RESEARCH ON THE CORROSION PERFORMANCE OF VARIOUS NON-METALLIC PIPING MATERIALS AND COATINGS IN POTABLE WATER

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EXECUTIVE SUMMARY

The objectives of this study were to critically evaluate the effect of mineralisation on the service performance of various non-metallic pipe materials and linings in the PWV/Klerksdorp areas, to determine which water parameters are important when selecting coatings and non-metallic piping materials for conveying potable water, and recommend candidate coatings and non-metallic piping materials such that internal corrosion of pipes can be reduced.

Since there are many types of coatings available for use as linings on carbon steel piping, it was necessary to evaluate the performance of generic coating systems in a systematic, scientific manner. These results will allow local authorities to decide on what type of coating systems to use in their piping systems in a cost-effective manner so that costly failures are avoided.

Non-metallic coatings, metallic coatings, non-metallic piping materials, cement mortar-lined and carbon steel pipe samples were exposed to potable water in a flow loop system. These samples were examined and evaluated every year for their corrosion performance and rated accordingly. The quality of the water was also monitored with a data acquisition system and was related to the corrosion rates of carbon steel pipe samples.

The results showed that organic coatings varied in their performance and that the quality of coatings is dependent on a number of factors such as adhesion, composition and water quality. The two polyamide cured epoxy linings and the solvent-free aliphatic amine-cured epoxy (hot applied) and the elastoplastic polyurethane performed well.

The results also reinforce the fact that unprotected carbon steel pipes conveying potable water are prone to internal corrosion which is often due to microbial corrosion. An effective way to reduce the effect of this corrosion is internal lining. The performance of metallic coatings (zinc) on carbon steel pipes was found to be good as was evident by the formation of hard uniform scaling on the internal surface of the pipe samples.

The performance of non-metallic piping materials was good and they may be considered in future as a satisfactory method of corrosion protection in potable water.

The results of this study could be compiled as a data base which can be used by municipalities and other organisations who supply bulk water to address their major problems of leaks.

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RESEARCH ON THE CORROSION PERFORMANCE OF VARIOUS NON-METALLIC PIPING MATERIALS AND COATINGS IN POTABLE WATER

The Steering Committee responsible for this project, consisted of the following members:

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

Cr	-	Chromium
CSIR	-	Council for Scientific and Industrial Research
EDS	-	Energy Dispersive Spectroscopy
HDPE	-	High Density Polyethylene
ISO	-	International Standards Organisation
PWV	-	Pretoria, Witwatersrand and Vereeniging
$ZnC0_3$	-	Zinc Carbonate
LPR	-	Linear Polarisation Resistance

LIST OF TABLES

1. INTRODUCTION

Whilst there are many methods which can be used for corrosion protection of pipelines, it has been found that for most applications it is cost effective to apply a protective material to the internal pipe surface. Choosing the right coating for an application is very often a process of elimination rather than selection. Due to the large number of options available, coating selection and piping selection is often performed. This results in a plethora of different materials being used within one distribution system. It would be beneficial for municipalities to perform coating selection according to scientifically determined guidelines such that possible errors could be avoided. Equally important, is the evaluation of the exact conditions under which the coating must operate. For this reason, comparative testing of candidate materials under actual operating conditions serves as an excellent method for selection.

In the Johannesburg municipal area, Osborn[1] has reported that out of the 307 km of 50 - 1020 mm diameter mains pipeline, 135 km was cement mortar-lined, 100 km was UPVC, 75 km was HDPE, 132 km was slip-lined with HDPE and 400 km was asbestos cement pipe. The remainder (2229 km) of the mains pipelines were mild steel. It is well known that even though potable water is treated, corrosion of bare steel readily occurs.

In 1989, 1663 bursts of mains water piping were reported by the Johannesburg municipality. This resulted in the replacement of 30 km of mains piping which obviously was a large expenditure but, more importantly, large amounts of water were lost. Water lost due to mains bursts and flushing amounted to 199131 kℓ with an additional 54 565 kℓ of water wasted due to bursts in the pipes leading to mains.

A number of references are presented in section 7 which describe the types of coatings and piping materials used in South Africa and Figures 15 to 17 summarise the pertinent data.

The objectives of the project were as follows:

* To evaluate the effect of increasing mineralisation on the service performance of various non-metallic pipe materials and linings in the PWV/Klerksdorp areas.

* Determine which water parameters are important when selecting coatings and non-metallic piping materials for conveying potable water.

* Recommend candidate coatings and non-metallic piping materials such that internal corrosion of pipes can be reduced.

2. MATERIALS AND METHODS

2.1 Test site and Facilities

One test site was used in this project situated at the CSIR in Pretoria. Two flow loops were constructed from 50 mm diameter polypropylene tubing. The flow loops are approximately 22 m high and each loop is in excess of 45 m long. Potable water was pumped through the loops by two pumps situated at the base of the facility. In order to have an accurate record of the quality of the water flowing through the flow loops, the water quality was measured on-line using a sophisticated computer-controlled data acquisition system. Various probes were inserted into the flow loop to monitor the pH, pressure, temperature, conductivity, oxygen content and corrosion rate of mild steel using an on-line LPR method.

The flow loops were operated on a continuous basis between Monday morning and Friday afternoon and were left full of water over the weekend. In this way, a simulation of actual service conditions was obtained since there are periods in reticulation systems when the water will be static inside the pipes.

2.2 Materials and Alloys

Materials used and investigated in this project were as follows:

Mild steel pipe (seamless)
Mild steel pipe (welded)
Galvanised steel pipe
Galvanised steel pipe (normalised)

HDPE
Polypropylene
Polykop
HDPE lined steel pipe

8 Organic linings as described in Table 1

Mortar lining

The purpose of this investigation was to evaluate generic coating systems, and not specific brands, and therefore no reference to individual coating brands will be made.

2.3 Evaluation of Samples

As requested by the steering committee, the evaluation was performed according to the ISO specifications (4268/1 to 6, 1982).

2.3.1 Evaluation of non-metallic coated pipe specimens

The exposed surfaces of the different non-metallic coatings were visually examined and notes were made on their appearance. In the case of defects and blisters the sizes and densities were rated according to the ISO specifications 4628/1 and 2. Adhesion of the coatings to the metal substrates was evaluated using a knife point and rated according to the degree of severity i.e. good to poor. After removal of the non-metallic coatings, rust formation of the carbon steel substrates was rated according to the ISO specification 4628/3. Considering the extent of rusting of the metal substrates, the performance of the coatings were ranked from **best (1) to worst (9)**.

2.3.2 Evaluation of metallic coated specimens

Duplicate specimens of the carbon steel, seamless and welded galvanised specimens were exposed. After their removal from the flow loops the surface morphologies of the corroded pipe specimens were visually examined. The corrosion products on the specimens were then removed by chemical cleaning methods as described in the standard (ASTM G1,1985) and the corrosion rates (reported as thickness loss/time) were determined.

2.3.4 Evaluation of non-metallic piping

The degradation of the non-metallic piping was evaluated by means of tensile tests and visual examination, and surface products were analysed by EDS.

2.3.5 Evaluation of mortar-lined specimens

The surface appearance of the mortar-lined specimens was examined visually for degradation of the lining and notes were made on the appearance.

2.4 On-line water quality monitoring

Water quality variables were continuously monitored using a five channel monitoring unit. The following variables were monitored: temperature, conductivity, pH, pressure and dissolved oxygen. In addition a Corrator Model 9030 was installed at the flow loop and interfaced to the monitoring unit in order to monitor the corrosion rate of carbon steel probes with time. All data were collected by using a computer-controlled data acquisition system, at a constant rate of 12 samples/hr. For comparison purposes the water composition was also determined using standard techniques.

3. RESULTS

The final set of specimens were removed from the flow loop on 5 December 1995 after approximately 42 months exposure. Specimens have been removed on a yearly basis and their performance summarised in yearly progress reports. (Ringas et al, 1992 and 1993).

The specimens were washed with a bottle brush under flowing water. They were then cut in half lengthwise. The coatings were stripped from one half of each pipe specimen. The coating present on the specimens was examined by:

(i) comparison with the original, unexposed reference specimens,
(ii) an evaluation of the appearance in accordance with ISO 4628/1,

(iii) measurement of the thickness,

(iv) an evaluation of blistering in accordance with ISO 4628/2,

(v) an evaluation of the adhesion of the coatings by a subjective test with a knife point,

(vi) the steel under the stripped portions of the specimens was examined in accordance with ISO 4628/3 for rusting.

3.1 Evaluation - Non-Metallic Coatings

3.1.1 Appearance

The ratings from the ISO Standards used for evaluation of the specimens are shown in Tables 2, 3 and 4 and determine the intensity of deterioration, quantity and size of defects. Table 5 shows the results of the appearance of the coatings on the test specimens.

3.1.2 Thickness

The thickness of the coatings on the specimens from the flow loop was measured using an Elcometer 345 electronic gauge calibrated, as directed, on a blast cleaned surface. The results are given in Table 6.

3.1.3 Adhesion

The adhesion was determined subjectively by prying the coating off with a knife joint. The results are presented in Table 7.

3.1.4 Blistering

Blistering was evaluated in accordance with the pictoral standards presented in ISO 4628/2. The evaluation is given in Table 8.

3.1.5 Rusting

Rusting of the specimens was evaluated in accordance with ISO 4628/3 after stripping off the coatings from a section of the specimens. The rating and the results are given in Table 9(a) and 9(b) respectively.

3.1.6 Overall Performance

The characteristics evaluated (apart from thickness) were given a weighted value as follows:

Change of appearance	**X1**
Adhesion	**very good 1 good 2 poor 3 very poor 4**
Blistering	**size X2**
Rusting	**value X3**

The results are presented in Table 10.

3.1.7 Grading of Coatings

On the basis of the weighted evaluation (which is not an accepted standard method), the grading of the coatings from **best** to **worst** is obtained.

3	Hot applied solvent free aliphatic amine cured epoxy (best)
2	Polyamide cured epoxy
9	Elastoplastic polyurethane
1	Polyamide cured epoxy
5	Hot applied-solvent free-amine cured epoxy
4	High solids-polyamine cured epoxy
6	Cold applied-solvent free-amine cured modified epoxy
8	High solids-polyamine cured epoxy (worst)

3.2 Non-Metallic Piping, HDPE Lining and Mortar Lining

The non-metallic pipe specimens were visually examined for deformation and cracks. Quantitative tensile tests were performed on these specimens up to 18 months only, and the results were compared to results obtained prior to installation. The results of the tensile tests did not indicate significant degradation in the yield strengths of the different pipe specimens after 18 months (Table 11). Brownish surface deposits were evident inside the pipe specimens. The surface products seemed to originate from other carbon steel pipes in the system, and did not seem to have affected the integrity of the non-metallic pipe specimens (Figures 9(a) and 9(b)).

The internal surface appearance of a HDPE-lined carbon steel was examined and brown corrosion product was evident (Figure 10(a)). After the removal of the lining, the surface of the carbon steel substrate was found to be in a good condition. No rust formation or obvious defects except the red corrosion product at the end of the pipe specimen caused by the crevice could be observed (Figure 10(b)).

The mortar-lined pipe specimen showed no obvious defects or deterioration except brown corrosion product. The surface was slightly uneven in places (Figures 11(a) and 11(b)).

3.3 Metallic Coated Specimens

Visual examination of the galvanised steel pipe (welded) showed no tuberculation but the formation of a uniform scale which probably consisted of zinc carbonates. Superficial red rust staining, which did not affect the protective zinc layer, was observed after 42 months testing. The substrate was protected due to the galvanic protection offered by the zinc except at the end of the specimen (threaded region). Figures 12(a) and 12(b) show the surface of the galvanised sample before and after cleaning respectively.

3.4 Metallic Specimens

The welded and seamless carbon steel specimens showed extensive brown mounds of corrosion product (tubercles), due to sulphate reducing bacteria. Removal of the corrosion product indicated pitting corrosion of the metal substrate and weld corrosion attack on normalised carbon steel pipe. The appearance of the uncoated welded carbon steel pipe was similar to that of the seamless carbon steel pipe. Figures 13(a) and 13(b) show the internal surface of uncoated pipe specimens before and after cleaning respectively.

3.5 On-Line Water Quality Monitoring

The following water quality parameters were monitored: pH, temperature, dissolved oxygen, pressure, conductivity and corrosion rate. Typical signal traces versus time for the different probes are shown in Figure 14. The averaged results are shown in Table 12. For comparison, the water analysis results from the flowloop are presented in Table 13.

As in previous reported results, the pressure remained constant at 200 ± 4 kPa. The pH was found to vary between a narrow range of 6,37 to 6,81. Interesting features are the regular peaks and troughs. Close inspection of temperature showed that it closely follow the diurnal and seasonal changes. Thus in the summer month a minimum temperature of

16,82°C at night was measured compared to 22,82°C at midday. Throughout the test period the conductivity remained constant at 36 mS/m, as compared to the initial stages of the test where conductivity varied over a wider band i.e. ranging between 10 and 28 mS/m. The dissolved oxygen and corrosion rate (recorded by the Corrator) followed a similar trend, and increases in corrosion rate were related to increases in the dissolved oxygen. The corrosion rate recorded by the Corrator averaged 0,325 mm/yr and the corrosion rate recorded by mass loss calculations was 0,308 mm/yr which is a close correlation.

The dissolved oxygen content and the pH followed a similar trend, with increases in pH corresponding to increases in dissolved oxygen. The periodic variability in the water quality and corrosion parameters would not have been detected had on-line monitoring not been carried out. On-line monitoring determines the rate of general and localised corrosion and indicates changes in corrosivity with time.

4. DISCUSSION

After 42 months of testing the performances of non-metallic coatings were somewhat varied and it was possible to rank their corrosion resistance performance. Some of the epoxies performed well, whereas others did not. Four of the coating systems, No.'s 3, 2, 9 and 1 performed excellently, while two coating systems (No.'s 4 and 5) performed adequately and coating No.'s 6 and 8 did not perform well. Of the four coatings that performed well, two of them are polyamide-cured epoxy resin based materials. The results therefore tend to strongly suggest that the performance of a coating type depends to a certain extent on the formulation of the coating (solvent content, pigment content etc.). The adhesion of the different coating types could not be correlated to the formation of rust underneath the coating. For example, some samples exhibited extensive rusting although their adhesion properties were found to be very good. The thickness of coating No. 9 is far higher than that of the other coatings and this may make the particular system non-competitive on a cost basis. It is also important to note that coatings were applied according to manufacturers recommendations and were usually more than one coat thick.

The measured average corrosion rate for the galvanised steel pipe samples was determined as 90 μm/yr after 12 months as compared to 4 μm/yr after 18 months of testing. The specimens after 42 months of testing did not show any obvious signs of corrosion only slight white staining which was probably $CaC0_3$ or $ZnC0_3$. These may be the cause of this significant decrease in the corrosion rate due to the formation of a protective film providing protection to the metal substrate.

The uncoated carbon steel showed obvious signs of corrosion in the form of tuberculation of the surface and pitting of the substrate. This aspect once again stresses the fact that all steel pipelines used to convey potable water should be internally lined. Lining will not only mitigate internal corrosion but also maintain the water quality. In the case of corrosion rate, there was a decrease from 220 μm/yr after 12 months of testing to 90 μm/yr after 18 months of testing. The decrease in the corrosion rate may be due to the formation of protective corrosion products which form a diffusion barrier to the transport of oxygen to the carbon steel, and the corrosion rate was determined by mass loss which is a best case scenario. The corrosion rate of carbon steel pipe after 42 months testing was down to about 30 μm/yr. The 90 μm/yr corrosion rate after 18 months is in fair agreement with previous recorded corrosion rates (70 μm/yr). The average pit depths measurements were 0,42 mm.

The performance of all the non-metallic piping was satisfactory and no obvious deterioration of these materials could be detected. The presence of surface deposits had no effect on the integrity of the non-metallic piping materials.

The mortar lined pipe samples performed very well after 42 months of testing. The presence of corrosion product seemed to have originated from the other pipe materials in the system.

The results of the water quality monitoring in terms of dissolved oxygen content, pH and temperature showed correlation and inverse relationships. The pH of the water was decreasing with an increase in temperature and a decrease in oxygen content. This periodic variability was also related to the corrosion rate of the mild steel pipe specimens. In addition, the statistical analyses of the water quality monitoring results suggest that the composition of the potable water did not change significantly with time. The benefits of on-line monitoring were apparent since changes in composition could be detected readily, whereas, if monthly monitoring was undertaken this would not have been possible.

5. CONCLUSIONS

5.1 The coating systems, No.'s 2, 3, 9 and 1 performed well after 42 months of testing and therefore polyamide-cured epoxy, solvent-free aliphatic amine-cured epoxy (hot applied) and elastoplastic polyurethane are suitable linings for piping conveying potable water.

5.2 The thickness of coating No. 9 was far higher than that of the other coatings and this may make this option non-competitive on a **cost** basis.

5.3 Organic coating No. 6 did not perform well.

5.4 Some epoxy coatings showed severe blistering. Blistering may be due to solvent entrapment or the use of incorrect solvents for pipe applications.

5.5 Organic linings (HDPE) are beneficial in reducing the corrosion rate of carbon steel in potable water.

5.6 The non-metallic piping materials have shown good performance after 42 months of testing.

5.7 A significant decrease in corrosion rates was observed for both carbon steel and galvanised specimens after 42 months of testing. The recorded corrosion rates for both materials were in close agreement with previous reported values for potable water in Pretoria area.

5.8 On-line water quality monitoring is more beneficial than monthly monitoring in assessing continuous corrosion under the test conditions.

5.9 There was a close correlation between the corrosion rate (measured by the Corrator), the dissolved oxygen content and the pH.

5.10 Although the corrosion rate of the unlined carbon steel specimens averaged 30 μm/yr, pits of 0,42 mm were present. This clearly illustrates the danger in basing corrosion rates on mass loss values, when localised corrosion such as pitting is the dominant corrosion process.

5.11 Unlined carbon steel piping should not be used to convey potable water.

6. RECOMMENDATIONS

6.1 Unlined carbon steel should not be used to convey potable water.

6.2 Non-metallic piping such as HDPE, polypropylene and polycarbonate is suitable to convey potable water. Corrosion product originating from corrosion of steel piping does adhere to the non-metallic pipe surface.

6.3 HDPE-lined steel piping performed well under the test conditions.

6.4 The performance of the epoxy coatings was variable. The performance of the polyamide-cured epoxy coatings was good as was the hot applied, solvent free aliphatic amine-cured epoxy.

6.5 The corrosion rate was affected by changes in oxygen content and pH. Since oxygen will always be present in potable waters to a greater or lesser degree corrosion of unlined carbon steel piping will occur, and hence linings should be used.

6.6 These results should be incorporated into the booklet being compiled for municipalities which is based on the results of project K5/587 i.e. Evaluation of Water Pipe leaks in the Johannesburg Municipality Area.

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Table 1: Coatings Examined

Specimen No.	Generic Description
1	Polyamine cured epoxy
2	Solvent free aliphatic amine cured epoxy-hot applied
3	Polyamide cured epoxy
4	Solvent free amine cured epoxy - hot applied
5	High solids polyamine cured epoxy
6	High solids polyamine cured epoxy
8	Solvent free-amine cured modified epoxy-cold applied
9	Elastoplastic polyurethane

Table 2: Uniform deterioration - Rating scheme for designating the intensity of deterioration consisting of a uniform change in the visual appearance of the paint coating (ISO 4628/1).

Rating	Intensity of Change
0	unchanged, i.e. no perceptible change
1	very slight, i.e. just perceptible change
2	slight, i.e. clearly perceptible change
3	moderate, i.e. very clearly perceptible change
4	considerable, i.e. pronounced change
5	severe, i.e. intense change

Table 3: Scattered defects - Rating scheme for designating the quantity of defects consisting of discontinuities or other local imperfections of the paint coating (ISO 4628/2).

Rating	Quantity of Defects (relative to a test surface area of 1 to 2 dm^2)
0	none, i.e. no detectable defects
1	very few, i.e. some just significant defects
2	few, i.e. small but significant amount of defects
3	moderate, i.e. medium amount of defects
4	considerable, i.e. serious amount of defects
5	dense, i.e. dense pattern of defects

Table 4: Rating scheme for designating the size (order of magnitude) of defects (ISO 4628/2).

Class	Size of Defect
0	not visible under X10 magnification
1	only visible under magnification up to X10
2	just visible with normal corrected vision
3	clearly visible with normal corrected vision (up to 0,5 mm)
4	range 0,5 to 5 mm
5	larger than 5 mm

Table 5: Results - Appearance of Specimens after 42 months exposure.

Specimen No.	Appearance of the original unexposed specimen	Quantity of defects ISO 4628		Size of defects ISO 4628		Intensity of Change and Type
		Original	**Exposed**	**Original**	**Exposed**	
1	Gloss-thickness variations	1	1	2	2	1 Small blisters increased in size
2	High gloss, pinholes	3	3	3	3	0
3	Low gloss, coarse orange peel, few small sinks	2	2	2	2	0
4	Low, gloss wrinkling, bits, roughness	2	5	2	4	4 Blistering
5	Low gloss, even surface	0	3	0	5	4 Blistering
6	Low gloss, pinholes	1	4	2	4	4 Blistering
8	Low gloss, few pinholes, lumps	1	4	3	5	4 Blistering
9	High gloss even smooth surface	0	2	0	2	2 Orange Peeling

Table 6: Results - Original thickness of Coatings.

Specimen No.	Thickness μm			Std deviation
	Minimum	Mean of 10 readings	Maximum	
1	324	377	438	42
2	206	304	433	79
3	76	108	186	32
4	421	450	481	23
5	277	293	327	15
6	379	445	505	36
8	512	577	717	66
9*		1200 to 1500		

* **Note:** The thickness of this coating exceeds the limit of the electronic thickness gauge used for the measurements. The thickness was measured visually by a scale at 10X magnification.

Table 7: Results - Adhesion of Coatings after 42 months exposure.

Specimen No.	Adhesion
1	Good
2	Poor dense pattern of black rust spots
3	Very good
4	Intercoat adhesion poor, undercoat to substrate good
5	Good, away from blisters
6	Black liquid in blisters poor Black corrosion under coating Darker black spots under blisters
8	Very poor, red rust under coating
9	Poor, black rust pattern under coating

Table 8: Blistering of Coatings after 42 months exposure.

Specimen No.	Blistering	
	Size	Density
1	Larger than original	Dense in patches but very fine
2	0	-
3	0	-
4	4 - 5	5
5	5	2
6	4 - 5	3
8	5	4
9	0	0

Table 9(a): Degree of rusting and area rusted.

Degree	Area Rusted %
Ri0	0
Ri1	0,05
Ri2	0,5
Ri3	1
Ri4	8
Ri5	40/50

Table 9(b): Results - Degree of rusting on specimens

Specimen No.	Degree of Rusting
1	Ri5
2	Ri1
3	Ri1
4	Ri5
5	Ri4
6	Ri5
8	Ri5
9	Ri5

Table 10: Overall performance on weighted basis

Specimen No.	Weighted Value				
	Appearance X1	**Adhesion vg1 g2 p3 vp4**	**Blistering X2**	**Rusting X3**	**Total**
1	1	2	2	15	20
2	0	3	0	3	6
3	0	1	0	3	4
4	4	2	10	18	31
5	4	2	10	12	28
6	4	3	10	15	32
8	4	4	10	15	33
9	2	3	0	15	20

Note: Vg - Very good
g - good
p - poor
Vp - Very poor

Table 11: Results of tensile tests.

Plastic Type	Initial Yield Point (kN)	Yield Point (kN) After 18 Months
PVC	19,3	19
HDPE	14,1	14,1
Polypropylene	20,2	20,5

Table 12: Summary of statistical analyses of water quality monitoring over 42 months.

Channel	Mean	Std Deviation	Minimum	Maximum
pH	6,51	0,15	6,40	6,71
Temp (°C)	19,82	0,96	16,82	22,82
Pressure (kPa)	205,24	4,31	193,68	221,15
0_2 (ppm)	2,75	0,20	1,47	4,03
cond (mS/m)	20,48	1,27	17,34	27,59
corr. (μm yr^{-1})	325	0	325	

Table 13: Results of water analysis at flowloop

pH		7,8
Electrical Conductivity	[25°C]	34,4 mS/m
Total Hardness	[$CaC0_3$]	90 mg/ℓ
Calcium	[Ca]	27, mg/ℓ
Magnesium	[Mg]	5 mg/ℓ
Sulphate	[$S0_4$]	32 mg/ℓ
Chloride	[Cℓ]	15 mg/ℓ
Total Alkalinity	[$CaC0_3$]	88 mg/ℓ
Total Dissolved Solids	[105°C]	187 mg/ℓ
Iron	[Fe]	0,16 mg/ℓ
Langelier-Index	[25°C]	-0,2
Corrosivity	[25°C]	0,6

Figure 1(a): Internal appearance of pipe specimen with non-metallic coating No. 1 before cleaning (X0,54).

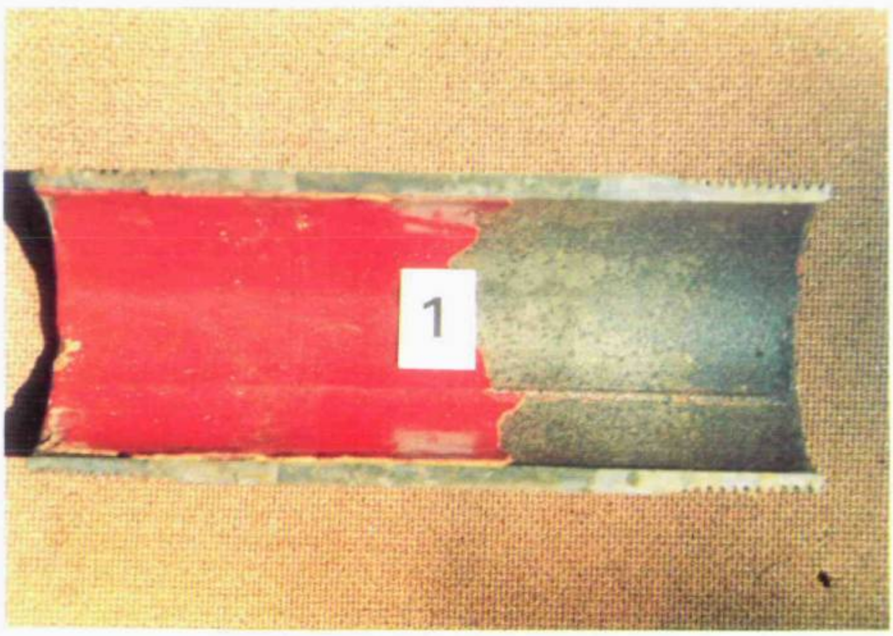

Figure 1(b): Surface appearance of non-metallic coating No. 1 and carbon steel substrate after 42 months testing (X0,64)

Figure 2(a): Internal appearance of pipe specimen with non-metallic coating No. 2 before cleaning (X0,54).

Figure 2(b): Surface appearance of non-metallic coating No.2 and carbon steel substrate after 42 months testing (X0,64).

Figure 3(a): Internal appearance of pipe specimen with non-metallic coating No.3 before cleaning (X0,54).

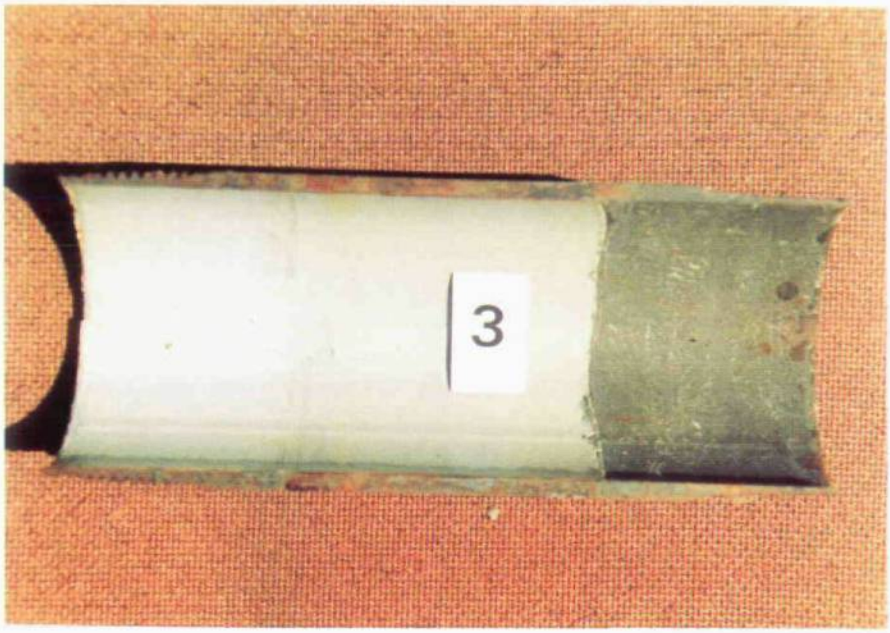

Figure 3(b): Surface appearance of non-metallic coating No.3 and carbon steel substrate after 42 months testing (X0,64).

Figure 4(a): Internal appearance of pipe specimen with non-metallic coating No.4 before cleaning (X0,54).

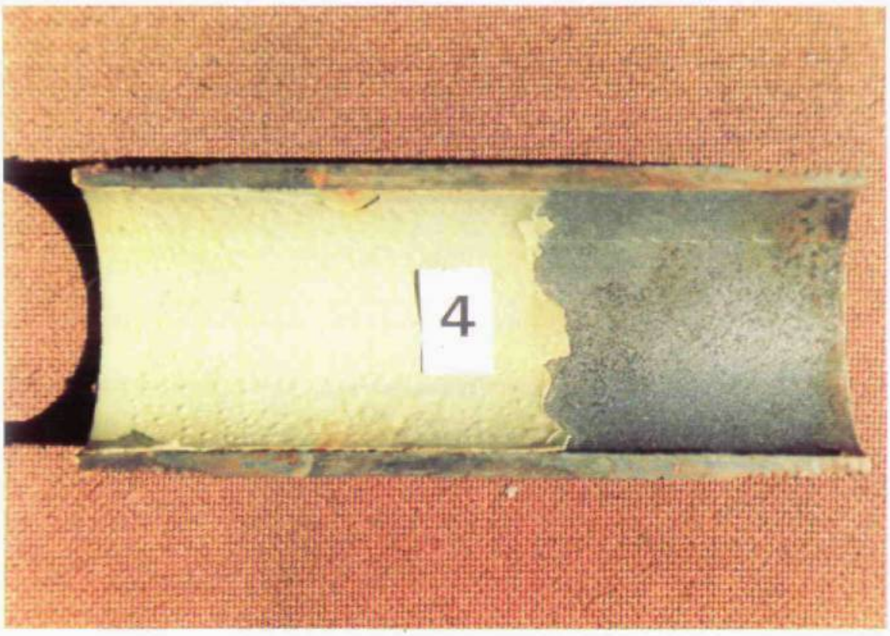

Figure 4(b): Surface appearance of non-metallic coating No.4 and carbon steel substrate after 42 months testing (X0,64).

Figure 5(a): Internal appearance of pipe specimen with non-metallic coating No.5 before cleaning.

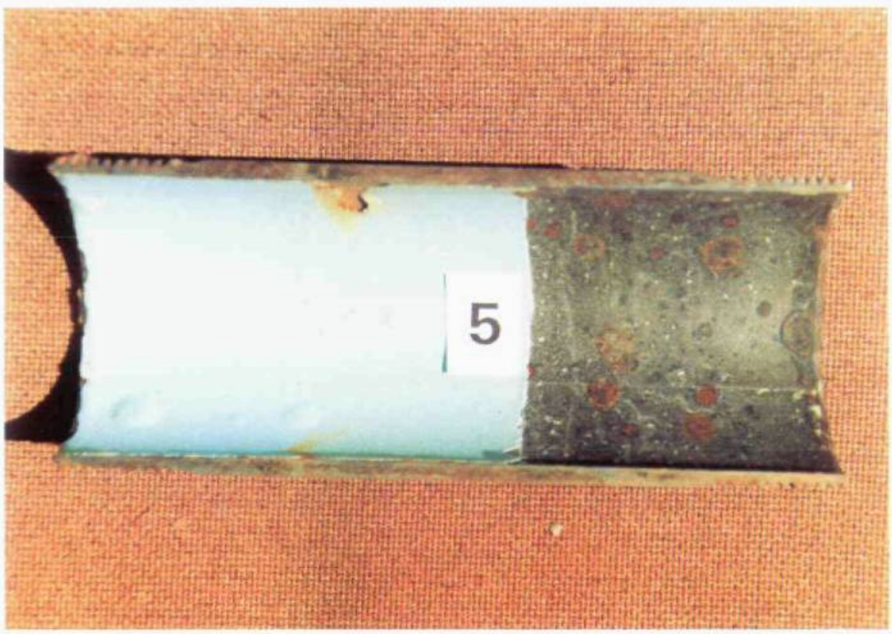

Figure 5(b): Surface appearance of non-metallic coating No.5 and carbon steel substrate after 42 months testing (X0,64).

Figure 6(a): Internal appearance of pipe specimen with non-metallic coating No.6 before cleaning. (X0,54)

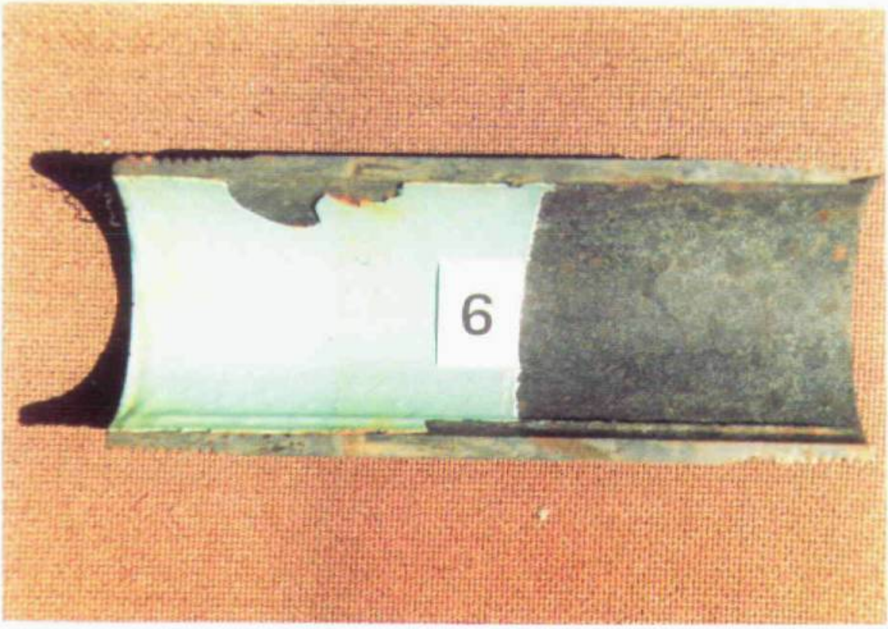

Figure 6(b): Surface appearance of non-metallic coating No.6 and carbon steel substrate after 42 months testing (X0,64).

Figure 7(a): Internal appearance of pipe specimen with non-metallic coating No.8 before cleaning (X0,54).

Figure 7(b): Surface appearance of non-metallic coating No.8 and carbon steel substrate after 42 months testing (X0,64).

Figure 8(a): Internal appearance of pipe specimen with non-metallic coating No.9 before cleaning (X0,54).

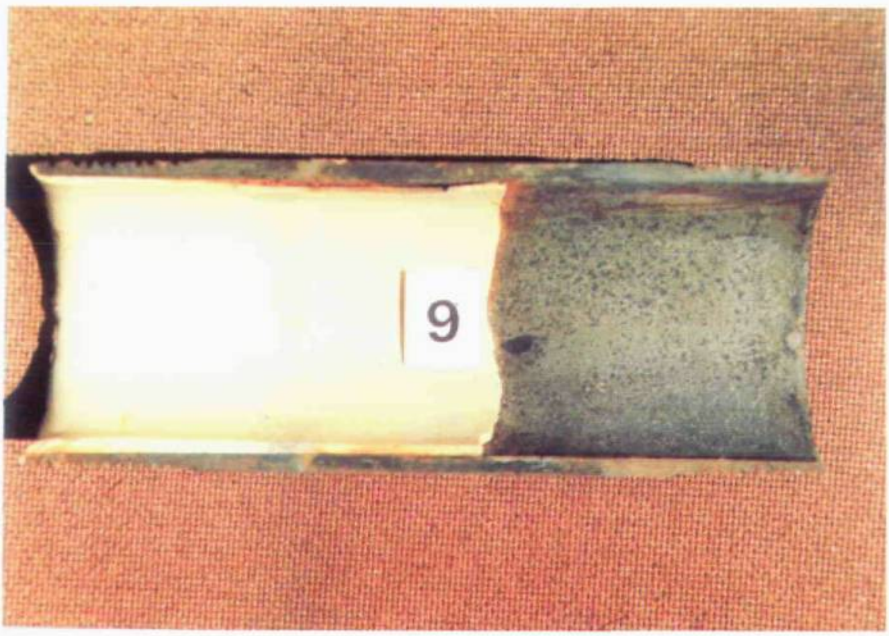

Figure 8(b): Surface appearance of non-metallic coating No.9 and carbon steel substrate after 42 months testing (X0,64).

Figure 9(a): Non-metallic piping specimen after (polykop) 42 months testing. (Note: Brown product from metallic pipes).

Figure 9(b): Non-metallic piping specimen (HDPE) after 42 months testing. (Note: Brown product from metallic pipes).

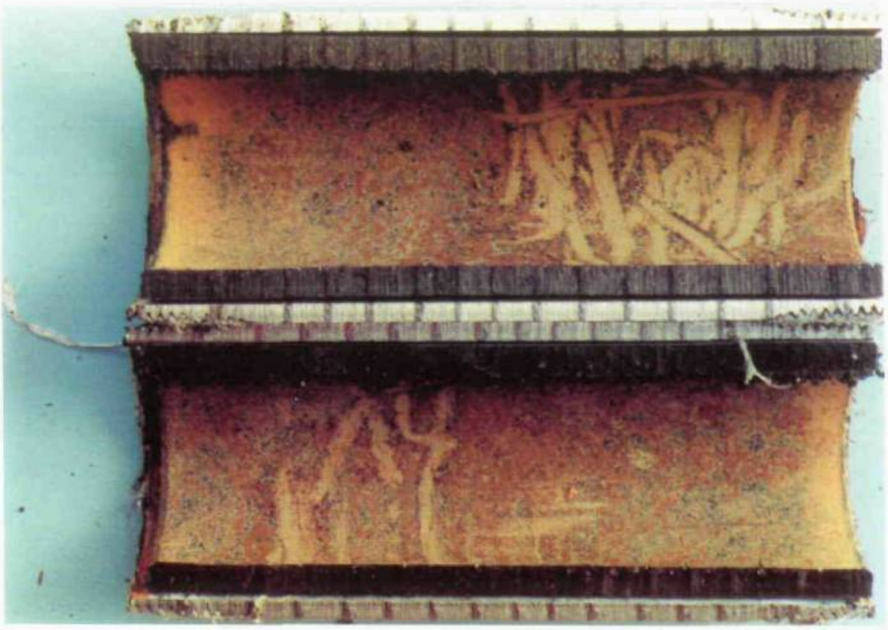

Figure 10(a): Internal surface of the HDPE lined steel pipe specimen (X0, 67).

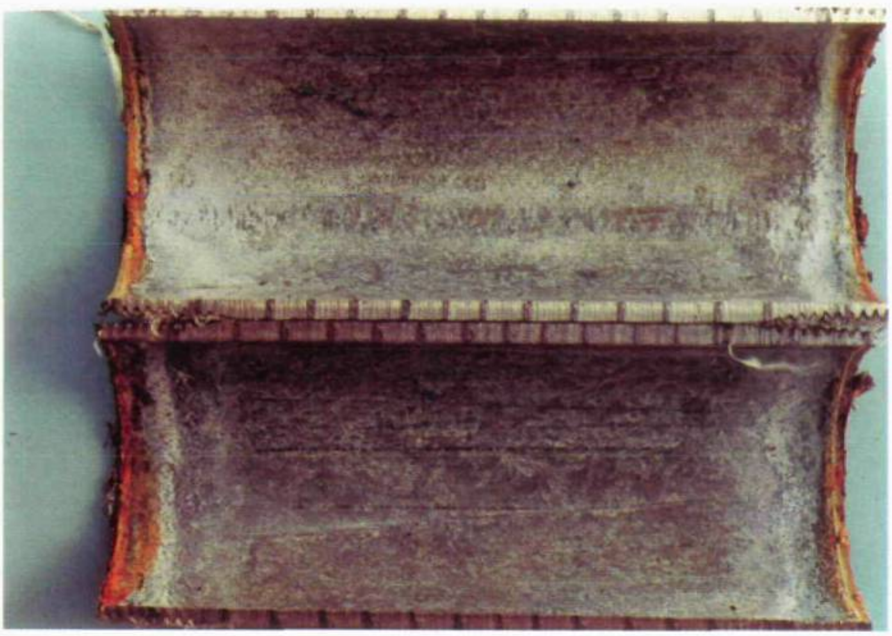

Figure 10(b): Internal surface of the carbon steel substrate after the removal of HDPE lining (X0,67). (Note: Some superficial rusting was evident on the edges of the specimen where a crevice existed due to the cutting and the threading of the sample).

Figure 11(a): Mortar-lined carbon steel pipe end-on (X0,39).

Figure 11(b): Mortar-lined carbon steel pipe showing the condition of the mortar lining (X0,42). No degradation of the cement mortar was noted.

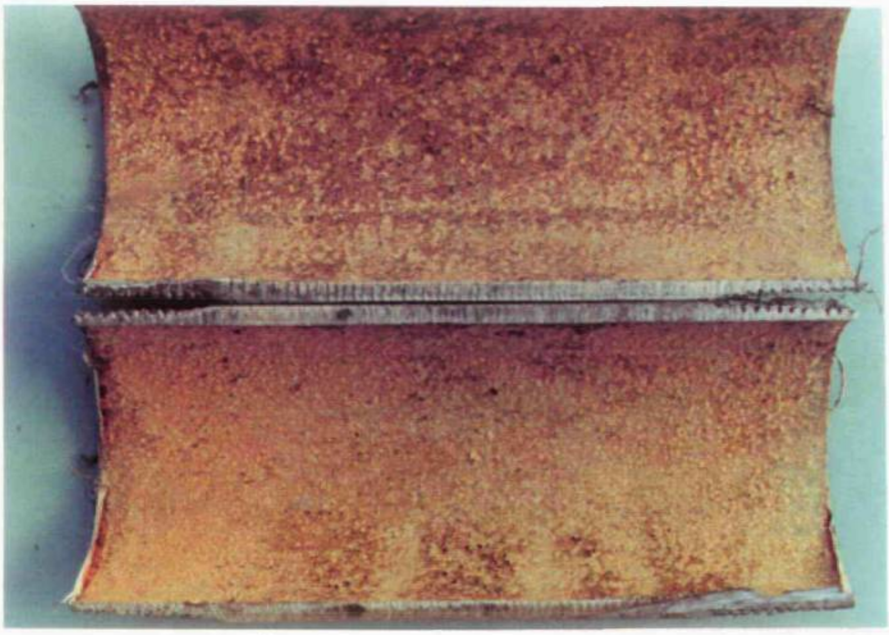

Figure 12(a): Internal surface of galvanised pipe specimen before cleaning. (Note: White uniform scaling) (X0,64).

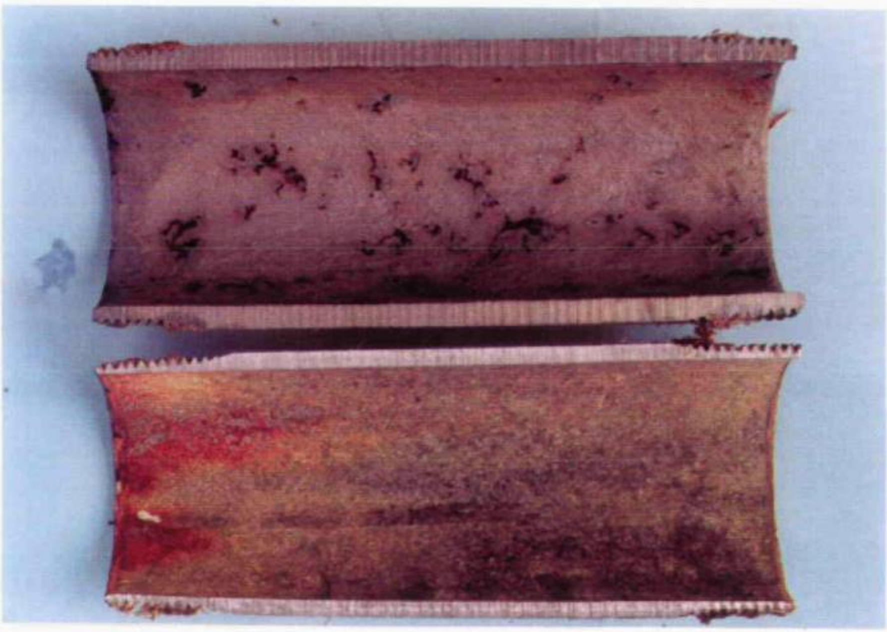

Figure 12(b): Internal surface of galvanised pipe after cleaning (X0,64).

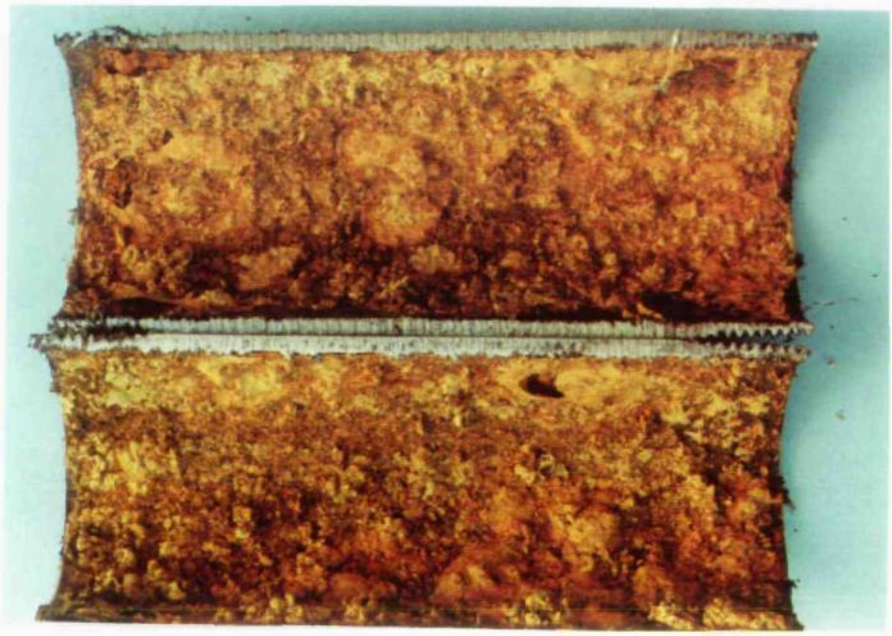

Figure 13(a): Internal surface of carbon steel pipe specimen cleaning (X0,64). (Note: Tuberculation).

Figure 13(b): Internal surface of carbon steel pipe specimen after cleaning (X0,62). (Note: Average pit depth (0,4mm).

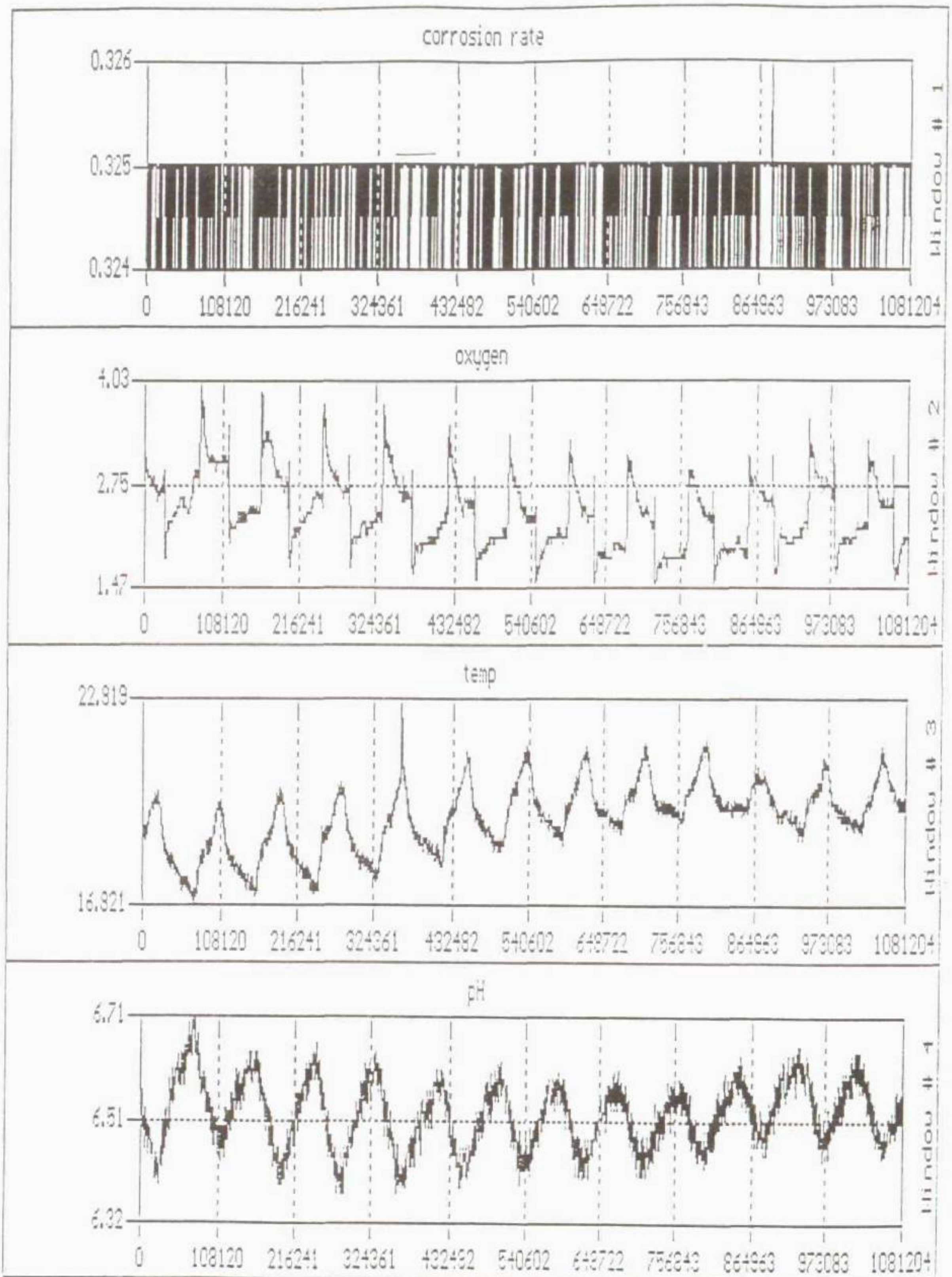

Figure 14: Typical changes of measured parameters from water quality monitoring over 9 months.

APPLICATIONS	CONSULTANTS	WATER DEPTHS ETC	ELECTRICITY	OIL AND GAS	MINING
Water (Potable)	10	17	1	2	Used
Water (Raw)	7	8		2	Used
Water (Mining)	5	1			Used
Water (Sea or Saline)	1	2	1		Used
Sewage	6	10	1	1	Used
Oil	3	1	1	2	
Gas	3	1		4	
Chemicals	4			2	Used
Slurry (Coal)	3				Used
Slurry (Silica)	4				Used
Slurry (Other)	3		Ash 1		
Other	3*	1**		1***	Used*

* Industrial Effluent

** Treated Sewerage Effluent

*** Oxygen Pipeline

Figure 15: Application to which pipeline transport is put in South Africa.. (Upfill Brown and Stead, 1983).

PIPE LINING MATERIAL	CONSULTANTS	WATER DEPTHS ETC	ELECTRICITY	OIL AND GAS	MINING
Hot dipped (Spun) Bitumen	5	15	1		Used (Major)
Coal Tar Epoxy	4	1			Used
Concrete	5	7	1		Used
Epoxy	8	12	1		Used (Major)
G.R.P	1				Used (Major)
Polyurethane	2				Used (Major)
Rubber	2		1*	1	Used (Major)
None				4**	Used
Blast & Nitrite Passivation				1***	

* Ash

** Corrosion Inhibitor Used

*** Oxygen Pipeline

Figure 16: Pipe lining materials used for interior coating of pipelines in South Africa. (Upfill Brown and Stead, 1983).

	CONSULTANTS	WATER DEPTHS ETC	ELECTRICITY	OIL AND GAS	MINING
Design Faults	6	7		4	Occurs
Selection of Wrong Materials	6	8		3	Occurs
Incorrect Protection System	7	12	1	4	Occurs
Bad Workmanship	9	12	1	4	Occurs
Poor Site Supervision or Inspection	7	12	1	4	Occurs
Mishandling of Pipes	7	13		5	Occurs
Aggressive Site Conditions	1	1			Major
Manufacturing Design of Joints		1			
Bad Laying		1			Occurs
Weld Zone Corrosion					Major

Figure 17: Major causes of pipeline failure in South Africa. (Upfill Brown and Stead, 1983).

APPENDIX

Literature Survey

BRIEF LITERATURE SURVEY

ON

CORROSION PERFORMANCE OF COATINGS AND NON-METALLIC PIPING MATERIALS

by

J.S. Ramotlhola and Dr C. Ringas

CONTENTS

1. INTRODUCTION

The effects of corrosion in drinking water distribution networks and house installations can lead to a number of problems. The transport system cannot only be damaged but also the water quality can deteriorate significantly. Great increases in operational cost can result due to pipe failures, increase in water leakages and pressure loss due to voluminous tubercles. By improving material qualities and corrosion protection technologies in combination with the knowledge and recommendation of the correct material for the correct location, a great number of these problems can be reduced or even avoided (Wagner, 1990).

In material selection, strength considerations must include not only sufficient capacity to handle predictable internal pressure, earth, traffic and impact loads but also differential temperatures and proximate construction. When considering possible strength loss due to corrosion or deterioration of pipe material, it must be assumed that any of the available materials can corrode under certain circumstances. Non-metallic materials, despite poor mechanical properties, such as asbestos cement, PVC and polyethylene frequently exhibit high resistance to corrosion. Cost-wise, no material can approach the tensile strength of mild steel and is likely to remain the most used structural material for many decades (Dittmer, 1975).

2 PIPING MATERIALS

There is a wide range of pipe materials used to convey potable water and these can be roughly divided into three groups, viz. the cementitious materials, ferrous materials and plastic materials.

2.1 Cementitious Piping Materials

This group of materials consists of pre-stressed concrete pipes, asbestos cement pipes and cement-mortar lined pipes. The use of such materials is dependent on the geographical locality of particular municipalities. For example, Durban Municipality (which conveys mainly soft waters) has most of its 1870 km of reticulation pipework made up mainly of fibre cement piping whereas Johannesburg Municipality only has approximately 400 km of asbestos cement pipe out of a mains pipeline network of over 3071 km.

Certain organizations such as Rand Water, make extensive use of cement mortar lining for their new large diameter pipelines, although only 15% of their reticulation system of 2600 km is cement-mortar lined. A further 10% is pre-stressed concrete and the rest is mild steel with either bitumen or an epoxy lining or no internal lining at all.

In the past, pipes transporting drinking water were coated with coal or with bituminous enamel. However, neither coating could prevent corrosion. Encrustation took place, red water was delivered to the consumer, and a decrease in the flow capacity of pipes followed. Even special coatings of bituminous enamel could not prevent problems that arose after long periods of service. Compared to coal tar or bitumen linings, cement-mortar lining has been successful in preventing corrosion. For example, in Dortmund, West Germany, cement-mortar lining was applied to reduce problems with red water. Because the purpose of cement-mortar lining is to guarantee uninterrupted operation during the life-time of pipeline, it is important that leaching does not affect durability of the lining and that softness of the cement-mortar layer does not occur or is limited.

2.2 Ferrous Piping Materials

Steel or cast iron pipes of one form or another make up the bulk of most reticulation networks in South Africa and worldwide. Cast iron pipes are often used in underground water supply lines. They are not however, ordinarily installed in potable water systems within buildings. This is due in part, to the unavailability of cast iron pipe in small size (under 10 cm).

Corrosion rates for cast iron in potable waters differ little from those of carbon steel. Slightly longer service life may be experienced with cast iron due to its thicker section but a protective coating is necessary for satisfactory performance in potable water systems. The older pipelines in use were fabricated from cast iron or ductile iron whereas the newer pipelines are fabricated from mild steel. Unfortunately, many of the older pipelines were not internally lined and this has resulted in "furring up" of the pipes and a variety of corrosion problems.

The newer mild steel pipelines were often lined or else a thin bitumen coating was applied. However, ageing of the bitumen caused embrittlement and cracking to occur resulting in various forms of corrosion. The corrosion of steel and cast iron in distribution systems is "general" or "localised". Tuberculation is a type of localised corrosion in which an active pit is covered by growing mounds of corrosion products and also can be caused by bacteria. Tuberculation reduces the pipe size and increases the roughness of the inside surface of the pipe, thereby restricting the flow of water significantly.

2.3 Plastic Piping Materials

Since their introduction in the early 1950's, the use of plastic pipes in the water industry has increased dramatically. A survey carried out in 1985 showed that plastic pipelines comprised just over 61% of new-laid pipes of distribution sizes and above in the UK. A similar survey conducted seven years later showed that plastics comprised over 81% of new installations. Only for trunk mains and in sewerage applications is their usage still limited. Such a dramatic increase in use suggests that plastics offer considerable advantages over traditional pipeline materials for supply and distribution systems.

There are numerous types of plastic materials used for water transport viz. polybutylene, cross-linked polyethylene, chlorinated polyvinyl chloride, polypropylene and glass-reinforced plastic. Polybutylene is used in much less quantities.

Polyethylene is usually characterised by its density i.e. high-density polyethylene (HDPE) is strong and brittle. Chlorinated polyvinyl chloride is a thermoplastic and for mains use it is unplasticized (UPVC). It is stronger than polyethylene, allowing thinner sections to be used and reducing both weight and cost. It is more brittle however, and therefore less tolerant of site handling. Glass-reinforced plastics (GRP) pipes have been available in the UK for over 20 years and are also available in South Africa. Two main types are available at which the centrifugally-cast pipes dominate the market. They are relatively lightweight, and can be easily tailored for specific application. GRP pipes are jointed by push-fit collars, usually supplied attached to the pipes. They are relatively easy to handle and are susceptible to impact damage.

Many plastic pipe manufacturers recommend an analysis based on axial stress only. This is typically an over simplification. Bending and torsion are usually significant and must be taken into account in any analysis. The effect of localised stresses in components and discontinuity stresses must also be considered. There can be too much allowable flexibility inherent in the layout of a plastic piping system. If there is a generous annular space and substantial thermal expansion takes place, early failure can occur because of a buckling mechanism. Buckling, therefore is usually a limiting criteria with respect to the performance of these materials. Lateral support can reduce the propensity for Euler buckling and therefore correct backfill is important. Rocky soils, in general, do not provide enough support and therefore the use of plastic piping in rocky terrain is limited.

High density polyethylene (HDPE) liners have been used extensively to recondition ageing pipelines. More recently, liners have been applied to new pipelines for internal corrosion protection of water injection pipelines e.g. in Oman, Syria and in South Africa.

An internal liner (solid plastic) is preferred when compared to using an internal coating system (for refurbishment of pipelines), as application of the latter by batch pigging through the pipeline has been found to be unreliable in providing 100% stable coating in all operating conditions. A solid liner also has the advantage that it can be leak tested in-situ prior to pipeline installation.

2.4 Organic Lining / Coatings Based on Epoxy

The bulk of the epoxies used in steel pipe have been solvent-based two-pack materials, which are usually built up as two or three coat applications. Performance is critically based on suitable surface preparation and strict adherence to the manufacturers' recommendations. This aspect is often overlooked (especially in field applications) and can result in failure of these coatings. For this reason, it is always important that effective quality control procedures are implemented during application.

It must also be stressed that organic coatings for use in potable water must be certified toxic free so as to avoid contamination of drinking water by leaching out of certain constituents.

2.5 Metallic Coatings

The corrosion rate of zinc in most domestic waters is considerably lower than that of steel. When applied over steel, zinc acts as a barrier coating and as an anode providing galvanic protection to steel to protect it from corrosive attack at breaks in the coating. Galvanized steel pipe is most suitable for potable water service in high hardness, high alkalinity well water supplies, but is generally unsatisfactory for low hardness surface water supplies (about 140ℓ total hardness and below). ASTM A120 pipe requires a hot-dipped zinc coating of not less than 489 g/m^2.

3. CURRENT AND FUTURE USE OF PIPING MATERIAL

A survey conducted by Upfill-Brown and Stead (1983) amongst major users and specifiers of steel pipelines revealed that by far the largest application to which pipelines are put to in South Africa is for the transportation of potable water as shown in Figure 15. This has also been found to be the case in the United Kingdom. Furthermore, of the internal linings used, the percentage of hot-dipped bitumen was equal to that of epoxy as shown in Figure 16. An interesting fact which emerged from the survey was the breakdown of the reasons of pipe failures as summarised in Figure 17.

A further survey conducted by Upfill-Brown and Stead (1983) in South Africa showed that of all the total pipes annually, approximately 55% were small bore (diameters below 150 mm). Of these, very few were bitumen or solvent-based epoxy coated or lined and about one third were galvanized. Of the larger bore pipes, 14% were protected by bitumen or solvent-based epoxy.

Osborn reported that out of the 307 km of 50 - 1020 mm diameter mains pipeline in the Johannesburg area, 135 km was cement mortar-lined, 100 km was UPVC, 75 km HDPE, 132 km was slip-lined with HDPE and 400 km was asbestos cement pipe. The remainder (2229 km) of the mains pipelines were mild steel of which a significant portion was unlined. Kohlmeyer (1989) stated that the largest proportion of pipeline systems built by the Department of Water Affairs were bitumen-lined steel pipes.

Durban Water has 1870 km of reticulation pipework made up mainly of fibre cement piping from 100 to 300 mm in diameter and 318 km of steel trunk mains from 300 mm up to 1400 mm in diameter.

However, the pipe materials under current use have suffered from a number of problems. Steel trunk mains often leak due to internal corrosion or external corrosion caused by stray currents. In fact, external corrosion is more of a problem than internal corrosion. Tuberculation of unlined steel mains increases the frictional force (and thus the cost of transporting water) and a deterioration in water quality due to the presence of micro-organisms. Cast iron mains are extensively corroded by sulphate-reducing bacteria as evidenced by the severe tuberculation often seen in these pipes. The bitumen used as a lining on some steel pipes degrades with time and can then allow corrosion of the underlying steel pipe to take place.

Fibre cement pipelines tend to fail in a more dramatic manner than steel mains and this is as a result of weakening of the pipe by soft acidic waters or earth tremors. The use of asbestos cement pipes varies considerably with some municipalities making extensive use of these materials and other not using them at all.

Problems with material quality of plastic piping have largely been overcome and the quality of plastic piping has improved over the last few years. Slip lining using HDPE was initially used due to its minimal disruption of traffic (and other advantages) and rapid installation. However, in municipal reticulation systems where additions are made to trunk and reticulation mains, slip lining causes problems due to lack of suitable fittings. The use of slip lining has therefore been discontinued by some municipal authorities because the operational department cannot maintain slip-lined pipe. However, HDPE is used extensively for house connections because it is easier and faster to work with than galvanized pipe for example, and is price competitive up to a diameter of 80 mm.

Plastic piping such as UPVC is used extensively up to a diameter of 150 mm whereas steel pipe is used for diameters larger than this.

The preceding discussion has highlighted the fact that asbestos cement and plastic piping is used for the smaller diameter piping but that steel piping is the preferred choice for larger diameter piping. However, much of the steel pipe installed is unlined and thus a variety of corrosion problems are encountered. The lining material for older steel pipe was traditionally bitumen but this has been superceded since the 80's by epoxies. Development in lining materials will centre mainly around existing epoxy technology and future development work with epoxies.

Relining of existing pipelines is widely used due to its economic advantages and bitumen is rarely used nowadays as a relining material. The two major, non-structural methods for relining currently in use are cement-mortar lining and lining with epoxy resin. Relining of pipelines is an area where much research work is being carried out and many new developments are anticipated. Refurbishment and upgrading of existing pipeline infrastructure will become more important in the future.

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