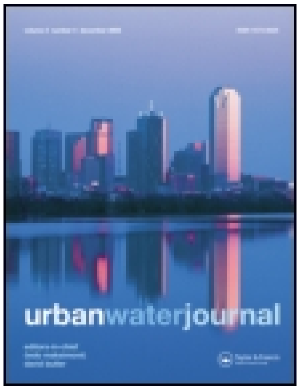

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External corrosion to concrete sewers: a case study

M. Oualit [a] , R. Jauberthie [b] , F. Rendell [c] , Y. Melinge [b] & M.T. Abadlia [a]

[a] Unit of Research Materials, Processes and Environment (URMPE), Frantz Fanon city, 35000, Boumerdès, Algeria

[b] Laboratory of Civil and Mechanical Engineering (LGCGM) - INSA of Rennes, France

[c] Consultant Engineer, 35190 St Thual, France

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CASE STUDY

External corrosion to concrete sewers: a case study

M. Oualit[a], R. Jauberthie[b], F. Rendell[c]*, Y. Melinge[b] and M.T. Abadlia[a]

[a]*Unit of Research Materials, Processes and Environment (URMPE), Frantz Fanon city, 35000 Boumerdès, Algeria;* [b]*Laboratory of Civil and Mechanical Engineering (LGCGM) – INSA of Rennes, France;* [c]*Consultant Engineer, 35190 St Thual, France*

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The aim of this study was to investigate the deterioration of concrete sewers and identify responsible factors; this investigation was a part of an ongoing asset evaluation for Rennes (France). The sewer studied was a 300 mm spun concrete pipe laid in 1992. Core samples (D 28 mm, L 40 mm) were taken from different areas of a pipe (invert, crown and side wall) and analysed to quantify the condition of the concrete and the extent of damage to the internal and external surface of the pipe. Physical and mechanical properties of the material were characterised. The depassivation of the concrete was measured by testing with a phenolphthalein solution. The study showed that in this particular case the external corrosion was extensive with minimal internal corrosion.

It is proposed that the corrosion was possibly linked to the use of a contaminated backfill or organic acids in the ground water. Recommendations are proposed concerning the direction of future research.

Keywords: durability; diagnostic study; anisotropic deterioration; sewerage system; bio-chemical attack; mechanical properties; concrete materials

1. Introduction

The condition of urban infrastructure has become an important issue in the world due to the costs of maintenance and repair. The durability of sewerage systems is a key issue for infrastructure management; the failure of the network can lead to health problems and can cause serious damage and disruption. It is essential that diagnostic studies should be taken to identify risk of failure and consequently form the basis of rehabilitation/replacement planning.

Concrete is a construction material that is widely used in sewerage systems; the environment, under certain conditions, can be extremely aggressive. Serious damage of concrete in such conditions has been reported in many countries including: Japan (Mori *et al*. 1992), in the Middle East (Saricimen *et al*. 1987, Saricimen and Maslehuddin 1987), in Germany (Sand and Bock 1984), and in South Africa (Barnard 1967). The costs involved in the repair and maintenance of these structures is very high. In the USA sulphuric acid attack in sewers and treatment plants is responsible for $1000 million expenditure (McGovern 1999). In Southern Australia the provisional budget for maintaining the existing infrastructure is $48 million per year (Stewart 1999). In Los Angeles, about 10% of the sewerage system is subject to extensive corrosion and the cost of rehabilitation is estimated to be 400 million Euros. The restoration of the deteriorated sewerage systems in Germany is estimated to be $70 million per year (Kaempfer and Berndt 1998).

The integrity of a concrete sewer is threatened internally and externally; internally by the wastewater and externally by contact with soil and groundwater. The internal face of a concrete sewer may be attacked by a biochemical reaction which leads to the formation of sulphuric acid (H_2SO_4), typically with a pH of the order of 2*;* this type of attack has been observed and studied since the 1950's. (Parker 1947) (Parker 1951, Forrester 1959, Fjerdingstad 1979, Bos and Kumen 1983, Kampen 1995). The nature of this reaction results from the aerobic oxidation of hydrogen sulphide gas by the bacteria Acidithiobacillus thiooxidans. The deterioration to the concrete normally occurs in the upper sector of the pipe in the aerated part of the pipe. The damage is often most marked in the 10 o'clock and 2 o'clock areas of the cross section. The kinetics of this reaction is accelerated by elevated temperatures and high gaseous H_2S levels in the sewer; in extreme cases the attack can lead to failure within two or three years. Much work has been carried out to

*Corresponding author. Email: Frank.rendell@wanadoo.fr

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understand the mechanisms involved in the corrosion process, and to estimate the rate of corrosion (Thistlethwaite 1972, Pomeroy and Parkhurst 1977, Cochet and Derangere 1990, Vollertsen *et al.* 2008, Vollertsen *et al.* 2011). A recent state of the art review of biochemical attack was made by O'Connell *et al.* (2010).

The external face of a pipe is equally open to attack; in this case study this is the principal type of deterioration. Subsoil corrosion of concrete can be attributed to the nature of the soil and/or the nature of the groundwater. When concrete is permanently submerged by groundwater the attack is usually of a chemical nature; in the case of partial immersion and cyclic variation in groundwater level the corrosion process may be accelerated. This acceleration is due to phenomena such as: crystallite formation on drying or 'salt damage' due to capillary rise. There are three possible vectors that potentially cause deterioration: sulphate attack, acid attack and microbial action. (Aziz and Koe 1990).

Sulphate attack on concrete is well documented. The most common form of sulphate attack results from the reaction between the C_3A hydrate and calcium sulphate; this results in the formation of expansive ettringite crystals (Building Research Establishment 1991). Under certain conditions, anaerobic and low temperatures, it is possible for the formation of another expansive crystal, thaumasite. (Crammond and Halliwell 1997). Sulphate content in subsoil is especially high in clayey soils; gypsum, pyrite and limonite formed from pyrite are frequently found in certain clays and alluvial soils. In general water soluble sulphate contents in the soil in excess of 0.5% lead to severe attack. Research at INSA Rennes has already identified sulphate related problems in the Rennes Basin (Jigorel 1989, Jigorel and Esteoule 1990, Jigorel and Jauberthie 2002).

Acid subsoil conditions may lead to acid attack on the portlandite in the concrete. Free acids occur in nature often in the areas of marshes or peat deposits. In areas of with dense vegetal cover the pH of the ground water may be as low as 3.5 due to the presence of humic acids and carbonic acids. (Biczok 1972, Fib 2009).

Microbial attack can also occur in subsoil conditions, with the presence of organic matter, the existence of fungi and various genus of bacteria, notably thiobacillus sulphate reducing bacteria. Bacteria can also break down proteins and carbohydrates in the soil to produce methane and hydrogen sulphide, which in turn can be oxidised anaerobically to sulphuric acid.

Deterioration of the integrity of the concrete inevitably leads to a loss in structural strength and increased risk of sewer collapse, which consequently leads to loss of hydraulic capacity, flooding, and rupture to other infrastructure services – road traffic, failure of water and gas pipes.

This study discusses the state and possible causes of deterioration of a section of the sewerage system in the City of Rennes (North West France). The project at Rennes aims to formulate a methodology for detection and surveillance of deterioration of the sewerage network; the results of the study are destined to be used by the Municipality of Rennes to assist in identification of problem areas and to aid with sewer rehabilitation/replacement planning.

2. Case study and sampling

2.1. *General description of the sewer*

The section of sewerage studied, rue Bahon Rault, Rennes, is a separate sewerage system constructed in 1992. The pipe is spun concrete of circular section with an internal diameter of 300 mm. The pipe bedding normally used in these areas was a crushed rock fill; the normal bedding being fill to below the springing of the pipe, Class B bedding. The sewer drains effluent from an urban area with some industrial activities. There has been annual cleaning of this section of the sewer by high pressure jetting. Rue de Bahon Rault is situated in a light industrial area close to undeveloped areas with vegetal cover. Approximately 300 m to the east of the site is a canal; the ground level at the site is approximately the same as the canal. The pipe was recovered during a road realignment project.

The nature of the subsoil in the area is as follows: Topsoil with clay, schist and flint; overlying heavily fissured decomposed Brioverien Schist.

The concrete used for the construction of the pipe is compact with a low porosity; the surface is relatively smooth, the wall thickness is estimated to be 40 mm and 12 mm internal cover to the longitudinal and transversal reinforcement.

The external surface of the pipe, from sidewall to the crown, exhibits a physical deterioration (loss of material and evidence of a significant dislodgement of aggregate); the corrosion has significantly reduced the pipe thickness over this area, see Figures 1a and 1b. The maximum observed wall thickness of 40 mm occurs at the invert of the pipe which appears not to be corroded.

2.2. *Preparation of core samples*

A section of the pipe was cored in three zones of the circumference with an aim to quantify the quality and condition of the concrete. The sampling zones and directions were chosen to identify any anisotropy due to the corrosion of the concrete. The sampling also

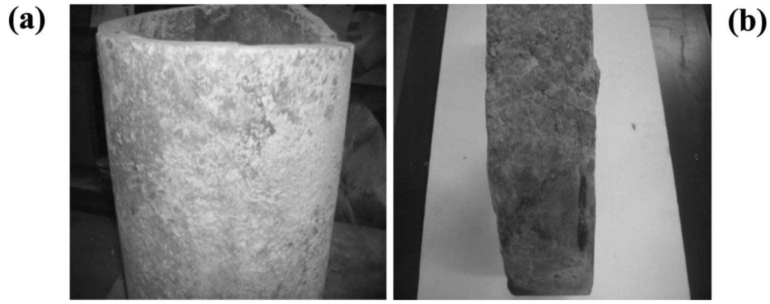

Figure 1. General view of the exterior of the pipe (Rue Bahon Rault).

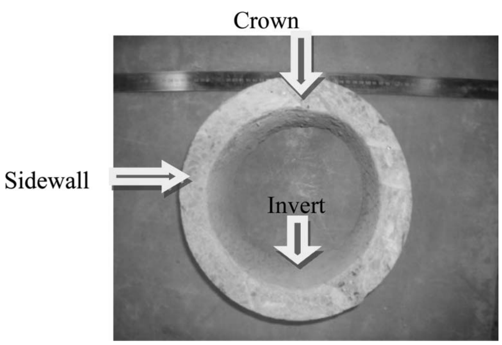

Figure 2. The three areas from which the samples are taken (crown, sidewall and invert).

enabled a study of the decomposition due to corrosion and to determine the depth of depassivation, (the depth to which the natural pH of the concrete has been reduced).

Coring of the samples was carried out in three directions, longitudinal (L) transversal (T) and radial (R) in three areas: invert, sidewall and crown, see Figure 2.

3. Test procedures and results

3.1. Determination of the depth of depassivation

The test for reduction in pH of concrete (phenolphthalein test) consists of spraying a freshly fractured surface of concrete with phenolphthalein solution, which turns pink when the pH is above 12, which is close to the pH of new concrete. One can consider the sections of coloured concrete to be sound, whereas those with no colour are considered to be depassivated. This test is only significant if the concrete has not been submitted to chemical attack that may perturb the reaction (a long exposure to air, for example, which will produce carbonation). In this study phenolphthalein solution was applied to the totality of the periphery of the pipe and over the full thickness.

Examination of surfaces tested revealed a significant difference in loss of pH between the internal and external surfaces, also between the invert and crown of the pipe. The damage to the interior of the pipe is relatively constant around the periphery of the pipe; the invert being slightly less affected than the rest of the pipe. The external surface, in contact with the soil, shows significant reductions in pH notably from the sides to the crown of the pipe; these areas have an estimated loss in thickness of 9 mm at the sides and 8 mm at the crown where there is a large loss of material. There is virtually no damage to the external bottom surface of the pipe.

Table 1 sets out the characteristics of sections of the corroded pipe; the loss in wall thickness, the depth of pH reduction are reported for the invert, sidewalls and crown of the pipe. It is assumed that the original thickness of the pipe is that measured at the invert which shows the least sign of deterioration.

The results set out in Table 1 show that there is a significant loss of material on the upper external face of the pipe, the maximum occurring at the crown. The internal face exhibits a small depth of depassivation, maximum at the soffit and virtually zero at the sides and invert.

Table 1. Wall thickness loss and depth of reduced pH in the damaged pipe.

	Initial thickness (mm)	Actual thickness (mm)	Internal face Depth of zone with $pH < 11$ (mm)	External face Depth of zone with $pH < 11$ (mm)	Erosion (%)	Relative thickness damaged (%)
Invert	40	40	0.5	0	0	1.25
Side	40	35.6	1	9	11	36
Crown	40	33.8	2	8	15.5	40.5

3.2. *Physical characteristics*

The cores taken have a diameter of 28 mm and an aspect ratio of 1.5, with the exception of cores taken in the radial direction (which are limited by the sidewall thickness). The cores were stored in an air conditioned chamber (T = 20 °C; RH = 50%) until the sample mass had stabilised.

Table 2 sets out the average values of the density and sample strength of the cored samples taken at the three zones (invert, sides and crown) and in the directions of coring, radial (R), longitudinal (L) and transversal (T). It can be seen that the density of the radial cores, which include the external and internal surfaces, are marginally smaller due to the deterioration at the both of the surface layers. On the other hand the transversal and longitudinal cores have a slightly higher density for all three zones. The densities of the concrete are generally high which signifies that the concrete is compact with a low porosity.

The compressive strength test was carried out using an INSTRON 4507 testing machine with a loading rate of 0.25 mm/m. The results obtained, see Table 2, are prone to a relatively high degree of error due to the low ratio of sample diameter to aggregate size and the length of samples being limited by the wall thickness. The measured strength was corrected for the aspect ratio of the samples using the standard ASTM Standard C42-90 (for an aspect ratio of 1.5 the correction coefficient is 0.96).

The reduced compressive strengths of the cores taken in the radial direction demonstrate the significant alteration that has taken place; this is in agreement with the visual observations previously discussed. These results are also in agreement with the phenolphthalein tests. One can distinguish a slight anisotropy in strength between the L and T cores but it is felt not to be statistically significant; taking into account the high values of compressive strength, it is suggested that the heart of the pipe sample has not undergone any significant deterioration. The strengths are high and attain values comparable with a high performance concrete which are compatible with the measured values of density.

The cores tested were cured and conditions as described above. The indirect tensile strength test, or Brazilian test, consists in applying a compressive force on two opposite generatrix of a cylinder. The stress induced produces a failure along a diametrical plane of the sample. Table 2 sets out the values for each zone and direction of sampling.

From the tensile strength test results one can see that the values taken from the cores in the longitudinal and transversal direction are of the same order and are equally of the same order for the three sampling areas. This would confirm that the heart of the material has not undergone any alteration.

The tensile strength of the radial core taken at the invert is also high; the phenolphthalein test indicated that there was no damage at the bottom of the pipe. Conversely the radial samples taken from the sides and crown do show a reduction in tensile strength, less marked than that seen in the case of compressive strength. This reduction is possibly due to the material deterioration at the ends of the sample; this said it should be noted that the failure plane in this test passes principally through concrete which has not been corroded.

3.3. *Investigation into the zone of reduced pH*

After samples had been split in the Brazilian tensile test, phenolphthalein solution was sprayed on the freshly fractured surface; this was carried out to further examine the extent of anisotropic damage to the material taken from the three zones (invert, side and crown). The results are shown in Figure 3.

One can see from Figure 3 that the damage to the concrete, externally and internally, is minimal at the invert of the pipe, whereas at the sides and crown of the pipe the damage is appreciable with an 8 mm to 9 mm section reduction on the outer surface. This further confirms results previously discussed.

Table 2. Average density and strength of cores (MPa). 394, 162-170 St Thual, France.

Zone	Direction	Density (kg/m^3)	Compressive Strength (MPa)	Tensile Strength *Brazilian Test* (MPa)
Invert	Core R	2398	58.21	13.23
	Core L	2444	114.18	11.32
	Core T	2435	115.16	11.61
Side	Core R	2312	52.53	10.53
	Core L	2512	108.99	11.01
	Core T	2435	109.77	10.53
Crown	Core R	2136	20.60	8.22
	Core L	2403	88.21	11.13
	Core T	2395	101.40	10.52

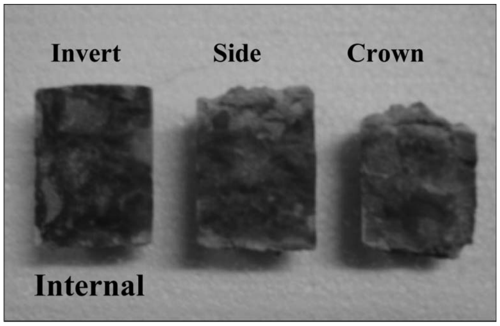

Figure 3. The variation in zone of reduced pH in the radial cores.

3.4. *Examination of micro-structure*

The micro-structure of samples taken from the internal and external surfaces of the pipe were examined and analysed using scanning electon microrosopy (SEM). The system used enabled visual images of the structure coupled with Energy-dispersive X-ray spectroscopy (EDX), a tool that enables atomic composition to be analysed at a point or over an area. These techniques are particularly powerful for the identification of chemical species within the mortar matrix. The EDX analysis showed no significant alterations to the internal surface of the pipe whereas analysis of the external surfaces revealed dense formations of carbonate crystallites.

4. Discussion

From the observation and test results it is evident that there is a high rate of corrosion to the external surface of the pipe; the internal surface being virtually uncorroded. It is also noted that there is anisotropy in the degree of corrosion; the bottom of the pipe being virtually uncorroded and the upper section being heavily corroded. Three possible hypotheses can be suggested to explain the anisotropy in the external corrosion:

(1) Contaminated backfill. With small diameter pipes, such as the one discussed here, it is normal to bed the pipe on clayey sand and then to cover the pipe in an imported well graded fill prior to backfilling with excavated material. In the region of Rennes crushed rock used for initial pipe backfill often contain traces of pyrite — crushed schist or hornfels. This would account for the corrosion being most prevalent above the level of the sand pipe bedding.
(2) In the area of Rennes there have been cases of sulphate attack on concrete due to the presence of pyrite in the decomposed Brioverien schists, as previously noted in the work of Jigorel (see references). The backfill above the pipe would inevitably be more porous than the surrounding soils and the trench could act as a reservoir for leached sulphates.
(3) As previously noted the surrounding topography has areas of vegetation and a proximity to a canal. It is possible that these conditions could lead to organic acid attack.

The first two hypotheses seem unlikely as no traces of sulphate were found during EDX analysis of the samples. Initial carbonation of the external surface of the pipe before placing would be minimal; once the pipe is backfilled the only mechanism open to produce the reduction in pH would be carbonation due to organic acids; the provenance of the organic acids being the vegetation and ground water seeping from canal. The anisotropy is possibly explained by higher porosity of the backfill above the bedding material; the less porous clayey bedding sand providing a degree of protection. The situation could also be accelerated due to crystallite formation due to 'salt damage' due to capillary rise; again this would result in damage to the upper part of the pipe.

5. Conclusion

This study has been the subject of an investigation into internal and external deterioration and the anisotropic deterioration of a section of a concrete sewer taken from rue Bahon Rault, Rennes. It is to be noted that the corrosion to the external face of the pipe is high, approximately 8 mm, whereas the internal surfaces are not corroded. During the ongoing study of the conditions of the sewers in the municipality of Rennes this type of external corrosion has been seen at other locations, however in this case the corrosion rate is the largest seen.

From the results obtained the following conclusions can be drawn:

- The cores taken from the interior of the concrete wall indicate that the concrete used has good characteristics: a high density and strength comparable with that of high performance concrete. The sample strengths show no significant anisotropy with respect to the transversal and longitudinal directions. The compressive strengths and densities of samples taken radially are lower; this is most likely due to deterioration of the ends of the samples.
- The internal surface of the pipe shows very little sign of corrosion.

- The most significant damage to the pipe occurs externally on the upper sections of the pipe, the bottom external and internal surfaces of the pipe are virtually untouched by corrosion. This is confirmed by visual observation, loss of section and reduction in the zone of passivity.
- The external corrosion rate is progressing at about 0.5 mm per year proceeded by a zone of depassivation of about 10 mm; on the basis of the observed corrosion rates the reinforcement will be depassivated in approximately 20 years. However with the rapid loss of section it is possible that the pipe will structurally fail before this time.

As previously stated the type of external corrosion seen in this case has been observed in several other samples taken from various locations in the municipality. It is recommended that the study of sewer condition is widened to include sampling of groundwater, soil and fill materials for each of the sewer sections studied. A supplementary study to map the age and location of pipes and soil condition would help to verify if an aggressive imported fill had been used on certain sections of the network; if this is the case this information would be of value in estimating service life and planning sewer replacement.

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