DETERIORATION OF WATER QUALITY – THE EFFECTS ARISING FROM THE USE OF FACTORY APPLIED CEMENT MORTAR LININGS

DoE 2723-SW

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DETERIORATION OF WATER QUALITY - THE EFFECTS ARISING FROM THE USE OF FACTORY APPLIED CEMENT MORTAR LININGS (ESP 9770)

FINAL REPORT TO THE DEPARTMENT OF THE ENVIRONMENT

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PREFACE

In April 1986 the Department of the Environment placed a contract (Ref. PECD 7/7/16) with WRc to investigate the effects of in situ cement mortar lining on water quality and to investigate methods that may be capable of alleviating adverse effects.

A summary report of this work, DoE 2435-SW(P), can be obtained from the WRc Publications Unit, Medmenham, (0491) 571531.

In April 1989 the contract was granted a two-year extension to examine the effects of factory applied cement mortar linings on water quality. The findings of the work carried out from April 1989 are presented in this document.
I OBJECTIVES

(i) To identify and quantify the water quality problems caused by the use of factory applied, cement mortar lined, iron water mains;

(ii) To provide guidelines on the limitations of application of factory applied cement mortar linings;

(iii) To recommend methods for overcoming the potential water quality problems associated with the use of such linings.

II REASONS

In 1986, the Department of the Environment (DoE) commissioned WRc Plc to investigate the effect that in situ cement mortar lining had on water quality. These studies\(^1\) showed conclusively that in situ lining of iron water mains in soft water supply regions can lead to pH, aluminium and lead levels which contravene the EC Directive\(^2\) on potable water quality and the Water Supply (Water Quality) Regulations 1989. The findings of this work led to concern that similar problems may be associated with factory applied cement mortar linings; the work reported in this document was commissioned by the Department of the Environment in April 1989 to investigate this.

III RESUME

A series of laboratory, full scale test-rig and field studies have been implemented in order to determine the effects of factory applied cement mortar linings on water quality.
Particular emphasis has been placed on the development of laboratory test-rigs which provide practical alternatives to costly full scale test-rig and field studies.

Data has been appraised in relation to previous in situ studies\(^{(1)}\), and recommendations for use of factory linings have been developed.

IV CONCLUSIONS

(a) Factory applied linings are more satisfactory for use at lower alkalinites than in situ linings. In the case of 100 mm diameter pipes, and provided that retention time does not exceed 8 hours at any time, factory linings can be used when the supply water alkalinity is greater than 25mg CaCO\(_3\)/l. At lower alkalinity levels leaching can cause pH levels to exceed the Standard of 9.5 prescribed by the Water Supply (Water Quality) Regulations 1989.

(b) When using cement mortar as a corrosion inhibitor for entire or large parts of distribution systems, the cumulative effect associated with long total retention times may result in pH in excess of 9.5 at the consumers tap. Very long retention times may result in high pH levels, even though the alkalinity is significantly greater than 25mg CaCO\(_3\)/l.

(c) Seal coatings appear to provide an effective method of pH control; however, their long term durability and the potential for any water quality problems associated with such coatings have not been established.

V RECOMMENDATIONS

(a) Factory applied cement mortar lined pipes should not be used in conditions of very low alkalinity (less than 25mg CaCO\(_3\)/l), where pipe diameters are small and retention times are relatively long. Caution should be exercised when considering
the use of such linings when the total retention time is very high, even though the supply water alkalinity may be in excess of 25mg CaCO$_3$/l.

(b) Theoretical extrapolation of the data should be used to provide an indication of the potential pH levels in a given defined system.

(c) The use of approved seal coatings, epoxy linings and other methods of preventing elevated pH should be considered in future investigations.

(d) Further field data should be collected to substantiate the findings of this work, which are mainly based on laboratory and test-rig data.
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SECTION 1 - INTRODUCTION

Cement mortar lining has been a popular and commonly used method for corrosion protection of iron water mains. Cement linings can be applied in situ as a means of renovation for old water mains and also in the 'factory' to provide protection for new pipes. The cement mortar lining, when exposed to water, becomes saturated and a highly alkaline, active corrosion inhibiting barrier is established.

It has been observed from previous studies on in situ linings\(^1\) that lime (\(\text{Ca(OH)}_2\)) can leach from the cement into the supply water resulting in pH levels in excess of the EC Directive on Water Supply (Water Quality). Regulations 1989.\(^2\) of 9.5; this problem is particularly pronounced in low alkalinity waters which have an associated low buffer capacity. This effect has been demonstrated for in situ cement linings, but less is known about the behaviour of factory applied cement mortar linings.

Prior to the inception of this reported programme of work on factory linings, it was considered that their behaviour may have been different to that of in situ cement linings because:

(i) Application processes are different, resulting in the factory linings having a greater density.

(ii) Compositions are different.

(iii) Factory linings can be 'seal-coated'.

In view of the potential differences in the behaviour of factory applied and in situ applied cement mortar linings, the programme of work documented in this report was initiated.

The aim of the work was to characterise the behaviour of factory cement linings, in order to provide recommendations for their use and for avoidance of water quality problems.
This report provides recommendations and guidance based on the observations of laboratory, full scale test-rig and field studies; an emphasis has been placed on developing and verifying laboratory simulations of actual field conditions.
SECTION 2 - LABORATORY STUDIES

2.1 INTRODUCTION

Previous work on in situ cement mortar lining, carried out on behalf of the Department of the Environment\(^1\), has shown that the pH of the water passing through cement mortar lined pipes is related to:

(a) Supply water alkalinity, mg CaCO\(_3\)/l;

(b) Retention/contact time of the supply water in the cement mortar lined pipe;

(c) Age of the lining.

The effect of these factors on the pH of supply water conveyed by factory applied linings has been quantified using a series of laboratory studies. In addition the effect of pipe diameter has been assessed.

2.2 METHODOLOGY

Factory applied cement mortar lined pipes have been examined using static and continuous flow methods in order to quantify the effects of the parameters identified in 2.1. The emphasis has been on the development of continuous flow systems, which accurately simulate 'site' conditions. The key determinant in this series of experiments was pH.

The laboratory studies were carried out using supply waters in the alkalinity range of 0-140mg CaCO\(_3\)/l. These waters were prepared by progressively diluting Swindon tap water (very high alkalinity, 220-300mg CaCO\(_3\)/l) with de-ionised water (zero alkalinity).

Pipes samples were obtained from the two main UK manufacturers and were of 100mm diameter except where specified; the cement linings were noted to be of different chemical composition (see Table 1). Please explain the differences in composition and the meaning of the abbreviations. What component contains the caustic soda?
Four basic designs of test-rig were used in laboratory trials:

(a) **Static** - 0.25m, cement mortar lined pipe lengths were mounted vertically on a plastic base and sealed with a waterproof sealant; the pipe was filled with the 'test' water and the top of the exposed pipe protected by covering with a removable plastic film.

(b) **Short-term continuous flow** - 0.5m pipe lengths were mounted horizontally and sealed with rubber bungs; an inlet and outlet were made to enable a supply of water to flow through the pipe. The pre-blended test water was fed through the pipe from a tank at a predetermined flow, regulated using a peristaltic pump and measured using in-line flow-meters. The pH was monitored at the outlet using an in-line probe; 'equilibrium' pH values were recorded after the system had been given sufficient time to stabilise.

(c) **Long-term continuous flow** - the set-up was the same as the short-term rig, except water of the desired alkalinity was provided by 'dosing' pumps which were used to blend de-ionised and tap water from two separate tanks.

(d) **Diurnal flow** - as for the short-term rig except a programmable logic controller was used to regulate the speed of a peristaltic pump supplying the test water.

In the case of the continuous and diurnal flow rigs, flow regulation was used to provide a range of retention times, if required; retention time can be defined as the time taken, at a given flow rate, for the supply water to travel from the beginning to end of the lined pipe.

In the case of static experiments, the cement linings were rinsed with de-ionised water to remove loose cement deposits prior to exposure. The cement linings used for the 'flow' experiments were flushed for 48 hours (1.2 hours retention time) prior to exposure to simulate the site practice of flushing.
2.2.1 The Use of Static Tests for the Determination of the Effects of Factory Applied Cement Mortar Linings on Potable Water Quality

Pipe samples of a range of diameters (80-150mm) were exposed to a range of supply water alkalinity (17-140mg CaCO₃/l) under static conditions using the test-rig described in Section 2.2 (a). Exposure times of up to 5 days were used; exposure time can be defined as the length of time the tests were carried out. This data is represented in Figure 1 (a) and 1 (b). Pipes from two separate sources, and of slightly different composition were also examined; the compositions are given in Table 1.

2.2.2 The Use of Continuous Flow Tests for the Determination of the Effects of Factory Applied Cement Linings on Potable Water Quality

Short term tests

These tests were conducted using the rig described in Section 2.2 (b). The effects of the variables alkalinity (mg CaCO₃/l), retention time, and pipe diameter were characterised.

By controlling flow conditions to give constant retention times, it was intended that the critical minimum alkalinity for factory applied cement mortar lining could be identified, for particular pipe diameters.

The rig was not suitable for investigating the effect of ageing of the cement mortar lining.

(a) Determination of the Effects of Water Alkalinity on Water Quality in Factory Applied Cement Mortar Lined Pipes.

Experiments were conducted using a range of supply waters, having mean alkalinites of 6, 22, 34 and 59mg CaCO₃/l. This range covered very low to moderate levels of alkalinity. The flow rate used in this experiment was equivalent to a retention time of 1.2 hours.
Pipe samples examined were from one UK manufacturer, and were of a type previously identified as giving rise to higher pH levels. 100 mm diameter, 0.5m length pipes were used.

Results are shown in Figure 2.

(b) Determination of the Effect of Retention Time on Water Quality in Factory Applied Cement Mortar Lined Pipes

The experiment described previously (a) was repeated using retention times of up to 24 hours.

Results are shown in Figure 2.

(c) Determinations of the Effect of Pipe Diameter on Water Quality in Factory Applied Cement Mortar Lined Pipes

This series of experiments examined the effect of changing the volume of water to surface area of cement ratio.

80, 100 and 150mm diameter pipe samples were examined using de-ionised water and a retention time of 3.6 hours.

pH data is presented, in Table 2.

(d) Determination of the Effect of a Different Source of Manufacture on Water Quality in Factory Applied Cement Mortar Lined Pipes

Cement mortar lined pipes were obtained from two UK manufacturers, and exposed to de-ionised water at a retention time of one hour.

Long Term Tests

These tests were conducted using the rigs described in Section 2.2 (c) and (d).
The effects of ageing and also the use of a typical diurnal flow regime were characterised.

(a) The long-term continuous flow rig was used to investigate the effect of ageing of the factory applied cement mortar lining on pH of the conveyed water.

The rig was supplied with water in the alkalinity range 5-10mg CaCO₃/l at a retention time of approximately 1.5 hours. At intervals of one week, the flow was stopped and static conditions were applied. Every hour a water sample was taken and pH measurement carried out. The sample was also analysed for metals content using inductively coupled plasma emission spectroscopy. The experiment was continued for two months.

These conditions were the same as those used previously for the full scale test-rig constructed in Strathclyde, Scotland and used to assess the effect on water quality of in situ cement mortar linings(1) (except that the Strathclyde Rig was run for over two years because of pH levels persisting in excess of 9.5).

Results are shown in Figure 3 (a), (b) and (c).

(b) The diurnal flow rig was used to examine the effect of typical diurnal flow regimes on the pH of the conveyed water. The flow regime employed is shown graphically in Figure 4 and with variable flows and dead periods throughout a 24 hour period represents a typical flow pattern for a dead-end main.

It was intended that this rig would provide a more accurate method for determining the limitation of use of cement lined pipes by providing a more realistic flow regime.

Initial studies were carried out using supply water of 35mg CaCO₃/l. The pipe samples used for this test were of a
composition previously found to give rise to lower pH levels, when compared with the other main composition of cement used in the UK; results are presented in Figure 4. The test was repeated using the alternative cement, exposed to a supply water of 25mg CaCO$_3$/l. In both cases, exposure was continued until pH levels were near to or below 9.5.

For convenience, the pH data obtained using 25mg CaCO$_3$/l supply water is shown in Table 3, and only mean, maximum and minimum pH levels are presented.

2.3 RESULTS

The results are presented in Tables 2 to 3 and Figures 1 to 4.

It was observed that the data follows the same qualitative trends predicted from previous studies on in situ cement mortar linings$^{(1)}$ i.e. the pH levels of the supply water conveyed through the pipe samples tend to increase with retention time and decrease with alkalinity of the supply water and age of the pipe.

pH levels were lower in larger diameter pipe, though lower than would be expected just by considering the dilution factor.

pH levels appeared to be related to cement composition.

The pH of the contact water in seal coated pipe samples remained below 9.5 throughout.

It was particularly of note that pH levels exceeded 9.5 given sufficient contact time for waters of alkalinity of up to 140mg CaCO$_3$/l.
2.4 DISCUSSION

2.4.1 Static Tests

It has been shown in previous studies by the use of static (zero flow) tests that exposure of factory applied cement mortar linings to supply water can result in pH levels in excess of the MAV of 9.5 prescribed in the Water Supply (Water Quality) Regulations 1989.

This is shown in Figure 1, which also shows the effect of pipe diameter on pH of the conveyed water and the effect of a 'seal coat' on cement mortar linings.

The pipes used for this experiment were new, having not been exposed to water other than an initial wash to remove loose cement dust.

It was observed that the pH levels exceeded 9.5 within 0.5 days in all cases, except where the cement mortar lining was seal coated. After five days of static exposure the pH level was between 11 and 11.7 for the 80, 100 and 150mm cement lined pipes. The pH of the water in the seal coated pipe remained well below the MAV of 9.5 throughout the tests.

This would indicate that the use of seal coats is an extremely effective method of controlling lime leaching and keeping pH levels below the MAV of 9.5. These bitumen-based seal coats offer the added advantage of being inexpensive and relatively easy to apply in the factory.

However, the longer term performance - the durability and effect on water quality - of the seal coat is not well understood. It has been suggested that the seal coat may only delay the pH problem if the mechanism for degradation was such that it 'fell away' in large patches at a latter date, exposing large areas of the underlying cement mortar. There is no conclusive evidence to show that this will be the case, but obviously, this merits investigation and it is understood that initiatives in this area are underway abroad and in the UK. Also under investigation are reports that the solvent in the seal coat can, under certain circumstances, give rise to taste and odour problems.
The data presented in Figure 1 suggests that the smaller the diameter of the pipe the greater the pH of the contact water, for a given exposure time and supply water alkalinity. This was presumably related to the associated increase in dilution factor with pipe diameter (the ratio of volume of contact water to surface area of cement is proportional to the pipe diameter); however, the differences in pH level for the pipes did seem greater than would be expected, simply from consideration of the ‘dilution factor’; pH levels in larger diameter pipes being lower than expected.

It was observed during the course of the five day exposure period that approximately 0.35 pH units separated the pH data for the 80 and 100mm pipes and likewise the 100 and 150mm diameter pipes. This was unusual because it would be predicted that as the exposure time increased the buffer capacity of the supply water would be exceeded and the pH would increase to the same maximum value, governed by the solubility of the hydroxides leached into solution.

Also of note from the use of static tests was that even when exposed to supply water alkalinities of up to 140mg CaCO₃/l relatively new cement linings could give pH levels in excess of 9.5. For example, after five days exposure (=five day retention/contact time) at an alkalinity of 140 mg/l, pH levels in the region of 11.5 were observed.

This is due to the leaching of sodium hydroxide (NaOH) which occurs in new pipes. Sodium hydroxide, being far more soluble than Ca(OH)₂, produces higher pH levels. This factor is highly significant and should be borne in mind when dealing with long lengths of large diameter new main which may contain large volumes of high pH water when first ‘charged’, resulting in an effluent problem, which will have to be treated prior to commissioning the main. Furthermore, low flow rates in very long, large diameter trunk mains may result in retention times of several days and consequently significant pH problems.

Data from static tests also highlighted that there appeared to be differences in the behaviour of the two types of cement composition
examined. The contact water in pipe lined with type B cement remained at a lower pH relative to the contact water in pipe lined with type A cement, rising from pH 8.4 to 10.6 over a long exposure time of 280 hours. The contact water in pipe lined with type A cement rose rapidly from pH 8.4 to 11.8 and then remained at this level. The cement which gave rise to higher pH levels was used for the majority of the continuous flow tests; however, it was not possible to establish whether these differences were 'batch' differences or real differences associated with the cement composition.

2.4.2 Continuous Flow Tests

Short Term Tests

(a), (b) Effect of Alkalinity and Retention Time.

The data presented in Figure 2 enables the effect of alkalinity (mg CaCO₃/l) and retention time on pH levels, to be quantified. Critical maximum retention times, for a given supply water alkalinity, can be identified in order to avoid pH levels in excess of the standard of 9.5.

For example it was seen that at mean alkalinity of 6mg CaCO₃/l the equilibrium pH for a retention time of 1.2 hours was approximately 9.4 and for a retention time of 3.6 hours was 9.6. The supply water pH was 7.72. It may be suggested that retention times should be kept below 3.6 hours, to prevent the MAV of 9.5 from being exceeded, when factory cement mortar lined pipes are exposed to equivalent 'in service' conditions of alkalinity and retention time.

Of interest is the minimum alkalinity where factory lined pipes may be used when retention times of up to 8 hours may occur, because such retention times are typical of small diameter dead-end mains and commonly considered to be a worst-case situation. If the data for exposure to supply water having an alkalinity of 22mg CaCO₃/l is considered: the pH of the water at
a retention time of 1.2 hours was approximately 8.9, 9.0 after 3.6 hours and 9.4 after 8.3 hours. In this case it may be suggested that retention times of greater than approximately 8.3 hours, should not be exceeded, otherwise the Standard may be contravened.

(c) Effect of Pipe Diameter

The 'dilution' factor is proportional to the pipe diameter i.e. volume to surface area ratio increases in direct proportion to diameter. This explains why higher pH levels were found in smaller diameter pipes - all other variables being constant - although pH levels in the larger diameter pipe was lower than would be expected (pH of 10.1 in 80mm diameter pipe compared with 8.9 in 150mm diameter pipe; the predicted pH level in the 150mm diameter pipe, based on the greater dilution factor would be 10.1 + log₁₀(80/150) = 9.8).

(d) Effect of Manufacture

It is difficult to make firm conclusions regarding the effects of different source of manufacture when pipes from only two manufacturers were examined and it should also be noted that 'batch' differences may also occur.

These tests did, however, substantiate the findings from static tests i.e. higher pH levels were associated with cement linings of a particular composition; the pH of deloined supply water in contact with type B cement was 7.8, in contrast with a pH of 9.7 for type A cement.

Long Term Tests

(a) The data presented in Figures 3a to 3c shows the variation of specific analyte levels for exposure of factory linings during
laboratory simulation of exposure conditions used previously to assess in situ linings\(^{(1)}\) on a full scale test-rig (see also Figure 5, Section 3, which provides a comparison of this data).

Figure 3a shows i) the increase in pH with increase in retention time and ii) the trend for a decrease in pH, at a given retention time, as the lining ages. It was observed that pH levels were generally less than 9.5 after 49 days for retention times of less than eight hours. This was significantly better than in situ cement linings\(^{(1)}\) which resulted in pH levels in excess of 9.5 for 2 years under similar conditions using the full scale rig.

In practical terms, contravention of the NWL of 9.5 for up to 49 days is excessive and this strongly suggests that factory lined pipes are unsuitable for application in waters of alkalinity less than 10mg CaCO\(_3\)/l, where retention times of 8 hours or more can occur.

Figure 3b and 3c show that the levels of aluminium (Al) and calcium (Ca) tend to increase as the retention time increases.

(b) Data from the diurnal flow rig (Figure 4) showed that pH levels did not exceed 9.5 when using a supply water of 35mg CaCO\(_3\)/l alkalinity. This implied that, in terms of pH levels, these factory linings were suitable for use under equivalent field conditions of relatively long retention times and alkalinities less than 10mg CaCO\(_3\)/l.
conditions i.e. for laying to 'dead-ends' where similar retention times occur and where the supply alkalinity is 35mg CaCO₃/l or above. Exposure of factory linings to supply water having an alkalinity of 25mg CaCO₃/l indicated that mean pH levels of less than 9.5 would be expected within three weeks of service. It should be noted that the maximum pH level under these diurnal exposure conditions was 10.2; the predicted maximum pH assuming a maximum retention time of approximately ten hours and constant leaching rates, would be 9.8.

2.5 CONCLUSIONS

Static (zero flow) laboratory tests provide a convenient and inexpensive method for investigating the effects of cement mortar linings on supply water quality.

pH levels in excess of 9.5 can occur even in moderately high alkalinity waters, provided that the retention time is sufficiently high e.g. pH of 11.7 after 5 days for a supply water alkalinity of 140mg CaCO₃/l.

Factory applied cement linings should not be used in very low alkalinity supply waters. When the alkalinity is less than 25mg/l, and where retention time is in excess of 8 hours, pH levels above 9.5 can occur. Under conditions of equivalent alkalinity and retention time the pH levels will be lower in larger diameter pipes. This effect is probably related to the increase in 'dilution factor' as pipe diameter increases. As a conservative estimate, retention times may be doubled as pipe diameter doubles to give similar pH levels.

Differences in cement composition appear to affect pH levels in supply water; however, these effects may be a result of 'batch' differences between samples rather than being associated with source of manufacture.

Seal coatings provide an effective method of controlling pH, though water quality problems associated with the seal coat itself may be an issue and requires investigation.
### Table 1 - Commonly used cement mortar lining materials

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>TYPICAL COMPOSITION (weight %)</th>
<th>METHOD OF APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OPC</td>
<td>PFA</td>
</tr>
<tr>
<td>1. OPC mortar</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>2. BFS mortar</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>3. OPC/PFA Type A</td>
<td>32</td>
<td>11</td>
</tr>
<tr>
<td>4. OPC/PFA Type B</td>
<td>28</td>
<td>12</td>
</tr>
</tbody>
</table>

### Table 2 – Effect of pipe diameter as determined by short term continuous flow tests

<table>
<thead>
<tr>
<th>PIPE DIAMETER (M)</th>
<th>PIPE LENGTH (M)</th>
<th>RETENTION TIME (HOURS)</th>
<th>SUPPLY ALKALINITY (mg/l CaCO₃)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>0.5</td>
<td>3.6</td>
<td>0</td>
<td>10.1</td>
</tr>
<tr>
<td>0.10</td>
<td>0.5</td>
<td>3.6</td>
<td>0</td>
<td>9.8</td>
</tr>
<tr>
<td>0.15</td>
<td>0.5</td>
<td>3.6</td>
<td>0</td>
<td>8.9</td>
</tr>
</tbody>
</table>

### Table 3 – pH data obtained using a diurnal flow rig and supply water alkalinity of 25mg CaCO₃/l

<table>
<thead>
<tr>
<th>pH</th>
<th>EXPOSURE TIME (DAYS IN SERVICE)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>DAY 5</td>
</tr>
<tr>
<td>Mean</td>
<td>9.8</td>
</tr>
<tr>
<td>Maximum</td>
<td>10.1</td>
</tr>
<tr>
<td>Minimum</td>
<td>9.4</td>
</tr>
</tbody>
</table>
Figure 1a - The effect of pipe diameter on pH as determined by static tests
EFFECT OF ALKALINITY ON pH

Alkalinity mg/l as CaCO₃

- 17 mg/l
- 35 mg/l
- 73 mg/l
- 140 mg/l

Diameter of pipe?

Figure 1b - The effect of alkalinity on pH as determined by static tests
Figure 2 - The effect of alkalinity and retention time on pH as determined by short term continuous flow tests.
Strathclyde duplicate rig
pH against retention time

Figure 3a - Effect of retention time and ageing on pH, as determined using a long term continuous flow laboratory rig
Figure 3c - Effects on calcium levels
Figure 4 - pH levels when simulating typical diurnal flows (supply alkalinity, 35mg/l).
3.1 INTRODUCTION

The achieve a simulation closer to service conditions and to characterise the effect of ageing, a full scale test-rig was set up. The rig consisted of four 50m lengths of 100mm pipe; the alkalinity of the supply water was 8mg CaCO₃/l.

3.2 METHODOLOGY

Flow through the pipes, controlled by throttling the outlet end, was normally set at 4l/min. Three visits to the rig were made, at 2 weekly intervals and on each occasion the flow through the pipes was adjusted to give a range of retention times. As with the laboratory studies, the equilibrium pH was recorded for each retention time examined.

3.3 RESULTS

Results are shown in Figures 5a, b and c.

It was observed that pH levels decreased with the length of time the pipes were in service, as would be expected.

The use of factory linings appears to offer advantages over in situ cement mortar linings, as supported by the laboratory data in Section 2.

3.4 DISCUSSION

When compared to in situ linings\(^1\), tested using a similar rig, the factory linings perform significantly better. The pH levels were as much as 1 unit lower under the same conditions of exposure (see Figure 5). It should be noted that the pH of the supply at the test-rig site was already close to the standard of 9.5.
The graph also shows data from the 'equivalent' laboratory test described in Section 2. The pH levels encountered are fairly similar for the laboratory and full scale test-rig; this indicates that the laboratory rigs may be a suitable substitute for quantitative assessment of the performance of cement mortar lined pipes.

The full scale test-rig data also supports the observation from laboratory studies that factory linings would be unsuitable for application in waters of very low alkalinity (<10mg CaCO₃/l), the pH at a retention time of 8 hours was in excess of 9.5 even after 28 days of service.

3.5 CONCLUSIONS

Factory applied cement mortar linings are significantly better than in situ linings in terms of their effect on the pH levels of the conveyed water, offering improvements of up to 1 unit reduction in pH level under the test conditions described.

Factory linings were not suitable for use in very low alkalinity water when tested under the described conditions.

why not quantify?
Figure 3b - The effect of retention time and ageing on pH as determined by the use of a full scale test rig (pH levels after 8 days)
Comparison of lining types
Day 14

Figure 5b - The effect of retention time and ageing on pH as determined by the use of a full scale test-rig (pH levels after 14 days)
Comparison of lining types
Day 28

Figure 5c – The effect of retention time and ageing on pH as determined by the use of a full scale test-rig (pH levels after 28 days)
SECTION 4 - FIELD STUDIES

4.1 INTRODUCTION

Previous studies involving laboratory experiments and field trials have demonstrated that the use of in situ cement mortar linings in small diameter water mains with low rates of flow in soft water areas may result in significant changes in water quality parameters\(^{(1)}\). Investigations following renovation of water mains have shown elevation of pH levels and aluminium concentrations above the limits specified in The Water Supply (Water Quality) Regulations 1989 for long periods of time. The Regulations give a maximum admissible value (MAV) for pH of 9.5 and a maximum admissible concentration (MAC) for aluminium of 0.2 mg/l. 200 microgrammes per litre.

Comparatively little is known about the effects of factory applied cement mortar linings on water quality, but similar problems may be encountered. The objective of the field trials was to fill this gap and to validate the findings of laboratory trials.

4.1.1 Description of Trial Sites

The trial sites were located in soft water areas with supply waters of different alkalinitities. Details of mains at each site in the first series of experiments are given in Table 4. A number of "worst case" situations such as recently laid 100mm diameter dead end mains with low alkalinity supply water were examined. The use of dead end mains which were part of the normal distribution system meant that the average flow of conveyed water would be low.

4.2 METHODOLOGY

A series of experiments were carried out at trial sites 1-9.

Water samples were taken, using fire hydrants, from recently installed distribution mains with factory applied cement mortar linings and from
the inlet supply water. There mains were all 'in service' mains and supplying customers during the course of these studies. It was not possible to determine actual flows, though it may be suggested that higher flows were present in the 'through' mains (Table 4).

The pH, alkalinity and aluminium, calcium, sodium, potassium, iron and magnesium concentrations of the water conveyed in the test mains and supply water were monitored.

4.3 RESULTS

Table 4 gives details of mains at the field trial sites.

The results of the field trials are shown in Tables 5 to 11.

Table 5 shows the pH levels of supply and test waters at the trial sites. Table 6 shows the alkalinity levels of supply and test waters at trial sites. Table 7 shows the principal ion concentrations of supply waters and tables 8 to 11 the concentrations of the principal constituents of the test waters.

4.4 DISCUSSION

The results of the field trials show pH levels elevated above the Water Act 1989 MAV for prolonged period of time were restricted to trial sites 5 and 6 (up to 11.2). These were both 100mm dead end mains laid during the last two years on new vacant developments, with low supply water alkalinites (13 and 25mg CaCO3/l). It was anticipated that problems would occur in dead end mains of this nature. However, it was surprising that pH problems were occurring on mains of this age in view of the laboratory studies (Section 2) and full scale test-rig studies (Section 3) which indicated even for waters in the alkalinity range 5-10mg CaCO3/l, that problems would only persist for a few weeks. It was later found that the mains had been virtually unused until our studies were undertaken, thus accounting for high pH levels observed.
In the case of site 5, elevated pH levels were temporarily alleviated by flushing the main until the pH fell to an acceptable level. Flushing is not a long term solution as pH levels increase to the original level after a few hours.

Aluminium levels were seen to be variable; in some instances exceeding the MAC even in the supply water, thus it is not possible to discern trends in this data.

It was intended that these field studies could be used to validate the laboratory data presented in Section 2. However, a major problem has been that data allowing retention time to be calculated has not been available and retention time is an important variable affecting pH. Qualitatively, the field data appears to support the laboratory data, but further field studies are required using mains where all variables affecting pH can be determined.

The excellent agreement between laboratory data and the full scale test-rig would strongly suggest, however, that laboratory trials offer a suitable alternative to field trials.

4.5 CONCLUSIONS

It is extremely difficult to quantify field data unless the variables:

(i) pipe age,
(ii) pipe diameter,
(iii) supply water alkalinity, and
(iv) retention time

are known accurately.

Exposure of cement linings to extremely low flow conditions can result in pH problems occurring a number of years after the main has been laid.
**Table 4 - Test mains at field trial sites used in the first series of experiments**

<table>
<thead>
<tr>
<th>TRIAL SITE</th>
<th>MEAN RESERVOIR ALKALINITY (mg/l CaCO₃)</th>
<th>MAIN</th>
<th>TYPE</th>
<th>YEAR LAID</th>
<th>LENGTH (m)</th>
<th>DIAMETER (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td></td>
<td>T</td>
<td>1989</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>33</td>
<td></td>
<td>DE</td>
<td>1987</td>
<td>230</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td></td>
<td>T</td>
<td>1987</td>
<td>500</td>
<td>150</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td></td>
<td>T</td>
<td>1989</td>
<td>170</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td></td>
<td>DE</td>
<td>1988/89</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td></td>
<td>DE</td>
<td>1989/90</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td></td>
<td>DE</td>
<td>1989</td>
<td>1235</td>
<td>300</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td></td>
<td>T</td>
<td>1989</td>
<td>420</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>25-77</td>
<td></td>
<td>DE</td>
<td>1990</td>
<td>420</td>
<td>100</td>
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<tr>
<td>10</td>
<td>T</td>
<td></td>
<td>T</td>
<td></td>
<td>200</td>
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</tr>
<tr>
<td>11</td>
<td>DE</td>
<td></td>
<td>DE</td>
<td></td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

T - Trunk/through main  
DE - Dead end main

**Table 5 - pH Levels of supply and test waters at field trial sites**

<table>
<thead>
<tr>
<th>TRIAL SITE</th>
<th>SUPPLY WATERS</th>
<th>pH.</th>
<th>TEST WATERS</th>
<th>WEEK 1</th>
<th>WEEK 2</th>
<th>WEEK 3</th>
<th>WEEK 4</th>
<th>MEAN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8.65</td>
<td>8.99</td>
<td>8.86</td>
<td>8.93</td>
<td>9.93*</td>
<td>9.93</td>
<td>9.18</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>8.15</td>
<td>7.79</td>
<td>9.0</td>
<td>8.84</td>
<td>9.03</td>
<td>9.03</td>
<td>8.67</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>7.65</td>
<td>7.81</td>
<td>7.77</td>
<td>7.54</td>
<td>7.58</td>
<td>7.58</td>
<td>7.68</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8.4</td>
<td>7.8</td>
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<td>7.3</td>
<td>-</td>
<td>7.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>9.83*</td>
<td>10.85*</td>
<td>11.2*</td>
<td>9.61*</td>
<td>10.03*</td>
<td>10.42*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>6.92</td>
<td>6.88</td>
<td>10.91*</td>
<td>10.71*</td>
<td>10.87*</td>
<td>10.87*</td>
<td>9.84*</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>7.76</td>
<td>6.78</td>
<td>8.72</td>
<td>7.75</td>
<td>8.01</td>
<td>8.01</td>
<td>7.82</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>6.93</td>
<td>6.99</td>
<td>8.41</td>
<td>8.41</td>
<td>7.62</td>
<td>7.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>8.04</td>
<td>8.24</td>
<td>7.9</td>
<td>7.52</td>
<td>-</td>
<td>7.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>8.01</td>
<td>8.24</td>
<td>8.06</td>
<td>7.21</td>
<td>-</td>
<td>7.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>7.05</td>
<td>8.39</td>
<td>7.84</td>
<td>8.6</td>
<td>-</td>
<td>8.28</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* pH Levels exceeding direct effect standard  
- No data collected

- 31 -
Table 6 - Alkalinity levels of supply and test waters at field trial sites

<table>
<thead>
<tr>
<th>TRIAL SITE</th>
<th>SUPPLY WATERS</th>
<th>TEST WATERS</th>
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<tbody>
<tr>
<td></td>
<td>ALKALINITY (mg/l CaCO₃)</td>
<td>WEEK 1</td>
</tr>
<tr>
<td>1</td>
<td>18</td>
<td>26.6</td>
</tr>
<tr>
<td>2</td>
<td>33</td>
<td>34.7</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>93.5</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>25.9</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>65.7</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>93</td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>34</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>29</td>
</tr>
<tr>
<td>9</td>
<td>25-77</td>
<td>73</td>
</tr>
<tr>
<td>10</td>
<td>58.7</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>138</td>
<td>-</td>
</tr>
</tbody>
</table>

- No data collected

Table 7 - Element concentrations of supply waters at field trial sites

<table>
<thead>
<tr>
<th>TRIAL SITE</th>
<th>ELEMENT CONCENTRATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ALUMINIUM (mg/l Al)</td>
</tr>
<tr>
<td>1</td>
<td>1.13*</td>
</tr>
<tr>
<td>2</td>
<td>0.11</td>
</tr>
<tr>
<td>3</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>0.23*</td>
</tr>
<tr>
<td>5</td>
<td>0.21*</td>
</tr>
<tr>
<td>6</td>
<td>0.04</td>
</tr>
<tr>
<td>7</td>
<td>0.06</td>
</tr>
<tr>
<td>8</td>
<td>0.1</td>
</tr>
<tr>
<td>9</td>
<td>0.24*</td>
</tr>
<tr>
<td>10</td>
<td>0.12</td>
</tr>
<tr>
<td>11</td>
<td>0.22*</td>
</tr>
</tbody>
</table>

* Aluminium concentrations exceeding the EC directive MAC standard.
Table 8 - Element concentrations of test waters at field trial sites: week 1

<table>
<thead>
<tr>
<th>TRIAL SITE</th>
<th>ALUMINIUM (mg/l Al)</th>
<th>CALCIUM (mg/l Ca)</th>
<th>SODIUM (mg/l Na)</th>
<th>POTASSIUM (mg/l K)</th>
<th>IRON (mg/l Fe)</th>
<th>MAGNESIUM (mg/l Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.16</td>
<td>14.2</td>
<td>3.8</td>
<td>0.4</td>
<td>1.8</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>0.23*</td>
<td>18.0</td>
<td>7.8</td>
<td>1.1</td>
<td>2.36</td>
<td>2.3</td>
</tr>
<tr>
<td>3</td>
<td>0.09</td>
<td>39.2</td>
<td>4.3</td>
<td>0.4</td>
<td>0.120</td>
<td>2.4</td>
</tr>
<tr>
<td>4</td>
<td>0.04</td>
<td>7.7</td>
<td>6.9</td>
<td>1.4</td>
<td>0.715</td>
<td>5.4</td>
</tr>
<tr>
<td>5</td>
<td>0.3*</td>
<td>31.1</td>
<td>4.7</td>
<td>1.7</td>
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<td>0.3</td>
</tr>
<tr>
<td>6</td>
<td>0.45*</td>
<td>42.9</td>
<td>7.7</td>
<td>6.6</td>
<td>0.047</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>0.05</td>
<td>17.6</td>
<td>8.5</td>
<td>1.2</td>
<td>0.111</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>0.04</td>
<td>16.2</td>
<td>5.2</td>
<td>0.6</td>
<td>0.027</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>0.04</td>
<td>34.0</td>
<td>7.7</td>
<td>4.0</td>
<td>0.050</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>0.14</td>
<td>44.0</td>
<td>13.5</td>
<td>0.8</td>
<td>0.026</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>0.08</td>
<td>46.7</td>
<td>9.8</td>
<td>1.9</td>
<td>8.40</td>
<td>-</td>
</tr>
</tbody>
</table>

* Aluminium concentrations exceeding the EC directive limits |
- No data collected

Table 9 - Element concentrations of test waters at field trial sites: week 2

<table>
<thead>
<tr>
<th>TRIAL SITE</th>
<th>ALUMINIUM (mg/l Al)</th>
<th>CALCIUM (mg/l Ca)</th>
<th>SODIUM (mg/l Na)</th>
<th>POTASSIUM (mg/l K)</th>
<th>IRON (mg/l Fe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.61*</td>
<td>16.6</td>
<td>3.8</td>
<td>0.5</td>
<td>9.55</td>
</tr>
<tr>
<td>2</td>
<td>0.06</td>
<td>18.3</td>
<td>8.0</td>
<td>1.2</td>
<td>0.257</td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
<td>41.7</td>
<td>4.5</td>
<td>0.4</td>
<td>0.019</td>
</tr>
<tr>
<td>4</td>
<td>0.12</td>
<td>10.5</td>
<td>7.5</td>
<td>2.1</td>
<td>0.202</td>
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<tr>
<td>5</td>
<td>0.32*</td>
<td>23.2</td>
<td>4.6</td>
<td>1.3</td>
<td>0.079</td>
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<tr>
<td>6</td>
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<td>32.0</td>
<td>6.2</td>
<td>4.6</td>
<td>1.05</td>
</tr>
<tr>
<td>7</td>
<td>0.04</td>
<td>16.8</td>
<td>8.1</td>
<td>1.1</td>
<td>0.064</td>
</tr>
<tr>
<td>8</td>
<td>0.04</td>
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<td>4.8</td>
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<td>0.055</td>
</tr>
<tr>
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<td>0.04</td>
<td>30.2</td>
<td>7.7</td>
<td>1.7</td>
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<tr>
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<td>14.4</td>
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<td>0.026</td>
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<td>0.04</td>
<td>57.7</td>
<td>9.7</td>
<td>1.7</td>
<td>0.143</td>
</tr>
</tbody>
</table>

* Aluminium concentrations exceeding the EC directive limits

* Could we have some consistency in the number of decimal places reported? 1.8 mg/l does not mean the same as 1.800 mg/l. 1.8 suggests ± 0.1 whereas 1.800 suggests ± 0.001

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### Table 10 - Element concentrations of test waters at field trial sites: week 3

<table>
<thead>
<tr>
<th>TRIAL SITE</th>
<th>ELEMENT CONCENTRATIONS</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ALUMINIUM (mg/l Al)</td>
<td>0.1</td>
<td>0.13</td>
<td>0.22*</td>
<td>2.13*</td>
</tr>
<tr>
<td></td>
<td>CALCIUM (mg/l Ca)</td>
<td>14.2</td>
<td>19.9</td>
<td>39.2</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>SODIUM (mg/l Na)</td>
<td>3.9</td>
<td>8.0</td>
<td>4.7</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>POTASSIUM (mg/l K)</td>
<td>0.8</td>
<td>2.7</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>IRON (mg/l Fe)</td>
<td>1.21</td>
<td>1.15</td>
<td>0.076</td>
<td>11.8</td>
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</table>

* Aluminium concentrations exceeding the EC directive MAC

### Table 11 - Element concentrations of test waters at field trial sites: week 4

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<th>ELEMENT CONCENTRATIONS</th>
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<th></th>
</tr>
</thead>
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<td>ALUMINIUM (mg/l Al)</td>
<td>0.2</td>
<td>0.05</td>
<td>0.11</td>
<td>0.51*</td>
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<td>CALCIUM (mg/l Ca)</td>
<td>20.2</td>
<td>16.4</td>
<td>35.5</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td>SODIUM (mg/l Na)</td>
<td>4.6</td>
<td>7.6</td>
<td>4.6</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>POTASSIUM (mg/l K)</td>
<td>4.2</td>
<td>2.5</td>
<td>1.4</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>IRON (mg/l Fe)</td>
<td>1.12</td>
<td>0.122</td>
<td>0.039</td>
<td>3.16</td>
</tr>
</tbody>
</table>

* Aluminium concentrations exceeding the EC directive MAC
SECTION 5 - APPRAISAL OF SEM METHODS FOR QUANTIFYING CEMENT LEACHING

5.1 INTRODUCTION

A series of studies was undertaken on behalf of WRC by the Materials Research Institute, Sheffield (MRI). This work was aimed at quantifying lime leaching rates by direct analysis of cement samples. It was hoped that this would enable a determination of how long it would take, under defined conditions, for all the lime to be leached; this in turn would provide a direct indication of how long water quality problems associated with lime leaching would persist and also a measure of the effective lifetime of the cement as an active corrosion inhibitor (the alkaline environment generated within the cement acts as an active corrosion inhibitor).

5.2 SUMMARY

Cement mortar lining samples were exposed under static conditions for up to four months to a range of alkalinities of supply water.

The following analyses were carried out on the exposed test samples and unexposed control samples:-

(i) Scanning Electron Microscopy (SEM) morphological analysis of the cement surfaces.

(ii) Energy Dispersive X-ray Analysis (EDXA) of the cement surfaces using ZAF correction. 

(iii) X-ray mapping of sectioned cement samples.

(iv) Microprobe analysis as a function of section displacement to determine the calcium (and hence CaOH₂) profiles of the cements.

The morphological analysis indicated that lime leaching was occurring from the exposed surface of the cement samples in all water types. This
process was resulting in a 'roughening' of the surface caused by the exposure of relatively insoluble silicate (SiO₂) aggregates, which were protruding from the surface.

Quantitative X-ray analysis of cement surfaces and sections gave unreliable results, the problem was related to the porous nature and uneven surface finish of the cements.

Elemental mapping of sectioned samples showed the distribution of SiO₂ aggregates surrounded by a distribution of O, Al, S, Ca and Fe containing materials. Potassium associated with Al formed clusters/particles within the samples. No significant elemental gradient was observed across any sample. However, surface depletion of Ca was observed for the four month exposed samples.

Most cement binder erosion occurred in the first 0 - 0.5mm layer. This may account for all the CaOH₂ leaching observed.

In conclusion, the quantitative methods of analysis examined were not capable of resolving the amount of lime leached for exposures of cement samples up to four months; this was because of the nature of the samples.

The qualitative method of X-ray mapping showed lime depletion to have occurred within the first 0.5mm of the surface exposed samples. This technique is comparable with the use of phenolphthalein indicator to show the distribution of free lime in cement sections; however, X-ray mapping is capable of showing the distribution of elements other than calcium e.g. Al, Fe, and Si.

The quantitative methods examined may prove useful for the analysis of cement samples exposed for significantly longer periods and this merits further examination.
SECTION 6 - RECOMMENDATIONS

(a) Factory applied cement mortar lined pipes should not be used in conditions of very low alkalinity (less than 25mg CaCO₃/l), where pipe diameters are small and retention times are relatively long. Caution should be exercised when considering the use of such linings when the total retention time is very high, even though the supply water alkalinity may be in excess of 25mg CaCO₃/l.

(b) Further work should be conducted to determine whether theoretical extrapolation of the data can be used to provide an indication of the potential pH levels in a given defined system.

(c) The use of approved seal coatings, epoxy linings and other methods of preventing elevated pH should be considered in future investigations.

(d) Further field data should be collected to substantiate the findings of this work, which are mainly based on laboratory and test-rig data.
SECTION 7 – REFERENCES


* Report available from WRC bookshop, Medmenham laboratory.