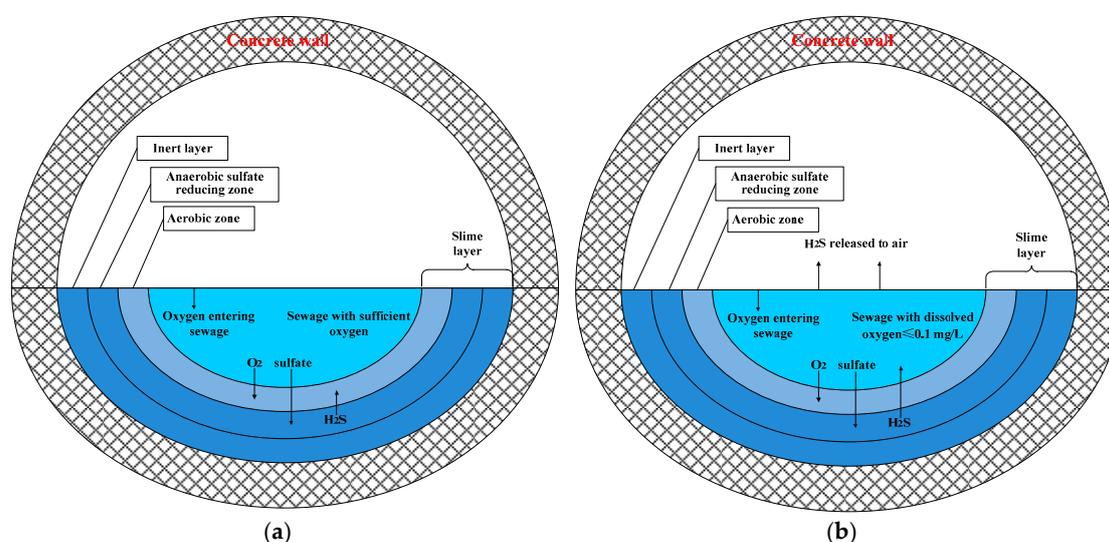


Figure 4. Process occurring in sewage with: (a) sufficient dissolved oxygen; and (b) insufficient dissolved oxygen.

The amount of H₂S that can be emitted from the slime layer is highly dependent on the DO level in sewage [10]. If the DO level is high, H₂S will be oxidized by the SOB in the aerobic zone—the first layer. As a result, no H₂S can escape from the slime layer to the sewage, as shown in Figure 4a. On the other hand, when the DO level in sewage is low, and DO is not enough to consume all the H₂S, the H₂S (aq) can diffuse through the aerobic zone—the first layer—and then disperse in the sewage as H₂S (aq), as shown in Figure 4b.



Many factors influence the concentration of dissolved H₂S in sewage, including the DO level, temperature, flow velocity, retention time, and biochemical oxygen demand (BOD). These factors are summarized in Table 1. Among these factors, the DO level is the most important [10,16] because other factors mostly affect the H₂S generation by altering the DO level in sewage. For example, temperature changes the oxygen solubility in wastewater; a high flow velocity encourages the aeration of wastewater; and a long retention of sewage gradually depletes DO in wastewater as a result of the relatively slow dissolution of new oxygen from the tunnel atmosphere. Another important parameter is the BOD that indicates the nutrient concentration—a high BOD level means that bacteria are more active in consuming DO in sewage.

Table 1. Summary of factors affecting H₂S generation.

Factors	Effects on H ₂ S Generation
DO	<ul style="list-style-type: none"> High DO enhances the oxidation of H₂S; thus, it reduces the release of H₂S from the slime layer.
BOD	<ul style="list-style-type: none"> High BOD accelerates bacteria activities and consumes oxygen.
Wastewater temperature	<ul style="list-style-type: none"> High temperature increases the microbial activity level in the slime layer. High temperature reduces the oxygen solubility in wastewater.
Flow velocity	<ul style="list-style-type: none"> High velocity accelerates the aeration of wastewater, so it increases the oxidation of H₂S, resulting in the lowered potential for sulfide build up.
Retention time	<ul style="list-style-type: none"> Long retention time depletes the DO in wastewater. Long retention time results in a loose slime layer that is easy for sulfate to penetrate.

2.2. H₂S Release from Sewage and Subsequent Sulfide Buildup at Crown

H₂S dissolves in sewage after it is diffused through the slime layer. The dissolved H₂S can exist as both aqueous H₂S and HS⁻ in wastewater, depending on the pH value. The reaction equilibrium (Equation (2)) determines the amount of aqueous H₂S in sewage. On the one hand, at a pH of 6, near 100% sulfur exist as aqueous H₂S in wastewater. On the other hand, when the pH rises to 9, H₂S content decreases significantly, and nearly 100% sulfur exists as HS⁻ [15]. The typical pH of sewage is in the range of 6 to 8 [17]. Thus, a large amount of sulfide exists as aqueous H₂S. The aqueous H₂S then is released in gaseous form from the sewage and disperses throughout the atmosphere in the sewer. This gaseous H₂S is a significant issue because it causes the acid corrosion of concrete during the subsequent process of MIC. In addition, gaseous H₂S results in odor problems when released out of the sewer system.



In addition to wastewater pH, the other two important factors that affect the release of aqueous H₂S are wastewater temperature and turbulence. They are summarized in Table 2. The first is the wastewater temperature—a high temperature improves the release of H₂S by reducing the solubility of H₂S. For example, it is reported that a variation of H₂S concentration at the crown corresponds with a daily variation in temperature [10]. The other factor is the turbulence—a strong turbulence directly exacerbates the release process of H₂S from sewage to the crown of the pipe. For instance, severe acid corrosion is often spotted in turbulent areas such as drop manholes, lift stations, and junction boxes [18]. Rather than these designated locations, strong turbulence can also result from high flow velocities or poor sewer construction.

After the release of gaseous H₂S into the sewer atmosphere, there is a sulfide buildup at the tunnel crown. That is, gaseous H₂S accumulates and dissolves around the tunnel crown. This buildup plays an essential role in MIC of concrete. There is a general idea that a higher gaseous H₂S concentration in the crown causes a higher level of corrosion. However, the relationship between H₂S concentration and the MIC rate remains unclear [19,20]. A wide range of H₂S concentration—from 2 ppm to several hundred ppm—can trigger severe acid corrosion [21]. For example, severe corrosion was also reported in a low concentration environment (e.g., 4 ppm) [13].

Table 2. Summary of factors affecting H₂S buildup.

Factors	Effects
Wastewater pH	Wastewater pH affects the H ₂ S _(aq) concentration in sewage
Wastewater temperature	Low temperature reduces the H ₂ S solubility in sewage
Turbulence	Strong turbulence exacerbates the H ₂ S release by increasing the area of sewage-air interface

2.3. Carbonation of Concrete Surface

Along with sulfide buildup, carbonation co-occurs at the tunnel crown (see Figure 3). Carbonation is a reaction between carbon dioxide and one of the concrete compounds (e.g., calcium hydroxide). Carbonation occurs when concrete is exposed to air.



Carbonation is a very slow process. The rate of carbonation is highly dependent on relative humidity (RH). The highest rates of carbonation occur when RH is in the range of 50% to 75%; CO₂ penetration would be restricted above 75% RH [22], thereby inhibiting the carbonation rate. Another factor that affects the carbonation rate is the permeability of the concrete. Low permeability concrete experiences slower carbonation than relatively permeable concrete because of the inhibited CO₂ penetration [23]. The low permeability usually comes with a low water-to-cement ratio and proper curing, leading to less carbonation [22]. Table 3 summarizes the effects of RH and permeability on the carbonation rate.

Table 3. Summary of factors affecting carbonation rate.

Factors	Effects
RH	The highest rates of carbonation occur in environments in which the RH of the surrounding atmosphere is kept in the range of 50% to 75% [22].
Permeability	Low permeability inhibits the penetration of CO ₂ , restricting the carbonation to the concrete surface.

Carbonation reduces the concrete surface pH by consuming alkaline calcium hydroxide (Equation (3)); as a result, the concrete surface pH decreases from 12–13 to as low as 8.5 [23]. This low pH is suitable to colonize microorganisms at the crown surface of the tunnel, allowing a further microbial process—sulfide oxidation.

2.4. Sulfide Oxidation

In this process, the H₂S is oxidized into sulfuric acid (H₂SO₄) through bacteria activities. First, moisture in the tunnel atmosphere condenses on the concrete wall, forming a moisture film. Then, due to carbonation, the surface pH of the concrete drops to around ~9, and the SOB starts to colonize on the crown of the tunnel [21]. The H₂S dissolved in the moisture film during the sulfide buildup is then oxidized by the SOB, which forms sulfuric acid.

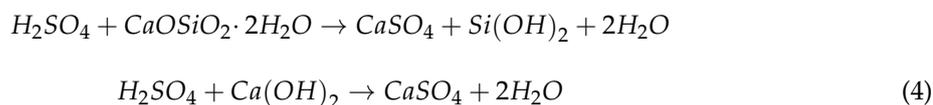
The sulfuric acid formation is mainly affected by two factors: atmospheric temperature and RH (see Table 4). Atmospheric temperature is critical for the intensity of microbial activities. High atmospheric temperature increase microbial activities [24,25], thereby raising the MIC rate. For example, the rates of sulfide oxidation at 25 °C were found 15% higher than those at 20 °C [21]. Temperature below 15.6 °C inhibits the bacteria's sulfide-oxidizing activity [26]. RH is the other influencing factor of the sulfuric acid formation. A minimum value of 87% RH is required for bacteria to be active [27]. In general, high humidity increases the rate at which sulfuric acid forms [28]. For example, the pH in a concrete surface was reduced more significantly when the RH was 95–100% than when the RH was 85–95% [29]. In other words, more sulfuric acid forms when the RH is between 95% and 100%.

Table 4. Summary of factors affecting H₂SO₄ generation.

Factors	Effects
RH	High RH increases the rate of H ₂ SO ₄ generation
Atmosphere temperature	High temperature accelerates microbial activities at the crown

2.5. Acid Corrosion Reaction

Because of its alkaline nature, concrete decomposes easily after sulfuric acid forms. In this process, aggressive ions in the sulfuric acid (i.e., H^+ and SO_4^{2-}) first penetrate the pore structures of the concrete, and then these ions react with hydration products such as calcium hydroxide ($Ca(OH)_2$) and calcium silica hydrate ($CaO \cdot SiO_2 \cdot 2H_2O$) (see Equation (4)). One immediate product is gypsum ($CaSO_4$), which is expansive—the volume increases by 124% [30,31].



Then, a subsequent reaction (see Equation (5)) occurs between gypsum and tricalcium aluminates. This reaction is destructive due to the formation of ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 31H_2O$) which expands the volume by ~227–700% [30–32]. The continuing generation of ettringite causes internal peeling and cracking, and finally leads to hydration products being removed from the conglomerate, and the concrete losing its integrity.



The chemical corrosion reaction rate is greatly regulated by the mixture design of concrete. For example, the acid corrosion rate decreased when calcareous aggregates were used in the mixture. This increases the alkalinity of the concrete surface and creates a local buffering environment for cement binder [33]. This research also observed higher levels of deterioration in concrete samples with higher cement content and lower water/cement ratios. In addition to concrete alkalinity, the porosity/permeability is considered the most important intrinsic property for predicting the durability of hardened concrete [10]. This also applies to the acid corrosion because aggressive sulfuric acid needs to penetrate through pore structures before attacking the inner part of the concrete. Therefore, when the mixture is designed properly, concrete can reach a low porosity that limits the corrosion rate. Another factor that changes the corrosion reaction rate is atmospheric temperature. Higher temperatures raise corrosion reaction rates [24]. Table 5 summarizes the factors affecting the corrosion reaction rate.

Table 5. Summary of factors affecting the corrosion reaction rate.

Factors	Effects
Porosity	High porosity enhances the penetration of aggressive ions
Atmosphere temperature	High temperature accelerates the corrosion reaction rate

3. Discussions about Potential Methods to Control Microbially Induced Corrosion

This section focuses on the potential methods to control MIC in the light of corrosion mechanism. As previously discussed, the rate of the MIC process is affected by many factors (summarized in Table 6). When these factors are controlled, the acid corrosion on drainage concrete may be mitigated or even prevented. Generally, these factors can be classified into three categories: environmental factors, sewer hydraulic parameters, and concrete mixture design. Environmental factors include RH, DO, BOD, wastewater temperature, atmospheric temperature, and wastewater pH; sewer hydraulic design parameters include flow velocity, turbulence, and retention; and concrete design parameters include porosity/permeability and alkalinity. In general, sewer hydraulic parameters mainly affect the processes of H_2S generation and the buildup process while proper concrete design reduces the corrosion reaction rate. Environmental factors can alter the rate of several subprocesses within the MIC. The control methods falling into these three categories are investigated and summarized in the following section.

Table 6. Summary of factors affecting MIC rate.

Factors	Effects
RH	<ul style="list-style-type: none"> The highest rates of carbonation occur in environments in which the RH of the surrounding atmosphere is between 50% and 75% [22]. A high RH increases the rate of H₂SO₄ generation
Porosity/Permeability	<ul style="list-style-type: none"> Low permeability inhibits the penetration of CO₂, restricting the carbonation to the concrete surface. High porosity enhances the penetration of aggressive ions
DO	<ul style="list-style-type: none"> A high DO increases the oxidation of H₂S, thereby reducing the release of H₂S from the slime layer
BOD	<ul style="list-style-type: none"> A high BOD encourages bacteria activities that consume DO
Wastewater temperature	<ul style="list-style-type: none"> A high temperature increases the microbial activity level in the slime layer A high temperature reduces H₂S and oxygen solubility in sewage
Atmosphere temperature	<ul style="list-style-type: none"> A high temperature accelerates the corrosion reaction rate A high temperature increases the microbial activity level at the crown
Flow Velocity	<ul style="list-style-type: none"> A high flow velocity encourages re-aeration resulting in the growth of sulfur-oxidizing bacteria (SOB), hence encourages chemical oxidation resulting in lowered potential for sulfide buildup
Turbulence	<ul style="list-style-type: none"> A strong turbulence exacerbates H₂S release by increasing the area of sewage-air interface
Retention time	<ul style="list-style-type: none"> A long retention time depletes the DO in wastewater A long retention time results in a loose slime layer, which is easy for sulfate penetration, hence increasing SRB activities.
Wastewater pH	<ul style="list-style-type: none"> Typical sewage pH ranges between 6 and 8 [17]. It affects the H₂S_(aq) concentration in sewage.

3.1. Changing Sewer Tunnel Environment

The first category of control methods is achieved by changing the sewer environment. The sewer tunnel environment includes the wastewater (sewage) and the tunnel atmosphere. The available control methods that the authors are aware of tend to adjust wastewater conditions by adding chemicals to the wastewater. Many chemicals dosed to the sewage have been effective in reducing sulfide concentrations in sewage. These chemicals include magnesium hydroxide, sodium hydroxide, iron salts, free nitrous acid (FNA), nitrate, oxygen, hydrogen peroxide, ozone, chlorine, and permanganate. There are three main mechanisms for these chemicals in controlling MIC: (1) raising the pH of sewage and hence reducing the H₂S state sulfide in sewage, such as by using magnesium hydroxide and sodium hydroxide [34]; (2) inhibiting SRB growth, thus reducing the production of sulfide, such as by using iron salt [35,36], FNA [37], nitrate [38–40], magnesium hydroxide and sodium hydroxide; and (3) oxidizing sulfide directly, such as by using oxygen [41], ozone, hydrogen peroxide, chloride and permanganate [42].

There are many drawbacks to these chemical-adding methods, beginning with the high cost of the required continuous dosing to the sewage. In addition, some chemicals dosed into the sewage can cause environmental problems. For example, unwanted chemicals may be generated as a result of the dosed chemical and the chemicals already in the sewage [21].

3.2. Using Proper Hydraulic Parameters in Sewer Design

The second category of control methods is the use of appropriate hydraulic parameters in design. These parameters include sewage flow velocity, retention, and turbulence [15]. In general, high velocity in the flow stream increases the DO level and accordingly reduces the aqueous H₂S content

in sewage [16], while sudden turbulence enhances the release of H_2S which accelerates the MIC process [10]. The DO level of sewage is key to the H_2S generation process. A high flow velocity of sewage enhances the turbulent diffusion of atmospheric oxygen into water, so it increases the DO level in wastewater. This high DO intensifies the oxidation of H_2S during its diffusion back to sewage; hence, it reduces the aqueous H_2S content in wastewater. Above a certain flow velocity, there will be no generation of H_2S [43,44]. In other words, low velocity and long retention time should be avoided in sewer system design to prevent DO depletion under such conditions. In practice, wastewater storage in pump stations and debris and sediment buildup in sewers are common sources for the long retention of wastewater in sewer systems. These locations tend to trap sulfate and organic matters, leading to more active SRB. This causes the high content of aqueous H_2S in wastewater. In this case, when H_2S has already appeared in sewage, high velocity/turbulence accelerates the release of H_2S from wastewater to the tunnel crown. There are many potential sources of turbulence in sewer systems: a hydraulic drop in a manhole, discharge from force mains, sharp bends, junctions, and sections with steep slopes [16].

Accordingly, some locations are particularly susceptible to MIC. These include locations with high turbulence where upstream have long retention or low velocity [15]. One example of such a location is a force main from which water is discharged. Wastewater, stored in the wet well of a pump station, is pumped through the force main and released to the sewer tunnels at the discharge. Long retention in wet well provides the perfect condition for the H_2S generation, while the high turbulence at the discharge of force main enhances the release of H_2S . Note that full flow in the force main will also increase the H_2S generation since no atmospheric oxygen is available to oxygenate the wastewater [45,46]. This further increases the potential for corrosion at the discharge.

In the authors' opinion, high velocity in the flow stream is recommended in sewer design, while sudden turbulence such as hydraulic jump should be reduced. When long retention and undue turbulence are impossible to avoid, proper supplementary measures should be taken to control concrete corrosion:

1. When debris and sediment buildup cause long retention or low flow velocity, a good maintenance plan is more efficient than proper tunnel design to minimize the buildup of hydrogen sulfide.
2. When the long retention is caused by the storage of wastewater—at locations such as pump stations—chemical dosing to the wastewater in a wet well will greatly reduce the chance of H_2S generation [47].
3. When sudden turbulence is inevitable, the quality of wastewater upstream of the turbulence should be carefully evaluated before selecting the pipe material.

3.3. Improving Concrete Mixture Design

The third category of control methods has to do with improving the concrete mixture design. Note that acid corrosion is unavoidable because the cement-based concrete is alkaline in nature, and decomposes under an acid environment [22]. However, improving the concrete mixture design is still a viable method because it changes the rate of the corrosion reaction process. Here, two additives are taken as examples in the concrete mixture design: one is the addition of pozzolans, and the other is the introduction of biocides.

The first type of additives are pozzolans. Some researchers partially replaced cement with pozzolans (e.g., ground granulated blast furnace slag, rice husk ash, pulverized fuel ash, palm oil fuel ash, silica fume, fly ash and metakaolin) [48]. The incorporation of pozzolans generally changes the acid resistance of concrete in two aspects: the change of chemical compositions and the reduction of porosity. The first aspect is the change of the chemical compositions due to pozzolanic reaction. When added in the mixture, pozzolans chemically reacts with calcium hydrate $Ca(OH)_2$ in the concrete matrix forming extra calcium-silicate-hydrate (CSH) which possess cementitious properties [49]. This reaction is called the pozzolanic reaction, which consumes the $Ca(OH)_2$ that is believed to be the primary reason for the poor acid resistance of plain concrete [50]. The reduced content of $Ca(OH)_2$ in concrete through pozzolanic reaction results in the lesser formation of expansive corrosion

products in acid attack [51]. This mitigates the corrosion rate of concrete under acidic environment. Furthermore, the extra calcium-silicate-hydrate (CSH) from pozzolanic reaction, is more stable than $\text{Ca}(\text{OH})_2$ under an acidic environment [52]. In addition to the chemical compositions, the second aspect is the reduction of porosity. The addition of pozzolans refines the pore structures of concrete and reduces its porosity. This is due to the CSH produced from pozzolanic reactions and the filling of small pozzolans particles [53,54]. The porosity is crucial to the acid resistance of concrete because it affects the penetration of aggressive ions from acids into concrete [55]. A higher porosity causes a larger diffusion of the aggressive ions into concrete, which increases the contact area between cement hydrates and the aggressive ions [56]. In other words, a lower corrosion could be expected in concrete with a lower porosity—this has been supported by many studies. For example, Chatveera et al. [57] found that a more porous concrete tends to show more negative effect from the acid attack. In addition, some other literature [49] reported the improvement in resistance to harmful solutions due to the refined concrete pore structure. However, the reduced porosity does not guarantee a better acid resistance of concrete. Under severe sulfuric acid attack, Senhadji et al. [58] found that refining the porosity had little effect on the improvement of the acid resistance. They observed that the addition of silica fume reduced the porosity of concrete, but the acid deterioration of concrete was not effectively prevented. Besides that, some controversial results were also reported regarding the effectiveness of pozzolan addition. Some studies observed opposite results [59–61] of pozzolan addition on acid resistance owing to variations in experimental conditions and the chemical composition of differently sourced pozzolans. Therefore, the chemical compositions of pozzolans should be individually examined, and experimental conditions should be mimicked as close as possible to the real sewer conditions before using it in an actual sewer. In this way, a better determination can be made whether they are effective at improving corrosion resistance.

Apart from the pozzolanic materials, the innovative addition of biocides into concrete mixture provides another possibility in combating MIC in sewer tunnels. For example, the addition of Conshield to concrete mixes inhibits the SOB (e.g., *Thiobacillus*) colonies on the concrete surface [62]. Different from pozzolans, Conshield is a highly charged cationic polymer that kills the gram-negative *Thiobacillus* on a concrete surface. As previously mentioned, the *Thiobacillus* on the tunnel crown converts the H_2S into sulfuric acid. The elimination of bacteria could prevent the generation of aggressive acid, which cuts off the MIC process fundamentally. However, this material has not been widely used due to the concerns from industry that the cationic polymer is consumptive, and the SOB may finally colonize the concrete surface when it is depleted. Besides Conshield, some literature has investigated many other materials for their use as biocidal additives in concrete. For instance, Park et al. [63] examined the effectiveness of Zeolite and Zeocarbon microcapsules on the prevention of fungi growth in concrete. In their study, no fungus growth was observed on the surface of concrete. Freed [64] patented reinforced concrete containing antimicrobial-enhanced fibers, which aimed to reduce the susceptibility of concrete against biogenetic attack. Although the addition of these materials has been verified to be effective for some microorganisms, their biocidal effects towards the SOB have not been examined. More research is needed specifically for combatting MIC in sewer tunnels.

3.4. Other Methods

In addition to previous three categories of control methods, there are more options to control MIC, and the number is still increasing. One of these methods is surface treatment on concrete. As the name suggests, surface treatment is a technology that uses physical or chemical additives sprayed on the surface of a concrete liner, so the SOB can be inhibited or deactivated. For example, coating with a sacrificial layer, such as magnesium, increases the surface pH, which inhibits bacterial colonization [65]; coating with incorrodible materials, such as epoxy [66], prevents concrete from coming into contact with the corrosive environment. Additionally, recent research reported that high-pressure washing increases the concrete surface pH by removing the corrosion layer and consequently decreasing the

bacteria. However, it only took 60–140 days for the SOB to recover to its pre-washing level [67]. The disadvantages of these methods are summarized in Table 7.

Table 7. Disadvantages of coating and surface wash.

Methods	Disadvantages
Coating with sacrificial layer	<ul style="list-style-type: none"> Applying the sacrificial layer requires regular treatment and preparation of concrete surface. The sacrificial material is costly.
Coating with incorrodible materials	<ul style="list-style-type: none"> Some coating chemicals are not environmentally friendly.
Surface wash	<ul style="list-style-type: none"> It is effective only in the short term. Must frequently be repeated.

4. Rehabilitation

In addition to the control methods, another important aspect in combatting MIC is the approach to make deteriorated structure functional again—this is called rehabilitation. In rehabilitating sewers deteriorated by MIC, there are three categories of techniques: repair, renewal, and replacement. The progression from repair to renewal to replacement requires increasing investment, targeting at decreasing level of concrete integrity [68]. As summarized in Figure 5, many rehabilitation methods are currently available, including point repair, shotcrete, cured-in-place pipe (CIPP), slip lining, fold-and-form pipe, and epoxy coating. Each method may be capable of one or more categories of rehabilitation. Renewal or replacement is often required to rehabilitate sewer infrastructure severely corroded by the MIC, and there are many technologies available for this, as shown in Figure 5. However, this paper will only investigate the advantages and limitations of cement-based renewal technologies and materials. Note that the term “renewal” is interchangeable with “rehabilitation” in the sewer industry. This paper follows the same convention.

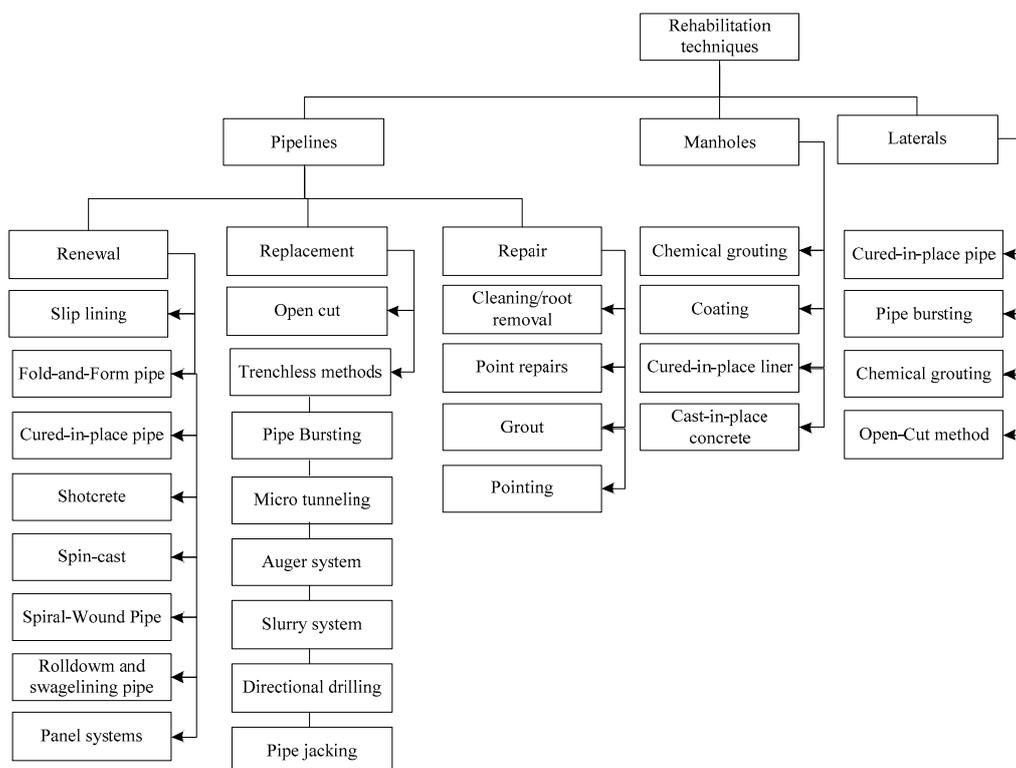


Figure 5. Rehabilitation techniques.

4.1. Cement-Based Rehabilitation Techniques

Cement-based rehabilitation methods are actively used in severely deteriorated sanitary sewer tunnels because of their excellent mechanical and bonding performance on damp surfaces. They can provide structural rehabilitation to deteriorated sanitary tunnels, where the existing pipe acts merely as a right-of-way in the liner installation [69]. Cement-based materials can be sprayed (shotcrete), pumped (cast-in-place concrete), and spin cast. More details are explained in the following section.

4.1.1. Shotcrete

Shotcrete is the method of pneumatically spraying fresh cement-based mixtures onto a surface through a hose at a high velocity [70]. There are two types of processes—wet-mix and dry-mix. In the dry-mix process, water is added at the nozzle, while, in the wet-mix process, all ingredients are mixed with water before being introduced to the delivery hose and the nozzle. As shown in Figure 6, shotcrete mixture is conveyed through a hosepipe and then sprayed via a nozzle onto the corroded tunnel wall. During the rehabilitation, mesh is often incorporated in operation to limit cracking and provide structural support.

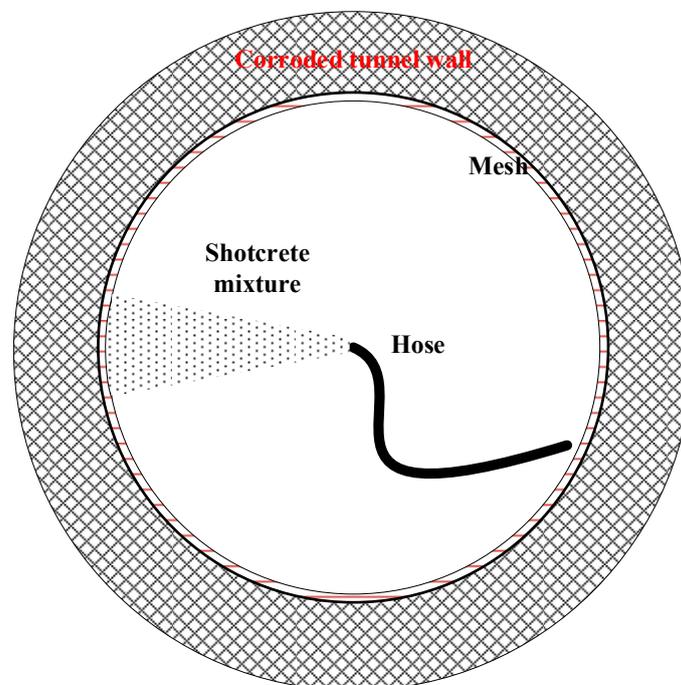


Figure 6. A schematic showing the shotcrete rehabilitation process.

Shotcrete has been actively used as a flexible and economic rehabilitation technique for sewer tunnels, providing better performance than conventional concrete. Shotcrete's high-speed pneumatic projection provides enhanced compaction, resulting in superior bonding characteristics and strength. It also gains increased density and reduced permeability. The high density and low permeability reduce the penetration of the aggressive solution into the concrete pore structures [71]. Consequently, shotcrete demonstrates more improved acid resistance than ordinary cast concrete [68]. In addition, shotcrete eliminates the necessity of formwork or an assembly system; thus, it can be applied at a faster rate and lower cost than conventional concrete placement methods.

However, there are limitations to using shotcrete in sewer tunnel rehabilitation. The first limitation is rebound, in which large aggregates with cement and sand bounce off the receiving wall. The second limitation is that shotcrete has a relatively rough surface, which increases the Manning's value and causes an accumulation of sediment and organic matter. This could, directly and indirectly, accelerate

the MIC progress. Thus, after shotcrete is applied in a sewer tunnel, troweling is highly recommended to make the surface smooth. In addition, in-situ shotcrete is not applicable in small diameter sewers, manholes and other structures because it requires personnel entry, and equipment and material handling. The preferred diameter for shotcreting is approximately 122 cm and larger [68].

4.1.2. Cast-in-Place Method

Cast-in-place concrete is an effective rehabilitation method for a variety of sewer shapes. The designed steel mesh is affixed to the existing pipe as reinforcement. As shown in Figure 7, formwork (slip-forms or fixed-forms) are set up to provide the finished wall section prior to concrete placement [68]. The gap between the formwork and the tunnel wall is the annular space that will be filled later. A venting or overflow hole is required at the highest point of the formwork that not only provides a path for air to escape when fresh concrete is injected. This venting hole also informs the worker to stop grouting when it is overflowed [72,73]. After the formwork, a grouting pipe can be laid in the crown of the sewer tunnel. Then concrete ingredients are introduced and mixed in the grout plant on the ground. The readily mixed fresh mixture is next pumped to the grouting location through the pipe laid on the crown of formwork. When the venting hole is overflowed, the grout operation stops, and then the venting hole is sealed with a plug.

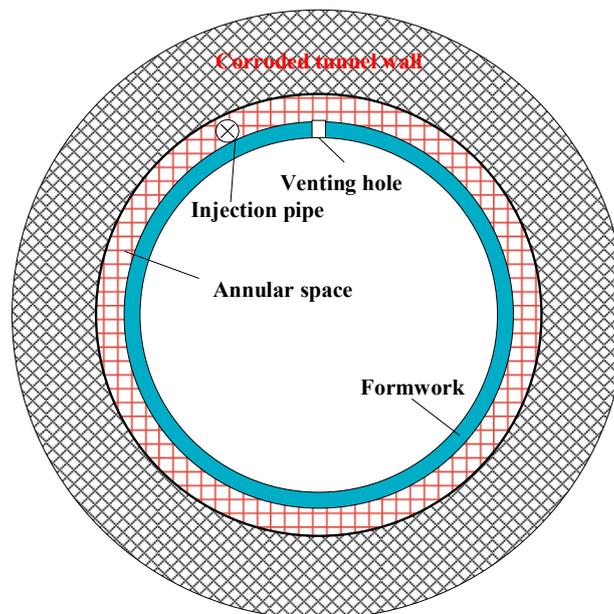


Figure 7. A schematic showing the cast-in-place rehabilitation process.

Studies reviewed for this paper showed that the cast-in-place method is seldom used in sewer rehabilitation. A recent literature review revealed only two documents [68,72] indicating such a use of the cast-in-place method. Possible reasons that this method is not widely used are that it requires extensive formwork and a minimum sewer diameter (approximately 122 cm or larger), and the material handling is labor-intensive.

4.1.3. Spin-Cast Method

The spin cast is an automated process that uses centrifugal force to spin cementitious materials onto the tunnel wall; it is an effective rehabilitation method for circular or near-circular sewers. First, a pumping plant is set up on the ground. Similar to cast-in-place method, all ingredients are introduced and mixed here. However, no coarse aggregates are introduced in spin-cast method. Then the readily mixed paste is transported to a spincaster (see Figure 8) that is located in the tunnel. During

rehabilitation, the spincaster rotates and sprays cementitious materials onto the old, corroded structure. This centrifugal projection produces a densely packed lining with little rebound [74]. As the projection proceeds, the spincaster moves along the tunnel axis. Theoretically, a thickness of one inch (25 mm) or more can be reached per pass [75]. Unlike the cast-in-place method, there is no need for man-entry in the confined sewer space; this makes spin-cast a safer technique that can be used in smaller sewer pipes. The major limitation is the difficulty in ensuring that the rehabilitation materials are distributed properly. In circular tunnels, spin-casting can provide uniform thickness if the spinning head is guided at a constant rate. However, for non-circular shapes, particularly shapes with sharp edges, it becomes almost impossible to achieve a uniform thickness of rehabilitation materials on the tunnel surface.

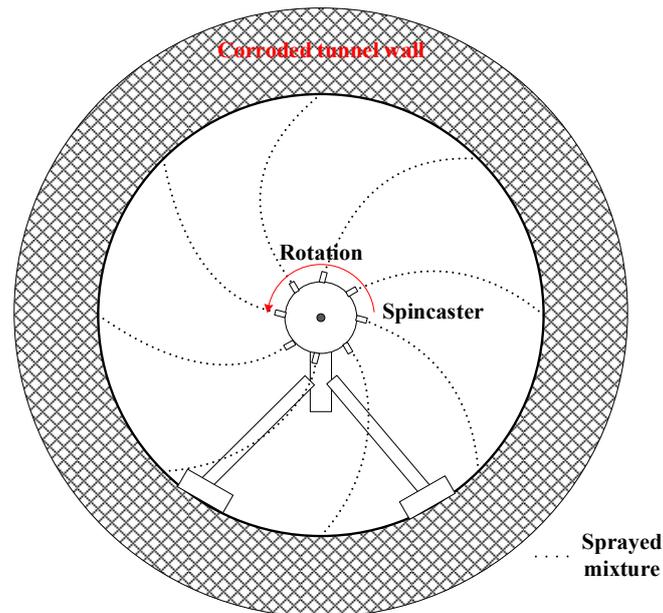


Figure 8. A schematic showing the Spin-cast rehabilitation process.

4.2. Cement-Based Rehabilitation—Method Selection

Rehabilitation methods and materials should be selected using criteria such as cost, inflow and infiltration (I & I), pipe cleaning, corrosion resistance, by-pass possibility, level of deterioration (structural or non-structural), access, above-ground conditions (i.e., access and traffic limitations), and underground conditions (i.e., depth of the pipe, groundwater, and crossing utilities). Table 8 compares the three cement-based rehabilitation methods using some of these criteria. As mature techniques, the three aforementioned cement-based methods have several advantages. First, they can rehabilitate sewers with various levels of deteriorations because the thickness of the rehabilitation layer is adjustable. Second, fiber or wire mesh can be incorporated into cement-based mixtures to enhance the mechanical performance and structural support. Third, cementitious material bonds well to damp surfaces, providing excellent integrity to the rehabilitated structure. Finally, the mixture design is adjustable, so its chemical resistance can be improved through optimized mixture design.

However, cement-based methods also have their disadvantages. First, tunnel surfaces have to undergo intense preparation, and infiltration and inflow must be removed to ensure proper bonding with old pipe. Second, a flow by-pass plan is needed, which greatly increases the cost. Third, because cement-based rehabilitation techniques reduce the cross-sectional area in all repaired tunnels, the sewage transport capacity of sewer tunnel will be reduced after rehabilitation. Finally, cement-based materials are subject to acid corrosion: all hydraulic-cement concretes, regardless of the composition, are unable to withstand for long in an acid with a pH below 3 [22]. Precautions must be taken to ensure the acid resistance of these cement-based materials.

Table 8. Summary of advantages and limitations of cement-based rehabilitation techniques.

	Advantages	Limitations
Spin-cast	Cost-effective Can be done without confined space entry Can be used in small diameter pipes	Limited acid resistance Flow by-pass required High level of cleaning required Removal of I & I required Decreased cross-sectional area
Shotcrete	Fiber-reinforced shotcrete shows excellent mechanical properties Improved compaction resulting in enhanced chemical resistance Applicable in most sewer shapes	Limited acid resistance Flow by-pass required High level of cleaning required Removal of I & I required Decreased cross-sectional area Applicable for tunnels with $\geq 35''$ in diameter Pumping length < 500 m Rebound impact
Cast-in-place concrete	Effective for a variety of sewer shapes	Limited acid resistance Flow by-pass required High level of cleaning required Removal of I & I required Decreased cross-sectional area Applicable for tunnels with $\geq 48''$ in diameter Formwork or assembly system required

4.3. Cement-Based Rehabilitation—Material Selection Based on the Acid Resistance

Acid resistance is the most important criterion to consider when selecting what kind of concrete/cementitious material to use in cement-based rehabilitation. Acid resistance is the term used to describe a material's ability to combat deterioration caused by acid [9]. However, it is not easy to evaluate acid resistance due to: (1) the lack of standard testing procedure; and (2) controversial results of acid resistance from various indicators. The first reason is the lack of standard specifying the testing procedure. This may lead to totally different results in different experiments for the same mix. The commonly used test procedure of assessment is to immerse concrete samples in an acid solution (known as the immersion method), which directly investigates the resistance of concrete to acid. Many researchers [48,51,76–82] have used this method to evaluate the effectiveness of supplementary cementitious materials (SCMs) in improving the acid resistance of the concrete. However, there are many drawbacks regarding the immersion method. First, this method requires long immersion time, often several months to several years. To shorten the test duration, acceleration is commonly required, such as increasing the testing temperature, using a high concentration of acid, a surface brush, and dry and wet cycling. Second, there is currently no standard specifying the detailed testing procedure, which may lead to totally different results in different experiments for the same mix. Variations in testing procedures and environmental conditions (e.g., temperature, concrete surface area-to-acid volume ratio, the frequency of acid replenishment, acid strength) can significantly alter the results. For example, improved acid resistance was found for silica fume concrete immersed in 1% sulfuric acid. However, Hewayde and Nehdi et al. [61] found little difference between the reference sample and silica fume samples with up to 15% replacement ratio after 61 days of immersion in 3% and 7% sulfuric acid. They concluded that this was attributed to the excessive acid concentration. Third, for the microbially induced corrosion (MIC) process, a simple acid immersion of samples cannot reflect the corrosion resistance of the mix as some mixes may inhibit the growth of bacteria instead of improving the chemical acid resistance. For example, Conshield, an additive to concrete mixes, was reported to be able to kill the sulfide-oxidizing bacteria (SOB) in the moisture film [62], but the chemical acid resistance was not improved. Thus, some researchers also tried to establish a test method that incorporates the microbial process occurred in sewer tunnels. For example, Mori et al. [83] and Sand et al. [84] built simulation chambers mimicking the sewer environment to test the biological corrosion of concrete. In these tests, specific conditions such as temperature, nutrients and humidity can be controlled. Furthermore, some researchers [12] mounted the concrete coupons in a real sewer

tunnel to observe the physicochemical process of MIC. However, the duration is even longer for these tests incorporating the microbial process than the immersing method, normally in the magnitude of years. More research is needed to develop a test method that is not only time efficient but also able to simulate the real sewer condition as close as possible.

In addition to the lack of testing procedure, the second difficulty comes from the controversial results of acid resistance from various indicators. Acid resistance itself is not a parameter that can be characterized by a single test; instead, it needs to be assessed by many different parameters. Some parameters are mass loss [9,52,85–88], strength loss [89–91], dimensional changes [85,86,92,93], corrosion depth [86,94,95], hydrogen ion consumption, and mineralogical changes [95]. Despite the frequent use of these parameters in the assessment of the acid resistance of concrete, low correlation between these parameters was reported in these studies. For example, Vlasta et al. [96] measured the concrete pH and the concentrations of Ca^{2+} and Si^{4+} in immersion solution as the indicators of the deterioration. They conducted analytical and statistical methods to correlate these parameters, but they found low correlations of Si/concrete pH and Ca/concrete pH and an inverse correlation of Si/concrete pH for samples immersed in a pH 3 sulfuric acid solution. In another study conducted by Chang et al. [92], a lack of correlation was also reported between mass change and strength change. This low correlation between assessing parameters may be due to the complex links between parameters and various processes. For example, among these parameters, mass loss that is the most commonly used one, is convenient to measure, and directly indicates the corrosion rate. However, the result of mass loss is greatly influenced by the sample density [97]. Strength is also not reliable because it is affected by three processes [97]: (1) corrosion reaction, which lowers the strength; (2) hydration reaction, which improves the strength; and (3) pore filling by corrosion products (e.g., gypsum), which improves the mechanical performance. Dimensional change and hydrogen ion consumption are not sensitive enough when acid used is at low concentrations. Thus, a combination of these indicators will be required to assess the acid resistance of concrete more accurately. However, there is very limited research focusing on this topic. The analytical and statistical models will be required to combine those assessing parameters.

5. Drainage Design Standards

A design standard would define requirements for planning, designing, constructing and maintaining drainage systems. Some standards [98] even include rehabilitating deteriorated sewer infrastructure. The review of microbially induced corrosion (MIC) fundamentals and rehabilitation showed that the progress of MIC is greatly related to the sewer design (hydraulic) and concrete mixture design. Proper design of drainage may be able to ease the MIC rate and extend the service life of concrete structures. This section is aiming to find out if the current municipal sewer design standards consider the MIC. Eight municipals design standards will be reviewed. Possible gaps will be identified, and recommendations will be made for further modifications to Edmonton's design standards. Building on the previous literature investigation of the MIC mechanism, design factors that can affect the MIC rate include flow velocity, concrete mix design, and retention time. The review will focus on these three aspects.

5.1. Flow Velocity

As mentioned in Section 2.1, flow velocity substantially affects the rate of MIC process. Eight municipal design standards were reviewed: those from Edmonton [99], London (Canada) [100], Hong Kong [98], Toronto [101], Saskatoon [102], Kamloops [103], Dallas [104], and Singapore [105]. Commonly, the flow velocity is calculated mainly to ensure that sewage is self-cleaning, and to minimize erosion and scouring. The effect of velocity on the progress of MIC is merely considered in the design standards. Table 9 lists the flow velocity specifications from various cities. Most cities use 0.6 m/s as the minimum velocity to ensure particle suspension in the flow. However, there is a wide range of the maximum velocity. A velocity of 3.0 m/s is adopted by most cities as the maximum value

to prevent scouring and abrasion of the tunnel wall. This value is increased to 6 m/s in Hong Kong when abrasion resistant pipe is used. Singapore and Kamloops use lower values of 2.4 and 2.5 m/s respectively. London (Canada) sets 4.5 m/s as the maximum allowable velocity.

A procedure to calculate velocity to prevent MIC was outlined in the United States (US) Environmental Protection Agency (EPA) design manual [15]. The change in flow velocity alters the dissolved oxygen (DO) level in sewage. Since the required DO level in sewage is related to temperature and the concentration of organic matter (or biochemical oxygen demand (BOD)), the EPA combined these two factors into effective BOD (EBOD) [15]. The required velocity to prevent MIC differs significantly depending on location. The EPA design manual [15] provides a detailed estimation of minimum pipe slope.

Table 9. Specifications for flow velocity.

City	MIC/Odor Issues	Min Velocity (m/s)	Max Velocity (m/s)	Comments
Edmonton	Yes	0.6	3.0	0.9–1.5 m/s (force main) Prevents undue turbulence, minimizes odors due to sulfide generation
London (Canada)	Not applicable	0.6	4.5	Ensures self-cleansing and minimizes erosion
Hong Kong	Yes [106]	0.7	3.0	Max velocity can be relaxed to 6 m/s for abrasion-resistant pipe Higher minimum velocities for larger sewers
Toronto	Yes [16]	0.6	3.0	Self-cleansing and minimizes erosion
Saskatoon	Not applicable	0.61	3.0	Reduces turbulence and scouring 1.0–1.6 m/s (force main)
Kamloops	Yes [107]	0.6	2.5	Self-cleansing and minimizes erosion
Dallas	Yes [108]	0.6	3.0	Self-cleansing and minimizes erosion
Singapore	Yes [109]	0.8–0.9	2.4	Self-cleansing and minimizes erosion

5.2. Retention Time

As previously discussed, a long retention of sewage enhances the generation of H₂S. Common causes for the long retention time are debris and sediment buildup, low flow velocity, and wastewater storage. Most city standards that were reviewed specified that sewers should be free of debris, and proper maintenance should be conducted to avoid grit and sediment buildup. The differences lie in the regulations concerning retention time in pump stations. Except for Edmonton and Hong Kong, the cities reviewed do not specify the shortest retention time for pump stations (see Table 10). In Edmonton, the maximum retention in a pump station is not to exceed 30 min; the total retention in a wet well and the force main should be less than four hours. However, such short retention times mean that the storage capacity is very low, which does not meet the high demand of pump capacity in wet seasons. Consequently, the actual design of many pump stations in Edmonton did not follow this design specification (10.10.1.IV); instead, a higher value was often used. For example, at the Duggan Lift station near Southgate Centre, Edmonton, the retention time is designed to be as long as 24 h. In this case, severe corrosion was observed at the discharge of the force main.

Table 10. Requirements of retention time in pump stations.

City	Retention Time
Edmonton	30 min in wet well 4 h in wet well and force main
Hong Kong	2 h

5.3. Mixture Design in the Concrete Liner

The material used in a liner is critical for extending the service life of concrete drainage structures under the MIC process. Most Canadian cities use Canadian Standards Association (CSA) standards for concrete mixture design and manufacturing, as listed in Table 11. In CSA standards, requirements for concrete are determined by the exposure level to the aggressive environment. Sewer concrete structures are subject to a class A exposure. For different classes of exposure, the CSA specifies various requirements for concrete. In an environment with more severe exposure, a lower water-to-cement ratio and higher strength are required. In class A-XL and A-1, concrete is expected to experience severe acid corrosion. Extra requirements for permeability are specified to extend the service life of a concrete structure subjected to class A-XL and A-1 exposure. For example, chloride penetrability should be <1000 coulombs within 91 days in class A-XL exposure [110]. In short, CSA standards have relatively comprehensive requirements for drainage structure concrete design.

Table 11. Canadian Standards Association (CSA) standards for concrete manufacture.

Construction	Standards
Precast concrete pipe (reinforced)	CSA/CAN A257.2-14 [111]
Precast concrete pipe (non-reinforced)	CSA/CAN A257.1-14 [112]
Precast concrete segment	CSA A23.4-16 [113]
Grouting	CSA-A23.1-14 [110] and ASTM C404-11 [114]
Cement	CSA-A3000 [115]
Shotcrete	CSA A23.2-14 [110]

However, since acid corrosion on concrete is unavoidable, acid resistant materials are preferred for sewer construction when possible. There is still a lack of regulations for commonly used non-cement materials in sewer systems. These materials include polyvinyl chloride (PVC), resin, and epoxy. Based on the findings in this paper, it is recommended to include a list of approved materials in the COE standards. The list should specify the characteristics of the materials such as the bonding strength with a substrate, acid corrosion resistance, correspondent rehabilitation techniques, and costs.

6. Concluding Remarks

Microbially induced corrosion (MIC) has been recognized as a destructive process posing a severe threat to the sustainability of concrete in sewer tunnel. To address this, this paper conducted a narrative review of acid corrosion regarding corrosion mechanism, control methods, cement-based rehabilitation techniques and materials, and drainage design standards. The main findings are summarized in the following:

1. Three categories of main influencing factors were identified for the rate of MIC: hydraulic parameters, environmental factors, and concrete mixture design.
2. Many chemicals dosed to the sewage have been effective in reducing sulfide concentrations in sewage such as magnesium hydroxide, sodium hydroxide, iron salts, free nitrous acid (FNA), nitrate, oxygen, hydrogen peroxide, ozone, chlorine, and permanganate.
3. A proper sewer tunnel design is an efficient and cost-efficient method to control MIC. It is recommended to consider MIC during the hydraulic design phase. However, the current COE standards do not include any related regulations.
4. All hydraulic-cement concretes, regardless of the composition, are unable to withstand for long in an acid with a pH below 3. However, improving the concrete mixture design is still a viable method for controlling MIC rate because it changes the rate of the corrosion reaction process.
5. Cement-based rehabilitation methods can be used in severely deteriorated tunnels to provide structural restoration. However, supplementary measures (e.g., coating and chemical dosing) should be taken to prevent future corrosion, due to the alkaline nature of the cement-based material.

6. No available testing standard was found that guides the acid resistance test of cement-based material at present.
7. There is a lack of regulations on commonly used non-cement materials in COE standards. It is recommended to include a list of approved materials in the COE standards specifying the characteristics of the materials such as the bonding strength with a substrate, acid corrosion resistance, correspondent rehabilitation techniques, and costs.

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