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DURABILITY OF CONCRETE SEWERS: MONITORING, ASSESSMENT AND ENVIRONMENTAL FACTORS

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Abstract. *The durability of concrete sewer pipes is affected by a variety of degradation mechanisms such as sulphuric acid, chloride and sulphate attack. The problem of degradation of concrete sewer pipes has been a growing problem as these infrastructure assets age. The destructive mechanisms can vary due to increase in the environmental factors such as acidity and temperature. This study aims to investigate and compare the current monitoring and assessment methods for concrete sewers with suggestions for improving their durability. The results of a comprehensive lab experiment in the UK for investigating the combined effect of temperature and acidity on concrete durability is also reviewed. The study also highlights the areas of research which need to be addressed for more sustainable concrete sewer systems (in terms of materials as well as management).*

1. INTRODUCTION

Sewers are vital infrastructure in all areas of concentrated population and development. The sewer networks collect domestic, commercial and industrial waste, and dispose them in accordance within Environmental Protection Authority (EPA) guidelines [1]. Among all types of sewer pipes, concrete sewer pipes are of high importance, since majority of sewer networks in the world have been made up of concrete. The main components of sewage are bacteria, sulphate and organic matters. Due to the sulphate content, biogenic sulphuric acid attack is the primary cause of structural deterioration in concrete sewer pipes [2]. In the UK, for example, 70,667km of concrete sewer pipes, built in 1950s, suffer directly from corrosion [3,4]. The results of another research by Water UK [5] show that, 55% of sewer flooding in the UK is occurred because of pipe blockage, while the other 45% is caused by pipe failures, which are mainly due to sulphide corrosion. There exists 110,000km of in service concrete sewer pipe in Australia, which are corroding at an average rate of 1 to 3mm per year [6]. A similar condition has been observed in the USA where 550,000km of concrete sewer pipes are more or less affected by corrosion.

When the sewer pipelines fail prematurely or without monitoring, the health and wellbeing of both society and the environment are negatively affected. Chemicals overflow into drinking water sources due to sewer pipes failure can causes dangerous diseases in human. On the other hand, deposited sediment affects aquatic insect habitats, for instance, organic matters can cause biochemical oxygen demand reactions which reduces dissolved oxygen levels in water, affecting fish, insects and micro-organisms.

In addition to social and environmental impacts of sewer pipeline failure, the aforementioned problem costs millions of dollars for governments and water companies. Water UK [3], reported that, between 2012 and 2013, more than $445 million has been spent by water companies for the serviceability maintenance of sewer networks. Additionally, corrosion of concrete sewer pipes causes annual costs of $130 million in the UK. In Sydney, Australia, a renewal program cost of about 900km of concrete sewer pipes is estimated $30 billion annually; while, corrosion has been reported as the main cause of deterioration.

Considering the deterioration of concrete sewer pipes, it is important to assess the structural integrity of these infrastructures in order to prevent probable failures. Although it is known that chemical corrosion, e.g. sulphuric acid corrosion, is one of the main reasons behind the failure in concrete sewer pipes, there is still a lack of experimental works investigating the involved factors in chemical corrosion of concrete sewer networks. This study intended to introduce and compare the assessment and monitoring methods for concrete sewer pipelines, which is followed by suggestions for improving the efficiency of the introduced methods. Finally the results of a lab experiment in the UK for investigating the combined effect of temperature and acidity on concrete sewer pipeline degradation is presented. The following section presents the mechanism and contributing factors in concrete sewers corrosion.

2. CORROSION IN CONCRETE SEWERS

The main cause of premature failure and deterioration of concrete sewer pipes is identified globally as sulphide corrosion, also known as microbiologically induced corrosion (MIC). Sulphide corrosion occurs when sulphate in wastewater is biologically converted to sulphide, that chemically converted to hydrogen sulphide gas, which is then biologically converted to sulphuric acid (H_2SO_4), as shown in Figure 1.

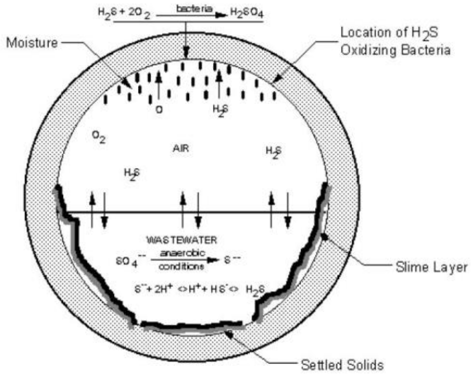

Figure 1 Sulphide generation in sewers [7]

The corrosion process of concrete sewer pipes involves stages [8] and occurs under anaerobic conditions where sulphate is reduced to sulphide. This occurs on the submerged pipe wall within the sewer, where a layer of slime builds up and intense microbiological action takes place [9].

The first stage is abiotic neutralisation of the (highly alkaline) concrete surface, where the cementitious material reacts with carbon dioxide and hydrogen sulphide (H_2S). This reaction reduces the surface pH of the concrete to levels where bacterial colonisation (also known as carbonation) is possible [10]. The second stage occurs at a pH of 9, where colonisation of the concrete surface by neutrophilic bacteria (neutrophilic sulphur oxidising microorganisms (NSOM), in combination with sufficient O_2), will oxidise hydrogen sulphide. This will diffuse into the water filled pores of the exposed concrete, producing hydrogen sulphate and lowering the surface pH of the concrete sewer. The third stage occurs once the pH falls to 4. This is where acidophilic sulphur oxidising microorganisms (ASOM) colonise the concrete surface. The final stage, loss of concrete mass, is where gypsum ($CaSO_4.2H_2O$) and ettringite form due to sulphuric acid reacting with silicate and carbonate compounds within the cement component of the concrete [8]. Gypsum has a weak structure, which becomes more vulnerable to erosion when it is wet. It is usually appeared as a pasty white mass on concrete surface above the water line. As gypsum is eroded overtime, more areas of surface are exposed of corrosive solution. This process is repeated until the pipeline fails. The chemical reactions of the aforementioned process can be found in Table 1.

Chemical Reactions	
Stage 1	$organic\ carbon + SO_4^{2-} \rightarrow (SRB) \rightarrow H_2S + CO_2$
Stage 2	$H_2S + 2O_2 \rightarrow H_2SO_4$
Stage 3	$H_2SO_4 + CaO.SiO_2.2H_2O \rightarrow CaSO_4 + Si(OH)_4 + H_2O$ $H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2CO_3$ $H_2SO_4 + Ca(OH)_2 \rightarrow CaSO_4.2H_2O$ $CaSO_4 + 3CaO.Al_2O_3.6H_2O + 25H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4.31H_2O$

Table 1 Chemical reactions of sulphate corrosion [8]

Before assessing the structural integrity of a concrete sewer pipe, it is important to understand which parameters are affected by corrosion, so that appropriate input data for assessment methods is selected. The following environmental and physical factors influence the rate of corrosion and eventually the service life of concrete sewer pipes.

The pH of wastewater has long been used to determine the percentage of dissolved sulphide in sewers [11]. This is due to absorbed hydrogen sulphide becoming further oxidised to sulphuric acid, lowering surface pH and causing corrosion of concrete. It is therefore important to identify which properties of sewage are affected by pH. This will then allow the corrosion rate to be determined. To discover what has the greatest impact on effluent pH, an experiment was conducted in 3 sewage systems located in Australia [12]. It was discovered from the measured pH levels that all three sites monitored displayed similar diurnal patterns of pH with large variations, and that the effluent pH was directly proportional to the ammonia content. The finding indicates that the wastewater properties of households will affect the effluent pH, which itself affects the percentage of dissolved sulphide in the sewer and eventually the corrosion rate in the sewer [11].

On the other hand, increased concentrations of hydrogen sulphide can drastically reduce the service life of concrete sewer pipes, with H_2S being the driving parameter of concrete sewer pipe corrosion [13]. Jiang [14] conducted an experiment in a laboratory to observe the effects of H_2S concentration, relative humidity and air temperature over a period of 3.5 years on pre-corroded coupons. The results showed that the H_2S concentration has the strongest influence on the rate of corrosion. It also revealed that, an increase in temperature results in an increase in H_2S uptake rate. However previous experiments have had varying results as to the degree which it will influence the rate of corrosion. The increase in corrosion rate due to an increase in temperature is attributed to the fact that the rate of sulphide production is raised when temperature increases [9]. Sun [15] also states that the increase in H_2S uptake rate with an increase in temperature is due to an increasing rate of diffusion of H_2S in air or water or increasing chemical and biological sulphide oxidation rates.

Humidity was investigated by Jiang [14] to determine its relationship to corrosion rate in gas phase and partially submerged coupons. For a gas phase coupon, it was found that an increase in relative humidity consistently leads to an increase in corrosion rate. For the partially submerged coupon, it was confirmed to have negligible impact on the corrosion rate. This is due to when the coupon is partially submerged, the humidity (and temperature) will have minimal impact on the water content in the corrosion layer [14].

Considering the mentioned factors affect the corrosion process, there also exist factors which are affected by corrosion. Therefore, it is necessary to consider them when assessing the structural integrity of concrete sewers. The following paragraphs introduce the factors which are influenced by corrosion.

Generally, Surface pH of concrete sewer pipes identifies the extent of corrosion within a concrete sewer pipe [8]. Moreover, the surface pH and the amount of concrete loss can be used in order to predict the current stage of corrosion. The results of a study conducted by [16] showed that, the drop in surface pH can be taken as indicator of the stage of corrosion within the concrete sewer pipe under aggressive conditions. The experiment was well set up with accurate results obtained from a real sewer transporting sewer flows from domestic, industrial and trade waste. However, for the sake of validation, the experiment should be conducted in numerous sewer pipe locations and in different environmental conditions, including gravity pipes downstream of rising mains and also less aggressive sewer conditions.

In addition to surface pH, the localized point of deterioration within a concrete sewer pipe is also important to investigate, since deterioration at different locations will affect the service life. This is especially important when there is turbulence within the pipe, which usually increases the rate of corrosion. Davis [10] investigated the localized points of deterioration along a section of concrete sewer pipe that exhibited moderate to severe corrosion. The author established that the loss of sound concrete was greater at the crown of the pipe compared to the spring line, except one location where the spring line had the largest reduction in diameter thickness (due to hydrodynamic characteristics of the sewer at this location). It was also found that neutrophilic sulphur oxidising microorganisms (NSOM) were greater in number at the spring line of the pipe, and acidophilic sulphur oxidising microorganisms (ASOM) were greater in number at the crown of the pipe, supporting the assertion that severe corrosion occurs at the crown of the pipe. The process and findings of this experiment were well documented with evidence of bacterial content to support the localized points of deterioration. A similar experiment has been conducted by Wells [8] on concrete sewer pipes located at different locations of Australia. The author established that the most severe concrete corrosion occurred at the crown of the pipe. Although, both [10] and [8] have not investigated the impact of turbulence flow on the rate of corrosion and also the effect rising mains would have on downstream gravity sewer pipes.

3. CORROSION MONITORING AND ASSESSMENT

After identifying the involved parameters in corrosion of concrete sewer pipeline, the proper method for assessing structural integrity of concrete sewers can be selected. The following section investigates the current methods for monitoring and analysing the structural integrity of corrosion affected concrete sewer networks.

3.1. CCTV push and crawler cameras

Closed Circuit Tele-Vision (CCTV) is the most widely used monitoring method for structural integrity assessment of infrastructures. This method has been provided by international companies [51,17] for monitoring corrosion in pipes with different size and length. In this method, visual data of corrosion in the concrete pipe is transmitted in real time to the operator. The CCTV can be used for detection of significant defects of pipe wall; however, the accuracy of the method highly depends on the proficiency of human operator [18]. The results of several researches [19,20,21] indicate that, using CCTV method may lead to 20-30% defect detection error. Although, using supportive methods alongside CCTV method can improve the accuracy of results leading to an accurate assessment of a concrete pipe defect [22]. For example, there are several supportive techniques available for improving the accuracy of the numeric interpretation of CCTV output data [23,24,25]. However, the following methods have not been used directly for corrosion defect monitoring so far.

3.2. Laser Scanning

Laser scanning method utilises laser scanning together with supportive software and a defect classification algorithm. This combination of detection hardware and numerical software allows for future automatic identification of defects by building-up of a signature database for specific defect types. For instance, using a defect classification algorithm alongside laser scanning and CCTV methods, pipe wall thickness can be calculated, which offers an overall pipe wall condition review that allows for determination of corrosion rate on a yearly basis [26]. However, available laser scanning methods show a measurement error equal to the diameter of the laser spot, which is normally about 4mm.

The Rotating Optical Geometry Sensor (ROGS), a laser sensor for monitoring the condition of buried pipes, has been developed by IOSB [27]. Using four laser beams together with an optical triangulation technique enables this method for 3D simulation of pipe wall surface. Results of a field experiment show that, the accuracy of the proposed technique is about 1mm.

3.3. Scanner Image Processing

Gutierrez-Padilla [28] proposed a method for measuring the rate of corrosion of concrete cubic samples immersed in sulphuric acid, using a scanner-based image analysis technique. A similar approach has been used by Kender and Smith [29], in which the geometry of corroded surface can be recovered using detected shadows. Additionally, a MATLAB-based algorithm was adopted for measuring the average corrosion depth. Compared to other methods, such as the mass loss measurement, this method showed a 1.55% error for the same cubes.

3.4. Acoustic detection

Lohr and Rose [30] implemented an experiment using ultrasonic guided shear and longitudinal waves propagating within the pipe wall for monitoring pipe and load properties. This method was able to detect hidden defects on the pipe wall. Several experiments have been carried out so far for validating the applicability of the proposed method for concrete pipes. Lewis and Fisk [31] adopted the technique for detecting wall thickness reduction of a concrete sewer pipe. The comparison between the propagated waves resonate frequency and the received resonate frequency revealed that, the pipe wall was thinned. However, there is no information available about the accuracy of the mentioned work. Further studies on applicability of the method for concrete sewer pipe assessment has been done by Fisk and Marshall [32], where 81 prestressed 48 inch concrete pipes were assessed. The method detected that 26 of the studied pipe were defected. The findings have been confirmed; although, no quantitative measures was published.

Further applications of the acoustic detection methods can be found in [33,34], where the authors showed that, the method is able to detect large defects such as blockages, roots, missing pipe segments, cracks, fat build-up and sediment, as well as small pipe permeability contrasts such as micro cracks, encrustation and pipe wall roughness.

3.5. Radar Penetration

Ground Penetrating Radar (GPR) is widely used for monitoring and assessment of civil infrastructures, such as concrete sewer networks. The technique has been successfully applied for identifying the exact location and burial depth of underground sewer pipes, regardless of pipe material. Koo and Ariaratnam [35] adopted GPR for identifying the internal sewer pipe damage in a sewer network consisted of 200m concrete and clay test pipes, followed by 1,800m concrete and PVC field pipes. Although the technique is difficult to implement due to huge size of devices; the results reveal that, even smallest material defects, such as corrosion, can be detected. Generally, in comparison with aforementioned methods, GPR method allows for identification of the defects, those are impossible to detect by the naked eye. Moreover, combining other methods, namely Digital Scanning and Evaluation Technology (DSET), with GPR can improve the quality of the assessment process [35].

Generally speaking, majority of the introduced methods in this section are only applicable for detecting the defect depths with resolutions larger than 1mm. While, achieving this resolution in a real concrete sewer pipe environment is very difficult [36]. Therefore, further development is needed to make these methods applicable for assessment of real case scenarios. The researchers must consider factors such as method implementation speed, implementation costs and operational complexity when attempting to develop the available methods.

4. PREDICTION MODELS AND RELIABILITY ANALYSIS

One of the most important issues for asset managers is to make sure about the safety of civil infrastructures. Structural integrity of infrastructures decreases over time, due to aging or chemical attacks such as corrosion. Failure of these assets costs billions of dollars for governments and stakeholders. Therefore, it is essential to repair or replace the structure in order to increase its service life. In order to obtain an optimum strategy for maintenance and rehabilitation of the structures, accurate prediction of failure likelihood is necessary. The probability of failure of a structure, like concrete sewer pipeline, is calculated using reliability analysis methods. The data gathered from monitoring methods can be used as the input database for reliability analysis methods, based on which the service life of pipe systems can be determined.

4.1. Deterministic models

Deterministic models use the laboratory experiments and field studies data, without considering the uncertainties associated with involved parameters, in order to obtain the relationship between different factors those affect the deterioration of concrete sewer pipes. Since almost every parameters involved in deterioration process contain some degrees of randomness, the probabilistic models, which consider the uncertain nature of deterioration processes, seem a better alternative. However, in comparison with probabilistic models, the deterministic models are easier to set-up. These models have been successfully applied for modelling corrosion in concrete sewer pipes in [37,38].

4.2. Statistical models

Compared with deterministic models, Statistical models are applied to a data-base consisted of recorded failure history and condition data of a concrete sewer network, in order to predict its future failures. Such models are therefore limited by inadequate recorded history data, especially when considering cases with insufficient assessment and monitoring data. To predict future conditions of sewer systems, a statistical deterioration model that incorporates Bayesian inference for parameter estimation has been proposed by Egger [39]. The combination of the deterioration and rehabilitation processes in a single model is the main innovation of this approach which improves the prediction accuracy of sewer pipe deterioration. The results from synthetic data showed that the model copes satisfactorily with lack of historical records of sewer conditions; however, the model needs to be applied to real data to confirm accuracy of results. It also needs to be tailored for different pipe material to ensure accuracy.

4.3. Probabilistic models

Probabilistic models can be used when failure history or monitoring data is not available. These models analyse the parameters involved in deterioration process instead of evaluating recorded inspection data-bases. Unlike deterministic models, probabilistic models can deal with uncertain parameters of deterioration process. In comparison with statistical models, probabilistic models do not need large inspection data for predicting probability of failure. Additionally, these models consider effect of environmental factors on degradation process, which results in more realistic failure prediction. However, designing probabilistic models requires deep knowledge and understanding of the principles and mechanisms of deterioration process. Mahmoodian and Alani [2,40,41] proposed several approaches based on probabilistic modelling criteria, for predicting probability of failure of concrete sewer pipes. The authors showed that probabilistic models such as stochastic gamma process model can be applied successfully for calculating probability of failure of corrosion affected concrete sewers. Additionally, the authors investigated the contribution of involved parameters in corrosion of sewer.

4.4. Artificial Neural Networks (ANN)

ANNs are biological inspired networks which can predict the probability of failure considering different involved factors altogether. Implementation of such networks requires huge data-base of involved factors i.e. environmental parameters, like temperature, humidity etc., and also skills in programming. ANN provides accurate and reliable predictions by consideration of both linear and non-linear relationship between involved parameters; however, it is usually comes with huge computational burden. Moreover, ANNs are “black box” techniques; so that the process of obtaining results is not apparent. In many cases, this issue makes interpretation of the results impossible. Several successful applications of ANN methods in sewer defects and reliability analysis can be found in [42,43].

4.5. Fuzzy logic

Fuzzy logic models provides criteria for analysing and decision making based on vague, ambiguous, imprecise or missing input information. Implementation of fuzzy logic-based models requires high level of expertise for constructing the rule set and deciding on defuzzification process. The mentioned factors determine the quality of outputs obtained from fuzzy models. Unlike many available models, fuzzy logic based models are able to integrate engineering judgment when predicting sewer pipes deterioration; however, construction of fuzzy rule sets and determination of defuzzification process are generally challenging tasks which make these models difficult to set up [44]. Kleiner [45,46] are among the applications of fuzzy logic models in deterioration assessment of sewer network, where authors defined the ordinary rate deterioration of the pipe by a fuzzy rule set. The results indicated the applicability of fuzzy logic for modelling deterioration of sewer networks.

5. EXPERIMENTAL WORK IN THE UK

In this section the results of a laboratory experiment, which is a part of a project supported by the Engineering and Physical Sciences Research Council (EPSRC), UK on the assessment of the service life of concrete sewer pipes in the UK are presented. The main goal of the research project was to investigate the effect of acidity of sulphuric acid and temperature on corrosion of concrete sewer pipeline. The majority of available literature have focused on the effect of temperature on the bacterial degradation of concrete [47,48] and to the best of the authors’ knowledge there are limited number of available research about the effect of temperature on chemical acid attack in concrete structures [49]. However, in practice concrete degrades differently in various climate and temperature conditions regardless of presence of bacteria.

In this research, a brand new concrete pipe has been selected in order to guarantee the quality and homogeneity of the samples. The experiment is consisted of three stages; sample preparation, sulphuric acid bath and test procedure. At the first stage of experiment, 162 cubic 100×100×100mm samples were cut from a brand new 0.7m diameter concrete sewer pipe. A tolerance of 10% for the measurement of each side is allowed to consider the probable errors in cutting process (Figure 2).

Figure 2 Sample preparation and acid bath stage

During the second stage, a total number of nine 700×700×400mm (196 L) PVC containers were filled by 130L of sulphuric acid solution (Figure 2). Sulphuric acid solutions were prepared by mixing de-ionized water with fixed amounts of condensed sulphuric acid in order to obtain the desired pH level. A digital thermometer with accuracy of ±0.1 and a digital pH meter with ±0.05 accuracy were used to determine the temperature and pH levels of the sulphuric acid solutions. Sulphuric acid was added periodically to the solutions to keep the pH level within an acceptable range of the predetermined concentration.

Finally, the specimens were dried at 105℃, until the constant mass is reached, weighted and then placed in the sulphuric acid tanks with different pH levels (i.e., 0.5, 1 and 2) and temperatures (i.e., 10, 20 and 30℃). This process was repeated before measuring mass loss and compressive strength of specimens at 7th, 14th, 28th, 42nd, 56th and 91st day of immersion. The deterioration of corrosion affected concrete structures is usually determined using mass loss concept. The following equation calculates the mass loss for each specimen, in which M_1 is the initial mass of the specimen and M_2 is the mass of the specimen after immersion:

$$Mass\ Loss\ (\%) = \frac{M_1 - M_2}{M_1} \times 100 \quad (1)$$

The compressive strength test was carried out using a hydraulic machine with a loading rate of 14.4 MPa/min, as per ASTM C39 criteria. On each date, reduction in compressive strength of three identical specimens, from each container, was evaluated using Equation 2 (ASTM C267) and the average value was recorded:

$$\text{Strength Loss } (\%) = \frac{\acute{f}_o - \acute{f}_t}{\acute{f}_o} \times 100 \quad (2)$$

In Equation 2, $\acute{f}_o$ is the initial compressive strength of samples and $\acute{f}_t$ is compressive strength after t days of acid immersion.

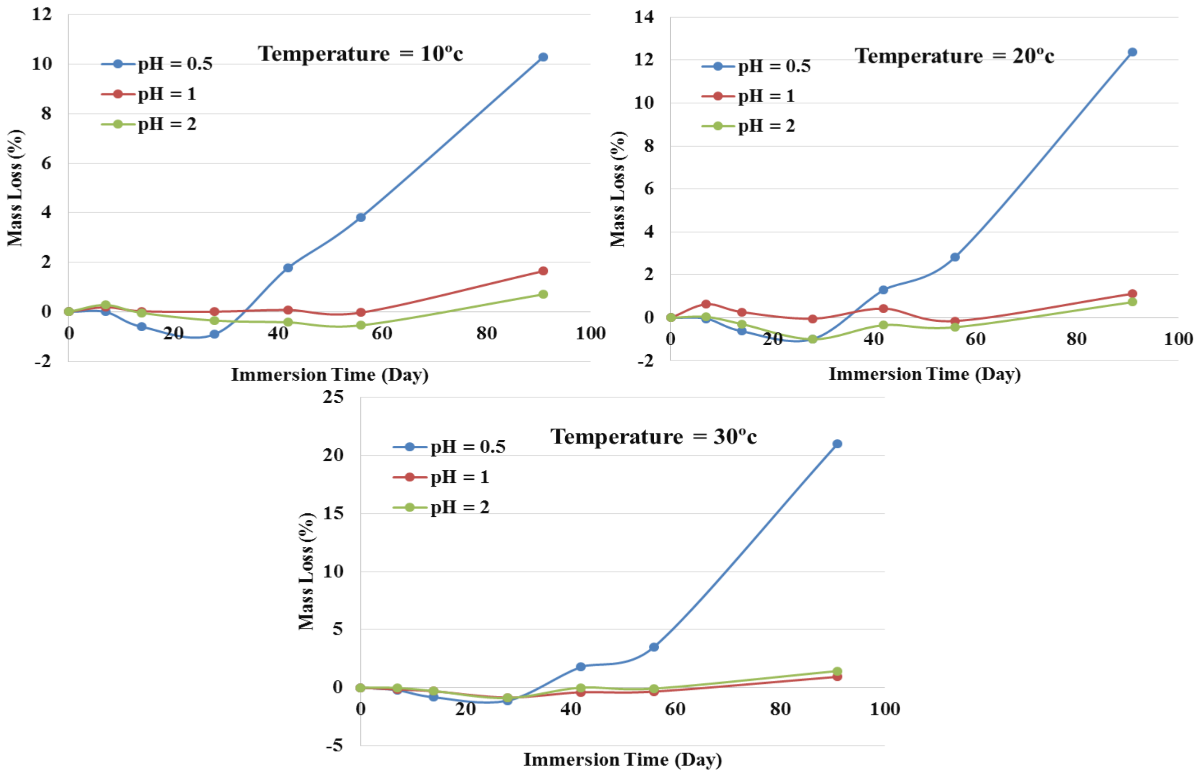

Figure 3 Mass loss of the specimens in three temperatures and three pH

6. RESULTS

Changes in mass loss for each temperature can be found in Figure 3. It can be seen that the mass of all specimens increases at the early stages. This issue has been usually described as producing a decrease in density and an increase in volume, so that when the volume increase is greater than the density loss, mass gain may occur [50]. Although, in this research the authors believe that, the mass increase during the early stages occurs because of the ability of acid-absorption of concrete via micro-pores and also the gypsum formation under the surface of concrete. It is also apparent from Figure 3 that, the amount of mass loss for the most acidic solutions (i.e., pH=0.5) is notably higher than that of other two pH levels. Moreover, the figure shows that, the increase in temperature accelerate the mass loss.

Figure 4 (a) original sample, (b) to (d) samples after 14, 56 and 91 days experiment, respectively.

The deterioration of concrete specimens over time has been illustrated in Figure 4. The appearance of a white material on the concrete surface at the beginning days of immersion reveals the creation of gypsum, which is not lose enough yet to be washed away from the specimens. Figure 4d shows that, as the corrosion progresses the production of gypsum increases. Therefore, significant mass loss occurs (i.e., after 91 days) when the accumulated gypsum is washed away from the surface. Figure 4 also reveals that, during the first 56 days, temperature did not affect the rate of mass change. However, considering 91 days immersed specimens in pH=0.5, significant mass loss can be observed at higher temperatures. The results indicate that, during the acid deterioration process, the high temperature of the sulphuric acid solution increases the mass loss by weakening the bonds between aggregates and cement paste. Figure 5 illustrates the changes of compressive strength of specimens in each condition over time. The results confirm that, the effect of temperature on compressive strength of concrete samples is negligible. The figure 5 also demonstrate that the more acidic solutions have more impact on the compressive strength reduction of specimens.

As it was mentioned in the previous section, concrete is generally considered as an alkaline material, mainly because of the calcium hydroxide formed when Portland cement reacts with water at the concrete production stage. During the acid immersion period, pH of the surface dropped. Phenolphthalein is used to determine the value of surface pH. The method was applied in this experiment for finding the changes in surface pH of samples in different temperatures overtime. Figure 6 reveals the changes in surface pH for samples immersed in different temperature acids during 91 days of immersion. It can be seen from the figure that, temperature has negligible impact on surface pH of concrete samples.

Figure 7 shows the percentage of reduction in compressive strength and mass loss at the end of immersion period. The figure shows the mass loss and compressive strength at the end of 91st day of experiment. Both bar charts indicate the dominant effect of most acidic solution (i.e., pH=0.5) on the concrete degradation process. Furthermore, to lesser extent, the temperature negatively affects the compressive strength and also mass loss. Consequently, the specimens immersed in 30℃ sulphuric acid solution of 0.5 pH experienced the most sever material degradation.

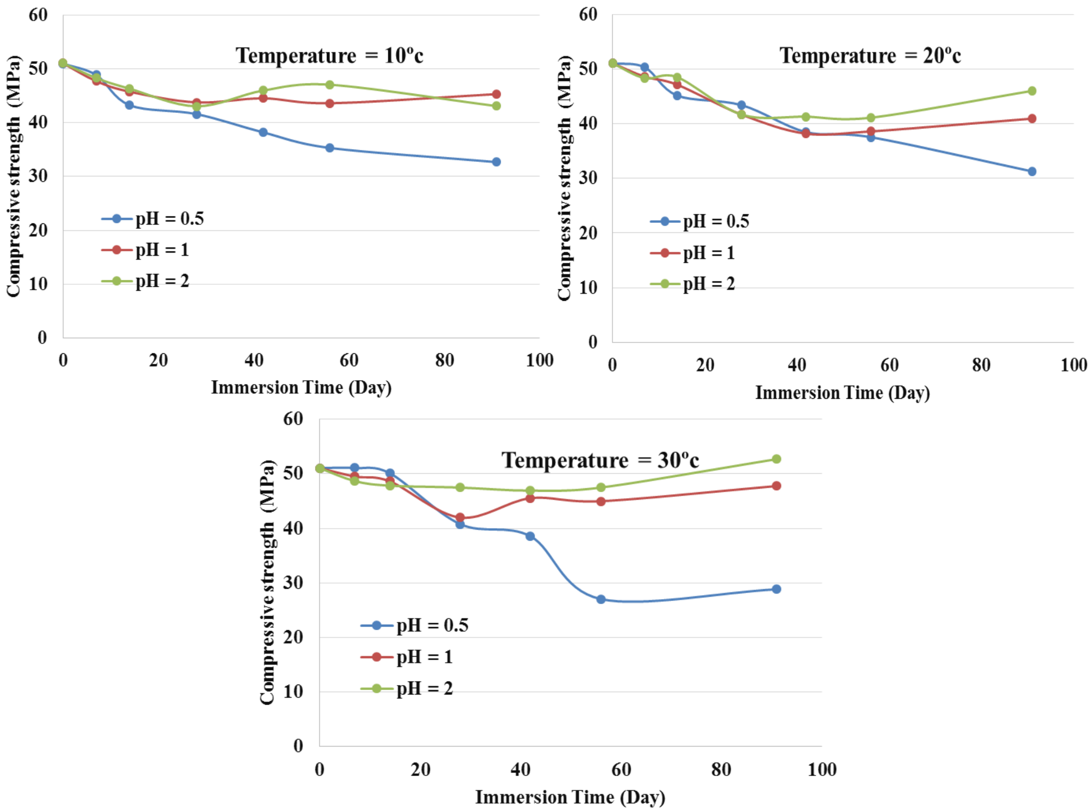

Figure 5 Compressive strength of the specimens in three different sulphuric acid solutions and three temperature

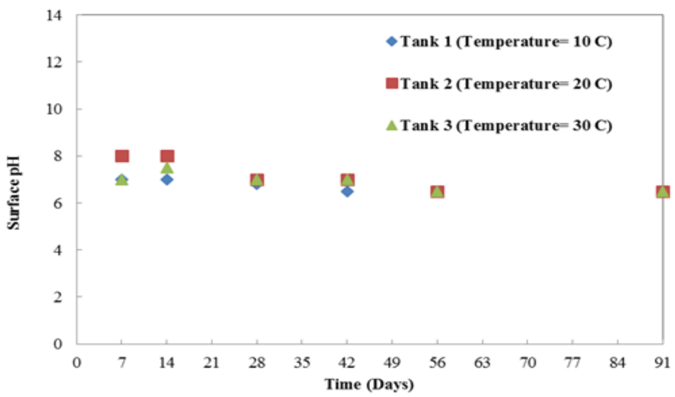

Figure 6 Effect of temperature on surface pH

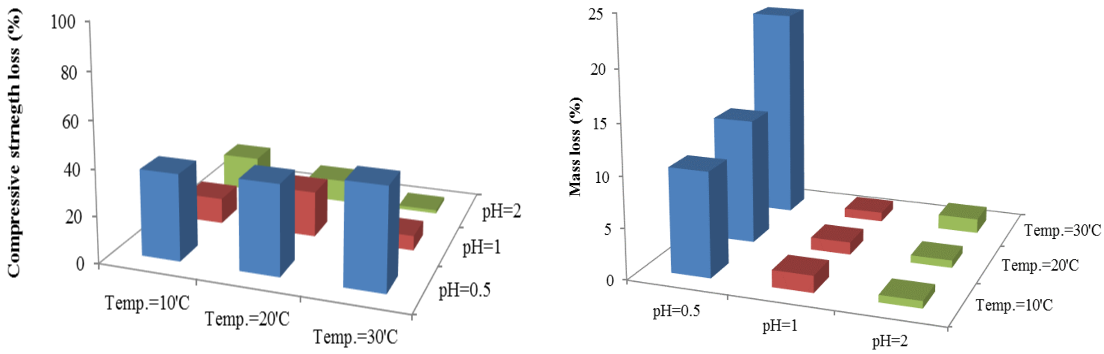

Figure 7 Variation in compressive strength loss and mass loss after 91 days experiment

7. CONCLUSION

This paper investigated the problem of deterioration, and specifically sulphide corrosion, in concrete sewers. Several monitoring and assessment methods alongside reliability analysis models have been presented, followed by description of an experimental laboratory research on concrete sewers in the UK.

Considering the advantages and disadvantages of monitoring and assessment methods mentioned in this research, it can be concluded that; acoustic and radar methods have been proved to be reliable, financially convenient and easy to set-up monitoring techniques which have great potential for further researches and improvements; however, more study is required in order to develop their functionalities, since those cannot determine the degradation scale yet.

Generally speaking, most of available databases are intermittent, containing missing and noisy data. Artificial intelligence based models such as artificial neural network models can be considered as good options, because the models are able to deal with noisy and inconsistent databases. However, these models have their own limitations and further research and development is still required.

This paper also presented the results of a laboratory experiment on investigating the combined impact of two environmental variables, temperature and acidity, for structural integrity assessment of concrete sewers in the UK. Mass loss and compressive strength loss of the specimens taken from a brand new concrete sewer pipe were investigated during 91 days of immersion in sulphuric acid solution of different pH levels and different temperatures. As an extension to this research, authors suggest that, investigating the effects of water absorptivity and permeability as well as chemical and/or microstructural analysis can help for better understanding of the deterioration mechanism of sulphide corrosion in concrete sewers.

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