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2 **Effect of temperature and acidity of sulphuric acid on concrete**
3 **properties**

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14 **ABSTRACT**

15 Concrete corrosion caused by sulphuric acid attack is a known phenomenon in sewer
16 systems, resulting in significant economic losses and environmental problems. However,
17 there is a scarcity of reported laboratory simulations and experimental work investigating the
18 contributing factors controlling the corrosion. In this EPSRC (Engineering and Physical
19 Sciences Research Council, UK) funded investigation the effect of temperature and the
20 acidity of sulphuric acid solution on concrete specimens extracted from brand new concrete
21 sewers has been investigated. In this investigation the concrete samples are submerged in
22 three sulphuric acid solutions (pH = 0.5, 1 and 2) for 91 days under different temperatures
23 (10°C, 20°C and 30°C). Mass loss and compressive strength of the concrete specimens were
24 tested and recorded at 7, 14, 28, 42, 56 and 91 days providing interesting data for visualising
25 the changes taking place in the concrete samples (change in properties) during the time of
26 immersion. The results revealed that samples overall mass increased at the early stages of the
27 corrosion process. It also was observed that the overall mass of the samples decreased
28 significantly at the later stages of the testing process with respect to the acidity of the
29 solutions used.

30 Although the change in temperature did not have a significant effect on the compressive
31 strength of the tested samples, rise in temperature however, had considerable effect on the
32 mass loss of the concrete samples which were immersed in the most aggressive solution (i.e.,
33 pH=0.5 and temperature = 30°C) at 91 days. This research clearly demonstrated a high
34 correlation between the acidity of the solution and the rate of corrosion with respect to time.

35
36 **KEYWORDS**

37 Concrete corrosion, sulphuric acid attack, corrosion rate, mass loss, compressive strength
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1. Introduction

The degradation of concrete sewer pipes by sulphuric acid attack is a substantial challenge globally, resulting in environmental impacts and economical losses of billions of dollars annually. Replacement and rehabilitation requirements related to the corrosion of concrete sewer pipes result in annual costs of \$130 million in the UK (Water UK, 2013a, 2013b) and \$120 million in Germany (Kaempfer and Berndt, 2013), which is a constantly growing threat for aging pipe sewer networks.

Concrete sewer pipe structural vulnerability is predominantly caused by sulphide corrosion which is dictated by the presence and high activity of sulphuric acid on the pipe wall and crown surfaces.

Generally the corrosion process goes through a three step chemical process: the sulphate contained in the wastewater transforms into sulphide (Figure 1), before the sulphide is released into the air in gas form, where the hydrogen sulphide is oxidised on moist surfaces into sulphuric acid (Parker, 1945a, 1945b; Vollertsen and Nielsen, 2008). The surface pH of new concrete pipe is generally between 11 and 13. Cement contains calcium hydroxide, which neutralises the acid. In active corrosion areas, the surface pH can drop to 1 or even lower and can cause a very strong acid attack. The corrosion rate of the sewer pipe wall is determined by the rate of sulphuric acid generation and the properties of the cementitious materials. As sulphides are formed and sulphuric acid is produced, hydration products in the hardened concrete paste (calcium silicate, calcium carbonate and calcium hydroxide) are converted to calcium sulphate, more commonly known by its mineral name, gypsum [ASCE 1989]. Gypsum provides little structural support, especially when wet. It is usually present as a pasty white mass on concrete surfaces above the water line. As the gypsum material is eroded, the concrete loses its binder and begins to spall, exposing new surfaces. This process will continue until the pipeline fails or corrective actions are taken.

To understand the process of concrete corrosion and its rate, accelerated experiments with the use of sulphuric acid have been undertaken. Jahani et al (2001a&b) exposed concrete samples to a sulphuric acid solution of 2-3 pH over 72 days, where a corrosion rate of 0.82mm/year was observed. In a research by De Belie et al (2004) subsequent steps of immersion and drying, combined with mechanical abrasion, were applied to simulate events occurring in sewer systems. To simulate sulphuric acid attack, three cylinders of each concrete type were subjected to 10 attack cycles consisting of an alternated immersion in a 0.5% sulphuric acid

74 solution (initial pH 0.9–1.0), drying by air and brushing. They also assessed the effect of W/C
75 ratio and the cement type on the corrosion rate. Gutierrez-Padilla et al (2009) estimated
76 corrosion rates of 2.19, 0.76 and 0.18mm/year for concrete samples exposed for 64 days in
77 0.5%, 0.2% and 0.05% sulphuric acid solution. Most research on the resistance of concrete to
78 sulphuric acid attack has considered the effectiveness of the change in concrete mix design on
79 concrete resistivity (Bassuoni and Nehdi, 2007; Hewayde et al, 2007; Nnadi and Lizarazo-
80 Marriaga, 2013). However, more rarely investigated is the effect of the main practical
81 environmental factor (i.e., temperature) on chemical corrosion.

82
83 The current study is a part of an extensive project supported by the Engineering and Physical
84 Sciences Research Council (EPSRC) on the assessment of the remaining life of the
85 cementitious sewer pipes in the UK. The research involves both lab and field experiments
86 and investigates the parameters affecting sulphide corrosion of concrete sewers and
87 consequently the structural reliability of the sewers. In this paper the results of the lab
88 experiments are presented. The aim is to assess the establishment of the corrosion process on
89 concrete samples exposed to sulphuric acid solution with different temperature regimes and
90 different levels of acidity, which has not been investigated in depth previously.

91 The deterioration of concrete could be evaluated by percentage of mass loss with respect to
92 time (time of exposure to acid solution) under laboratory conditions. This also could be
93 extended to the variations in the compressive strength of the samples tested within the context
94 of the mechanical property of the concrete.

95 The output of this study can be helpful for research in the area of modelling the deterioration
96 of concrete sewers as well as service life prediction and reliability analysis of these types of
97 corrosion affected pipelines (Mahmoodian and Alani, 2013; Yuan et al, 2013; Alani et al,
98 2014; Mahmoodian and Alani, 2014).

99

100 2. **Experimental work**

101

102 To consider the effect of temperature and level of acidity on concrete properties, a test plan is
103 proposed in this study based on the immersion of concrete samples into sulphuric acid and
104 measurement of the mass and strength loss of the specimens. The concrete samples are
105 submerged in three sulphuric acid solutions (pH = 0.5, 1 and 2) for 91 days under 10°C, 20°C
106 and 30°C temperature regimes. Therefore, a total of nine series of test specimens will be
107 investigated (three temperature levels and three pH levels). Mass loss and compressive

108 strength of the concrete specimens are measured after 7, 14, 28, 42, 56 and 91 days of
109 immersion.

110 **2.1. Sample preparation**

111
112 Manufacturing process of concrete pipes has a significant effect on durability related
113 properties of concrete pipes such as permeability, porosity and water absorption (Binici et al
114 2012). While in the most of the laboratory based experimental investigations the concrete
115 specimens are fabricated in-situ (in the laboratory) (Jahani et al 2001a&b, Hewayde et al,
116 2007 and Nnadi and Lizarazo-Marriaga, 2013), in order to simulate the real field condition, in
117 this research however, concrete cubes were cut from a brand new sewer pipe. This approach
118 ascertains the high quality as well as the uniformity (in size) and homogeneity (consistency of
119 the mix) of the samples used in this research.

120 A brand new non-reinforced concrete pipe produced by a concrete pipe manufacturer in the
121 UK was selected for sample preparation. The diameter and the length of the pipe were 0.7m
122 and 2.5m respectively and the manufacturer did not declare the concrete mix design due to
123 commercial sensitivity of the design mix. It is important to point out that the aim of this
124 investigation was not to investigate concrete design mixes and/or finding the optimum
125 concrete design mix resistant against acid attack. The main aim of this research was to
126 investigate the effect of environmental conditions (temperature and acidity) on the
127 mechanical properties of concrete sewer pipes, therefore as long as the samples used were of
128 similar dimensions and ingredients, the concrete mix design should not impose or be
129 considered as a technical challenge or shortfall. Nevertheless, the samples used for this
130 research were all in compliance with the sewer pipe design standard and code of practice in
131 the UK.

132 Considering three samples for testing at six different immersion times for nine series of
133 solution conditions, a total number of 162 cubic specimens were cut from the brand new
134 circular concrete sewer pipe to be used in the experiments. In order to ascertain the
135 compressive strength of the concrete before immersion, six extra samples were also prepared.
136 Each cube had approximate dimensions of $100 \times 100 \times 100$ mm and was cut with a
137 diamond-blade rotating saw. However, as the process of cutting a circular pipe is very
138 challenging and labour consuming, a tolerance of 10% for each side measurement of the cube
139 was allowed (Figure 2).

140 **2.2. Sulphuric acid baths**

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143 Nine containers made of acid resistant PVC with dimensions of 700x700x400mm and a
144 volume of 196 L were filled to two-thirds of their height with sulphuric acid solutions (Figure
145 3). All sulphuric acid solutions were prepared by mixing de-ionized water with
146 predetermined amounts of condensed sulphuric acid to gain the desired pH level. The
147 temperature and pH levels of the sulphuric acid solutions were monitored daily using a digital
148 thermometer with accuracy of ± 0.1 and a digital pH meter with ± 0.05 accuracy. Figures 4 and
149 5 show examples of pH and temperature monitoring records for sulphuric acid baths with
150 pH=0.5 and temperature=10, 20 and 30°C, respectively. Concentrated sulphuric acid was
151 added periodically to the solutions to maintain the pH level within an acceptable range of the
152 designated concentration.

153 2.3. Test procedure

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156 As previously mentioned, 18 concrete specimens were immersed in each of the nine sulphuric
157 acid tanks containing 130L of solution. Therefore, a total of 162 test specimens were oven
158 dried at 105°C until they reached constant mass, weighed using a digital scale (accuracy of
159 ± 0.01 g) and then immersed into the sulphuric acid tanks with pH = 0.5, 1 and 2 and three
160 different temperature levels (i.e., 10°C, 20°C and 30°C).

161 Measurements were performed at 7, 14, 28, 42, 56 and 91 days of sulphuric acid immersion;
162 at each date three specimens were removed from each tank, rinsed and carefully brushed and
163 oven dried at 105°C until constant mass was achieved. The specimens were subsequently
164 cooled at room temperature, weighed and prepared for compressive strength testing.

165 The percentage of mass loss at each date was calculated according to the following equation:

$$166 \text{ Mass Loss (\%)} = \frac{M_1 - M_2}{M_1} \times 100 \quad (1)$$

167 where M_1 is the mass of the specimen before immersion and M_2 is the mass of the specimen
168 after immersion. Mass loss is commonly used to evaluate the deterioration of concrete under
169 acid attack (Ehrich et al, 1999; Hewayde et al, 2007; Nnadi and Lizarazo-Marriaga, 2013).

170 Compressive strength tests were also performed at 7, 14, 28, 42, 56 and 91 days using a
171 hydraulic machine with a loading rate of 14.4 MPa/min as per ASTM C39 guidelines. Three
172 identical specimens from each series were tested at each date and the average value is
173 reported. The reduction in compressive strength of the corroded specimens was calculated as
174 follows (ASTM C267):

$$175 \text{ Reduction in compressive strength (strength loss)} = \frac{f_o - f_t}{f_o} \quad (2)$$

177
178 where f'_o is compressive strength of control samples (before immersion) and f'_t is compressive
179 strength after t days of immersion in sulphuric acid.

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183 3. Results and discussion

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185 3.1. Effect on mass loss

187 Figure 6 shows the evolution of the mass loss of the specimens for each temperature level. In
188 the early stages, mass gain occurred for all the specimens. This mass increase had been found
189 in other research undertaken by Nnadi and Lizarazo-Marriaga (2013). They describe this
190 reaction as producing a decrease in density and an increase in volume. If the increase in
191 volume is greater than the loss of density, mass increase could occur. However, the authors of
192 the current research believe that the mass gain during the early ages can be explained by the
193 ability of concrete to absorb the acid via micro-pores and the formation of gypsum that
194 occurs under the concrete surface. The corrosion products under the surface layer of each
195 specimen are not loose enough to be easily washed away, resulting in mass gain. As acid
196 reaction continues, corrosion products at the surface become greater than what has been
197 formed in the micro pores; they are loose enough to be washed away and so subsequent mass
198 loss occurs. In Figure 7, degradation of the concrete samples with time is visually
199 investigated. The production of a white coloured material on the concrete surface at the early
200 ages of immersion is evidence of the creation of gypsum, but this corrosion product is not
201 large enough or loose enough to be washed away from the surface of the specimen. At later
202 stages, for example after 91 days (Figure 7g), the progress of corrosion has resulted in
203 relatively substantial gypsum production; as this is washed away significant mass loss occurs.

204

205 It can also be observed that, within the first 56 days, the rate of mass change is not affected
206 by temperature. However for 91 day specimens in pH=0.5, much greater mass loss is
207 observed at higher temperature levels. This result, together with a visual inspection of the
208 samples, reveals that, during the acid degradation process, the temperature of the sulphuric
209 acid solution accelerates the mass loss by loosening the bonds between aggregates and
210 cement paste. The main focus of large proportion of the available literature within the field
211 has been on the effect of temperature on the bacterial degradation of concrete (Alexander et
212 al 2013, Alani et al 2014 and House and Weiss 2014) and to the best of the authors'
213 knowledge there are rather limited investigation results available on temperature effect on

214 chemical acid attack progression in concrete specimens (Okochi et al. 2000 and Zhang et al.
215 2012). However, in practice concrete can potentially degrade differently in various climate
216 and temperature conditions regardless of presence of bacteria. It also should be appreciated
217 that the investigation of bacterial degradation of concrete, and in particular in cementitious
218 sewer pipe scenarios, is a major research and development field which requires specialist and
219 dedicated infrastructure and equipment as well as expertise.

220 The results of mass loss measurements presented in Figure 6 also clearly show that the trend
221 of mass loss for the most acidic solutions (i.e., pH=0.5) is considerably higher than for the
222 other two pH levels.

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3.2. Effect on compressive strength

227 Figure 8 shows the change in compressive strength of concrete samples in each condition
228 within time of immersion. The results confirm that the effect of temperature change on
229 corrosion progress is negligible. However, the trend in the graphs demonstrates that the more
230 acidic the solution, the greater the reduction in compressive strength. This is similar to the
231 mass loss and can be also illustrated in the form of Figure 9. In this figure the mass loss and
232 compressive strength after 91 days immersion in the three temperature conditions are
233 illustrated. Both bar charts show the maximum effect caused by the most acidic solution (i.e.,
234 pH=0.5) on the concrete properties.

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3.3. Relationship between mass loss and compressive strength degradation

238 The relationship between the mass loss experienced by all concrete specimens subjected to
239 sulphuric acid and the reduction in their compressive strength is shown in Figure 10. It is
240 observed that compressive strength declined as mass loss increased. This directly
241 proportional relationship can be attributed to the fact that immersing concrete specimens in
242 sulphuric acid results in loss of cement paste and structural integrity, weakening of the
243 concrete matrix and a reduction in the specimen's diameter.

244 The graph in the figure is divided into four quadrants, with their point of intersection
245 represented by the average compressive strength and mass loss of all the samples. It is clear
246 from the figure that all the points for solutions with pH=0.5 are located in the upper right
247 quadrant, which have above average values for both mass loss and loss in compressive
248 strength. The mass loss and loss in compressive strength at the other two pH levels (i.e.,
249 pH=1 and pH=2) are considerably lower. This confirms the fact that the effect of acidity level

250 on concrete resistance does not follow a linear correlation and, as the pH of the acid reduces,
251 the chemical reaction occurs progressively.

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254 4. **Conclusion**

255

256 This study investigated the effect of temperature and acidity level on the resistance of
257 concrete to chemical sulphuric acid attack. Mass loss and loss in compressive strength of
258 concrete samples extracted from a brand new concrete pipe were checked after immersion in
259 solutions of three pH levels (pH=0.5, 1 and 2) and kept at three temperature levels (T=10°C,
260 20°C and 30°C) for 91 days.

261 It was noted that, at the very early stage of the corrosion process, concrete mass increased for
262 all conditions. For the higher temperature acid solutions, greater mass loss was observed in
263 the long term.

264 Overall, in the acid degradation process, the temperature of the sulphuric acid solution
265 accelerates the mass loss by loosening the bonds between aggregates and cement paste. This
266 results in aggregate loss and eventually higher depth of corrosion. This finding confirms the
267 mechanical effect of temperature on the degradation process in concrete sewers.

268 It was also found in this study that the level of acidity of acid solutions progressively affects
269 the concrete properties (i.e., mass loss and compressive strength).

270 It needs to be noted that mass loss and compressive strength were used in this research as
271 major and common indicators for change in durability and mechanical properties of concrete
272 subject to acid attack. However, other measures such as water absorptivity and permeability
273 as well as chemical and/or microstructural analysis also can be used in future studies to
274 further investigate concrete behaviour in an acidic environment.

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276

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278

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292 **References**

293

294 Alani, A., Faramarzi, A., Mahmoodian, M. and Tee K. F., (2014), Prediction of sulphide
295 build-up in filled sewer pipes, *Journal of Environmental Technology*, Aug;35(13-16):1721-8

296 Alexander, M., Bertron, A. and De Belie, N., (2013) Performance of cement-based materials
297 in aggressive aqueous environments, *State-of-the-Art Report*, RILEM TC 211 - PAE

298 Bassuoni, M.T. and Nehdi, M.L., (2007), Resistance of self-consolidating concrete to sulfuric
299 acid attack with consecutive pH reduction, *Cement and Concrete Research* 37, 1070–1084

300 Binici, H., Durgun, M.Y., Rızaoğlu, T. and Koluçolak, M., (2012), Investigation of
301 durability properties of concrete pipes incorporating blast furnace slag and ground basaltic
302 pumice as fine aggregates, *Scientia Iranica*, Volume 19, Issue 3, June, Pages 366–372

303 CPAA (2014), *Concrete Pipe Facts*, the Concrete Pipe Association of Australasia

304 De Belie, N., Monteny, J., Beeldens, A., Vincke, E., Van Gemert, D. and Verstraete, W.,
305 (2004) Experimental research and prediction of the effect of chemical and biogenic sulfuric
306 acid on different types of commercially produced concrete sewer pipes, *Cement and Concrete*
307 *Research* 34, 2223–2236

308 Ehrich, S., Helard, L., Letourneux, R., Willocq, J. and Bock, E., (1999) Biogenic and
309 chemical sulfuric acid corrosion of mortars, *Journal of Materials in Civil Engineering*, Vol.
310 11, No. 4, November

311 Gutierrez-Padilla, M.G.D., Bielefeldt, A., Ovtchinnikov, S., Pellegrino, J. and Silverstein, J.
312 (2009), Simple scanner-based image analysis for corrosion testing: Concrete application, *J.*
313 *Materials Processing Technology*, 209, 51-57.

314 Hewayde, e., Nehdi, M., Allouche, E. and Nakhla, G., (2007), Effect of Mixture Design
315 Parameters and Wetting-Drying Cycles on Resistance of Concrete to Sulfuric Acid Attack,
316 *Journal of Materials in Civil Engineering*, Vol. 19, No. 2, February 1.

317 House, M. W. and Weiss, W. J., (2014), Review of Microbially Induced Corrosion and
318 Comments on Needs Related to Testing Procedures, 4th International Conference on the
319 Durability of Concrete Structures 24–26 July 2014 Purdue University, West Lafayette, IN,
320 USA

321 Jahani, F., Devinny, J., Mansfeld, F., Rosen, G., Sun, Z. and Wang, C., (2001a),
322 Investigations of sulfuric acid corrosion of concrete. I: Modeling and chemical observations,
323 Journal of Environmental Engineering-ASCE 127(7): 572-579.

324 Jahani, F., Devinny, J., Mansfeld, F., Rosen, G., Sun, Z. and Wang, C., (2001b),
325 Investigations of sulfuric acid corrosion of concrete. II: Electrochemical and visual
326 observations, Journal of Environmental Engineering-ASCE 127(7): 580-584.

327 Kaempfer, W. and Berndt, M., (1998), Polymer modified mortar with high resistance to acid
328 corrosion by biogenic sulphuric acid, Proceedings of the IX ICPIG Congress, Bologna, Italy,
329 pp 681-687.

330 Koch, G.H., Brongers, M.P.H., Thompson, N.G., Virmani, Y.P. and Payer, J.H, (2002),
331 Corrosion Costs and Preventive Strategies in the United States, NACE International

332 Mahmoodian, M. and Alani, A., (2013), Multi failure mode assessment of buried concrete
333 pipes subjected to time dependent deterioration using system reliability analysis, Journal of
334 failure analysis and prevention: Volume 13, Issue 5, Page 634-642

335 Mahmoodian, M. and Alani, A., (2014), Modelling deterioration in concrete pipes as a
336 stochastic Gamma process for time dependent reliability analysis, Journal of pipeline systems
337 engineering and practice, ASCE, Volume 5, Issue 1, 04013008

338 Mori, T., M. Koga, et al. (1991), Microbial Corrosion of Concrete Sewer Pipes, H₂S
339 Production from Sediments and Determination of Corrosion Rate, Water Science and
340 Technology 23(7-9): 1275-1282.

341 Mori, T., T. Nonaka, et al. (1992), Interactions of Nutrients, Moisture and Ph on Microbial
342 Corrosion of Concrete Sewer Pipes, Water Research 26(1): 29-37.

343 Nnadi, E. O. and Lizarazo-Marriaga, J., (2013), Acid Corrosion of Plain and Reinforced
344 Concrete Sewage Systems, Journal of Materials in Civil Engineering, ASCE, Vol. 25, No. 9,
345 September 1

346 Okochi, H., Kameda, H., Hasegawa, S., Saito, N., Kubota, K. and Igawa, M, (2000),
347 Deterioration of concrete structures by acid deposition- an assessment of the role of rainwater
348 on deterioration by laboratory and field exposure experiments using mortar
349 specimens, Atmospheric Environment, Volume 34, Number 18, 1 December, pp. 2937-
350 2945(9)

351 Parker, C. D. (1945a), The Corrosion of Concrete .1. The Isolation of a Species of Bacterium
352 Associated with the Corrosion of Concrete Exposed to Atmospheres Containing Hydrogen
353 Sulphide, Australian Journal of Experimental Biology and Medical Science 23(2): 81-90.

354 Parker, C. D. (1945b), The Corrosion of Concrete .2. The Function of Thiobacillus-
355 Concretivorus (Nov-Spec) in the Corrosion of Concrete Exposed to Atmospheres Containing
356 Hydrogen Sulphide, Australian Journal of Experimental Biology and Medical Science 23(2):
357 91-98.

358 Vollertsen, J., A. H. Nielsen, Jensen, H. S., Wium-Andersen, T. and Jacobsen, T. H., (2008),
359 Corrosion of concrete sewers - The kinetics of hydrogen sulfide oxidation, Science of the
360 Total Environment 394(1): 162-170.

361 Water UK, (2013a), Expenditure variables – Wastewater
362 Water UK, (2013b), Industry Data Share 2013

363 Yuan, H., Dangla, P., Chatellier, P. and Chaussadent, T., (2013), Degradation modelling of
364 concrete submitted to sulfuric acid attack, Cement and Concrete Research 53, 267–277

365 Zhang, Y., Fan, Y. and Li, H., (2012), Influence of Simulated Acid Rain Corrosion on the
366 Uniaxial Tensile Mechanical Properties of Concrete, International Journal of Corrosion
367 Volume 2012

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387 **List of figures**

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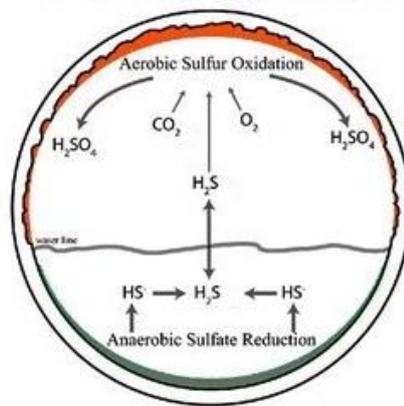
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403 Figure 1. corrosion process in concrete sewers, [Water Stinks, Understanding sewer
404 condition, <http://waterstink.com/tag/concrete-sewers/>]
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420 Figure 2. cube specimens extracted from a brand new concrete pipe
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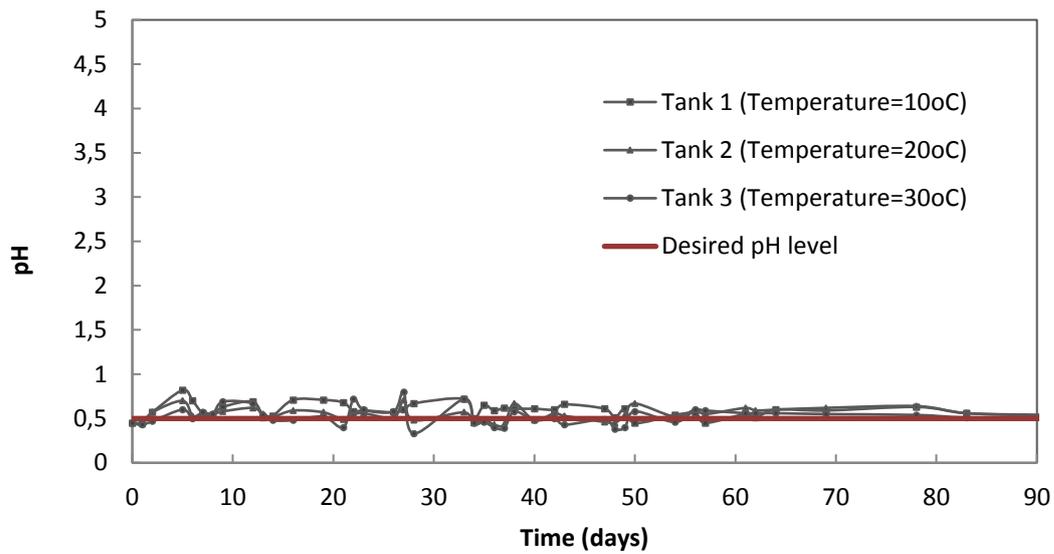


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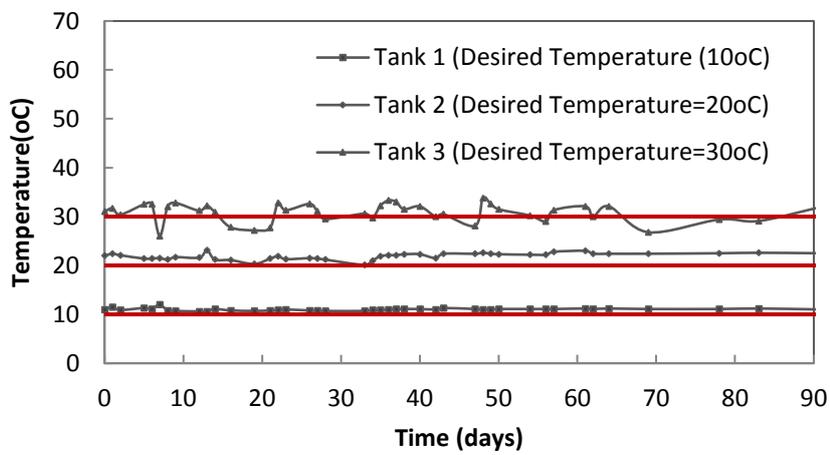
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Figure 3. Sulphuric acid bath with controlled pH value and temperature



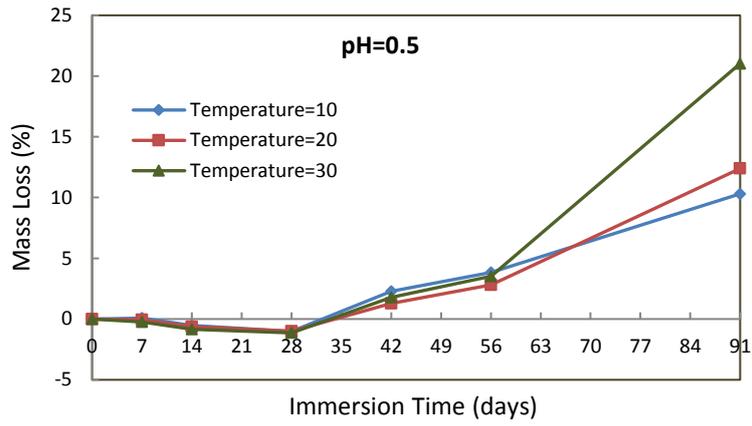
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Figure 4.pH monitoring records for the three temperature regimes during period of immersion

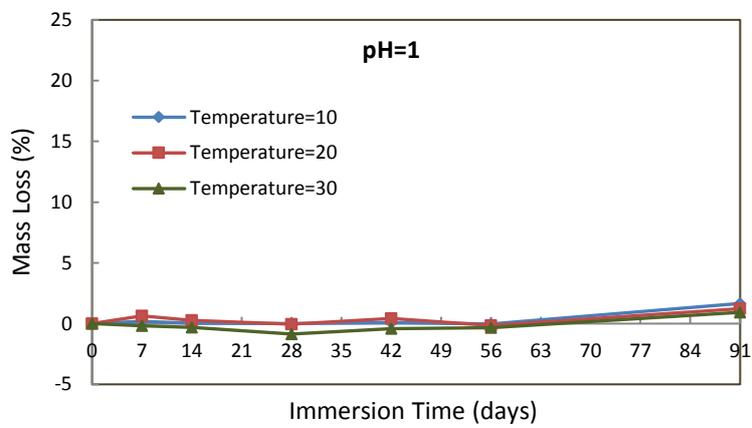


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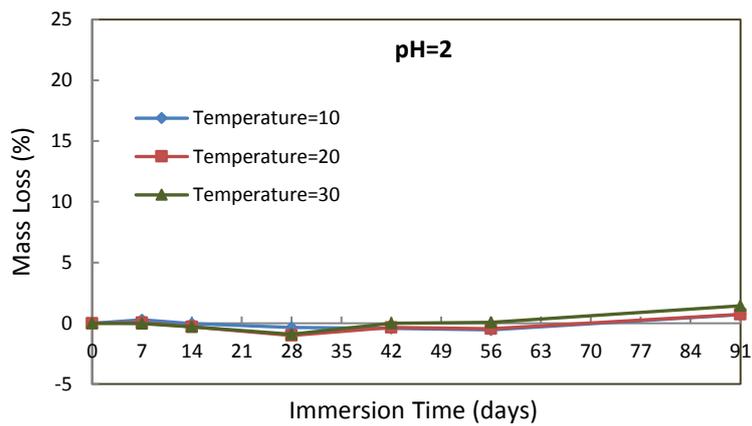
Figure 5.Temperature monitoring records for sulphuric acid solutions with pH=0.5 during period of immersion in the three temperature regimes



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Figure 6. Mass loss of the specimens in three different sulphuric acid solutions and three temperature regimes

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(b)

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(d)

(e)

(f)

(g)

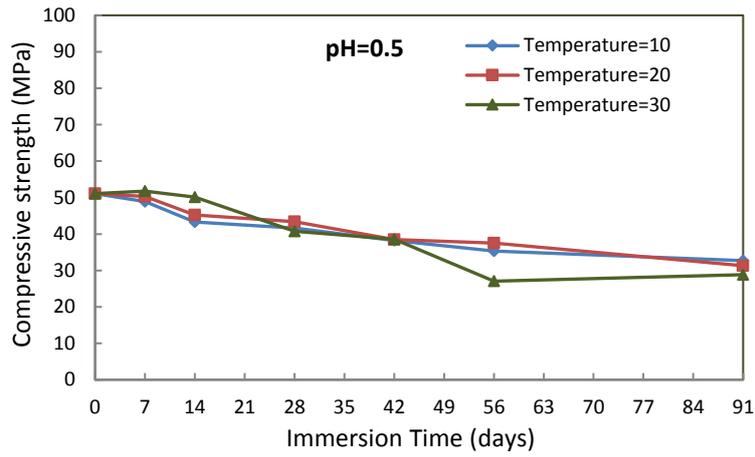
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Figure 7: (a) control specimen before immersion, (b) to (g) specimens after 7, 14, 28, 42, 56 and 91 days immersion in sulphuric acid, respectively.

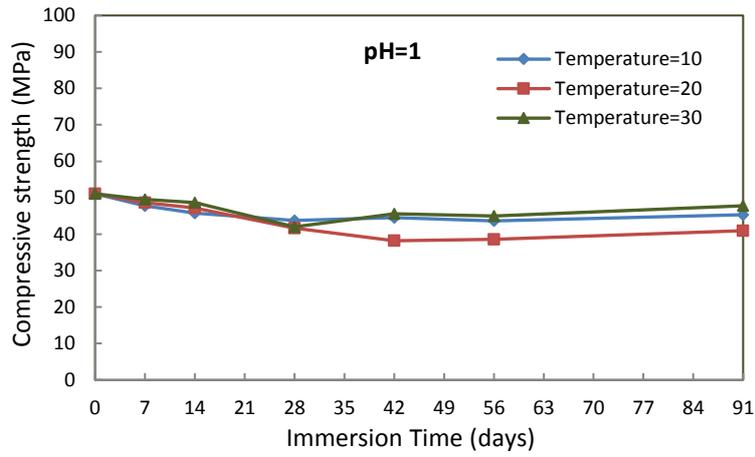
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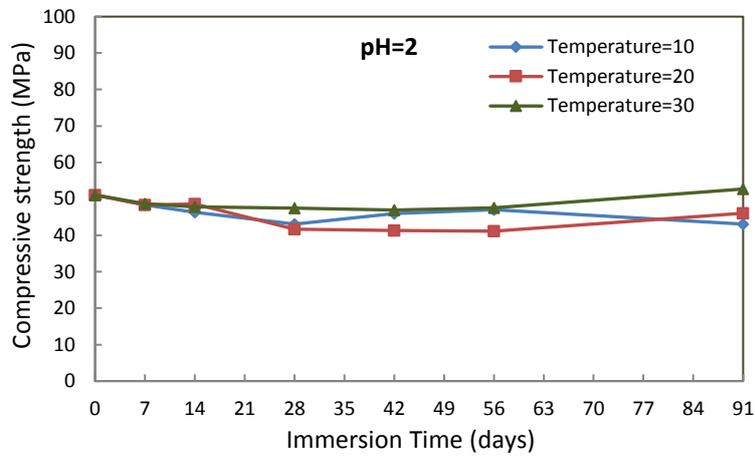
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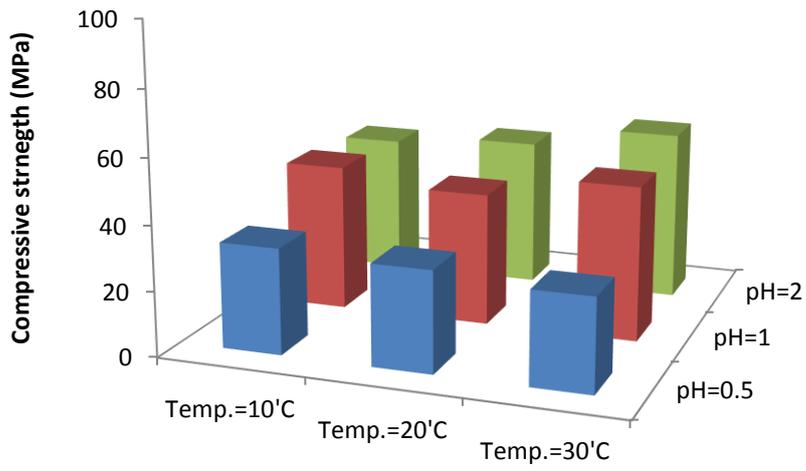


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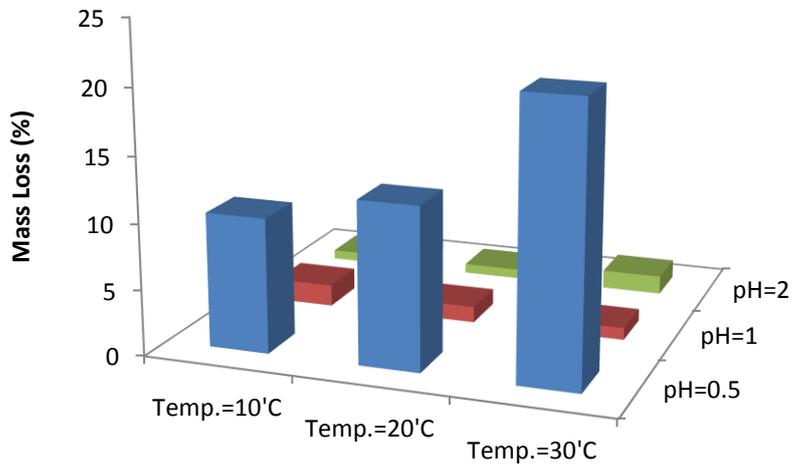
462 Figure 8. Compressive strength of the specimens in three different sulphuric acid solutions
 463 and three temperature regimes.

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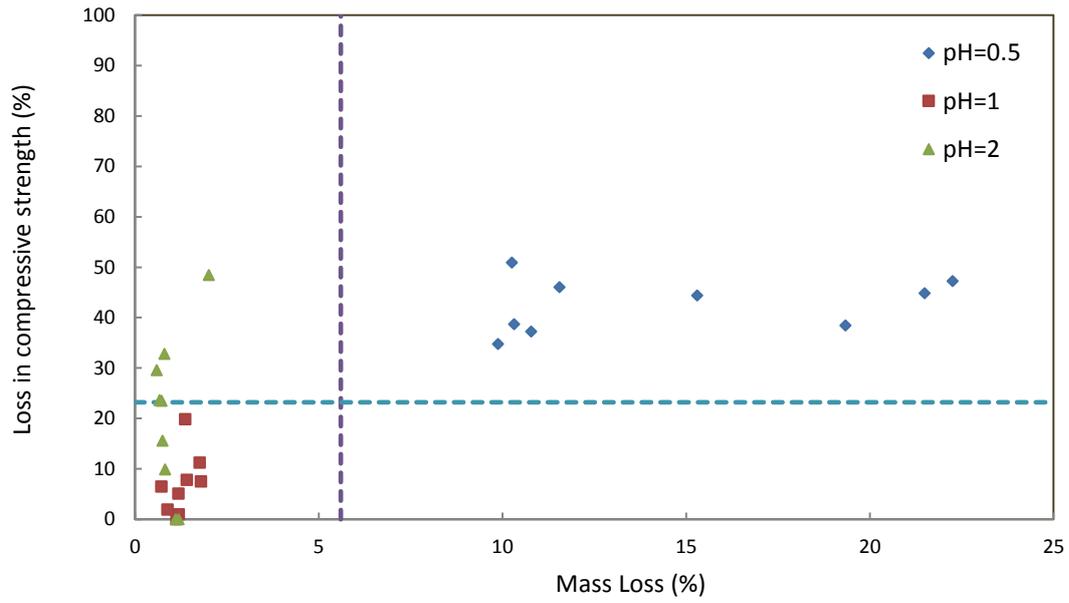


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Figure 9. Variation in compressive strength and mass loss after 91 days immersion



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 471 Figure 10. Relationship between mass loss of concrete specimens and loss in their
 472 compressive strength due to 91 days of immersion in sulphuric acid solutions