

A SUCCINCT OVERVIEW OF PROTECTIVE COATING MATERIALS AND STRATEGIES FOR CONCRETE SEWER AGAINST BIOGENIC CORROSION

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Abstract

Concrete sewer systems are prone to microbiologically induced corrosion (MIC). This process starts when hydrogen sulfide is converted into sulfuric acid by microbial activity, lowering the surface pH and speeding up the breakdown of Portland cement. Because of this, durable protective coatings have become increasingly important. This review summarizes recent developments in coating materials that can resist MIC, including polymer-based films, cementitious barriers, magnesium hydroxide layers, geopolymers, super hydrophobic treatments, antimicrobial options, and new hybrid or self-healing systems. Studies show that magnesium hydroxide coatings can keep the surface pH above 9.5 for nearly 90 days in 3% H₂SO₄, indicating strong neutralizing ability. Epoxy coatings generally show low mass reduction during accelerated acid testing, while geopolymer and super hydrophobic coatings help reduce gypsum formation and improve acid resistance. Hybrid Zn-PU coatings also improve durability through self-repairing features and multiple bonding interactions. Although the progress is promising, gaps still remain, particularly the limited availability of long-term field data and the absence of standardized test methods specific to MIC. Future research should focus on improved laboratory models of biocorrosion, practical criteria for selecting suitable coatings, and trenchless rehabilitation design. Better coatings and testing approaches are essential for durable wastewater systems.

Keywords: Concrete Sewer; Environmental Risk; Microbiologically Induced Corrosion; Protective Coatings; Sewage Pollution

Introduction

Concrete sewer systems play an important role in urban wastewater management because they are economical, strong, and suitable for complex pipeline layouts. Despite these advantages, they are highly susceptible to microbiologically induced corrosion which is a major cause of concrete

deterioration. MIC mainly develops from the biological generation of hydrogen sulfide and its oxidation to sulfuric acid (H₂SO₄) in humid environments. The resulting acidic conditions lower the pH of surface, dissolve calcium hydroxide, and develop the formation of expansive products such as

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gypsum and ettringite. With time, this leads to cracking and a gradual loss of structural integrity (Merachtsaki *et al.*, 2021a; Moa *et al.*, 2025). Further studies shows that MIC can reduces the service life of concrete sewer structures by 50 to 70%, which causes major economic impacts (Gonen and Uygunoglu, 2022). Traditional Portland cement based materials are widely adopted for their availability and low cost (MortezaNia and Othman, 2012; Wu *et al.*, 2021), but they are inadequate against corrosive environments. This has been an additional and important motivation for investigating other durable materials and coating systems. Recently, geopolymer concretes and polymer-based coatings have gained considerable interest owing to their improved acid resistance and mechanical durability (Di Emidio *et al.*, 2015; Glasby *et al.*, 2019; Almutairi *et al.*, 2021; Liu *et al.*, 2024) (shown in Figure 1).

The economic impact of sewer biocorrosion is a global problem. According to Yadav and Pramanik (2024), countries like the USA, UK, Germany, and Australia spend billions of dollars every year on the maintenance and rehabilitation of sewers. It is estimated that infrastructure renewal costs are projected to be in excess of \$125 billion AUD in Australia alone over the next 20 years. In India, although consolidated data at the national level is scarce, various municipal authorities have documented increasing rehabilitation costs, ushering in an immediate need for efficient, long-lasting, and sustainable corrosion protection measures (Yadav and Pramanik, 2024; Gupta *et al.*, 2025).

The corrosion in sewer systems proceeds through a series of interlinked biological and chemical changes, which has been identified as the sulfur cycle. Anaerobic conditions in sewage pipelines foster growth of SRB, which reduce sulfates into hydrogen sulfide gas. Upon volatilization into the sewer atmosphere and contact with concrete surfaces, this gas dissolves into the surface moisture film and is oxidized by SOB into sulfuric acid. The formation of this acid significantly reduces the pH of the concrete surfaces and allows the dissolution of calcium compounds and production of expansive corrosion products induced by acid (Suleiman *et al.*, 2014; Wang and Zeng, 2020; Yao *et al.*, 2025).

Historically, protective coatings including epoxy resins, coal tar, polyurethane, and mineral-based systems have all been used in the protection of concrete from biocorrosion. While these coatings have demonstrated varying levels of success, limitations including chemical degradation, inadequate bond performance under continuous wet exposure, high environmental impact, and inconsistencies in long-term performance have restricted their widespread reliability (Vipulanandan and Liu, 2005; Gonen and Uygunoglu, 2022).

Recent studies show several new coating materials for protecting concrete in sewer environments, like magnesium hydroxide coatings (Moa *et al.*, 2025), geopolymer binders (Pacheco-Torgal *et al.*, 2012), super hydrophobic composites (Roghianian, 2018; Wang and Zeng, 2020), and hybrid self-healing systems.

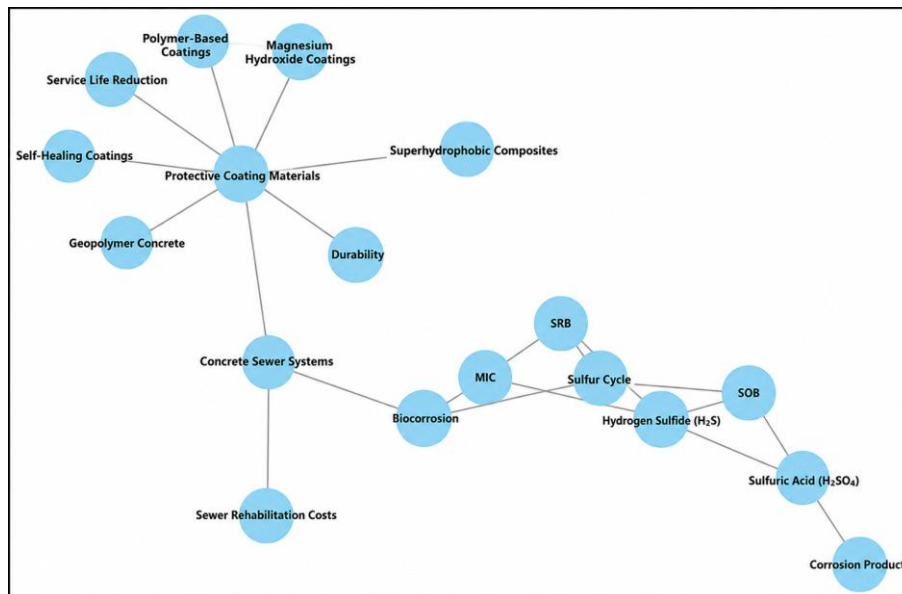


Figure 1. Keyword co-occurrence network for sewer concrete biogenic corrosion study

This review combines information on coating materials, MIC deterioration processes, and evaluation methods. It compares a broad range of protective systems including polymeric, cement-based, geopolymer, nano-modified, and hybrid coatings under exposure conditions such as MIC. Also included are recent improvements such as seawater-derived $\text{Mg}(\text{OH})_2$ coatings, super hydrophobic geopolymer composites, and self-healing Zn-PU systems, which are rarely discussed together. By combining results from both laboratory and field investigations, this review aims to determine which coating technologies offer the most practical and reliable protection against MIC.

Background

Concrete sewer systems are particularly susceptible to MIC due to complex biochemical, chemical, and environmental interactions within wastewater systems. Deterioration of sewer concrete with the generation and oxidation of hydrogen sulfide (H_2S), which leads to the production of sulfuric acid (H_2SO_4) and further corrosion of concrete surfaces (shown in Figure 2). The sulfuric acid reduces the pH of concrete surfaces and form corrosion products like gypsum and ettringite (Merachtsaki *et al.*, 2020; Merachtsaki *et al.*, 2021a; Merachtsaki *et al.*, 2021b). These low-pH environments offer favorable conditions for the growth of acidophilic bacteria, which further accelerate the rate of corrosion by producing biogenic sulfuric acid (Pacheco-Torgal *et al.*, 2012; Iglesias and Díaz, 2025).

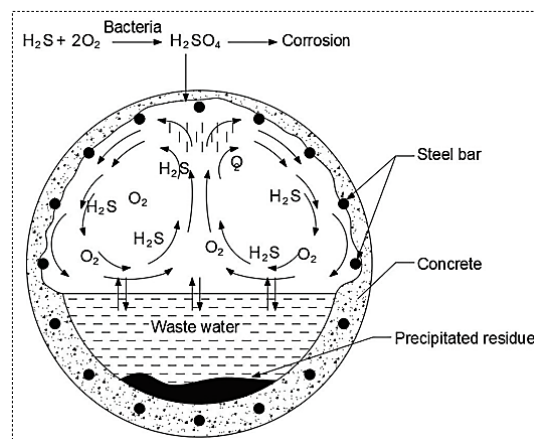


Figure 2. Formation of the H_2SO_4 in sewage systems (Gonen and Uygunglu, 2022)

Stages of Biogenic Corrosion in Sewer Environments

Biogenic corrosion proceeds through a series of successive steps, led mostly by the activities of sulfate-reducing bacteria (SRB) and sulfur-oxidizing bacteria (SOB). First, under the anaerobic conditions of the submerged sewage zone, SRB reduces sulfates in wastewater to hydrogen sulfide gas. The diffusion of this gas into the sewer atmosphere and its dissolution in the moisture film at the pipe surfaces makes it a substrate for SOB. These bacteria can oxidize the dissolved H_2S into sulfuric acid (shown in Figure 3 and Table 1), which progressively reduces the pH of the concrete surface from approximately 12-13 to values as low as 2.0

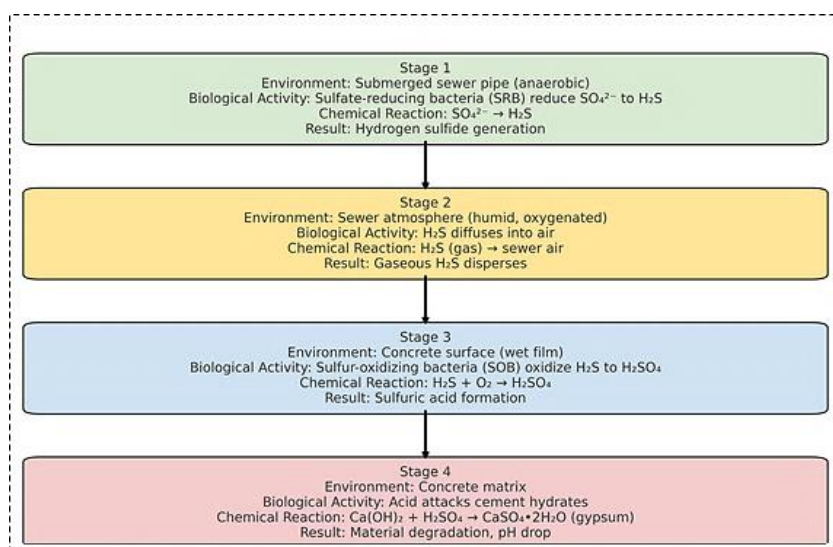


Figure 3. Flow diagram showing stages of biogenic corrosion

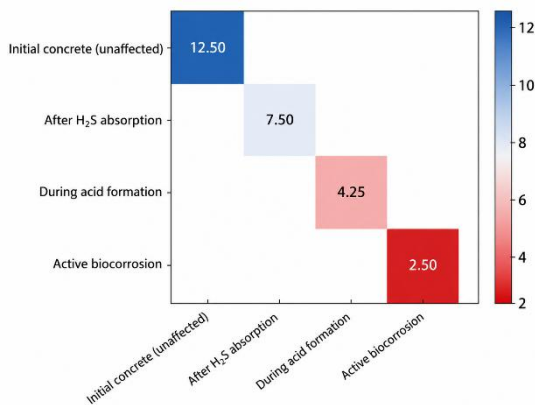
Table 1. Stages of Biogenic Corrosion in Sewer Systems

Stage	Environment	Biological Activity	Chemical Reaction	Result
Stage 1	Submerged sewer pipe (anaerobic)	Sulfate-reducing bacteria (SRB) reduce SO_4^{2-} to H_2S	$\text{SO}_4^{2-} \rightarrow \text{H}_2\text{S}$	Hydrogen sulfide generation
Stage 2	Sewer atmosphere (humid, oxygenated)	H_2S diffuses into air	$\text{H}_2\text{S (gas)} \rightarrow \text{sewer air}$	Gaseous H_2S disperses
Stage 3	Concrete surface (wet film)	Sulfur-oxidizing bacteria (SOB) oxidize H_2S to H_2SO_4	$\text{H}_2\text{S} + \text{O}_2 \rightarrow \text{H}_2\text{SO}_4$	Sulfuric acid formation
Stage 4	Concrete matrix	Acid attacks cement hydrates	$\text{Ca(OH)}_2 + \text{H}_2\text{SO}_4 \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O (gypsum)}$	Material degradation, pH drop

Table 2. Typical Surface pH Ranges Across Corrosion Stages

Corrosion Stage	Approximate Surface pH
Initial concrete (unaffected)	12.0-13.0
After H_2S absorption	6.0-9.0
During acid formation	3.5-5.0
Active biocorrosion (with gypsum formation)	2.0-3.0

(Figure 4). This acid environment promotes severe acid attack of the cement matrix, causing the generation of expansive corrosion products and subsequent deterioration of the structure (Suleiman *et al.*, 2014; Wang and Zeng, 2020).

**Figure 4. pH range across corrosion stages**

This was confirmed by (Merachtsaki *et al.*, 2021a; Merachtsaki *et al.*, 2021b; Moa *et al.*, 2025) as a continuous cycle that constitutes the principal driver for severe MIC in sewer pipes, especially the enclosed ones. This sequence continues cyclically, progressively worsening degradation overtime.

Moa *et al.* (2025) observed that concrete surfaces exposed to MIC could reach a pH as low as 2.0 within 30 days of acid exposure under accelerated conditions, as shown in Table 2.

The Sulfur Cycle in Sewer Environments

The sulfur cycle within sewer systems plays a central role in the development of biocorrosion. According to (Kong *et al.*, 2019) sulfate present in wastewater is biologically reduced to hydrogen

sulfide in anaerobic conditions at the pipe invert. This H_2S diffuses into the sewer atmosphere and dissolves in the moist film along the crown of the pipe where it is subsequently oxidized by sulfur-oxidizing bacteria into biogenic sulfuric acid. The acidification of the concrete surface not only promotes material dissolution but also establishes ideal conditions for acidophilic microbial colonization (Merachtsaki *et al.*, 2021b; Merachtsaki *et al.*, 2021c).

Corrosion Mechanisms in Concrete Sewer Systems

Concrete corrosion in sewer systems involves a combination of chemical, physical, and biological degradation processes. The primary chemical mechanism involves the reaction of sulfuric acid with calcium hydroxide and other calcium-rich phases in the cementitious matrix to form soluble calcium sulfate, which leads to material softening and increased permeability (Chindaprasart and Rattanasak, 2016; Hewayde *et al.*, 2007; Imperatore, 2022).

This is further intensified by the microbiological processes maintaining conditions that continuously produce sulfuric acid. According to (Valix *et al.*, 2012), there are various fungi and thiobacilli strains that coexist within the sewer atmosphere, contributing organic and biogenic acids, respectively. This microbial synergy accelerates the corrosion process, resulting in significant material loss over time.

In addition, (Vipulanandan and Liu, 2018) established that these physical factors, including surface porosity and cracks, facilitate ingress of corrosive agents and microbes, thereby reduces pipe integrity.

Biocorrosion Assessment Methods

Assessing the durability of protective coatings for concrete sewers involves accelerated lab tests, including chemical exposure studies, microbial simulations, and in-situ inspections. The objective of these studies is to establish long-term coating behavior in highly aggressive environments (Figure 5).

Chemical Immersion Tests

The most common method for evaluating acid resistance involves immersing coated concrete specimens in sulfuric acid solutions with controlled concentrations. Typical immersion tests expose samples to 1%, 2%, and 3% H_2SO_4 solutions for 30, 60, 90 days. Key parameters to be monitored include weight loss percentage, visual deterioration, reduction of surface pH, and gypsum or ettringite formation. Acid immersion tests have indeed been effective for the rapid screening of magnesium hydroxide, geopolimer, and polyurethane-based coatings regarding their acid resistance, as confirmed by (Moa *et al.*, 2025; Merachtsaki *et al.*, 2021a; Merachtsaki *et al.*, 2021b).

Synthetic sulfuric acid tests are being highly utilized as standardized, repeatable methods to simulate the primary chemical contributor of MIC: biogenic sulfuric acid attack on cementitious materials. These tests are of particular value during preliminary coating system screening and relative ranking, since they allow quantification of resistance and neutralization of, the acid under controlled conditions. Several investigators further

develop a more realistic determination of performance related to MIC by combining such acid exposure tests with other methods that may involve microbial simulation, surface pH determination, micro structural characterization, and long-term field verification when possible.

Accelerated Sulfuric Acid Spray Testing

In this test method, a controlled mist of sulfuric acid solution (2-3%) is sprayed continuously or intermittently over coated concrete panels in a chamber to simulate the scenario of acid attack in sewer conditions. This test accelerates the degradation process while reproducing realistic atmospheric and condensation conditions inside enclosed sewer pipes. (Gonen and Uygunglu, 2022) applied this test to polymeric coatings and observed major surface degradation within 45 days in low-resistance systems.

Artificial Sewage and MIC Simulation Tests

Laboratory setups that reproduce the actual sewer conditions are increasingly used to simulate both the chemical and microbiological components of MIC:

- I. Concrete samples are immersed in a sulfuric acid-based synthetic sewage mix.
- II. The system introduced with SOB, for example, *Thiobacillus thiooxidans*.
- III. The experimental setup controls temperature, pH, and dissolved oxygen to closely similar to sewer pipe environments. These arrangements provide valuable insight into the interactions occurring

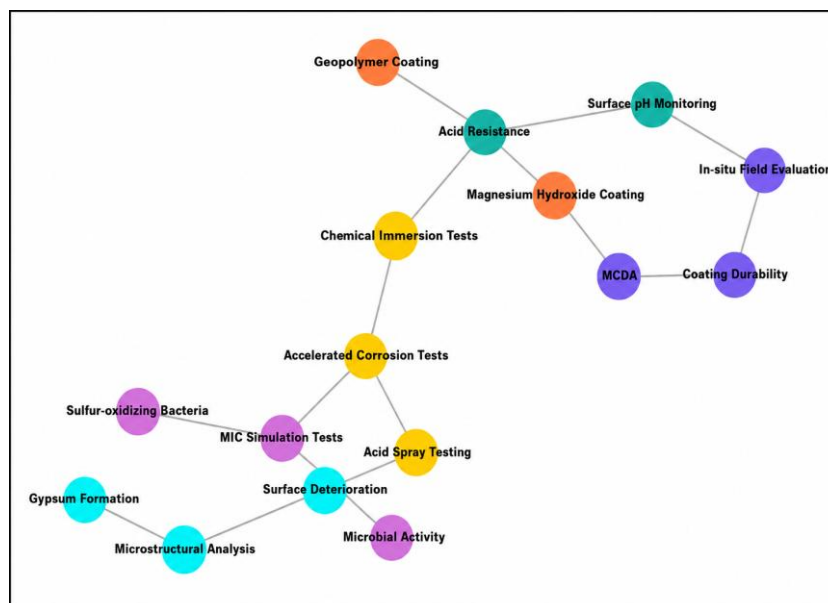


Figure 5. Cluster map showing biocorrosion assessment methods

among the microbial activity, acid attack, and coating degradation (Wang and Zeng, 2020; Suleiman *et al.*, 2014; Gupta and Lataye, 2019).

Surface pH Measurement and Monitoring

Surface pH measurements directly represent acid penetration and degradation progress:

- I. Concrete coatings usually have an initial surface pH > 12.
- II. Sudden decline to < 4 indicates severe acid attack and loss of alkalinity.
- III. Coatings are rated by their capability to maintain pH above 9 over long acid exposure periods. Moa *et al.* (2025) that seawater-derived $\text{Mg}(\text{OH})_2$ coatings maintained surface pH values above 9.5 after 90 days in 3% H_2SO_4 solution, outperforming conventional coatings.

This review places particular emphasis on surface pH because microbiologically induced corrosion in concrete sewer systems is fundamentally caused by biogenic sulfuric acid, and the loss of surface alkalinity represents the earliest stage of deterioration. Maintaining an alkaline surface pH > 9 limits the activity of sulfur-oxidizing bacteria and postpones the formation of gypsum and ettringite, making pH retention a useful and mechanistically relevant indicator of acid-neutralizing performance. In contrast to mass loss and penetration depth that generally reflect advanced damage and often require destructive testing, surface pH can be repeatedly and non-destructively monitored under both laboratory and field conditions. Microbial activity measurements offer valuable biological insight but their complexity restricts routine application. This review will discuss surface pH together with complementary indicators of mass loss, gypsum formation, adhesion performance, micro structural changes, and microbial inhibition for a balanced evaluation of coating effectiveness against MIC.

Microstructural Analysis (SEM, XRD, FTIR)

Post-exposure tests by the means of SEM, XRD, and FTIR allow evaluation of the formation of gypsum and ettringite; micro cracking and changes in surface porosity; degradation of geopolymer or polymeric matrices, and mineralogical changes upon acid attack. These techniques give qualitative and quantitative proof of the durability of the coatings (Merachtsaki *et al.*, 2021b; Persson *et al.*, 2023).

In-situ Field Performance Evaluations

Field trials involve applying candidate coatings inside operational or decommissioned sewer pipelines, and monitoring visual deterioration, surface pH changes, water absorption, microbial colonization and pull-off bond strength after months of exposure. Though time-consuming, field testing offers definitive validation of laboratory predictions (Vipulanandan and Liu, 2018; He, 2025).

Decision-Support Tools: MCDA and Risk Ranking

Recent studies introduced Multiple Criteria Decision Analysis (MCDA) to rank coating systems based on multi-parameter performance, durability, cost, environmental impact, and workability. (Merachtsaki *et al.*, 2022) successfully applied MCDA for selecting optimum magnesium hydroxide coatings for sewer systems. Such models help streamline material selection for municipal authorities and contractors.

Acid immersion and microbial tests require strict safety control. Sulfuric acid must be handled with proper PPE and neutralized before disposal, while microbial cultures should be contained in bio-safe setups to prevent accidental release (Gupta and Lataye, 2017). Safe waste management and compliance with environmental guidelines are essential during MIC testing.

Currently, there are no fully standardized MIC specific coating protocols for sewer environments, but several widely used benchmarks are applied in practice. Chemical resistance is commonly evaluated using the ASTM C267 acid immersion procedure, while coating adhesion and pull-off strength follow ASTM D4541 and ASTM D7234 methods. MIC studies also use surface pH retention and gypsum formation as indicators of long-term coating performance (Berndt, 2011). Utilities and research groups additionally employ modified H_2S exposure chambers and wet-dry cycling tests to simulate real sewer conditions. These procedures collectively serve as practical benchmarks in the absence of dedicated MIC specific international standards.

Protective Coating Strategies and Materials

Effective corrosion protection in sewer infrastructure requires durable, acid-resistant coatings that can resist aggressive biochemical

conditions resulting from microbiologically induced corrosion. The protective coatings developed and evaluated for sewer concrete protection include systems from organic polymeric to inorganic mineral-based systems. Geopolymers, or inorganic polymers synthesized from aluminosilicate materials activated by alkalis, have dense 3D network structures that are highly resistant to attacks by acids and sulfates (Almutairi *et al.*, 2021; Byrnes, 2017; Gupta *et al.*, 2022). Their applications in marine and sewer environments have been validated under laboratory and field trials. Polymeric coatings such as epoxy, polyester, and crystalline waterproofing mortars have also been used as surface barriers to limit acid ingress (Gonen and Uygunoglu, 2022; Yu *et al.*, 2015).

Polymeric Coatings:

Epoxy Coating:

Epoxy resin coatings have been widely applied in the protection of sewers due to their excellent chemical resistance, mechanical strength, and easy application. Applied typically as a two or three-layer system, epoxy coatings provide an impermeable acid barrier. Their long-term performance may deteriorate with continuous wet exposure manifested through blistering and delamination. (Berndt, 2011; Grella *et al.*, 2016) studied microbiologically influenced corrosion in cooling tower basins in geothermal power plants, as well as supplementary cementitious materials, epoxy coatings, latex-modified mortars, and calcium aluminate cement mortar. In laboratory tests with *Thiobacillus ferrooxidans*, 40% GGBS and 5-10% silica fume improved MIC resistance; 60% slag performed similarly to OPC or sulphate-resistant cement. Epoxy and styrene-butadiene mortars provided partial protection; epoxy coatings provided strong resistance (Archer and Adams, 1983; Onuaguluchi and Banthia, 2022) and lastly, calcium aluminate cement mortar showed outstanding durability in both the laboratory and field trials. (Berndt, 2011; Abdou and Abuseda, 2016; Amaral *et al.*, 2025) tested the resistance of coated and uncoated concrete panels to *Thiobacillus ferrooxidans* in an Atlas cell according to ASTM C868 (Figure 6). The apparatus, normally used to test liner systems, offered immersion and vapor zones under controlled thermal gradients. Panels were secured to glass cylinders containing a nutrient medium at pH $\approx$ 2.59 that was inoculated with *T. ferrooxidans* and incubated at 40°C for 60 days. Control tests were conducted with un-inoculated media. At the end of testing, the panels were rinsed and condition-rated visually. Bond strength testing was carried out on coated specimens. Weight loss

was not measured because of concerns over the accuracy of such measurements and condition ratings were, therefore, based solely upon visual inspection.

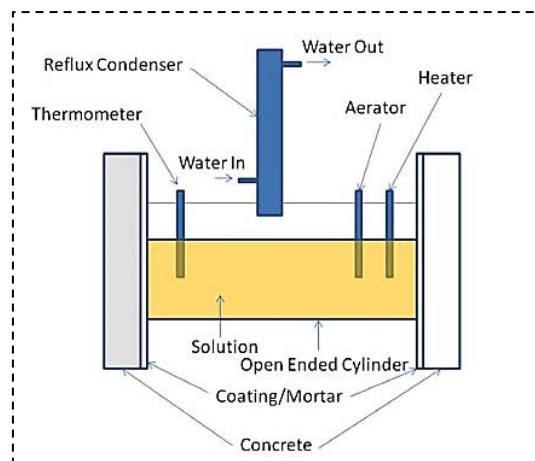


Figure 6. Atlas cell used in assessing resistance to sulphur oxidising bacteria (Berndt, 2011)

Pacheco-Torgal *et al.* (2012) highlighted the use of different surface treatments with a polymeric coating like epoxy, silicone, and polyurethane, while their limitations under ultraviolet and highly alkaline environments were reported.

Polyurethane Coating:

Vipulanandan and Liu (2005) evaluated polyurethane coatings and reported significantly higher bonding strength with dry concrete surfaces, whereas substantially reduced bonding strength was observed with wet surfaces. Specimens containing pinholes failed sooner than those without pinholes, while the time to failure depended on the type of coating and the dimensions of the pinholes. The study showed good acid resistance but also identified several disadvantages, including water vapor permeability and loss of adhesion after long-term exposure to sulfuric acid mist.

Polyurethane coatings provide superior flexibility in challenging sewer conditions. Their adhesion and chemical resistance are excellent in such environments. Advanced waterproofing and acid durability were achieved with various advanced formulations, such as asphaltic polyurethane coatings, at optimized NCO/OH ratios. (Elnaggar *et al.*, 2019; Kong *et al.*, 2018; Sarcinella and Frigione, 2023), illustrated that an increase in the NCO/OH molar ratio up to 1.4 significantly enhanced acid resistance and also increased adhesion strength under acidic environments for PU coatings.

The biological corrosion resistance of mortar samples coated with epoxy, polyester, and

crystallized waterproofing mortar was studied by (Gonen and Uygunoglu, 2022), when exposed to sulfuric acid solutions at different acid concentrations. (Gonen and Uygunoglu, 2022) determined that the epoxy coatings showed best protection against acid-induced weight loss and surface deterioration, while crystallized waterproofing mortars gave a similar performance in dilute acid concentrations and presented a more economically viable option. On the contrary, polyester coatings performed very poorly when the acid solution was highly concentrated. (Shing *et al.*, 2012; Gonen and Uygunoglu, 2022) recommended crystallized waterproofing mortars for extending the concrete sewer component service life economically in moderately aggressive environments (Figure 7, 8, 9, 10).

Magnesium hydroxide-based coatings are widely favored in sewer protection due to their strong acid-neutralizing capacity and environmental compatibility. The alkaline nature of $\text{Mg}(\text{OH})_2$ maintains surface pH levels above 9.5, effectively neutralizing biogenic sulfuric acid. (Moa *et al.*, 2025) tested seawater-derived $\text{Mg}(\text{OH})_2$ coatings and reported excellent acid resistance, with surface pH remaining above 9.5 after 90 days in 3% H_2SO_4 exposure. (Merachtsaki *et al.*, 2021a) also validated $\text{Mg}(\text{OH})_2$ performance using both laboratory and field trials. The magnesium hydroxide slurry was found to effectively protect the concrete from MIC by maintaining alkaline surface pH values and neutralizing sprayed sulfuric acid (Figure 11).

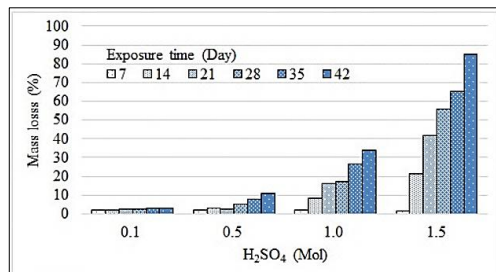


Figure 7. Weight losses of the samples coated with epoxy. (Gonen and Uygunoglu, 2022)

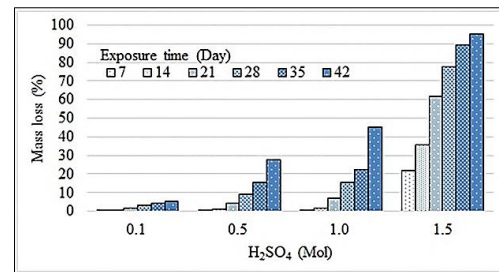


Figure 9. Weight losses of the samples coated with crystallized waterproofing mortar. (Gonen and Uygunoglu, 2022)

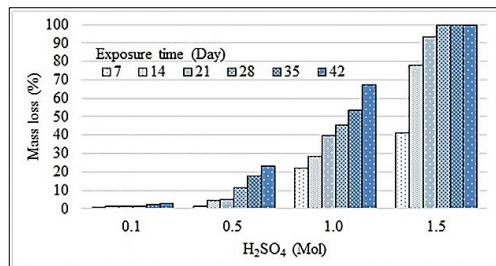


Figure 8. Weight losses of the samples coated with polyester. (Gonen and Uygunoglu, 2022)

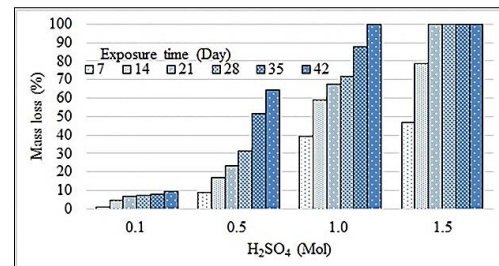


Figure 10. Weight losses of the uncoated control samples. (Gonen and Uygunoglu, 2022)

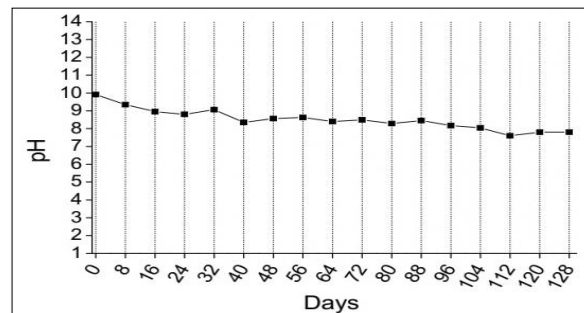


Figure 11. The evolution of surface pH values of coated concrete specimens, during the application of the long-term duration acid spraying test (Merachtsaki *et al.*, 2021a)

Geopolymer-Based Coatings:

Pacheco-Torgal *et al.* (2012) and Chen *et al.* (2021) highlighted the eco-friendliness and trenchless application potential of geopolymer-based coatings. Wang and Zeng (2020) developed superhydrophobic geopolymer composites with improved water repellency and acid resistance for sewer environments. However, long-term in-situ MIC-specific validations remain limited. Superhydrophobic coatings are designed to repel water and inhibit microbial colonization by minimizing moisture retention on concrete surfaces. Nanomaterials such as nano-silica and graphene oxide have been incorporated to enhance acid resistance, self-cleaning properties, and microcrack sealing. Wang and Zeng (2020) reported significant improvements in acid resistance using superhydrophobic geopolymer coatings under laboratory-simulated sewer conditions. Glasby *et al.* (2019) and Wong (2022) reported superior performance of a proprietary geopolymer concrete in a 12-month MIC exposure test, surpassing conventional acid-resistant concretes by an order of magnitude.

Antimicrobial and Nano composite Coatings

Haile *et al.* (2010) evaluated that nano-copper oxide and functionalized zeolite coatings effectively inhibited the growth and activity of *Acidithiobacillus thiooxidans* on concrete sewer pipes. The study found that higher copper ion release from nano-copper oxide coatings on severely corroded surfaces provided enhanced bactericidal action, while zeolite coatings restricted microbial activity through controlled silver ion exchange in the presence of active bacteria. An inhibitory copper concentration between 2.3-2.6 mg Cu per mg dry cell weight was identified, indicating the coatings' potential in MIC protection. However, the authors suggested further assessment under actual service conditions to confirm long-term performance (Haile *et al.*, 2010; Hudson and Cardenas, 2025; Rihayat *et al.*, 2019).

Nanomaterials and metallic dopants improve the resistance of coatings against MIC due to enhanced coating density, reduced porosity, and restricted microbial activity. The nano-sized fillers such as CuO, TiO₂, and zeolite tend to release antimicrobial ions, suppress the growth of sulfur-

oxidizing bacteria, and strengthen the microstructure to inhibit acid penetration (Wang and Zeng, 2020; Haile *et al.*, 2010; Arumugam *et al.*, 2025; Zhang *et al.*, 2024). Metallic dopants in hybrid or self-healing coatings drive faster crosslinking, improve crack-bridging, and allow efficient healing under the formation of microfractures (Yadav and Pramanik, 2024; Santos *et al.*, 2024). All these additives combine to significantly enhance durability and improve long-term protection under MIC conditions.

Hybrid and Self-Healing Coating Systems

Recent research has focused on hybrid systems where organic polymers have been combined with inorganic fillers, self-healing microcapsules, or nano-materials. Zn-PU hybrid coatings with triple bonding mechanisms for enhanced durability under exposure to MIC. In this novel self-healing polyurethane-based coating, the addition of zinc metal ions achieved enhancement in mechanical integrity and durability (Yadav and Pramanik, 2024; Gupta and Lataye, 2018). It has been illustrated that dynamic coordination and hydrogen bonding within the Zn-polyurethane matrix enhance both the self-healing efficiency and water stability of the material, thus rendering it fitting for sewer management (Takada *et al.*, 2023). Additionally, the approach holds potential for customization using other metal ions and dynamic bonds, enabling the development of durable, self-repairing coatings to resist damage and mitigate fat, oil, and grease (FOG) accumulation in sewer systems (Yadav and Pramanik, 2024; Gautam and Khan, 2025). Table 3 summarizes the protective coating materials reviewed, Table 4 presents case-study-level findings from individual studies, and Table 5 compares coating types by application method and performance under acidic/MIC conditions, and Table 6 provides a quantitative comparison of the key coating materials, including pH retention, mass loss, and adhesion strength.

Field application of hybrid and self-healing coatings remains challenging due to moisture-saturated sewer surfaces, uneven curing, and the need for skilled application. Their healing efficiency can also reduce under low temperatures and continuous wet conditions, and long-term field data are still limited.

Table 3. Protective Coating Materials for Concrete Sewer Protection (Summary)

Sr. No.	Coating Material	Application Method	Evaluation Parameters	Key Conclusion	Reference
1	Epoxy coatings and calcium aluminate cement mortar	Brush/Roller	Durability under acidic condition and MIC	Epoxy coatings demonstrated strong protective capability for concrete, while calcium aluminate cement mortar exhibited outstanding durability in both laboratory and field evaluations.	(Berndt, 2011)
2	Epoxy Resin Coating	Brush/Roller/Spray	Acid resistance, adhesion, surface pH retention	Good chemical resistance, but prone to blistering and adhesion loss under continuous wet conditions	(Vipulanandan and Liu, 2004)
3	Polyurethane (PU) Coating	Spray/Brush	Adhesion, acid resistance, flexibility	Excellent acid resistance and flexibility, improved with higher NCO/OH ratios	(Elnaggar <i>et al.</i> , 2019)
4	Epoxy, Polyester, Crystallized Waterproofing Mortar	Surface coating on mortar specimens	Weight loss (%), Visual deterioration, Microstructure changes under 0.1–1.5 M H ₂ SO ₄ exposure (7–42 days)	Epoxy coating provided highest acid resistance, followed by crystallized waterproofing mortar as a more economical alternative. Polyester showed poor durability at higher acid concentrations.	(Gonen and Uygunoglu, 2022)
5	Polymer-acrylic and Epoxy resin	Spray/Brush	Performance of coating, bond strength, acid resistance	Epoxy performed best in chloride penetration. Ammonium hydroxide caused insufficient degradation on coated concrete.	(Aguai <i>et al.</i> , 2008)
6	Magnesium Hydroxide (Mg(OH) ₂)	Spray	Surface pH retention, acid resistance, weight loss	Maintained pH above 9.5 in 3% H ₂ SO ₄ for 90 days, excellent MIC protection	(Moa <i>et al.</i> , 2025)
7	Seawater-Derived Mg(OH) ₂	Spray	Acid resistance, visual integrity	Comparable acid resistance to industrial Mg(OH) ₂ coatings	(Moa <i>et al.</i> , 2025)
8	Magnesium Hydroxide-Based Coating	Surface application on concrete sewer specimens	Surface pH, Pull-off adhesion, SEM, XRD, ATR, Acid spray exposure tests (short and long duration), Mass and thickness loss	The coating maintained alkaline surface pH (>8.0), exhibited good adhesion, minimized gypsum formation, and demonstrated prolonged MIC protection under simulated sewer conditions.	(Merachtsaki <i>et al.</i> , 2021a)
9	Magnesium Hydroxide-Based Coatings	Surface coating on concrete specimens	Weight loss, Visual surface degradation, Multiple Criteria Decision Analysis (PROMETHEE), Acid spraying tests (dry/wet)	Magnesium hydroxide coatings demonstrated effective acid neutralization, with optimal performance varying by exposure condition. C5 performed best overall in dry tests, with C6 and C3 outperforming in other scenarios.	(Merachtsaki <i>et al.</i> , 2022)
10	Super hydrophobic Geopolymer	Trowel	Water contact angle, acid resistance, crack resistance	Excellent water repellency and improved MIC durability in lab tests	(Wang and Zeng, 2020)
11	Nano-Copper Oxide Coating, Functionalized Zeolite Coating	Electro-chemical deposition (Nano-CuO) and surface coating (Zeolite) on concrete sewer pipes	Bacterial dry cell weight, ATP production, Oxygen Uptake Rate (OUR), Cu leaching, Bio film analysis	Nano-CuO coatings on severely corroded pipes achieved highest microbial inhibition due to increased Cu ion leaching. Zeolite coating effectively inhibited <i>A. thiooxidans</i> with controlled silver ion release in microbial presence.	(Haile <i>et al.</i> , 2010)
12	Nano-Copper Oxide Functional Coating	Electro-chemical deposition on UC, MC, SC concrete pipes	Specific growth rate, OUR, ATP, Cu leaching rate, Biomass, Sulfate concentration, Bio film activity	Severely corroded pipes with Nano-CuO showed superior bactericidal action due to higher Cu leaching. Effective Cu inhibition limit determined as 2.3–2.6 mg Cu/mg DCW.	
13	Zinc-doped clay	Spray/Brush	Chemical resistance, bond strength	significantly more stable to biogenic acid attack.	(Roghianian and Banthia, 2019)
14	Asphaltic Polyurethane (As/PU)	Brush	Acid resistance, bond strength	Improved adhesion and acid durability at optimized NCO/OH ratios	(Elnaggar <i>et al.</i> , 2019)
15	Zn-PU Hybrid Coating	Spray/Brush	Self-healing, acid resistance, bond strength	Enhanced durability via triple bonding and self-healing mechanisms	(Yadav and Pramanik, 2024)

Table 4. Case Studies on Protective Coatings for Concrete Sewer Systems

Sr. No.	References	Coating Type	Method / Exposure	Key Findings
1	(Berndt, 2011)	Epoxy	Field (18 months)	No bond loss or microbial degradation
2	(Vipulanandan and Liu, 2004)	Polyurethane	Spray/brush; pressure and acid tests	Good acid resistance on dry surfaces; adhesion drops when wet
3	(Elnaggar <i>et al.</i> , 2019)	Asphaltic PU	Brush	Better adhesion and acid durability at optimized NCO/OH ratio
4	(Gonen and Uygungoglu, 2022)	Epoxy, Polyester, Crystalline mortar	Acid immersion (42 days)	Epoxy showed highest MIC resistance
5	(Aguar <i>et al.</i> , 2008)	Acrylic and Epoxy	Spray/brush	Epoxy best; ammonium hydroxide inadequate
6	(Moa <i>et al.</i> , 2025)	Seawater Mg(OH) ₂	Spray; acid test	Maintained pH above corrosion limit; sustainable
7	(Moa <i>et al.</i> , 2025)	Industrial Mg(OH) ₂	Spray; acid test	Similar durability to seawater-derived coating
8	(Merachtsaki <i>et al.</i> , 2021a)	Mg(OH) ₂	Acid spray, SEM	pH > 9; minimal gypsum; strong acid resistance
9	(Merachtsaki <i>et al.</i> , 2022)	Commercial Mg(OH) ₂	Accelerated acid spray	High-surface-area Mg(OH) ₂ + cellulose improved adhesion and resistance
10	(Wang and Zeng, 2020)	Super hydrophobic composite	Spray	Better MIC durability and waterproofing; good for trenchless repair
11	(Haile <i>et al.</i> , 2010)	Nano CuO/AgO	Bio film chamber	>90% bacterial inhibition; delayed corrosion
		Nano CuO	Electrochemical deposition	High bactericidal action; more Cu leaching
12	(Roghanian and Bantia, 2019)	Zinc-doped clay	Spray/brush	Improved resistance to biogenic acid attack
13	(Yadav and Pramanik, 2024)	Zn-PU hybrid	Spray/brush; FOG test	Strong self-healing; >80% Ca ²⁺ leaching reduction
14	(Chindaprasit and Rattanasak, 2016)	Fly ash geopolymers	20 mm layer; acid test	High acid resistance; low Ca ²⁺ leaching; strength retained
15	(Kong <i>et al.</i> , 2019)	ECTPC, CBC, CCCWC	Surface coat; sewage immersion	ECTPC performed best; CCCWC weakest
16	(Abubaker <i>et al.</i> , 2017)	Bitumen	Buried concrete	Moisture barrier; poor acid durability
17	(Grella <i>et al.</i> , 2016)	Epoxy	Storm water pipe test	Controlled pH rise; protected water quality

Table 5. Comparative Summary of Coating Types, Application Methods, and Performance Under Similar Acidic Conditions

Sr. No.	Coating Type	Common Application Method	Key Performance Metrics	Summary of Performance Under MIC / Acidic Conditions	Reference
1	Epoxy	Brush / Roller / Spray	Weight loss, adhesion, surface integrity	Lowest weight loss; strong chemical resistance but prone to blistering under continuous wet exposure.	(Gonen and Uygungoglu, 2022; Berndt, 2011)
2	Polyurethane (PU)	Brush / Spray	Flexibility, bond strength, acid resistance	Good flexibility and acid durability; adhesion decreases on wet surfaces.	(Elnaggar <i>et al.</i> , 2019; Vipulanandan and Liu, 2004)
3	Magnesium Hydroxide (Mg(OH) ₂)	Spray	Surface pH retention, gypsum formation	Maintains pH > 9.5 in 3% H ₂ SO ₄ ; excellent neutralization and MIC resistance.	(Moa <i>et al.</i> , 2025; Merachtsaki <i>et al.</i> , 2021a)
4	Geopolymer Coatings	Trowel / Spray	Acid resistance, microcracking, stability	High acid resistance; reduced gypsum formation; minor shrinkage issues at early age.	(Pacheco-Torgal <i>et al.</i> , 2012; Wang and Zeng, 2020; Glasby <i>et al.</i> , 2019)
5	Superhydrophobic Composites	Spray	Water repellency, acid resistance	High contact angle; lower moisture retention; improved resistance to acid-induced softening.	(Wang and Zeng, 2020)
6	Nano-Modified Coatings (CuO, Zeolite)	Electrochemical deposition / Surface coating	Bacterial inhibition, ion release	Strong suppression of SOB activity; effective for MIC prevention on corroded surfaces.	(Haile <i>et al.</i> , 2010)
7	Hybrid / Self-Healing (Zn-PU)	Brush / Spray	Self-healing efficiency, durability	Excellent durability through multi-bond networks; improved resistance to cracking and acidic degradation.	(Yadav and Pramanik, 2024)

Table 6. Quantitative Comparison of Key Coating Materials Under Acidic Conditions

Sr. No.	Coating Type	pH Retention	Mass Loss in Acid Tests	Adhesion Strength	Findings	Reference
1	Epoxy	-	< 5% weight loss in 0.1–1.5 M H ₂ SO ₄	2–4 MPa (depending on surface condition)	Lowest mass loss; strong chemical resistance	(Gonen and Uygungoglu, 2022; Berndt, 2011)
2	Polyurethane (PU)	-	Moderate (higher than epoxy)	2–3 MPa, reduced on wet surfaces	Good flexibility; adhesion drops under wet exposure	(Elnaggar <i>et al.</i> , 2019; Vipulanandan and Liu, 2004)
3	Geopolymer Coatings	Maintains higher pH than OPC	Very low gypsum formation	-	Strong acid resistance; minimal strength loss	(Wang and Zeng, 2020; Pacheco-Torgal <i>et al.</i> , 2012; Glasby <i>et al.</i> , 2019)
4	Magnesium Hydroxide (Mg(OH) ₂)	pH > 9.5 for 90 days in 3% H ₂ SO ₄	Very low mass loss	-	Excellent neutralization capacity; stable MIC protection	(Moa <i>et al.</i> , 2025; Merachtsaki <i>et al.</i> , 2021a)

Future Challenges and Research Directions

Despite the tremendous strides that have taken place in improving protective coating materials for concrete sewer infrastructure, several challenges remain particularly under the severe biochemical and environmental conditions within most sewage systems. Epoxy based coatings are chemically resistant but tend to suffer adhesion loss when subjected to continuous wet conditions or biogenic corrosion. (Yu *et al.*, 2015; Vipulanandan and Liu, 2002) emphasized an urgent need to develop modified epoxy formulations with enhanced wet adhesion properties and enhanced resistance against bio film colonization. Similarly, (Elnaggar *et al.*, 2019) reported that polyurethane and polymer modified bitumen coatings showed limited acid resistance unless properly modified. To address this issue, the use of nano-materials, fiber additives, and other compatibility enhancing agents should be explored, as these can improve mechanical strength, flexibility, and overall chemical resistance.

A major limitation is the absence of long-term in-situ data for magnesium hydroxide based coatings. Although laboratory studies shows strong acid neutralizing capacity and stable surface pH, their actual performance must be verified through multi-year field trials in active sewer networks (Moa *et al.*, 2025).

Geopolymer coatings also pose other challenges, such as early age shrinkage and micro cracking, despite their much better acid resistance and environmental sustainability. Fiber reinforcements, super hydrophobic additives, and curing protocols have been tried to overcome these issues and enhance the long-term integrity of coatings in sewer environments. (Wang and Zeng, 2020; Li *et al.*, 2022; Rihawi *et al.*, 2025; Sukontasukkul *et al.*, 2023).

Merachtsaki *et al.* (2021a) emphasized the lack of standardized protocols for performance evaluation and selection tools related to sewer coating applications. They called for MIC specific performance benchmarks to be developed and MCDA frameworks to be integrated in order to pave the way for straightforward coating selection by municipal authorities and sewer asset managers. Among advanced hybrid coatings, Yadav and Pramanik (2024) presented self-healing Zn-PU hybrid systems. Although the initial laboratory results were encouraging, field scale trials are required to establish the durability and cost effectiveness of such systems in real sewer environments.

Lastly, while (Pacheco-Torgal *et al.*, 2012) acknowledged the high resistance of geopolymer coatings to acid attack, long-term performance data specific to sewers is scarce. Accelerated aging, acid spray, and sewer bio film simulation tests should be conducted in future work to verify the durability of geopolymers under realistic conditions (Pacheco-Torgal *et al.*, 2012).

According to (Gonen and Uygunoglu, 2022), standardized testing protocols for biological corrosion resistance are still lacking. There is a further need for detailed methodologies which allow materials to be compared with each other and for service performance to be predicted with accuracy. In summary, new protective coating strategies for concrete sewer infrastructures will require new material systems, together with refined application techniques and appropriate long-term field monitoring and decision-support tools. The aim is to ensure cost effective, durable, and sustainable solutions for controlling MIC in an aging urban sewer network. Figure 12 depicts the comparative performance of coating material.

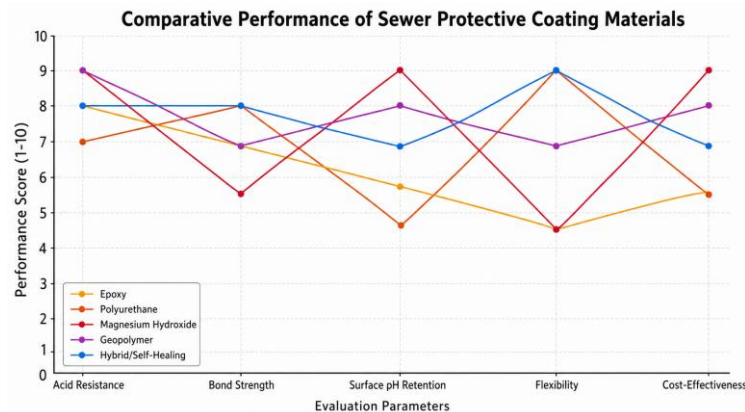


Figure 12. Comparative performance score of coating material

The present work provides a systematic review of comparative analyses of protective coating systems is based on results reported in independent investigations conducted under varying experimental conditions, including differences in exposure environment, acid concentration, test duration, and evaluation criteria. Consequently, direct comparison under identical conditions is not always feasible. Accordingly, this review emphasizes relative performance trends rather than absolute equivalence among coating systems. Where possible, studies employing comparable exposure conditions are discussed together, and commonly reported indicators such as surface pH retention, mass loss behavior, visual degradation, and micro structural characteristics are used to support qualitative comparison. The comparative figures and summary tables therefore provide an integrated overview of reported performance trends and highlight the need for standardized MIC-specific testing approaches in future studies.

Radar plot comparing the performance of sewer coating systems over six parameters is represented in (Figure 13). Hybrid or self-healing coatings surpass others in acid resistance, sustainability, and MIC durability, while magnesium hydroxide shows strong cost effectiveness and lab based MIC performance.

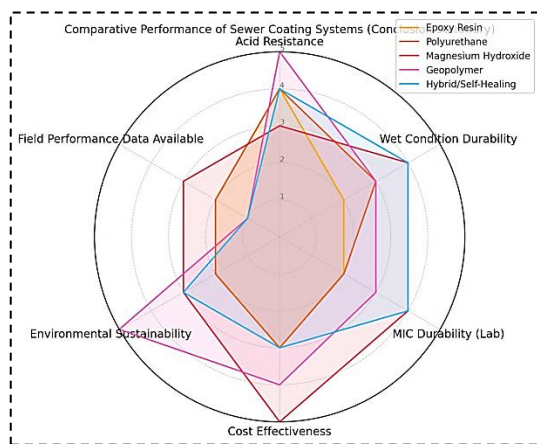


Figure 13. Radar Summary of coating material

Whereas laboratory tests typically offer accelerated and controlled insights into MIC resistance, their predictive accuracy is limited by fluctuating moisture, temperature, gas concentration, and microbial activity in real sewer environments. Many of the coatings that performed well in acid immersion or spray chambers showed reduced durability in field trials due to continuous wetting-drying cycles, uneven bio-film growth, and mechanical abrasion. This performance gap

indicates the need for improved test methods and long-term field validation.

The cost-effectiveness of the reviewed coatings varies widely. Epoxy and PU systems deliver strong performance but come with higher material costs and lower environmental compatibility. Geopolymer and magnesium hydroxide coatings are generally more affordable and offer better sustainability because of their lower carbon footprint and the use of locally available materials. Hybrid and nano-modified coatings show good durability, but their high cost limits their suitability for large scale projects.

Laboratory parameters such as pH retention, mass loss, adhesion strength, and microbial inhibition can be directly applied when planning in-situ application. These results help municipalities to identify coatings that show good durability under acidic and MIC conditions. When integrated into asset management practices, these data help utilities to schedule preventive maintenance more effectively and they can also choose cost-effective coating systems, and plan rehabilitation work with greater accuracy. Long term monitoring of coated sewer sections further strengthens decision making by validating whether laboratory findings hold true in real operating conditions.

Future research should prioritize on long-term in-situ monitoring of coated sewer structures in real operating conditions to verify whether laboratory results remain consistent in practice. Extended field trials are needed to understand real performance trends more clearly. This requires regular check of surface pH, coating deterioration, microbial activity, and overall structural condition of the structure. For long term assessment, reliable sensor based monitoring tools and standard field evaluation protocols need to be developed.

Conclusion

This succinct review shows a critical assessment of recent progress and practical issues related to protective coating materials and strategies. Based on evidence gathered from various laboratory investigations and new experimental approaches, it examines both established and emerging coating technologies that can perform under highly aggressive sewer conditions.

Among traditional coating options, epoxy resin coatings still offer strong acid resistance but often experience adhesion loss and blistering when exposed to continuous moisture and biogenic activity. Polyurethane coatings, particularly asphaltic polyurethane, show better flexibility and chemical resistance. The performance of

polyurethane coatings improves further when the NCO/OH ratio and additives are properly optimized. Magnesium hydroxide based coatings, including seawater-derived variants, consistently maintained surface pH above 9.5 during accelerated acid tests. It shows that magnesium hydroxide-based coatings are durable and economical.

Although epoxy coatings exhibit consistently low mass loss (<5%) under acidic exposure, indicating strong chemical resistance, their effective service life in sewer environments is often governed by interfacial adhesion rather than bulk material degradation. Prolonged exposure to high humidity and wet-dry cycling can promote moisture ingress at the coating-concrete interface, leading to adhesion loss, blistering, or localized delamination. Such interfacial degradation may accelerate failure by facilitating acid penetration and microbial colonization, even when the epoxy matrix remains chemically intact. Accordingly, this review emphasizes that epoxy durability under MIC conditions should be assessed using both chemical resistance indicators and interfacial performance metrics to obtain a realistic estimate of service life.

Polyurethane maintained adhesion strengths of 2-3 MPa, and geopolymers exhibited very limited gypsum formation. Together, these results indicate that laboratory and short-term exposure studies, epoxy, polyurethane, and magnesium hydroxide based coatings demonstrate effective resistance to MIC related acid attack; at the same time, their long term suitability in sewer environments is governed by distinct material-specific failure mechanisms and requires validation through extended field performance. This review also highlights the potential of geopolymer coatings, which offer improved acid resistance along with sustainability benefits. However, these coating shows early-age shrinkage, micro cracking, and variable adhesion when exposed to continuous moisture. This indicates the need for further refinement through fiber reinforcement, balanced alkali activator contents, and controlled curing practices. Super hydrophobic geopolymer formulations and nano-modified variants have shown stronger MIC resistance in laboratory studies. However, their in situ performance is still untested.

Recent developments in hybrid and self-healing coating technologies, such as Zn-PU composites, show good laboratory results and may support future trenchless rehabilitation methods. Future research should focus on improved biocorrosion simulation methods, systematic field monitoring programs, and MCDA based selection frameworks so as to assist municipal agencies and asset managers in choosing appropriate protective materials.

While considerable advances have been made in improving concrete sewer protective coatings' performance, further coordinated efforts are needed to significantly overcome the current limitations and provide long-lasting, environmentally friendly, cost-effective protection needed for sewer infrastructure globally.

CRediT authorship contribution statement

Ankit I. Malviya: Conceptualization, Literature review, Data analysis, Writing original draft, Visualization.

Tripti B. Gupta: Supervision, Critical review, Writing review and editing, Guidance on structure and content.

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References

- Abdou, M. I., & Abuseda, H. (2016). Upgrading offshore pipelines concrete coated by silica fume additive against aggressive mechanical laying and environmental impact. *Egyptian Journal of Petroleum*, 25(2), 193-199. <https://doi.org/10.1016/j.ejpe.2015.04.004>
- Abubaker, F., Cripps, J. C., Lynsdale, C. J., & Pouya, H. S. (2017). Performance of bitumen protective coatings for buried concrete. *Proceedings of the Institution of Civil Engineers - Construction Materials*, 170(5), 258-264. <https://doi.org/10.1680/jcoma.15.00022>
- Aguiar, J. B., Camões, A., & Moreira, P. M. (2008). Coatings for concrete protection against aggressive environments. *Journal of Advanced Concrete Technology*, 6(1), 243-250. <https://doi.org/10.3151/jact.6.243>
- Almutairi, A. L., Tayeh, B. A., Adesina, A., Isleem, H. F., & Zeyad, A. M. (2021). Potential applications of geopolymer concrete in construction: A review. *Case Studies in Construction Materials*, 15, e00733. <https://doi.org/10.1016/j.cscm.2021.e00733>
- Amaral, M., Oliveira, I. A., de Bem, D. H., Réus, G. C., Macioski, G., Farias, M. M., & Farias de Medeiros, M. H. (2025).

- Influence of silica fume (SF) content on passive film formation of steel reinforcement inside hardened concrete. *Corrosion and Materials Degradation*, 6(1), Article 3. <https://doi.org/10.3390/cmd6010003>
- Archer, G. L., & Adams, A. J. (1983). The behavior of concrete over thin film epoxy coatings on offshore pipelines. In *Proceedings of the Offshore Technology Conference* (pp. 85-95). Offshore Technology Conference. <https://doi.org/10.4043/4453-MS>
- Arumugam, H., Srinivasan, H., Mohanapriya, S. N., & Muthukaruppan, A. (2025). Development of tertiary butyl hydroquinone-based polybenzoxazine for effective antimicrobial and anti-corrosion coating applications. *Next Materials*, 8, 100723. <https://doi.org/10.1016/j.nxmte.2025.100723>
- Berndt, M. L. (2011). Evaluation of coatings, mortars and mix design for protection of concrete against sulphur oxidising bacteria. *Construction and Building Materials*, 25(10), 3893-3902. <https://doi.org/10.1016/j.conbuildmat.2011.04.014>
- Byrnes, T. (2017). Pipeline coatings. In *Trends in oil and gas corrosion research and technologies: Production and transmission* (pp. 563-591). Elsevier. <https://doi.org/10.1016/B978-0-08-101105-8.00024-3>
- Chen, K., Wu, D., Xia, L., Cai, Q., & Zhang, Z. (2021). Geopolymer concrete durability subjected to aggressive environments: A review of influence factors and comparison with ordinary Portland cement. *Construction and Building Materials*, 279, 122496. <https://doi.org/10.1016/j.conbuildmat.2021.122496>
- Chindaprasirt, P., & Rattanasak, U. (2016). Improvement of durability of cement pipe with high calcium fly ash geopolymer covering. *Construction and Building Materials*, 112, 956-961. <https://doi.org/10.1016/j.conbuildmat.2016.03.023>
- Di Emidio, G., Mazzieri, F., Verastegui-Flores, R., Van Impe, W., & Bezuijen, A. (2015). Polymer-treated bentonite clay for chemical-resistant geosynthetic clay liners. *Geosynthetics International*, 22(1), 125-137. <https://doi.org/10.1680/gein.14.00036>
- Elnaggar, E. M., Elsokkary, T. M., Shohide, M. A., El-Sabbagh, B. A., & Abdel-Gawwad, H. A. (2019). Surface protection of concrete by new protective coating. *Construction and Building Materials*, 220, 245-252. <https://doi.org/10.1016/j.conbuildmat.2019.06.026>
- Gautam, B. R., & Khan, N. I. (2025). Study of surface hardness and self-healing ability of DA-modified polyurethane coating. *Next Materials*, 9, 100955. <https://doi.org/10.1016/j.nxmte.2025.100955>
- Glasby, T., Day, J., Genrich, R., & Kemp, M. (2019, September 8-11). *The use of a proprietary geopolymer concrete in sewer infrastructure applications* [Conference paper]. Concrete 2019: The 29th Biennial National Conference of the Concrete Institute of Australia, Sydney, NSW, Australia.
- Gonen, T., & Uygunoglu, T. (2022). The effect of various polymer-based coating types on the biological corrosion resistance of mortar. *Revista Matéria*, 27(3), Article e20220085. <https://doi.org/10.1590/1517-7076-RMAT-2022-0085>
- Grella, C., Wright, I. A., Findlay, S. J., & Jonasson, O. J. (2016). Geochemical contamination of urban water by concrete stormwater infrastructure: Applying an epoxy resin coating as a control treatment. *Urban Water Journal*, 13(2), 212-219. <https://doi.org/10.1080/1573062X.2014.951660>
- Gupta, T. B., & Lataye, D. H. (2017). Adsorption of indigo carmine dye onto *Acacia nilotica* (Babool) sawdust activated carbon. *Journal of Hazardous, Toxic, and Radioactive Waste*, 21(4), 04017013. [https://doi.org/10.1061/\(ASCE\)JHZ.2153-5515.0000365](https://doi.org/10.1061/(ASCE)JHZ.2153-5515.0000365)
- Gupta, T., & Lataye, D. (2018). Adsorption of indigo carmine and methylene blue dye: Taguchi's design of experiment to optimize removal efficiency. *Sadhana*, 43(10), Article 170. <https://doi.org/10.1007/s12046-018-0931-x>
- Gupta, T., & Lataye, D. (2019). Removal of crystal violet and methylene blue dyes using activated carbon of *Acacia nilotica* sawdust. *Indian Journal of Chemical Technology*, 26, 52-68. <https://nopr.niscpr.res.in/bitstream/123456789/46985/1>
- Gupta, T., Ansari, K., Lataye, D., Kadu, M., Mohammad, A., Mubarak, N., Garg, R., & Karri, R. (2022). Adsorption of indigo carmine dye by *Acacia nilotica* sawdust activated carbon in fixed bed column. *Scientific Reports*, 12, 15522. <https://doi.org/10.1038/s41598-022-19595-6>
- Gupta, T., Dharaskar, A., Gupta, S., & Jaiswal, A. (2025). Sustainable waste management through development of organic composts using laboratory synthesized liquid activators. *International Journal of Environmental Research*, 19(6), 268-290. <https://doi.org/10.1007/s41742-025-00932-2>
- Haile, T., Nakhla, G., Allouche, E., & Vaidya, S. (2010). Evaluation of the bactericidal characteristics of nano-copper oxide or functionalized zeolite coating for bio-corrosion control in concrete sewer pipes. *Corrosion Science*, 52(1), 45-53. <https://doi.org/10.1016/j.corsci.2009.08.046>
- He, D. (2025). Review of corrosion evaluation methods for steel reinforcement in concrete. *Corrosion and Materials Degradation*, 6(3), Article 37. <https://doi.org/10.3390/cmd6030037>
- Hewayde, E. H., Nakhla, G., Allouche, E. N., & Mohan, P. K. (2007). Beneficial impact of coatings on biological generation of sulfide in concrete sewer pipes. *Structure and Infrastructure Engineering*, 3(3), 267-277. <https://doi.org/10.1080/15732470500424260>
- Hudson, J. A., & Cardenas, H. E. (2025). Corrosion behavior of Fe-Ni electrodeposited coatings in weak ammonium hydroxide solution. *Corrosion and Materials Degradation*, 6(2), Article 15. <https://doi.org/10.3390/cmd6020015>
- Iglesias, N., & Diaz, E. (2025). Influence of H₂S and CO₂ partial pressures and temperature on the corrosion of superduplex S32750 stainless steel. *Corrosion and Materials Degradation*, 6(2), Article 20. <https://doi.org/10.3390/cmd6020020>
- Imperatore, S. (2022). Mechanical properties decay of corroded reinforcement in concrete: An overview. *Corrosion and Materials Degradation*, 3(2), 210-220. <https://doi.org/10.3390/cmd3020012>
- Kong, L., Fang, J., & Zhang, B. (2019). Effectiveness of surface coatings against intensified sewage corrosion of concrete. *Journal of Wuhan University of Technology-Materials Science Edition*, 34(5), 1177-1186. <https://doi.org/10.1007/s11595-019-2175-y>
- Kong, L., Fang, J., Wu, Z., & Zhang, B. (2018). Evaluation of the effect of surface coatings on protection of concrete against sewage-induced degradation based on gray correlation analysis. *Journal of Coatings Technology and Research*, 15(6), 1311-1323. <https://doi.org/10.1007/s11998-018-0079-y>
- Li, W., Shumuye, E. D., Shiyang, T., Wang, Z., & Zerfu, K. (2022). Eco-friendly fibre reinforced geopolymer concrete: A critical review on the microstructure and long-term durability properties. *Case Studies in Construction Materials*, 16, e00894. <https://doi.org/10.1016/j.cscm.2022.e00894>
- Liu, Y., Beaumont, D., Zhou, X., Burnett, T., Morsch, S., Lyon, S., Iannarelli, P., Di Lullo, C., Hijnen, N., Emad, R., Coghlan, L., & Hashimoto, T. (2024). Multi-analytical study of damage to marine ballast tank coatings after cyclic corrosion testing. *Corrosion and Materials*

- Degradation*, 6(1), Article 1. <https://doi.org/10.3390/cmd6010001>
- Merachtsaki, D., Fytianos, G., Papastergiadis, E., Samaras, P., Yiannoulakis, H., & Zouboulis, A. (2020). Properties and performance of novel $Mg(OH)_2$ -based coatings for corrosion mitigation in concrete sewer pipes. *Materials*, 13(22), 5291. <https://doi.org/10.3390/ma13225291>
- Merachtsaki, D., Tsardaka, E. C., Anastasiou, E. K., Yiannoulakis, H., & Zouboulis, A. (2021b). Comparison of different magnesium hydroxide coatings applied on concrete substrates (sewer pipes) for protection against bio-corrosion. *Water*, 13(9), 1227. <https://doi.org/10.3390/w13091227>
- Merachtsaki, D., Tsardaka, E. C., Anastasiou, E., & Zouboulis, A. (2021a). Evaluation of the protection ability of a magnesium hydroxide coating against the bio-corrosion of concrete sewer pipes, by using short and long duration accelerated acid spraying tests. *Materials*, 14(17), 4897. <https://doi.org/10.3390/ma14174897>
- Merachtsaki, D., Tsardaka, E.-C., Anastasiou, E., & Zouboulis, A. (2021c). Study of magnesium hydroxide protective coating against corrosion, applied on poly(methyl methacrylate) plates, by using the sulfuric acid attack acceleration test. *Materials Proceedings*, 5(1), Article 4. <https://doi.org/10.3390/materialsproc2021005004>
- Merachtsaki, D., Tsiaras, S., Peleka, E., & Zouboulis, A. (2022). Selection of magnesium hydroxide coatings for corrosion mitigation in concrete sewer pipes by using multiple criteria decision analysis. *Environmental and Sustainability Indicators*, 13, 100168. <https://doi.org/10.1016/j.indic.2021.100168>
- Moa, J. P. S., Gaw, B. A. C., Co, J. L. O., Co, K. A. C., Elevado, K. J. T., & Roxas, C. L. C. (2025). Performance of seawater-derived $Mg(OH)_2$ as a sustainable coating solution for hydrogen sulfide-induced corrosion mitigation in concrete pipes. *Cleaner Engineering and Technology*, 24, Article 100872. <https://doi.org/10.1016/j.clet.2024.100872>
- MortezaNia, S., & Othman, F. (2012). Cost analysis of pipes for application in sewage systems. *Materials & Design*, 33, 356–361. <https://doi.org/10.1016/j.matdes.2011.01.062>
- Onuaguluchi, O., & Banthia, N. (2022). The influence of $CaCl_2$ -blended acrylic polymer on steel rebar corrosion and acid attack resistance of mortar. *Corrosion and Materials Degradation*, 3(1), 160–177. <https://doi.org/10.3390/cmd3010009>
- Pacheco-Torgal, F., Abdollahnejad, Z., Miraldo, S., Baklouti, S., & Ding, Y. (2012). An overview on the potential of geopolymers for concrete infrastructure rehabilitation. *Construction and Building Materials*, 36, 1053–1058. <https://doi.org/10.1016/j.conbuildmat.2012.07.003>
- Persson, D., Thierry, D., & LeBozec, N. (2023). The effect of microstructure on local corrosion product formation during initial SO_2 -induced atmospheric corrosion of ZnAlMg coating studied by FTIR-ATR FPA chemical imaging. *Corrosion and Materials Degradation*, 4(3), 503–515. <https://doi.org/10.3390/cmd4030026>
- Rihawi, B., Maras, M. M., Ekinci, E., & Kutlusoy, E. (2025). Development of novel fiber-reinforced eco-friendly concrete: Application in geopolymer concrete pipes infrastructure systems. *Clean Technologies and Environmental Policy*, 27(10), 5165–5182. <https://doi.org/10.1007/s10098-025-03171-3>
- Rihayat, T., Suryani, S., Satriananda, S., Riskina, S., Syahputra, W., Nurhanifa, N., & Mawaddah, M. (2019). Formulation of polyurethane with bentonite-chitosan as filler applied to carbon steel as an antibacterial and environmentally friendly paint. *IOP Conference Series: Materials Science and Engineering*, 536, 012093. <https://doi.org/10.1088/1757-899X/536/1/012093>
- Roghanian, N. (2018). *A novel functionalized composite coating for controlling bio-corrosion in wastewater concrete pipes* [Doctoral dissertation, University of British Columbia]. <https://doi.org/10.14288/1.0365537>
- Roghanian, N., & Banthia, N. (2019). Development of a sustainable coating and repair material to prevent bio-corrosion in concrete sewer and waste-water pipes. *Cement and Concrete Composites*, 100, 99–107. <https://doi.org/10.1016/j.cemconcomp.2019.03.026>
- Santos, A. N. B., Gouveia, J. R., Garcia, G. E. S., Antunes, R. A., Santos, D. J. dos, & Carastan, D. J. (2024). Self-healing epoxy coatings via microencapsulation of aromatic diisocyanate in lignin-stabilized Pickering emulsions. *Next Materials*, 3, 100176. <https://doi.org/10.1016/j.nxmte.2024.100176>
- Sarcinella, A., & Frigione, M. (2023). Sustainable and bio-based coatings as actual or potential treatments to protect and preserve concrete. *Coatings*, 13(1), 44. <https://doi.org/10.3390/coatings13010044>
- Shing, C. K., Wu, C. M. L., Chen, J. W. J., Yuen, C. S., & Tsui, R. Y. C. (2012). A review on protection of concrete for sewage installations and an accelerated test on protection systems. *HKIE Transactions*, 19(3), 8–16. <https://doi.org/10.1080/1023697X.2012.10668992>
- Sukontasukkul, P., Intarabut, D., Phoo-ngernkham, T., Suksiripattanapong, C., Zhang, H., & Chindaprasirt, P. (2023). Self-compacting steel fibers reinforced geopolymer: Study on mechanical properties and durability against acid and chloride attacks. *Case Studies in Construction Materials*, 19, e02298. <https://doi.org/10.1016/j.cscm.2023.e02298>
- Suleiman, A. R., Soliman, A. M., & Nehdi, M. L. (2014). Effect of surface treatment on durability of concrete exposed to physical sulfate attack. *Construction and Building Materials*, 73, 674–681. <https://doi.org/10.1016/j.conbuildmat.2014.10.006>
- Takada, R., Hirasawa, K., Takahashi, H., & Chiba, M. (2023). Self-healing coatings consisting of an outer electrodeposited epoxy resin layer and an inner porous anodic oxide layer with healing agents for the corrosion protection of Al alloys. *Corrosion and Materials Degradation*, 4(3), 516–527. <https://doi.org/10.3390/cmd4030027>
- Valix, M., Zamri, D., Mineyama, H., Cheung, W. H., Shi, J., & Bustamante, H. (2012). Microbiologically induced corrosion of concrete and protective coatings in gravity sewers. *Chinese Journal of Chemical Engineering*, 20(3), 433–438. [https://doi.org/10.1016/S1004-9541\(11\)60150-X](https://doi.org/10.1016/S1004-9541(11)60150-X)
- Vipulanandan, C., & Liu, J. (2002). Glass-fiber mat-reinforced epoxy coating for concrete in sulfuric acid environment. *Cement and Concrete Research*, 32(2), 205–210. [https://doi.org/10.1016/S0008-8846\(01\)00660-3](https://doi.org/10.1016/S0008-8846(01)00660-3)
- Vipulanandan, C., & Liu, J. (2005). Performance of polyurethane-coated concrete in sewer environment. *Cement and Concrete Research*, 35(9), 1754–1763. <https://doi.org/10.1016/j.cemconres.2004.10.033>
- Vipulanandan, C., & Liu, J. (2018). Polymer coatings for concrete surfaces: Testing and modeling. In *Handbook of environmental degradation of materials* (3rd ed., pp. 69–94). Elsevier. <https://doi.org/10.1016/B978-0-323-52472-8.00004-6>
- Wang, T., & Zeng, C. (2020). Study of cement-based superhydrophobic composite coating: New option for water drainage pipeline rehabilitation. *Materials*, 13(21), 5004. <https://doi.org/10.3390/ma13215004>
- Wong, L. S. (2022). Durability performance of geopolymer concrete: A review. *Polymers*, 14(5), 868. <https://doi.org/10.3390/polym14050868>

- Wu, L., Huang, G., & Liu, W. V. (2021). Methods to evaluate resistance of cement-based materials against microbially induced corrosion: A state-of-the-art review. *Cement and Concrete Composites*, 123, 104208. <https://doi.org/10.1016/j.cemconcomp.2021.104208>
- Yadav, S., & Pramanik, B. (2024). Novel hybrid coating material with triple distinct healing bond for fat, oil, and grease deposition control in the sewer system. *Chemical Engineering Journal*, 499, 156226. <https://doi.org/10.1016/j.cej.2024.156226>
- Yao, C., Lin, J., & Zhang, S. (2025). Polyhexanide derivatives-reinforced silver-polytetrafluoroethylene coatings for enhanced antibacterial properties. *Next Materials*, 8, 100541. <https://doi.org/10.1016/j.nxmte.2025.100541>
- Yu, X., Riahi, E., Entezarmahdi, A., Najafi, M., & Sever, V. F. (2015). Experimental and numerical analyses of strength of epoxy-coated concrete under different load configurations. *Journal of Pipeline Systems Engineering and Practice*, 7(2), Article 04015022. [https://doi.org/10.1061/\(ASCE\)PS.1949-1204.0000224](https://doi.org/10.1061/(ASCE)PS.1949-1204.0000224)
- Zhang, C., Li, Z., Li, J., Gao, P., Wang, R., Xia, C., & Deng, G. (2024). Multi-particle impact behavior of Cu nanoparticles: A molecular dynamics investigation. *Next Materials*, 6, 100305. <https://doi.org/10.1016/j.nxmte.2024.100305>