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Quantifying microbially induced deterioration of concrete: initial studies

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Abstract

Microbially induced concrete corrosion damages concrete structures, especially sewage collection systems, throughout the world, costing municipalities millions of dollars worldwide. The overall theory explaining microbial deterioration of concrete is quite well developed in the literature. There is, however, very little information of a quantitative nature that can be used to model the process. This manuscript presents a review of the current literature, shares the initial results of studies designed to quantify and model the process, and makes some suggestions of further areas of research needed to advance modeling of the process. Initial results have revealed that widely varying numbers of acidophilic sulfur-oxidizing microorganisms (ASOM) and neutrophilic sulfur-oxidizing microorganisms (NSOM) are present in the sewage inoculum. Numbers as high as 10^6 MPN/100 ml and as low as non-detectable have been found in sewage. A small number, 0.12 (MPN/cm^2)/(MPN/100 ml) ASOM and 0.04 (MPN/cm^2)/(MPN/100 ml) NSOM are able to attach to initially weathered concrete and then even smaller numbers of these, 1% ASOM and 3% NSOM, survive to colonize and further reduce the pH of the concrete. These set up the microbial succession required for the full development of the concrete deterioration process. More data quantifying the environmental conditions that effect the numbers of SOM in sewage and their survival on concrete is required before an accurate model of the entire deterioration process can be developed.

1. Literature review

1.1. Occurrences of microbial induced concrete corrosion

The first mention of concrete corrosion in the literature was by Olmstead and Hamlin (1900). In this study, a concrete sewer pipe was being converted to a white pasty material. This conversion was theorized to be the result of chemical attack of the concrete by hydrogen sulfide. Parker (1945a, b, 1951) refined this theory to include microbial agents by isolating sulfur-oxidizing bacteria from the surface of a corroding concrete sewer pipe and demonstrating their ability to grow and produce acid in a sewage environment. Five strains of *Thiobacillus* were isolated which converted hydrogen sulfide to sulfuric acid and it was postulated that this biogenic acid reacted with the cementitious material of the concrete. Others have observed extensive microbially induced concrete corrosion (MICC) in sewers, in both pipes and at pipeline junctions (Parker, 1945a; Diercks et al., 1991; Mori et al., 1992; Cho and Mori, 1995).

Since these initial reports of corrosion in sewage collections systems, MICC has been shown to occur in other types of concrete facilities. Some of these are wastewater treatment facilities (Redner et al., 1991) swimming pools (Chandra and Berntsson, 1988), cooling towers (Zherebyateva et al., 1991), and hydraulic facilities (Zherebyateva et al., 1991). The most rapid cases of deterioration always occur in areas with elevated H_2S concentrations, moisture, and oxygen in the atmosphere. These conditions are commonly found in sewage collection systems.

The removal of metals from industrial wastes prior to entering the municipal wastewater collection system has had the synergistic effect of accelerating the corrosion of concrete. The removal of heavy metals from waste water for water quality benefits has resulted in a decreased toxicity to sulfate reducing bacteria (SRB) and has resulted in increased production of sulfides in the waste stream (Morton et al., 1991). The metals were also responsible for the precipitation of sulfides from the waste stream. This increased sulfide production has resulted in increased sewer odors and an increase in the microbially induced deterioration of concrete structures (Morton et al., 1991).

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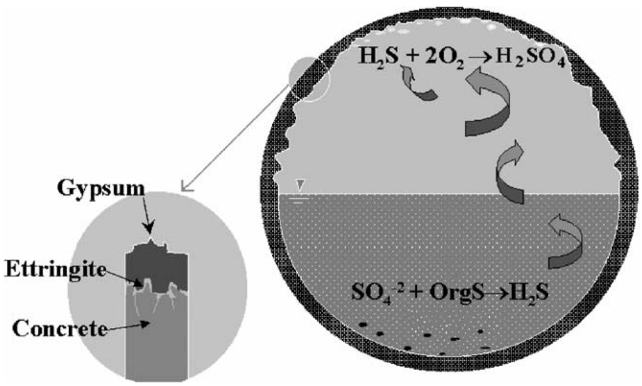

Fig. 1. The sulfur cycle in a sewage collection system causes concrete deterioration. The H_2S generated, by sulfate reducing bacteria in biofilms, partitions into the headspace of the collections system. The H_2S then repartitions into the condensate layer on the exposed surface of the concrete and is converted to various partially reduced sulfur compounds. In the presence of oxygen, and moisture, sulfur-oxidizing bacteria convert these reduced sulfur compounds to sulfuric acid. The sulfuric acid reacts with the binder in the concrete producing ettringite and gypsum.

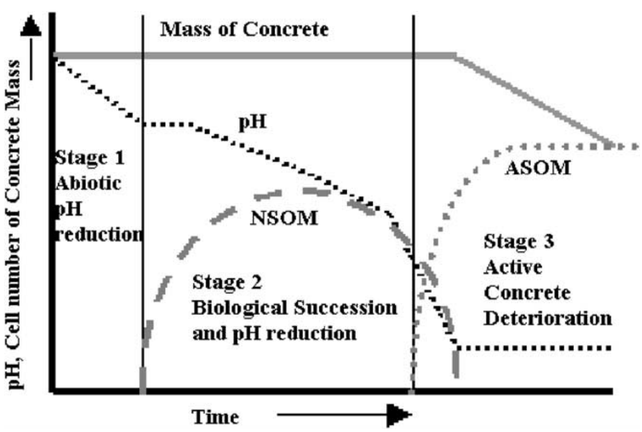

Fig. 2. Theoretical changes in the biological and physical properties of concrete with time during the deterioration process. Adapted from Islander et al. (1991).

1.2. Current theory of MICC

Figs. 1 and 2 are graphical representations of MICC in sewage collection systems and are detailed below. The lengths of time for the three distinct phases of MICC shown in Fig. 2 are still not available from the literature. Anecdotal information suggests that the age of the concrete in sewage collection systems is not the determining factor in the degree of corrosion. Further examination of the processes during the three phases of MICC is required.

1.2.1. Sulfide production and flux to concrete

Before the corrosion process can begin, the conversion of sulfate present in the sewage to hydrogen sulfide must occur. This conversion is performed by SRB. SRB are heterotrophic bacteria found in almost any environmental sample and the energy for the reduction of sulfate is supplied by the oxidation of organic compounds or H_2 (Barton and Tomei, 1995). Sulfate is present in many municipal wastewaters, especially in waters near coastal areas.

The normal pH of sewage is slightly acidic (pH 5–6). At these pHs, H_2S is the dominant sulfide species (pKa = 7.05). H_2S is poorly soluble in water and will partition into the headspace of the sewer based on Henry's Law. The H_2S then re-partitions into the condensate on the surface of the exposed concrete. The initial driving force for this repartitioning is the high pH of the condensate layer on the concrete surface. The H_2S is converted to HS^- or S^{-2} at these pHs, which pulls more H_2S into the condensate layer. In the presence of oxygen the sulfide species will react to form partially oxidized sulfur species such as thiosulfate, elemental sulfur and polysulfate species. These reactions will provide additional driving forces to pull more H_2S into the condensate layer. Other factors that influence the flux of sulfide from the sewage to the pipe walls are the turbulence of the waste stream, the diameter of the pipe, and the depth of the flow. The USEPA has developed flux curves for MICC modeling assuming the pipe is flowing $\frac{1}{2}$ full and a correction curve to be used if the pipe is not flowing $\frac{1}{2}$ full (Webster and Loehr, 1996).

1.2.2. Initial concrete pH reactions

Concrete is typically highly alkaline and has a pH in the range of 11–13 (Lea, 1970). The microorganisms capable of converting hydrogen sulfide to sulfuric acid cannot grow at this elevated pH so fresh concrete is protected from corrosion. The surface of the concrete does not remain basic throughout its whole life. CO_2 and H_2S are both present in the headspace of sewage collection systems and they both have acidic properties (Thistlethwayte and Goleb, 1972). Ismail et al. (1993) studied the effects of CO_2 on the pH and carbonation of the concrete surface. The results showed that atmospheric CO_2 was capable of reducing the concrete pH to 9.5, with the most rapid pH reduction occurring in atmospheres containing 5000 ppm of carbon dioxide. The paper did not give a reduction rate for the surface pH of the coupons. This action is termed chemical pH reduction and is depicted as the first phase of MICC in Fig. 2.

1.2.3. Microbial colonization and further pH reduction

The colonization of the concrete is an excellent example of microbial succession. Once the pH of the surface of the concrete is reduced to ∼9, and with sufficient nutrients, moisture and oxygen, some species of sulfur bacteria like *Thiobacillus sp.* can attach to the concrete surface and reproduce (Rigdon and Beardsley, 1956; Mori et al., 1992). Five species of *Thiobacillus* are found to play important roles on corroded and corroding concrete; they are *T. thioparus*, *T. novellus*, *T. neapolitanus*, *T. intermedius* and *T. thiooxidans*. The first four species listed are neutrophilic sulfur-oxidizing microorganisms (NSOM).

Table 1
Five species of *Thiobacillus* and their characteristics

Species	pH range for growth	Lifestyle	Sulfur substrates	Products
T. thioparus	4.5–10	Autotrophic aerobe	Thiosulfate, H_2S, thiocyanate	Sulfur, polythionic acids
T. novellus	5–9.2	Mixotroph	Thiosulfate	Sulfur
T. neapolitanus	4–9	Autotroph	H_2S, S, thiosulfate	Polythionic acids, sulfuric acid
T. intermedius	1.7–9	Mixotroph	Thiosulfate	Polythionic acids, sulfuric acid
T. thiooxidans	0.5–4	Autotroph	Thiosulfate, sulfur	Sulfur, sulfuric acid

The last species listed is an acidophilic sulfur-oxidizing microorganism (ASOM). General characteristics of these organisms are listed in Table 1. Fungi have also recently been found to be involved in the corrosion process (Cho and Mori, 1995; Gu et al., 1998; Nica et al., 2000).

The bacteria and fungi grow on the alkaline surface of the concrete and further reduce the surface pH of the concrete to pH 5 or lower. This is the start of a microbial succession that is determined not only by the pH of the concrete condensate layer, but also by the different types of sulfur compounds that are present at different times during the succession. The NSOM produce some acidic products, and they convert a lot of the sulfide present to elemental sulfur and polythionic acids. As the different organisms grow, acidic metabolic products accumulate and the pH of the concrete drops. At about pH 4–5 the acidophilic SOM (ASOM) like *T. thiooxidans* begin to colonize the surface and oxidize the sulfur and polythionic acids to large amounts of sulfuric acid, and the sulfur cycle in sewage system is completed (Parker, 1945a, b, 1951; Rigdon and Beardsley, 1956; Milde et al., 1983; Sand, 1987; Diercks et al., 1991; Islander et al., 1991).

The initial colonization and the microbial succession involved in the process are difficult to quantify. The numbers of the different organisms in the inoculum (sewage), their ability to colonize the concrete and to grow and produce acid under environmental conditions is very poorly understood. Research using concrete coupons inoculated with known numbers of SOM, or sewage and incubated in environmental chambers has been reported in the literature, but in most cases the only parameter evaluated is the rate of mass loss of the concrete coupon, and not the numbers and types of organisms that are colonizing the concrete (Sand, 1987; Sand et al., 1987; Mori et al., 1992). In many cases these studies use fully grown cultures of ASOM in acidic solutions to inoculate the coupons, thus bypassing the microbial succession. The acid present in the growth media of fully grown ASOM cultures will lower the pH chemically, thus rapid colonization of the concrete by ASOM is possible, but the rates do not reflect the rates that would be found in natural systems. These studies are very helpful in determining rates for the rapid acid production and concrete deterioration that occur once the concrete is well into the deterioration stage. They are also currently the most efficient way to test new materials for their resistance to microbial deterioration.

Table 2
Corrosion penetration rates during late stage corrosion conditions

Source	Corrosion penetration rate (mm/yr)
Morton et al. (1991)	2.7
Mori et al. (1992)	4.6–4.7
Ismail et al. (1993)	2–4
Davis (1998)	3.1

1.2.4. Concrete deterioration

The final step in the corrosion process is the reaction of the biogenic sulfuric acid with the cementitious material of the concrete and the eventual structural failure of the facility. This step is characterized by the production of a corroding layer on the surface of the concrete. This layer consists of gypsum ($CaSO_4$ of various hydration states) and moisture (Mori et al., 1992). The thickness of this layer expands into the concrete as more and more acid is produced to react with the concrete. The formation of ettringite ($3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O$ or $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 31H_2O$) during the acid reaction process causes another facet of the problem. Ettringite is expansive and causes internal cracking and pitting which provides a larger surface area for the chemical reaction to occur. This will also provide further sites of penetration of the acid into the concrete. Davis et al. (1998) analyzed the populations in slices of cores of concrete from corroding sewage collection systems and found that the ASOM and unidentified heterotrophs move into the concrete with the corroding layer, but the NSOM do not. This suggests that the microbial succession is a surface phenomenon, and once the surface pH is low enough for the ASOM to survive and produce acid, they follow the acid into the concrete.

The conversion of the concrete to gypsum and ettringite weakens the structural integrity of the concrete pipe. This reduces the load bearing capacity of the concrete and can result in the eventual collapse of the sewer.

To model this aspect of the process, both the microbial acid generation rate and the reaction rate of the acid with the concrete must be taken into account. Studies mentioned above that have examined the rate of the penetration of the acid into the concrete (or the rate of concrete loss for the surface) have calculated very similar rates for the penetration of corrosion into the concrete. Table 2 presents a summary of the literature concerning the rate of steady-state concrete corrosion. This is limited data, but an assumption of a steady-state corrosion penetration rate of ~ 3 mm/yr would not be unrealistic at this time.

1.3. Current models

The current models that can be used to predict MICC divide the modeling into three parts. The first is the prediction of sulfide generation. The second is predicting the flux of sulfide to the pipe wall. Information concerning these two processes can be found in Kwan et al. (1997) and USEPA (1974). The models use the carbonaceous or biochemical oxygen demand of the sewage as well as the hydraulics of the collection systems to predict the sewage or sewage collections system headspace concentrations of hydrogen sulfide. The flux of sewage to the concrete pipe can also be calculated.

The final modeling step predicts the rate at which the biogenic acid reacts with concrete. The USEPA (1974) presented a model by Pomeroy to approximate the reaction of sulfuric acid with concrete. The equation used to model this reaction is

$$C = \frac{\phi_{sw} k Y_{rxn}}{A\rho},$$

where C is the corrosion rate (L/T), ϕ_{sw} the H_2S flux to the pipe wall (M/L^2T), A the alkalinity of the cement bonded material expressed as $CaCO_3$ equivalent (M/L^3), Y_{rxn} the 0.32—reflects the reaction stoichiometry, ratio of S and $CaCO_3$, ρ the density of cement bonded material, and k is the coefficient of efficiency for acid reaction (0.3–1).

The coefficient k is an empirical parameter that accounts for inefficiencies in the reaction of acid with concrete. Actual determinations of k have not been made but it appears that k approaches unity when the rate of acid production is slow and can be as low as 0.3 when acid production is rapid and much condensate is formed. This model may be used to estimate loss of concrete at steady-state concrete deterioration, but does not include the kinetics of microbial acid production, nor the time it takes for the population to establish itself on the concrete and arrive at the point at which steady-state deterioration will occur.

Other than these attempts, the problem of MICC has not been studied as a quantitative problem, especially the initial stages of concrete colonization. The results presented in this paper are the initial attempts to answer some of the quantitative questions that must be answered to develop a model that truly reflects the microbial succession.

2. Methods and materials

2.1. Initial surface pH reduction

2.1.1. Mortar coupon preparation

Coupons of calcium aluminate, microsilica, and Portland mortar were prepared by spraying the mortar paste into cylindrical PVC molds 3 in in diameter and 0.5 in tall on a Teflon board. After spraying the mortar paste, the exposed surface was trowelled level and allowed to harden. The calcium aluminate mortar was sprayed by William Strong Jr. of Strong Seal, Pine Bluff, AR. The microsilica and Portland mortars were sprayed by Mario Tamez of Standard Cement, Houston, TX. The mortar was removed from the mold after setting for 3 days. The coupons were cured in humid conditions for 28 days. A 0.5 in diameter hole was drilled through the mortar to allow them to be suspended in an environmental chamber (described below) on aluminum rods. All coupons were soaked in water for at least 1 week prior to their use in experiments to ensure they were saturated. This reduced the effects of capillary action.

2.1.2. Coupon inoculation

Coupons were incubated in the chambers either uninoculated (to determine the effect of the headspace gasses or as controls) or inoculated with raw sewage from the City of Houston 69th Street Waste Water Treatment Plant. The inoculation of the concrete coupons was performed by soaking replicate coupons in 100 ml of sewage for 5 min on an orbital shaker at 50 rpm. After inoculation, one coupon from each group was washed with 100 ml phosphate buffered saline (PBS) solution and then inoculated again. The wash solution was used to determine the ability of the inoculum to adhere to the coupon from the inoculum. A 5-tube MPN enumeration method (described below) was used to determine the numbers of ASOM and NSOM in the 100 ml washing solution and the sewage inoculum. The numbers were converted to MPN/cm^2 by dividing the MPN results by the surface area of the coupon. After inoculation, coupons were put back into the chamber and the chamber was sealed and the H_2S concentration was adjusted to 100 ppm.

2.1.3. Coupon incubation

The coupons were suspended in an environmentally controlled chamber constructed as described by Davis (1998). The chamber was kept at room temperature (22–24°C) and 98–99% humidity (condensing conditions), a tray of water in the bottom of the chamber supplied sufficient moisture. Water droplets were visible on the surface of the coupons during the entire incubation. The H_2S concentration in the chamber headspace was monitored using a membrane sensor (Analytical Technology Inc.) that measured H_2S concentrations in the range of 0–300 ppm. The H_2S level was controlled using LabView™ software. The gas was supplied from a cylinder of 3% H_2S, 3% CO_2 balance nitrogen. Oxygen concentrations were monitored on a periodic basis to ensure aerobic conditions existed. The concentration of oxygen never became limiting during the biological incubations. The chambers contained 50, 100 or 250 ppm H_2S in the headspace, depending on the experiment.

2.1.4. Coupon sampling

Coupons were monitored periodically to determine the surface pH and the microbial numbers on the coupons. The surface pH of each coupon was determined using a Cole-Parmer flat surface electrode. A small droplet of DI water was placed on the coupon surface and allowed to equilibrate. The pH of this droplet was then measured. At least 3 replicate coupons were set up for each test or control condition.

The SOM were enumerated by washing randomly selected coupons for each test and control condition with 0.1% peptone water (Difco). Serial dilutions of this broth were made and a 5-tube MPN analysis was performed. The coupons were re-inoculated and replaced in the chambers for further incubation.

2.2. Enumeration of NSOM and ASOM

A 10-fold serial dilution 5-tube MPN test was used to enumerate ASOM and NSOM in sewage and coupon washings. The dilutions were made in PBS diluent (8 g/l NaCl, 0.2 g/l KCl, 0.2 g/l KH_2PO_4, 1.15 g/l Na_2HPO_4). The medium used to enumerate NSOM contained (per liter) 5 g $Na_2S_2O_3 \cdot 5H_2O$, 2 g K_2HPO_4, 2 g KH_2PO_4, 0.1 g $(NH_4)_2SO_4$, 0.1 g $MgSO_4 \cdot 7H_2O$, 0.1 g $CaCl_2$, 0.002 g $FeCl_3 \cdot 6H_2O$, 0.002 g $MnSO_4 \cdot 4H_2O$, 3.0 ml Bromcresol Green (saturated solution), the pH of the medium was adjusted to pH 6.5 initially. The medium used to enumerate ASOM contained (per liter) 4 g elemental sulfur (or 5 g $Na_2S_2O_3$), 1.5 g KH_2PO_4, 0.1 g $CaCl_2$, 0.1 g $MgCl_2 \cdot H_2O$, 0.1 g NH_4Cl. After inoculation, the MPN tubes were placed in a tube rotator and incubated for 21 days. The tubes with growth and pH decrease were judged as positive tubes. Cell growth was indicated by the change in turbidity of the medium and the decease in pH was indicated by color change of pH indicator. The pH indicator—thymol blue (Sigma) was added into the ASOM test tube after 21 days because the indicator was dissolved in an ethanol solution which is inhibitory to some SOM. The numbers of the positive tubes were converted to cell numbers using a 5-tube MPN table.

3. Results and discussion

3.1. Initial surface pH reduction

To determine the rate of reduction of the surface pH of the concrete coupons, triplicate coupons of Portland mortar, Calcium aluminate mortar and microsilicate mortar were incubated in the environmental chambers in the presence of 50, 100 or 250 ppm H_2S with atmospheric levels of CO_2. The surface pH of the coupons reduced from initial values (10.7 ± 0.6, 10.3 ± 0.2) to about 9, at rates of about -0.025 pH/day regardless of the H_2S concentration for microsilicate and calcium aluminate cement. The concentration of H_2S in the atmosphere did have an effect on the

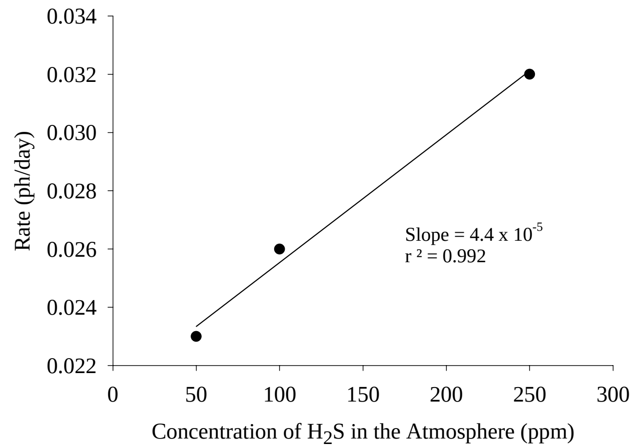

Fig. 3. The effect of atmospheric H_2S on the rate of the initial chemical reduction of the surface pH of fresh Portland cement coupons.

reduction of the surface pH for coupons of Portland cement (Fig. 3). The effect of the concentration of H_2S on the rate of surface pH reduction could be modeled with a straight line up to 250 ppm H_2S ($r^2 = 0.992$). The slope of the line was determined to be 4.38×10^{-5} pH/day ppm H_2S (Fig. 3). If significant quantities of H_2S (> 50 ppm) are present in the headspace of the sewage collection system the initial stage of concrete pH reduction would be complete in about 60–90 days.

3.2. Enumeration of NSOM and ASOM in sewage

To model the colonization of concrete by NSOM and ASOM, an estimate of the numbers of NSOM and ASOM in the inoculum (sewage) is necessary. Sewage was collected during 23 sampling events from sewers in the Houston area. The locations were originally chosen on a random basis, and then later, more concerted efforts were made to characterize one location to allow an evaluation of the reproducibility of the data, and to obtain a consistent inoculum for other studies. Fig. 4 presents the results of the enumeration of NSOM in sewage; Fig. 5 presents the ASOM data. After the first three sampling periods a decision was made to change the media used for enumerating ASOM from thiosulfate based media to sulfur based media. The sulfur-based media resulted in significantly higher counts of ASOM than the thiosulfate-based medium over the next six sampling events, so only the sulfur based medium was used after the ninth sampling event.

A statistical analysis of the data using the method of Cochran (1950) revealed that the numbers of NSOM and ASOM in several of the samples were significantly different ($p = 0.05$), this is probably due to the environmental conditions during sampling, the age of the collection system and the amount of flow in the system. These factors were all recorded during the sampling events, but there is not enough data for any one condition to allow further analysis of the

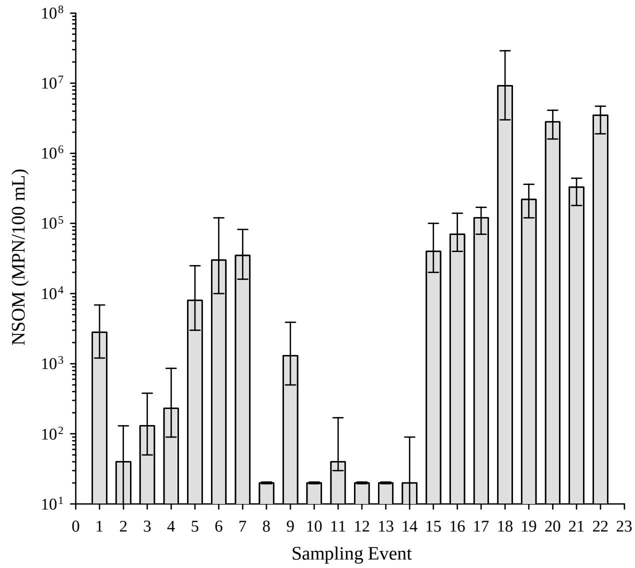

Fig. 4. Enumeration of the neutrophilic sulfur-oxidizing microorganisms in sewage samples. Thiosulfate was used as the energy source in a mineral media at pH 6.5. Error bars represent 95% confidence limits from a 5-tube MPN analysis.

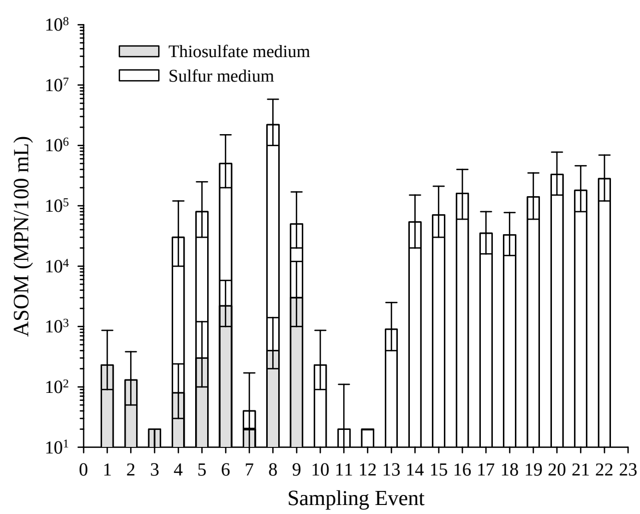

Fig. 5. Enumeration of the acidophilic sulfur-oxidizing microorganisms from different locations in the sewage system, using thiosulfate (shaded bars) and elemental sulfur (open bars) as energy sources. Error bars represent 95% confidence limits from a 5-tube MPN analysis.

results. Many more samples must be collected and analyzed to populate the data set to allow this type of comparison.

The last nine sampling events (events 14–22) were from the influent to the 69th Street Sewage Treatment plant in Houston TX. These represent cumulative samples of a sewage collection system that is known to collect sewage from many places where active microbial deterioration is underway. A statistical analysis of the results from the last nine samplings showed that there were significant

Table 3
Attachment and survival of sulfur-oxidizing microorganisms on coupons of portland cement

	Attachment ratio ((MPN/cm^2)/(MPN/100 ml))		Survival ratio ((MPN/cm^2)/(MPN/cm^2))	
	ASOM	NSOM	ASOM	NSOM
High	0.42	0.2	0.07	0.19
Low	0.001	0.001	0	0
Mean	0.120	0.040	0.01	0.03
S.D.	0.154	0.070	0.01	0.06
size	9	8	9	8

differences observed in this subset of the data for the NSOM enumerations ($p = 0.05$). There were no significant differences in the numbers of ASOM found in these samples. The average number of ASOM in the last nine sampling events is 1.4×10^5 MPN 100 ml. The average of the NSOM data for the last nine sampling events is taken as a single data set is 2×10^6 MPN/100 ml, but as indicated by the statistical analysis these data might not represent a single population for NSOM since there were significant differences within the group.

As mentioned above, many more samples must be taken and analyzed in order to get an accurate understanding of what the numbers of ASOM and NSOM are under different environmental circumstances.

In order to develop an early succession model the ability of the organisms present in the sewage to attach to the concrete and colonize it must be quantified. A limited series of experiments were performed in which concrete coupons were inoculated with fresh sewage. The attachment and the survival of the organisms on the coupons were measured for several coupons of ordinary Portland mortar. The data are summarized in Table 3. The range of the data indicates that the attachment of the organisms to the concrete is not consistent from test to test. The data do suggest that the ASOM attach more readily to the coupons than do the NSOM, but that the NSOM survived the incubation on the coupons more easily. This is expected because the pH of all of the coupon surfaces was above pH 8. Fig. 6 presents the results of the recovery of NSOM and ASOM from coupons of ordinary Portland cement during the course of a 500 days incubation. The coupons were not in constant contact with sewage but were inoculated approximately once a month. The environmental chambers were kept with 98% relative humidity (condensing conditions and 100 ppm H_2S, atmospheric oxygen concentrations and elevated CO_2 levels in the headspace). There were no detectable NSOM or ASOM surviving to be recovered from the coupons until after 200 days of incubation. The last two sampling periods at 450 and 500 days were the only two consecutive periods in which both NSOM and ASOM survived on the coupons. Although there were often more ASOM in the sewage and attaching to

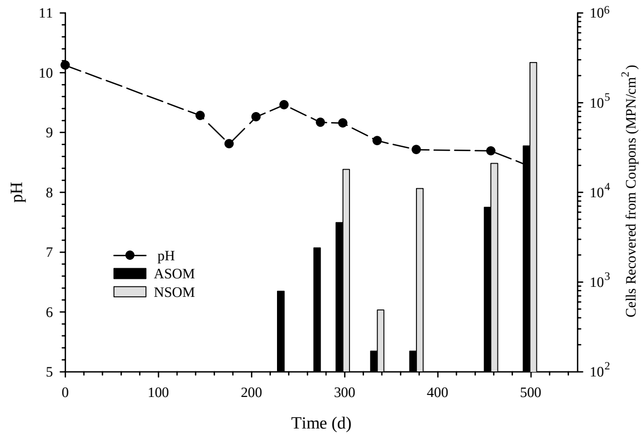

Fig. 6. Survival of sulfur-oxidizing microorganisms on concrete coupons incubated at room temperature in an environmental chamber with 100 ppm H_2S, atmospheric O_2 levels and 99% humidity. The coupons were inoculated with fresh sewage periodically. The circles represent the surface pH of the coupons, light bars the NSOM, and the solid bars the ASOM recovered from the coupons.

the coupons, the NSOM were more capable of surviving at the pH of the coupons. It is surprising that ASOM survived at all on coupons with high surface pH.

4. Conclusion

The theory of microbially induced concrete deterioration that has been presented in the literature explains the microbial and chemical aspects of concrete corrosion, but does not provide the information necessary to develop an accurate model that can be used to predict the lifecycle of the concrete nor be used to determine maintenance and repair schedules. More information is needed about the size of the inoculum, the number of organisms that can bind to the concrete and how long the microbial succession will take to produce the proposed steady-state corrosion conditions. Without this knowledge long range forecasting of concrete effectiveness and the testing of new materials or cures for corrosion will be hampered. Many researchers throughout the world will be needed to cooperate, supplying data, and data analysis techniques to allow the modeling of concrete deterioration in sewage collection systems. Once this is well underway, and an understanding of the quantitative effects of environmental factors on the organisms and the concrete, the model can be adapted to other concrete systems, perhaps, to other corrosion problems.

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