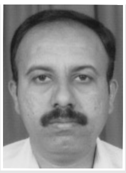
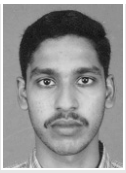
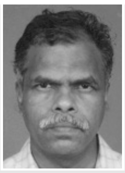
Proceedings of the Institution of Civil Engineers
Municipal Engineer 159
March 2006 Issue ME1
Pages 11–20

Paper 14373
Received 11/08/2005
Accepted 14/12/2005

Keywords:
concrete technology & manufacture/corrosion/sewers & drains







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Deterioration of reinforced concrete in sewer environments

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Millions of dollars are being spent worldwide on the repair and maintenance of sewer systems and wastewater treatment plants. Microbially-induced corrosion causes damage via micro-organisms. Deterioration is caused by acid excretion which etches the surface of concrete, penetrating the mortar surface, especially in sewer systems. The mechanisms of concrete and reinforcement deterioration in sewer environments and microbially-induced corrosion is discussed in detail in this paper. A comprehensive review is given of the role of hydrogen sulphide and micro-organisms in the deterioration of concrete in sewer environments and of repair and rehabilitation measures, including the following preventative measures: (*a*) modification of the materials used in construction of sewer pipes; (*b*) coatings; (*c*) sewer treatments. A complete review of the microbial deterioration of concrete and its remedies is also included.

1. INTRODUCTION

Nowadays, concrete is the material that is being used for pipelines for sewage waste disposal. The corrosion of concrete in sewers poses a major problem in the modern world. Millions of dollars are being spent on the repair and maintenance of sewer pipelines and wastewater treatment plants. The presence of various bacteria—such as the sulphur-reducing and the proteolytic bacteria in the sewer—together with animal and plant wastes is the main reason for the corrosion of concrete.

Most of these sewer pipelines are concrete that has been either cast in place or precast. Brick manholes have been replaced over the years because of concerns about infiltration and a realisation that the mortar holding the bricks together is subjected to corrosion. Prefabricated plastic manholes have been introduced, but in some cases they are difficult to install; for example, in high groundwater areas they tend to float out of the hole if proper ballast or anchorage has not been applied. Care should be taken in these areas, and also with regard to water passing through these manholes, therefore all the joints should be properly sealed with rubber gaskets.

There are two major causes of internal corrosion in a sanitary sewer. The first is conventional acid attack caused by low pH industrial waste discharged directly into the sewer system. The second cause is grouped together as sulphide corrosion, hydrogen sulphide (H_2S) corrosion or sulphide attack. These types are easy to identify. Sulphide corrosion occurs above the sewage surface while low pH sewage will cause corrosion below the waterline.[1] Sulphate attack, sometimes confused with sulphide corrosion, occurs when soils with high sulphate levels contact the concrete pipe structure and the deterioration is external. Sulphate attack does not occur inside the sewer structure or pipe. Sulphide corrosion starts when sulphate in the sewage is converted to sulphur. The most corrosive agent that leads to the rapid deterioration of concrete pipelines in sewers is (H_2S), which also attacks concrete floors in barn buildings housing animals. H_2S also attacks the concrete in sewer and wastewater treatment plants. The aerobic bacteria present oxidise the H_2S dissolved in the moisture to sulphuric acid (H_2SO_4). The H_2S dissolves in moisture films on the exposed concrete surfaces where it undergoes oxidation by aerobic bacteria to H_2SO_4, commonly referred to as biogenic sulphuric acid (BSA), which attacks the concrete surface.[2] The corrosion process is caused by the reaction of the BSA with the cementitious material of the concrete, which leads to eventual structural failure. This step is characterised 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. 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 is 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. 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.

The action of anaerobic proteolytic bacteria in sulphur-containing organic compounds results in the H_2S. Design of sewer structures is an important parameter. In general, any configuration that results in significant hydraulic energy loss will accelerate corrosion and may also induce serious corrosion of the downstream pipe. The concrete can be prevented by two subgroups: prevention of corrosion of concrete and corrosion of reinforcement. The latter subgroup has the following characteristics

(*a*) altering the material used for the pipelines
(*b*) providing corrosion-resistant coatings
(*c*) providing cathodic protection
(*d*) modifying the engineering aspects of the structure.

This paper discusses the mechanisms involved by H_2S in sewers that cause the deterioration of concrete, together with subsequent control measures.

2. DETERIORATION OF CONCRETE: CAUSES AND DETERMINATION

A general consensus has been that H_2S is the most corrosive agent that leads to the rapid deterioration of concrete pipelines in sewers. The aerobic bacteria present oxidise the H_2S, which is dissolved in the moisture, to produce H_2SO_4.[2] At normal domestic sewage pH levels, from one-quarter to one-third of the dissolved sulphide exists as molecular H_2S, which is released to the air and deposited on the moist structure wall. Bacteria on the wall convert the H_2S to H_2SO_4, which reduces wall moisture pH values to the 1–2 range, and the acid corrodes the structure wall above the flow line. A highly corrosive environment is created by the presence of volatile hydrocarbons and H_2S. Both concrete and steel are susceptible to accelerated corrosion rates under such conditions. Few researchers have discussed the methodology for carrying out experimental work to determine the corrosion rate, along with their main corrosion mechanism and the factors controlling the corrosion rate, and consequently there is a paucity of published papers in this area.[3]

Factors affecting increased sulphide in sewage are outlined below.

(*a*) High sewage temperature, accelerating the sulphate/sulphide conversion process.
(*b*) High biochemical-oxygen-demand (BOD) sewage, particularly high-soluble BOD sewage.
(*c*) Flat sewer slopes producing oxygen-deficient, or ‘septic’ sewage; and the low velocities lengthen detention time and increase settling of organic solids and grit in the sewer invert.
(*d*) Long detention times in wet wells, force mains, inverted siphons or surcharging gravity sewers.
(*e*) Steep slopes and high flow velocities.
(*f*) Turbulence caused by inadequate or poor design of structures: examples are junction structures with colliding flows, and drop structures and intercepts or force mains that discharge significantly above the wastewater surface in the main line.
(*g*) Changes in slope that lead to hydraulic jumps, abrupt flow direction changes (angle points) and short radius curves.

Other factors tend to increase the amount of H_2S escaping from the wastewater. H_2S is released primarily as a gas and will spread in the air. When released as a gas, it will form sulphur dioxide and H_2SO_4 in the atmosphere. Sulphur dioxide, a major component in acid rain, can be broken down further and accelerates corrosion rates. H_2S remains in the atmosphere for approximately 18 h. In some instances, it may be released as a liquid waste from an industrial facility.

Beck[4] studied the cause of concrete sewer pipe corrosion. The objectives of the project were to compare the cost for routine cleaning of interceptors and the accumulative corrosive effects that excessive deposition have on sewer pipes. Manhole locations were set up and data were collected from them for pipe wall deterioration and deposition, throughout the 12 000 ft (3657·6 m), 42 in. (1·07 m) and 30 in. (0·76 m) concrete interceptor. Sewer sediment is a type of settleable particulate and form bed deposit. It has been established that excessive pipe deterioration and an excessive amount of deposition existed in the upstream half of the interceptor and low amounts of deposition and minor deterioration were present in the lower half.

To monitor the corrosion of the iron pins in the specimen, electrochemical impedance spectroscopy (EIS) and open-circuit potential (OCP) serve as valuable tools. Jahani *et al.* [5] studied the degradation of a mortar specimen exposed to an acidic sulphate solution, using iron pins set within the sample with their ends close to the surface. The corrosion behaviour was monitored using the EIS and the OCP of the pins. The pH of the test solution was maintained in the range 4–5 for eight days and 2–3 for 73 days. By using the experimental data, the role of the diffusion reaction in the deterioration of concrete surfaces was determined. It is indicated from the OCP of the pins that the pin closest to the surface of the mortar deteriorates after 36 days. Also it was observed that 0·82 mm of the mortar was corroded at the end of the experiment. This establishes the validity of the moving boundary paradigm for the sulphide corrosion of concrete.[5]

The cause of deterioration is mainly determined by petrographic examinations. A study conducted by Cady and Richard[6] showed that the affected area in an entrained air void system was the main reason for the deterioration caused by inadequacy of entrained air in these areas. Their examinations showed that the magnesium oxide (MgO) content of the Portland cement in the affected areas was 3·5 times more than that present in the unaffected areas. MgO (9·1%) was more than its permissible value prescribed as per ASTM C-150. Enhanced deterioration was observed in manhole sections that were located below the frost line. Freezing and thawing attack caused typical fracture planes parallel to exposed surfaces. These crack patterns were characteristic of the expansive reactions. Ramachandran[7] stated that dead burnt magnesia expands some 17%. This was in the context of the slow hydration of unreactive material requiring additional water for hydration over the original mix water. The volume changes with reactive magnesia as it hydrates in the cement matrix containing Portland cement and can be engineered to be neutral. Owing to the fact that hydration of dead burnt magnesia is a slow process, the change in the volume that occurs when magnesia hydrates is

$$\begin{array}{ccl} \mathrm{MgO(S)} + \mathrm{H_2O(l)} & \longleftrightarrow & \mathrm{Mg(OH)_2} \\ 40{\cdot}31 + 18{\cdot}0 & \longleftrightarrow & 58{\cdot}3 \text{ molar mass} \\ 11{\cdot}2 + 18{\cdot}0 & \longleftrightarrow & 24{\cdot}9 \text{ molar volumes} \end{array}$$

This reaction, as in the case with dead burnt magnesia produced as a result of high-temperature thermal deposition, occurs after most of the free mixing water has been taken up by the hydration of the cementitious minerals, mainly comprising tricalicum silicate and dicalcium silicate, or vacated through bleeding or evaporation.[7]

It has been generally accepted that concrete corrosion is caused by bacterial oxidation of H_2S in sewer systems. Costs related to sewer replacement and remedies are quite high, but there is limited knowledge and documentation on the relationship between H_2S levels and corrosion rates. This information is necessary in order to select the appropriate means of H_2S control and to conduct a cost–benefit analysis. The effect of the wastewater composition on corrosion damages in the sewer pipelines was considered, especially for the steel and cast iron pipes. The concrete pipes are also susceptible to corrosion damage, especially in the presence of H_2S and/or fatty acids.[8]

3. ROLE OF MICRO-ORGANISM IN DETERIORATION OF CONCRETE IN SEWER PIPELINES

Culture-dependent studies have implicated that sulphur-oxidising bacteria, combined with the bacteria of the acidiphilium genus, are the main agents of concrete corrosion in sanitary sewers.[9]

Acidophilic iron oxidising bacteria are responsible for the corrosion of reinforcement. They attack steel to convert ferrous to ferric oxide and, along with the sulphur-oxidising bacteria, lead to the corrosion of concrete in many sewers. When the concrete samples were exposed to a sewer environment containing H_2S of more than 600 ppm, the surface pH of the specimen reduced from an initial value of 12–13 to a very low value of <2. This reduction in pH is attributed to the fact that sulphur-oxidising bacteria grow on the surface of the specimen, which converts the H_2S to H_2SO_4. The reduction in pH also takes place internally where bacterial growth is absent. This may be attributed to the penetration of H_2SO_4 into these areas. Formates, such as calcium formate, inhibited the growth of sulphur-oxidising bacteria and iron-oxidising bacteria when present in concentrations of more than 50 ppm.[10]

This type of H_2SO_4 is known as BSA. The main species of acid-producing bacteria in sewers is *thiobacillus* supported by *acidiphilum.* Fluorescent in situ hybridisation (FISH) studies were used to identify and enumerate selected bacteria in homogenised biofilm samples taken from the corroding crowns of concrete. Direct epiflourescent microscopy demonstrated the ability of FISH to identify significant numbers of active acidophilic bacteria among concrete particles, products of concrete corrosion and other mineral debris. FISH analyses with the species-specific probe Thio820, and a domain level probe that recognises all bacteria. Thio-ferro-oxidans and Thio-thio-oxidans comprised between 12% and 42% of the total active bacteria present in corroding concrete samples.[10]

Babushkin *et al.* [11] have elaborately studied the mechanism of chemical and biochemical processes taking place in sewage. Davis *et al.* [12] have studied the effect of microbial population in the loose outer corrosion layer (OCL) and the bound inner corrosion layer (ICL) of concrete from a corroded sewage collection system. In order to determine the mineralogical composition and the strength of samples, chemical and physical studies were carried out. It was also found that the strength of concrete was reduced by 20% at crown and springline. Furthermore, it was demonstrated that after the initial corrosion of concrete, further corrosion was controlled by the penetration rate of the acid produced by the acidophilic sulphur-oxidising micro-organisms (ASOM) and the ASOM itself. This was not the case in neutrophilic sulphur-oxidising micro-organisms (NSOM).[12]

The alkaline nature of concrete with a pH of around 11–13 creates an unfavourable condition for the growth of micro-organisms.[13] However, the presence of CO_2 and H_2S brings acidic properties to the concrete.[14] The detrimental effects of CO_2 on concrete were studied by Ismail *et al.*[15] Their experiments showed that atmospheric CO_2 reduces the pH of concrete to 9·5. A drastic reduction in pH was observed at an atmosphere containing 5000 ppm of CO_2. The theory behind this pH reduction was studied by Thistlethwayte and Goleb.[16]

Bacteria of the *thiobacillus* species stick to the concrete surface and, if adequate nutrients, moisture and oxygen are available, begin to reproduce once the pH of the solution is reduced to approximately 9.[17,18] The five major species of *thiobacillus*, which play important roles on concrete, are (*a*) *Thio-oparus*, (*b*) *Thio-novellus*, (*c*) *Thio-neapolitanus*, (*d*) *Thio-intermedius* and (*e*) *Thio-oxidans*. Of these, the first four are categorised as NSOM and the fifth as ASOM.

Jahani *et al.* [19] studied the deterioration of concrete in acid sulphate solutions. The experiments were conducted at a pH of 4–5 for eight days and 2–3 for 13 days. The efficacy of the diffusion-reaction-based model with a moving boundary for the corrosion process was analysed from the experiment. The corrosion rate constant for the specimen and the effective diffusion rate of H_2SO_4 in the corrosion layer were calculated from the acid neutralisation rates in the solution. It was observed that the cross-sectional area of 0·8 mm^2 of the sample was corroded at the end of the experiment. The moving boundary model was validated by the experimental data obtained and it can be inferred that the effective diffusion rate reduced with age of the corrosion product being formed.[19]

Maintenance holes are provided to access a sewerage system for investigations, clearance of blockages and maintenance purposes. Van Mechelan and Polder [20] have studied the rate of attack of concrete in sewer manholes and subsections by BSA attack. Scanning electron microscopy (SEM) revealed details of the attacked concrete layer. The corrosion is predominantly caused by diffusion of sulphate into sound concrete beyond the gypsum-rich layers. Microstructural properties were also studied. Investigations show that the highest rate of attack of concrete by H_2SO_4 is 3 mm per year,[20] which may vary depending on the pore structure and permeability of concrete.

3.1. Chemistry behind H_2S attack

Bacteria reduce the sulphur-containing organic compounds and sulphates to form sulphides. As a result of this property, septicity arises in the biowastes from the activity of the bacteria under anaerobic conditions. A part of the sulphur, after reduction, is released into a large percentage of sulphide ions into the environment, and a part is released as free H_2S. Only the bacteria assimilate a very meagre part of the reduced sulphur. *Proteolytic* bacteria in the absence of oxygen act on the organic compounds of sulphur to form initially H_2S. The proportions of these sulphide ions are very sensitive to the pH of the solution, temperature and ionic strength. As a result, various ions are formed. They are predominantly H_2S, HS^- and S^{2-}. The sulphate-reducing bacteria do not reduce the contaminants of fresh manure. This defect is, however, overcome by the fact that the bacteria from the digestive system can assimilate these organic compounds into lactic acid, which is one of the common substances used by the H_2S-reducing bacteria.[21]

$$\begin{aligned}&CH_3CHOHCOOH + 0{\cdot}43\,H_2SO_4 + 0{\cdot}067\,NH_3 \xrightarrow{\text{Desulphovibriod desulphuricans}}\\&\quad 0{\cdot}33\,CH_{1{\cdot}4}N_{0{\cdot}2}O_{0{\cdot}4} + 0{\cdot}96\,CH_3COOH\\&\quad + 0{\cdot}43\,H_2S + 0{\cdot}7\,CO_2 + 0{\cdot}94\,H_2O\end{aligned}$$

Generally sulphate-reducing bacteria suffer from an inability to use the acetic acid as a source of carbon. There are, however, exceptions, one of which is *Desulphotomaculum acetoxidans*, an acetic-acid-based H_2S, the production of which is illustrated below

$$CH_3COOH + SO_4^{2-} \xrightarrow{\text{Sulphate reducers}} H_2S + 2HCO_3^-$$

Aerobic *Thiobacilli* bacteria generally convert the H_2S developed during the decomposition of the organic substances to sulphate. Oxidation of H_2S occurs in several stages as follows[21–25]

$$\begin{aligned}&2H_2S + O_2 \xrightarrow{\text{Green sulphur bacteria}} 2H_2O + 2S + 528J\\&S_2 + 3O_2 + 2H_2O \xrightarrow{\text{Purple sulphur bacteria}} 2H_2SO_4 + 1231J\end{aligned}$$

The H_2SO_4 formed as shown above is very corrosive to the concrete tanks and sewer pipelines.

In addition to the above, the sulphate ions also attack the concrete directly thereby resulting in major corrosion. They also react with the calcium present in the cement to form gypsum, as shown below

$$2H_2O + Ca^{2+} + SO_4^{2-} \longrightarrow CaSO_4 \cdot 2H_2O$$

and with the calcium aluminium hydrate to form ettringite. In the above reactions, the formation of products causes a major increase in the volume of the cement and thereby leads to cracking and damage in the structure. The volume increase rate is 124% for gypsum and 227% for ettringite. There is a large increase in the stress on the surface of the cement. This is even further worsened by the fact that H_2S also attacks the concrete and the steel reinforcement. It reacts with lime to produce a soluble product

$$Ca(OH)_2 + 2H_2S \longrightarrow Ca(HS)_2 + 2H_2O$$

Ferrous sulphide is formed as a result of the H_2S reaction with the reinforcing steel through the cracks produced by sulphate attacks. Water and oxygen, also migrating through the cracks, form iron oxides and hydroxides. The products formed here also increase the volume of the concrete surface thereby leading to cracks and corrosion.

4. PREVENTING CONCRETE DETERIORATION

How does an engineer design a wastewater system to counter the corrosion effects of H_2S gas and H_2SO_4? The simple answer is to reduce the conditions that generate H_2S. However, this is not always possible or economical. Excluding piping, approximately 40% of a wastewater system is made up of concrete structures; therefore, some means of reducing concrete corrosion must be utilised. It must be effective and economical. It can be achieved either by treatment of the sewer or the modification of the concrete. Concrete protection methods commonly used for structures include modifications of concrete mix, design; coatings painted or rolled onto the concrete surface; and liners that have integral locking projections cast into the concrete. Modifying the concrete mix usually involves increasing the alkalinity, since the corrosion rate is inversely related to concrete alkalinity. The following points are to be considered during the construction of sanitary works

(*a*) use of ASTM type V rather than ASTM type II cement, or ASTM type II low alkali cement rather than type II
(*b*) addition of microsilica to precast concrete sewer pipe doubles the corrosion rate of conventional concrete pipe when exposed to acid
(*c*) high-alumina cement increases corrosion rates at typical pH moisture levels of 1–2 on structure walls.

4.1. Treatment of sewers

Sydney *et al.* [26] studied the control of concrete sewer corrosion by the crown spray process. In this method, a high pH mixture is sprayed onto the crown area of the sewer. Deactivation of sulphur-oxidising bacteria and neutralisation of the acid are some of the main principles in this process. The sewer crown environment must be rendered unfavourable for the growth of sulphur-oxidising bacteria. A residual alkali on the sewer crown has been left to neutralise the acid produced. These are some of the major applications of the crown spray process. Measurements were made before and after the treatment for the surface pH of the sewer ground to check the effectiveness of the treatment. Various chemical treatments with biocides were studied for deactivation and regrowth of organisms. It has been established that magnesium hydroxide slurry of pH 10·5 is used to neutralise acidic wastes and is the most effective and non-hazardous chemical tested to date. The above chemical, applied at a rate of 50%, has reduced the population of sulphur-oxidising bacteria to about one-millionth of the initial value, and achieved a constant pH of 9 for approximately nine nine months.[26] In another study, the effect of the total dissolved organic carbon (DOC), suspended solids; dissolved oxygen present in the sewers on the deterioration of concrete was studied by Chen *et al.*[27] They also established a treatment technique for the reduction of the DOC, where the sewer was passed through a 1·5 km section having inner diameter of 450 mm constructed over a slope of 0·0075. Approximately 14% of the DOC was removed for a retention time of 18 min. Batch tests were carried out for raw sewage, suspended solids or settled solids. As a result, the raw sewage yielded 1·3 mg DOC/mg of sample, whereas the suspended solids yielded a 2·6 mg DOC/mg dry weight. From this study they concluded that for a 15 km pipeline approximately 39·133 kg of DOC can be stabilised per day.

4.1.1. Modification of material structures. Werner and Krausewald[28] studied an innovative presentation consisting of a concrete pipe shaft system for municipal wastewater along with an integrated air/H_2O press-testing function for the detection of leakages in the structure of the pipe or the pipe joints: a socket seal. The main function was to detect exfiltration or infiltration and achieve an integrated electronic memory for a network storage in-house sewer information system. Heil and Kloss[29] studied the concrete corrosion caused by SO_4^{2-} in sewage systems. According to German communal environmental laws the limit for SO_4^{2-} is 400–600 mg/l. In view of the current state of technology, however, the adonising plant cannot comply to this limit. Heil and Kloss suggested that the maximum SO_4^{2-} values for the anodising plants should be determined individually according to the composition of sewage or the quality of concrete pipes. Investigations have shown, however, that SO_4^{2-}-contaminated anodising effluents with concentrations of >600 mg/l have not caused any corrosion of concrete pipes.[29]

The corrosion phenomena caused by both chemical and bacterial activity have been given special emphasis recently. New aspects of the subjects are highlighted by investigations on particularly aggressive sites, which suggest that calcium-aluminates-based binders can be appropriate in such environments.[30] In view of the above, Cabiron and Heliard[31] commented that the proliferation of bacteria produces bio-H_2SO_4 as a result of which the bacterial corrosion occurs. It has been reported that the concrete matter made of alumina cements has a better resistance than Portland cement. This is because the resistance to sulphates is attributed to the absence of $Ca(OH)_2$ in hydrated high alumina cement and also to the protective influence of the relatively inert alumina gel formed during hydration. Lean mixes are much less resistant to sulphates and also the chemical resistant decreases drastically after conversion of both CAH_{10} and C_2AH_8

$$3CAH_{10} \longrightarrow C_3AH_6 + 2AH_3 + 18H$$

Maeda[32] postulated that synthetic sheets, having integrally moulded anchors and concrete placed on the anchor side so as to protrude the anchors from the concrete surfaces, should comprise the lining sheets. The anchors are buried in the mortar applied to the surfaces so as to bond the lining sheets firmly to the inner surfaces of sewers and sewer systems.

In another study, Northwood *et al.*[33] studied the deterioration of concrete sewer pipelines in America owing to the presence of chloride ions and the performance of the modified structure in the same environment. A conventional dry process plant modified the composition of cement so that the intrusion of chloride ions was controlled. Inter-ground silica fume cement was used to reduce the handling difficulties of silica fumes. The material was tested for its chloride permeability and chloride ion diffusivity. This resulted in a very small increase in the total construction cost owing to the modification of the material and a change in the casting process.

Silica reacts with $Ca(OH)_2$ in the presence of water to form cementing compounds consisting of calcium-silicate hydrate. The silica fume (SF) concrete improves the strength efficiency and durability characteristics. Typically 5–10% of SF is added. During the chemical reaction between SF and components in the pore water, the content of components keeping a high pH value is reduced, especially $Ca(OH)_2$ and potassium. A high level of alkali content in the cement accelerates the reaction rate of the SF. It has been reported that the addition of up to 8% SF significantly reduces permeability. Owing to reduced pH value in concrete with SF, it is expected that the chloride binding capacity also should be reduced. Chloride binding in cementing materials is dominated by the content of C_3A (tricalicum aluminate) and C_4F (tetra calcium ferrite) regardless of the chloride source, both forming Fridels salts. Sulphates in cement, however, form stronger bonds than the chloride so only a fraction of the C_3A and C_4F is accessible for chloride-binding capacity. Since these materials form additional calcium aluminates hydrates in their reaction, SF will decreases the chloride-binding capacity.

Dumas[34] studied in detail the characteristics and durability of aluminous cements in relation to their suitability for repair of sewers. An effective solution based on a hydraulic binder has been suggested for sewers and sewer systems. A detailed study has been made of concrete containing pozzolans such as silica fume and fly ash, more than in conventional cement, for converting the calcium hydroxide generated by the hydration of cement to calcium silicate fumes H-type hydrates.[35] Soutsos *et al.* [36] concluded that different mix proportions for concrete with regard to silica fumes offer better durability for concrete in terms of chloride and sulphate-induced corrosion. The corrosion process of reinforced concrete may be divided into two stages: initiation period and propagation. Silica fume affects both stages. In the initiation period, carbonation is occurring or chloride ions are transported into the concrete. The carbonation results in reduced pH values, allowing corrosion to start. SF may be expected to reduce the resistance against carbonation owing to the level of $Ca(OH)_2$; SF will also improve the resistance against CO_2 ingress. Addition of SF also improves pore refinement structure thereby reducing permeability. The concentration of chloride ions in the pore solution reducing the ion mobility may be another reason.

4.1.2. Coating for corrosion prevention. The behaviour of concrete with polymer when exposed to H_2SO_4 medium has been studied since 2002.[37] The mass transfer coefficient ratio of the concrete to the polymer was over 12. The chemical resistance of the coating was studied using coated concrete with pinholes. The effect of the pinhole sizes on the performance of concrete was studied by modelling the weight change in the coated concrete.[37] A further study by Wehr [38] deals with development of a polymer-modified resin cement mortar which, when coated over the concrete surface, increases the corrosion resistance of the sewer concrete pipeline. The important pretreatments adopted for this are that the surface of the concrete should be flushed and a wash primer should be sprayed over the surface. The total lining thickness was 10–14 mm.

Polymer modification of concrete influences to a large extent the microstructure of the material. Owing to the film-forming capacity of the polymer particles, an interpenetrating network of cement hydrates and polymer particles exists in which the aggregates are embedded.[39] Polymer modification also influences the transition zone between the bulk cement-polymer co-matrix and the aggregates. The growth of large crystals is decreased and possibly the calcium ions react with certain carboxylate groups of the polymers. The main improvements attributed to the presence of the polymer film are bridging of micro-cracks, reduction of pore size and blocking of pores, which results in a reduced permeability of the concrete. All of these properties should lead to an improved resistance of the concrete against acid attack. In fact, the lower permeability should slow down the penetration of H_2S, the ingress of the micro-organisms and the produced acid. Also, in the case of production of expansive reaction products, polymer-modified concrete is expected to be more resistant to this detrimental action because of the capacity of the polymer film to bridge microcracks.

Cathodic protection by electrochemical methods can be applied for the protection of steel-reinforced rods from corrosion in sewage lines.[40]

4.1.3. Engineering design. The major factors that come into play in sewer pipes are: (*a*) internal pressure; (*b*) pressure resulting from external load; (*c*) temperature stresses; and (*d*) flexural stresses. Sewer maintenance manholes should be of a size and shape that provides reasonable access for personnel and equipment to flow channels, with a minimal likelihood of problems. General access is maintained on lengthy sewers by providing intermediate maintenance holes. Maximum maintenance hole spacing is dependent on whether entry into the pipeline is possible. For pipelines of less than DN600, a numerical designation of the size of a unit or a component within a structure is given, which is a convenient integer approximately equal to the manufacturing dimension in millimetres for internal diameter (DN): in other words, the nominal diameter (ND) external of a pipe or a manhole. The exact external diameter corresponding to an ND is specified in the relevant standards subjected to a tolerance limit. DN600 is the nominal size of pipe capacity used in sewage systems. The maximum spacing is dependent on the type of equipment available to maintenance crews. The DN sizing is given in Table 1. It is considered that curved alignments will require more maintenance than straight alignments. Visual inspection from maintenance hole to maintenance hole is generally not possible. As a consequence, closer maintenance hole spacing is required on these alignments.

In order to increase the watertightness of shaft rings and cones of precast components for sewer pipelines, different joint types were adopted and wall thickness was increased. The hidden defects in the joints were rectified by introducing a concrete joint structure.[41] Some of the case studies are given and discussed below.

The East Bay, California, USA, municipality effected the rehabilitation of the wood street interceptor by using the Danby and Linabond process. By doing so, the lifespan of the pipeline, which was already 50 years old, was increased by 50–100 years. In the Danby process, profiled polyvinyl chloride (PVC) strips are spirally wound through existing manholes to form a liner that needs grouting. PVC forms are installed over the interior surface of the pipe and a cementitious grout is placed behind the forms in sewer lifts. In the Linabond rehabilitation a high-strength thermosetting is sprayed over the surface of the concrete pipe. A rigid cellular plastic is formed when the resin expands owing to an exothermic reaction.[42]

		Maximum maintenance hole spacing: m	
Sl No.	Pipe size (DN)	Straight sewers	Curved sewers
1	150–450	100	80
2	525–900	150	100
3	1050–1650	300	300
4	>1800	500	500

Table 1.

An interesting observation was made in a Los Angeles county concrete sewer. Following an industrial waste pretreatment, the corrosion rate increased sharply. When investigated, it was found that the corrosion was not only increased by sulphide generation but also by an increase in the concentration of transition metals such as Ni, Fe, Pb, Cd and Cr. None of these metals was present before the pretreatment process. Morton *et al.*[43] also conducted a series of experiments in order to determine the effects of transition metals. They also found that Cr, Cn^{-}, Cu, Zn and Ni inhibited the sulphur-reducing bacteria (SRB) activity in the reactor. A model with a Monod-type function has been made in a pilot scale with a maximum corrosion rate of 16 mm/year at 25°C at 2 ppm H_2S. Maintaining the H_2S concentration at zero ppm can prevent concrete corrosion. This can be done by controlled treatment with nitrate. The nitrate dose is made based on the Nutriox concept where the dosage is dependent on the flow, temperature, sewer design and the sewage concentration. For a more cost-effective treatment it is advisable to have a longer hydraulic retention time.[44]

Van Mechelen and Polder[45] studied the level of aggressiveness of BSA present in ten different manholes on four different types of concrete. Significant differences in corrosion rates in different concrete types were observed.

5. REPAIRS AND REHABILITATION

Permeable slag sand waste concentration for repairing was studied by Pernice[46] in different ratios in concrete containing 5–20% cement, 4–20% vitrified and milled blast furnace slag, 5–20% crystal and milled blast furnace slag and 50–75% sand of blast furnace slag. The concrete is sprayed onto the walls of the galleries and smoothened. Pernice suggested that the application of this repair material prevented further deterioration.

Kaempfer and Berndt[47] stated that Germany spends approximately US$100 billion in maintenance and repair of private and public sewage systems. About 40% of the damage in concrete pipelines is caused by bio-generated H_2SO_4 as a result of long flow durations and improper ventilation of wastewater. Kaempfer and Berndt have investigated the corrosion of concrete in BSA. They have devised a simple reproducible comparative simulation method for testing the service life in the cases of dissolute and expansive chemical attack.

Atsunori and Maeda[48] commented that sulphur-oxidising bacteria deteriorate a repair system of concrete structures used for sewerage treatments or sewer piping by oxidising the H_2S and producing H_2SO_4. The rate of corrosion has exceeded 4 mm/year. A repair method for corroded concrete by employing high-density polyethylene (HDPE) sheets is described in their paper. An innovative method was designed in which fresh mortar containing bacterium inhibitors was applied directly by HDPE sheets. This repair method is advantageous because it can be applied to large sheets without making wrinkles, there are less holes to support the concrete panels and there are fewer welding spots. If sulphate were to remain in the concrete, it would react with the fresh mortar in the cement and produce ettringite that would peel the mortar from the concrete. It was observed that when the sulphate content of the cement was within 2–5%, the adhesive strength between the old concrete and mortar was $>1{\cdot}47$ N/mm^2. Sulphate, which is present in Portland cement as gypsum, is added during the manufacture to control the set, but is limited to 3% expressed as SO_3 by the mass of cement. There is no test available which can determine the safe sulphate content. A limit of 4% by mass of cement is, however, considered reasonable. The primary product of concrete decomposition by H_2SO_4 is calcium sulphate. This provides little structural stability in the wet condition and it generally exists in paste form on the concrete surface. This paste layer lowers corrosion rate and, as H_2SO_4 has to penetrate through this layer, this is sometimes advantageous. Consequently, if this layer is removed by high flow then the corrosion is accelerated.

6. ODOUR

Odour can be defined as the 'perception of smell' or in scientific terms as 'a sensation resulting from the reception of stimulus by the olfactory sensory system'. Whether pleasant or unpleasant, odours are induced by inhaling airborne volatile organics or inorganics. With a growing population, industrialisation and urbanisation, the odour problem has been reaching an objectionable proportion. Urbanisation without proper sanitation facilities is a major cause of odour problems. Rapidly growing industrialisation has aggravated the problem through odour produced in industrial operations. Undesirable odours contribute to air-quality concerns and affect human lifestyles. Odour is undoubtedly the most complex of all the air pollution problems.

6.1. Measurement and monitoring of odour

6.1.1. Odour intensity. Odour intensity is the strength of the perceived odour sensation. It is related to the odorant concentration. The odour intensity is usually stated according to a predetermined rating system. A widely used scale for odour intensity[49] is the following

0	no odour
1	threshold level
2	definite odour
3	strong odour
4	overpowering odour

Gunster[50] stated that, if the natural microbial activity of micro-organisms in sewer systems can be supported by controlled dosage of a special nitrate solution, the problems of corrosion by H_2SO_4 and odour of H_2S can be solved. The growth of denitrifying micro-organisms in place of sulphate-reducing micro-organisms is done by the addition of the above special nitrate solution. As a result, denitrification prevents the occurrence of anaerobic conditions and hence sulphide formation. Barjenbruch and Matthias[51] published a review on methods to minimise the odour formation and corrosion caused by H_2S in sewer systems. A dosage of $Ca(NO_3)_2$ is given to prevent H_2S formation: this is adjusted for anoxic conditions. According to Eiswirth *et al.*[52] oxygen-containing liquids (e.g. H_2O_2, H_2O with dissolved O_2) or gases (air or pure oxygen) should be transported through a perforated flexible tube into sewers as far as 10 km and distributed homogeneously to combat odour and prevent corrosion. The tube containing polyurethane is individually perforated. Using accurate injection, the required amount of oxygen can be decreased by $\leqslant 80\%$. Table 2 gives the causes of odour from the industry.

6.1.2. Odour measurement. The olfactometric methods of odour measurement fall into two categories: determination of the threshold concentration of odoriferous gases; and determination of the type and intensity of odour.

(*a*) Threshold concentration of odoriferous gases. European threshold concentration ranges for some unpleasant odours are presented in Table 3.
(*b*) Determination of the type and intensity of the odour. Generally odour intensity increases with the odorant concentration. The relationship between intensity and concentration can be expressed as

$$P = K \log S$$

where P is the odour intensity, K is a constant and S is the odour concentration.

Currently, the preferred and internationally standardised methods of measuring odour are the Dutch Standard Method (NVN 2820)[53] and the more recent European Standard Method.

6.2. Odour control

An array of treatment technologies are available for control of odour from gas streams collected through process

Sl No.	Industry	Odorous material
1	Pulp and paper	Mercaptans, hydrogen sulphide
2	Tanneries	Hides, flesh
3	Fertilisers	Ammonia, nitrogen compounds
4	Petroleum	Sulphur compounds from crude oil, mercaptans
5	Chemical	Ammonia, phenols, mercaptans, hydrogen sulphide, chlorine, organic products
6	Foundries	Quenching oils
7	Pharmaceuticals	Biological extracts and wastes, spent fermentation liquors
8	Food	Cannery waste, dairy waste, meat products, packing house wastes, fish cooking odours, coffee roaster effluents
9	Detergent	Animal fats
10	General	Burning rubber, solvents, incinerator, smoke
11	Swine operations	Hydrogen sulphide and ammonia
12	Wastewater treatment/plant	Hydrogen sulphide
13	Municipal solid waste landfill	Hydrogen sulphide

Table 2. Sources of odour

Compound	Detection threshold: mg/m^3	Compound	Detection threshold: mg/m^3
Acetic acid	25–10 000	Indole	0·6
Propanic acid	3–890	3-methyl indole	0·4–0·8
Butanoic	4–3000	Methanethiol	0·5
3-methyl butanoic acid	5	Dimethyl sulphide	2–30
Pentanoic acid	0·8–70	Dimethyl disulphide	3–14
Phenol	22–4000	Dimethyl trisulphide	7·3
4-methyl phenol	0·2–35	Hydrogen sulphide	0·1–180

Table 3. European threshold concentration ranges

ventilation systems. These include: mist filtration; thermal oxidation/incineration; catalytic oxidation–biofiltration; adsorption; wet scrubbing/absorption; chemical treatment; and irradiation.

The choice of the technology is often influenced by the following factors

(*a*) volume of gas (or vapour) being produced and its flow rate
(*b*) chemical composition of the mixture causing the odour
(*c*) temperature
(*d*) water content of the stream.

In 1991 Lian *et al.* [55] studied the comprehensive system-wide odour/corrosion control programme using multiple technologies to achieve short- and long-term odour control. This programme primarily formulates methods for the reduction in production and release of H_2S and installation of better odour control. The programme consists of three phases

(*a*) analysis of odour and corrosion problem areas
(*b*) short-term implementations to provide immediate relief
(*c*) long-term analysis and recommendations.

There is no single treatment technique that could provide a remedy for all of the conditions that were found. Implementation of a combination of treatments could solve each individual problem.

7. CONCLUSIONS

The theory of microbial-induced concrete deterioration that has been presented in this review explains both the chemical and mechanical aspects of concrete. The suggestions of various researchers for modification of structures, composition of cement and biological activities taking place in sewers that lead to the deterioration of concrete are to be practiced. Suitable measures are to be adopted before installation of sewer pipelines, and treatment of sewage should be carried out for durability and performance of structure. Manholes should be provided at regular intervals, which can avoid damage. Odour impact assessment is an effective tool for the preparation of environmental management plans, development of appropriate regional and local planning and development control instruments and odour regulation. Odour impact areas should be plotted using nomograms of odour concentration corresponding to the same values for odour impact criteria.

Suitable materials and design can be used to safeguard the structure from deterioration by sulphide attack from sewage. Repair work should be carried out at regular intervals to check the sedimentation layer formed in the sewer pipelines. This can prevent severe damage—that is, the collapse of the whole structure.

8. ACKNOWLEDGEMENT

The authors thank the Director of the Central Electrochemical Research Institute (CECRI) for kind permission to publish this paper.

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