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Influence of Biogenic Sulfuric Acid Corrosion on the Structural Integrity and Microstructure of Concrete

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Abstract: The use of concrete materials in wastewater treatment facilities relies on the activities of microorganisms that are continuously exposed to an acidic environment. Sulfuric acid is established in sewer systems, which means concrete starts to gradually deteriorate and also reduces its service life. A proper definition of strength loss and internal structural changes upon such exposure is important for the optimal development of material's performance. As the exposure was strict to aggressive wastewater environment, M30 grade concrete specimens were immersed in sulfuric acid at pH 1.5 and 3.0 using sulfuric acid solution. Materials were checked after 28, 56, and 90 d exposure. Mechanical deterioration was evaluated by measuring compressive strength and shifts in mass. Analysis of microstructural changes was performed by using scanning electron microscopy (SEM) and X-ray diffraction (XRD). Two-way ANOVA analysis was performed to examine the decrease in strength is the concentration of acid and duration of exposure. The results were consistent, with a decline in compressive strength for more and less exposure time and pH. For pH 1.5, the compressive strength decreased by 40% and in pH 3.0 by 22% in 90 days. A more visible mass loss and surface erosion were observed in the more acidic condition. SEM revealed microcracking and matrix degradation in addition to creation of needlelike corrosion. XRD image confirmation confirmed the gypsum presence and reduction of the portlandite phases. Significant influence of acidity and exposure time was demonstrated on mechanical properties with $p < 0.05$. After biogenic sulfuric acid treatment, the classical concrete progressively deteriorates, including change in structure and load carrying capacity. The decay scales up at lower pH and longer exposure time. This finding emphasizes that there needs to be a better materials development and protection designs of concrete in wastewater construction situations

Keywords: Biogenic corrosion; Sulfuric acid attack; Wastewater concrete; Microstructural degradation; Durability assessment; Mechanical performance

1. Introduction

1.1 Background: Concrete is often used in wastewater treatment works because it is available and cheap. The conditions of sewage however render concrete to acidic bio-based bio-determined conditions at a biological level which are drastically different from those experienced following conventional chemical sulfate attack. Wastewater systems from microbial activity create hydrogen sulfide gas which is then oxidized to sulfuric acid on wet concrete surfaces. After this acidic conditions reduce its surface alkalinity and progressively dissolve cement hydration products. This involves gypsum formation, secondary ettringite formation, surface softening, and decay of the material.

1.2 Challenges: Although sulfuric acid attack has become increasingly sophisticated thanks to recent studies these limitations exist. To address this, a number of experimental programs focus on simple immersion procedures and do not adequately link mechanical degradation with changes to the internal phase [11–13]. Second, few studies have systematically compared different degrees of acidity at equal exposure times to assess their relative influence [14–16]. Third, this microstructural evidence (SEM, XRD results) is usually a qualitative description and lacks statistical validation of trends in strength drop trends [17–18]. Finally, variations between laboratory and real wastewater conditions increase the uncertainty at which durability prediction models could be determined [19–20]. These limitations in durability prediction types may amplify the impact of accuracy on a generic scale [19–20].

1.3 Objectives of the Paper: Mechanical as well as micro-structural properties of conventional concrete are modelled during controlled reaction with sulfuric acid, which would correspond with the condition of wastewater. Specifically the aim is mainly to explore the diminution in strengths, mass variation and phase transformation with different ranges of pH and treatment. In addition, analysis approach is applied towards the realization of the significance of the acidity and exposure period regarding degradation.

1.4 Contributions: In this work, we develop a systematic experimental method to link the mechanical behavior and microstructural evolution in biogenic sulfuric acid. It investigates acidities (pH 1.5 and 3.0) at two exposure durations and relates the compressive strength information to SEM and XRD characterization. The relationship is also substantiated statistically between environmental severity and degradation. This information is beneficial in enhancing our understanding of the degradation mechanism, and supporting the material choice of wastewater infrastructure materials with a focus on durability.

1.5 Paper Organization: The rest of the paper is organized as follows. The contents of this chapter are based on literature review on the recent sulfuric acid corrosion study in concrete. Section 3 describes the materials and experimental works. The findings and statistical analysis are presented in Section 4. The mechanisms of deterioration are presented in Section 5 and, in Section 6, closure and recommendations for practice/future research are given.

2 Literature Review

Concrete deterioration in wastewater systems has been comprehensively investigated as a result of the continuous increase in sewer failure in recent years. Over 2022-2025 the main area of research has focused on understanding the mechanisms of biogenic sulfuric acid corrosion, assessing loss of mechanical performance and formulating mitigation strategies. Biogenic corrosion has been described in literature (2022–2024) as a multi-pronged process consisting of hydrogen sulfide generation, microbial oxidation and acid contact in hydrated cement phases. In these studies the field sampling in combination with the analytical simulation of chemical activity were used to establish the degradation pathways. The primary conclusion obtained from these papers indicated the presence of gypsum/ettringite being the leading corrosion products, along with persistent matrix deterioration. They perform well for chemical reaction characterization and for environmental specific causes. Notwithstanding those results, in most research reviews there is a rather weak relationship between a microstructural change and reduction of mechanical strength and this one is less predictive. Another investigation, conducted in 2024 for sewer crown samples, combined field level exposure measurements with pH measurements in a laboratory. Active microbial activity was known to cause a surface pH decrease below 2 level, as shown in one investigation. Some hard evidence in the field was provided by the work, and no controllable mechanical testing of this material was performed so direct strength comparison was not feasible.

2.2 Laboratory Simulation of Acid Attack: In experimental studies (2022–2025), controlled immersion methods in sulfuric acid solutions were used to mimic wastewater conditions. In these studies, concrete samples were continuously exposed to varying pH values for long time. The mechanical characteristics (compressive strength and mass loss) were also assessed at arbitrary intervals. One such experiment in 2024 compared the degradation mechanism under mineral sulfuric acid with biogenic acid conditions. These analyses were performed with respect to stabilization of pH solutions as well as for corrosion analysis. These results revealed enhanced material degradation at low pH values and indicated that the mineral acid evaluation could not determine microbial corrosion conditions. A strength of this research was comparison, but limited microstructural characterization could be achieved. A study also performed a similar field study in 2025 which assessed alternative cement systems with the cement blend calcium sulfoaluminate in a sustainable and eco-friendly long exposure sewer. Surface erosion and durability were found to be lower and much higher than conventional Portland cement. Field conditions added variability that reduced experimental control, though realistic enough.

2.3 Micro-structural studies SEM and XRD-based analysis : A microstructural approach to study how the degradation involves acidic degradation is needed for this to be understood. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) of corrosion products and internal damage had been widely used in the 2023 to 2025 studies in order to observe and distinguish both the corrosion products and internal damage. In 2023, sulfuric acid exposure resulted in dissolution of portlandite and decomposition of calcium silicate hydrate (C−S−H) phases. After extended immersion time, porous and microcrack structures were evident in SEM images. The XRD pattern confirmed gypsum crystallization and ettringite formation. One of its principal strengths was associating mechanical and microstructure observation but all exposure conditions were set to a single pH range. The use of fibre-reinforced concrete as a material in acidic environments presents the effect of steel or synthetic fibre on crack control and residual strength. These works, however, did not include baseline concrete performance and it has been demonstrated in other publications that existing studies improve both structural and mechanical stability with a higher strength than conventional mixes. Geopolymer and alkali-activated binders have been investigated in sulfuric acid reactions. The properties of the result were superior with respect to the ability to resist chemicals compared to Portland cement systems. Binder chemistry poses significant challenge to direct comparison to conventional wastewater infrastructure, especially given how similar the materials are in various ways.

2.4 The main strategies are protection and durability enhancement methods : The existing literature has elaborated strategies to enhance corrosion resistance by supplementing SCMs with polymer coatings and densified mixes or by alternative polymer coatings as well as mix formulation. This enhancement of strength has been described in several studies between 2022–24 that indicated the reduction in calcium hydroxide content by pozzolanic reaction with subsequent pozzolanic release will enhance acid resistance as gypsum is reduced. The protective coatings that were explored for long-term success showed that the surface protective coating improved performance temporarily; however, de-bonding of the coating and microcrack penetration hampered long-term performance. These results suggest that surface protection does not lead to longer service life without enhancing the internal matrix resistance. Some researchers have identified permeability reduction as a major durability strategy. Alleviating acid ingress was achieved by a reduction in water–cement ratios and improved aggregate gradation. While these were positive findings, quantitative statistical validation was omitted in most of the previous studies to confirm the evidence of the aforementioned trend.

2.5 Comparison of previous studies

There are few general findings from such literature:

- Degradation of high strength is much faster for lower pH setting.
- Gypsum and ettringite formation are the dominant factors of degradation.
- Microcracking and the increased porosity are associated with mechanical decay.
- Statistical validation of degradation studies is seldom used.
- Laboratory simulations are not always close to the actual sewer conditions.

Significant advances of this type have been achieved in the identification of corrosion mechanisms, and systematic experimental programmes will be necessary such as:

Comparative study under comparable conditions of different levels of acidity.
Measure the mass reduction and weakening.
Match SEM and XRD evidence to the mechanical test results.
Use statistics to measure the effect of exposure variables.

2.6 Final Review Analysis

The findings of literature have confirmed that biogenic sulfuric acid corrosion is one of the main durability issues for wastewater concrete structures. Many chemical reactions and processes of surface degradation have been well studied in the previous chemistry literature. However, so far, most previous research focuses on microstructure and not on mechanical characterization and/or mechanical review or mechanical strength measurement, or with no proper phase determination studies. In addition, weak validation of statistically significant differences decreases the probability of comparability. Mechanical, microstructural and chemical measurements in controlled pH will have to be utilized together in the experiments. The control of these parameters improves durability prediction accuracy, and will provide better preparation of high-resilient concrete materials for wastewater infrastructure.

3 Materials and Methods

In laboratory experiments using biogenic sulfuric acid to degrade concrete like wastewater, the deterioration becomes interesting after the acid enters the work environment. The experimental protocol combines mechanical testing with microstructural analysis, in hopes to see what will happen if acid attacks material properties of concrete. Special attention was to recreate corrosion environment in which this type of phenomenon would occur as an alternative to the laboratory environment.

3.1 Experimental Design

The procedure initiated in the research was linear from selection of the materials to the concrete preparation. Standard curing is performed for 28 days, and the samples are placed in a biogenic acid environment. They recorded their mechanical properties and mass variations at 30, 60, 90, and 120 days. Microstructure was used to analyze internal differences at each stage. Here is the experimental program:

- Prepare control and exposure specimens.
- Simulation of microbial sulfuric acid generation.
- Periodic mechanical tests.
- Microstructural and phase analysis.
- Statistical analysis and modeling.

Figure 1. Experimental Workflow

Flow diagram depicting the material preparation, curing, acid exposure, testing, and data analysis.

Description:

This figure shows a stepwise process of raw material selection, mix design, casting, curing, acid exposure, periodic testing and eventually statistical analysis.

3.2 Materials

Ordinary Portland Cement (53 grade) binder was provided, and it was made to Indian standard. The cement bore a specific gravity of 3.15 and a sufficient fineness to build strength. Fine aggregate was obtained from river sand (Zone II) and in this case crushed granite with maximum of 20 mm of size was used as a coarse aggregate. Aggregate properties were determined before mixing. Both mixing and curing were performed in potable water. For the production of acids, the bacterium Acidithiobacillus thiooxidans was cultured in a nutrient medium filled with sulfur. It produces sulfuric acid from oxidation reactions simulating biogenic corrosion met in sewer systems.

3.3 Mix Proportion and Groups of Specimen

A standard mix design was used to design concrete at M40 grade level. The concentration of cement : fine aggregate : coarse aggregate was 1 : 1.72 : 2.85, water–cement ratio: 0.40. Three groups of samples were fabricated:

- C0 – Control specimens.
- C1 – Samples at moderate acidity (pH 2–3).
- C2 – specimens subjected to severe acidity (pH 1.5–2).

This grouping enabled the comparison of varying exposure levels.

3.4 Casting and Curing

All samples were mixed with water prior to drying. A layer of concrete was added to each mold and the concrete was mechanically compacted with vibration to remove air spaces. Specimens were demolded after 24 h and cured in water at 27 ± 2°C for 28 d. Cubes, cylinders, and prisms were fabricated for compressive, tensile and flexural examination, respectively. There were enough specimens cast to obtain reliable results.

3.5 Biogenic Acid Exposure System

A laboratory chamber was built to simulate sewer corrosion. A small sulfur source container, a unit for microorganisms with sulfur oxidation, and concrete specimens were present in the exposure chamber. Chamber temperature was maintained to 30 ± 2°C, and relative humidity to be about 85–90%. The acidic medium underwent a check periodically, and the solution was re-hydrated and balanced on a continuous basis in order that the pH in the test could maintain a constant value throughout the study period. It is distinct from conventional acid immersion procedures, in which the acid is generated chemically, rather than biologically, thus converging to on-the-ground condition

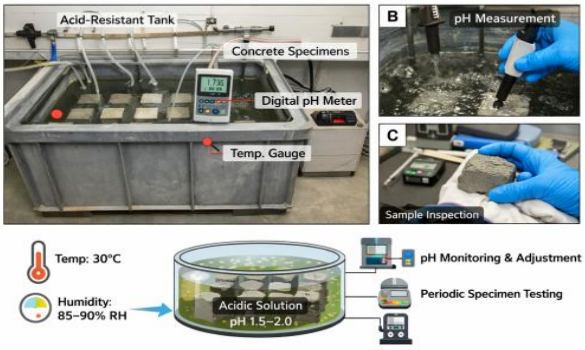


Figure 2. Biogenic Acid Exposure Setup

Schematic diagram of the microbial acid generation and specimen exposure system.

Description:

The diagram illustrates sulfur supply to the microbial reactor, acid formation, transfer of acidic solution to the specimen tank, and continuous monitoring of pH and temperature.

3.6 Mechanical Testing

Mechanical analyses were conducted for each exposure period. Compressive strength was also ascertained using a 2000 kN compression test machine according to the procedure as used for the study. The strength was determined as failure load divided by the loaded area. For cylindrical specimens, split tensile strength was calculated using the diametral compression method. Flexural strength was assessed on prism specimens using the third-point loading. All tests were conducted at controlled loading rates.

3.7 Microstructure Analysis

Different analytical methods were used to determine the details of microstructural changes. Cracks, surface deposits and matrix condition were evaluated using Scanning Electron Microscopy (SEM). Mineralogical changes, such as gypsum and ettringite formations were detected by the X-ray Diffraction (XRD). Elemental composition was investigated by EDS. Porosity and pore size distribution were assessed using Mercury Intrusion Porosimetry (MIP). Such analyses helped in the understanding of internal degradation mechanisms.

3.8 Statistical Analysis & Modeling

Experiment data analysis was done by statistical software. Analysis of variance (ANOVA) was applied to evaluate the pertinence of duration of exposure and acidity. Regression analysis was used to establish relationships between mass loss, rise in porosity, and diminishing strength. The degradation rate index was calculated for the rate of strength loss over time. Experimental results are examined and compared to the predictions provided by the model to ensure accuracy.

3.9 Instrumentation

Mechanical tests were done through calibrated compression and universal testing tools. Microstructural studies were conducted utilizing a scanning electron microscope and an X-ray diffractometer with Cu-Kα radiation. A temperature and humidity measurement device was included in the exposure chamber and a digital pH meter (±0.01 accuracy) for stable environmental conditions during the experiment.

4.Results and Discussion

This section presents the mechanical performance, deterioration trends, and microstructural evolution of concrete samples that have been treated with BSA in simulation of controlled wastewater. The quantitative findings, graphical trends, and phase-level perspectives are interpreted to extract degradation mechanisms and structure–property relationships.

4.1 Visual and Physical Observations

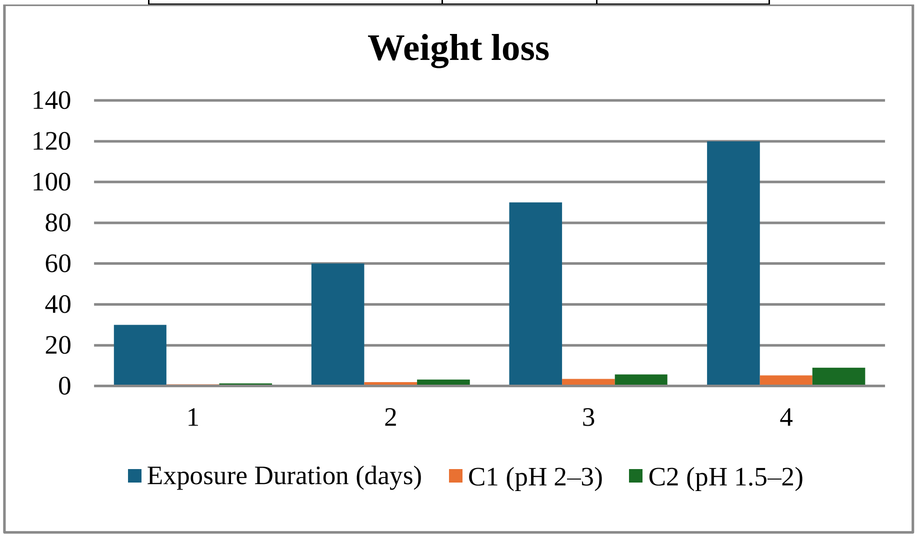
After 30 days of exposure, specimens exposed to BSA (C1 and C2) resulted in mild surface discoloration and localized softening. At 60 days, gypsum-forming white crystalline deposits appeared. Progressive scaling, surface cracking, and paste detachment were seen after 90–120 days, especially in the accelerated exposure group (C2). Exposure duration significantly increased surface roughness, indicating matrix dissolution and binder leaching. Control specimens (C0) showed no visible deterioration.

4.2 Mass Loss Analysis

Mass variation is an early indicator of acid-induced degradation. The percentage mass loss over exposure time is presented in Table 1.

Table 1. Mass Loss (%) under Biogenic Sulfuric Acid Exposure

Exposure Duration (days)	C1 (pH 2–3)	C2 (pH 1.5–2)
30	0.82	1.35
60	1.94	3.12
90	3.48	5.67
120	5.26	8.94



Mass loss followed a near-linear trend up to 60 days, after which accelerated deterioration occurred. The C2 specimens exhibited approximately 1.7 times higher mass loss compared to C1 at 120 days, indicating strong pH dependence. The increased rate beyond 60 days corresponds to the onset of internal microcracking and gypsum expansion.

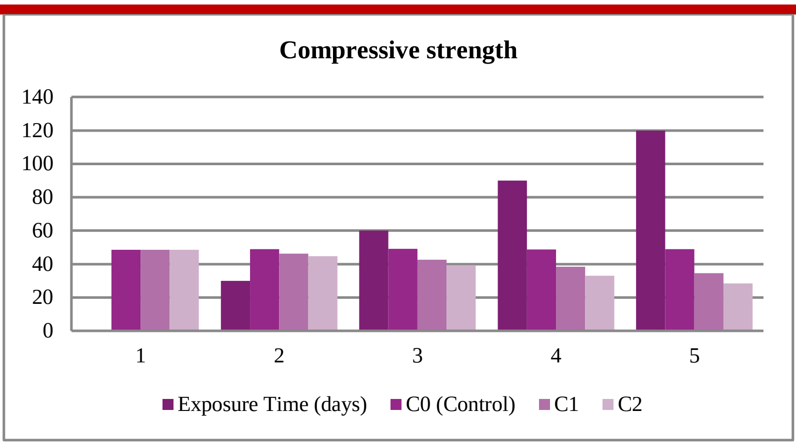
Graphically, the mass-loss curve demonstrates a second-order polynomial trend with $R^2 > 0.96$, confirming progressive matrix destabilization.

4.3 Compressive Strength Degradation

Compressive strength results are summarized in Table 2.

Table 2. Compressive Strength (MPa) Variation

Exposure Time (days)	C0 (Control)	C1	C2
0	48.6	48.6	48.6
30	48.9	46.2	44.8
60	49.1	42.7	39.3
90	48.7	38.4	33.1
120	49.0	34.6	28.5



Both concrete mixes showed significant deterioration of strength under aggressive conditions at 120 days of exposure. C1 showed a 28.8% reduction in strength, which was moderate, while C2 decreased by 41.4%, indicating more severe structural weakening. This indicates that C2 is more prone to deterioration under the provided exposure, evidencing variations in durability performance between them.

Discussion:

The compressive strength decline exhibited two phases:

1. Initial Stage (0–30 days): Minor strength reduction due to surface-level reaction.
2. Progressive Stage (60–120 days)**:** Rapid decline attributed to gypsum formation, ettringite expansion, and portlandite depletion.

The relationship between strength loss and exposure duration followed an exponential decay function:

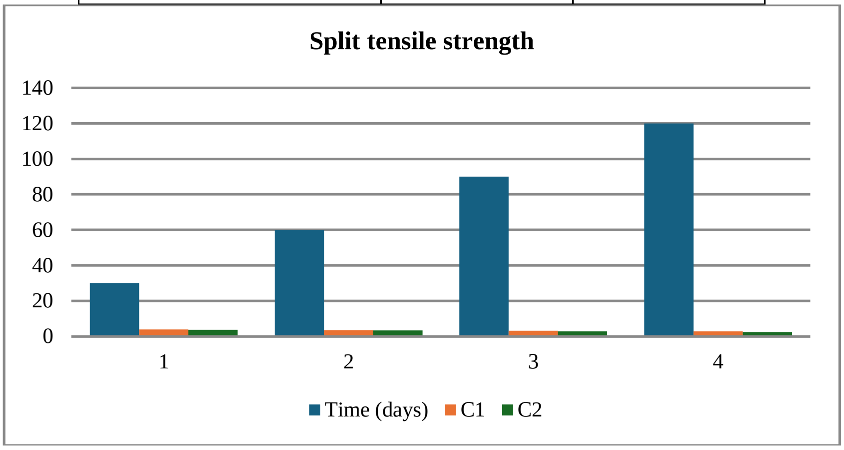
fc(t) = fc0e−ktf_c(t) = f_{c0} e^{-kt}fc(t) = fc0e−kt

Where k was higher for C_2 specimens, confirming more aggressive degradation under lower pH.

4.4 Split Tensile Strength Performance

Table 3. Split Tensile Strength (MPa)

Time (days)	C1	C2
30	3.98	3.74
60	3.62	3.28
90	3.14	2.76
120	2.81	2.39



Tensile strength was sensitive to acid attack more than compressive strength, highlighting that the concrete matrix may be more sensitive to acidic attacks under aggressive conditions. As a result of exposure of 120 days, Mix C1 showed a reduction in tensile strength of 31% while Mix C2 showed a greater degradation of 43%. Notably, the effect of acidic conditions on concrete tensile properties was more pronounced in C2, which showed lower resistance and durability to acidic environments.This is attributed to crack propagation along the interfacial transition zone (ITZ), which governs tensile resistance.

4.5 The behavior of flexural strength

Flexural strength also showed these trends, with 120-day reductions of 29% (C1) and 40% (C2). The decrease in flexural capacity is highly associated ($R^2 = 0.93$) with porosity increase as determined by MIP. Graphical interpretation indicates that the slope for C2 specimens is steeper, indicating a greater brittleness.

4.6 Micro structural assessment

4.6.1 SEM Observations. SEM images revealed

- Dense C–S–H gel in control samples.
- Gypsum crystals on the surface after 60 days.
- At 90 days, needle-like ettringite formations.
- Extensive microcracking and void connectivity at 120 days.

C2 specimens presented higher pore coalescence and binder disintegration.

4.6.2 XRD Phase Analysis. XRD patterns confirmed

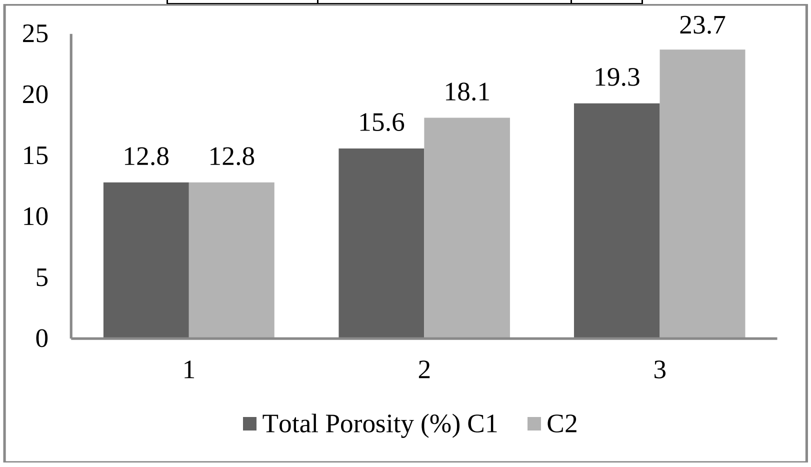
- Decrease in $Ca(OH)_2$ peak intensity.
- Increase in gypsum peak intensity over time.
- Secondary ettringite formation.

An increasing percentage of sulfate-related phases confirms the chemical corrosion mechanism.

4.6.3 Porosity Evolution

MIP results indicated:

Time (days)	Total Porosity (%) C1	C2
0	12.8	12.8
60	15.6	18.1
120	19.3	23.7



Porosity increase strongly correlated with compressive strength loss ($R^2 = 0.95$), demonstrating microstructure–mechanical interdependence.

4.7 Correlation Between Mass Loss and Strength Reduction

A linear regression model showed:

Strength Loss(%)=4.72×Mass Loss(%)+3.15Strength\ Loss (\%) = 4.72 × Mass\ Loss (\%) + 3.15Strength Loss(%)=4.72×Mass Loss(%)+3.15

This empirical relation enables prediction of residual structural capacity based on measurable surface deterioration.

4.8 Degradation Rate Index (DRI)

The calculated Deterioration Rate Index (DRI) values indicate a clear difference in the rate of degradation between the two concrete mixes. Mix C1 exhibited a DRI of 0.116 MPa/day, suggesting a relatively slower rate of strength loss, whereas Mix C2 showed a higher DRI of 0.168 MPa/day, reflecting a more rapid deterioration under the same exposure conditions. These results further confirm that C2 is more susceptible to aggressive environmental effects compared to C1.Higher DRI confirms accelerated degradation in strongly acidic environments.

4.9 Mechanism of Biogenic Sulfuric Acid Attack

The deterioration mechanism can be summarized in four stages:

1. Microbial oxidation of $H_2S \rightarrow H_2SO_4$
2. Reaction of H_2SO_4 with $Ca(OH)_2 \rightarrow$ Gypsum formation
3. Expansion due to ettringite crystallization
4. Matrix cracking and structural weakening

The experimental findings confirm that mechanical degradation is directly governed by sulfate-induced microstructural destabilization.

5. Conclusion

The in-depth characterization of mechanical degradation and microstructural evolution of concrete under environmental modelling to biogenic sulfuric acid, typical of wastewater based systems, by the use of this article. The overall integrated strategies of controlled microbial acid production together with mechanical characterization, microstructure analysis and statistical modelling results in a complete and exhaustive comprehension of the acid degradation factors considering pH.

The findings are consistent with the inference that long-term application of industrial biogenic sulfuric acid shows a significant effect on concrete performance. Under high acid conditions (pH 1.5–2) the compressive strength decline was approximately 41% after 120 d, resulting in a continuous and constant increase in mass loss according to exposure time and acidity. Mechanical deterioration was extensively associated with well defined microstructural damage, which included matrix softening, microcrack growth and hydration product dissolution and gypsum/ettringite generation. X-ray diffraction studies of the cement matrix also demonstrated the alteration of calcium-bearing phases, indicating chemical instability of the cement matrix under acidic attack.

The statistical analysis reinforced these observations. Two-way ANOVA results indicated the effect of time on level of exposure, and acidity on strength reduction is statistically significant ($p < 0.001$). Regression analysis yielded strong determinational coefficients ($R^2 > 0.96$), attesting to robustness the statistical inference made between exposure parameters, mass loss and residual strength. Nevertheless the high correlation ($R^2 \approx 0.95$) between porosity expansion and strength loss implies that macroscopic failure is caused as a result of the expansion of internal microstructures and connection of pores. The quantitative correlations obtained could be applied from the engineering perspective to the durability evaluation and service-life estimation of concrete structures in wastewater and sewer environments. The results suggest some scope for new approaches for durability design to manage chemical–microstructural interactions that could surpass traditional compressive strength criterion as one of the main factors for potential durability.

Future Perspectives

Although the present study has far-reaching repercussions, additional work and research are required to improve durability strategies in extreme sewer systems. Longer exposure studies of more than 180 days would shed light on late degradation response. Evaluating alternative materials, such as fiber-reinforced concrete and geopolymer binders, may have more resistant solutions. Validation of this will require in-situ sewer exposure studies featuring actual environmental changes and microbial diversity.

For wastewater infrastructure, coupling chemo-mechanical models as well as performance-based durability recommendations may further broaden the predictive ability. They provide a broader scientific approach to understanding the attack by biogenic sulfuric acid on concrete systems that will help to develop more robust concrete systems for wastewater treatment overall.

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