ER 357E

INCREASES IN LEAD AND pH LEVELS
FOLLOWING CEMENT MORTAR LINING IN LOW
ALKALINITY WATER AREAS
INCREASES IN LEAD AND pH LEVELS FOLLOWING CEMENT MORTAR LINING IN LOW ALKALINITY WATER AREAS
SUMMARY

I OBJECT

To determine whether the increase in pH levels seen after cement mortar lining will increase lead concentrations at the consumers' tap.

II REASON

When small diameter mains with low flows in low alkalinity water areas are lined with cement mortar, the pH of the conveyed water can be elevated above the EC directive MAV of 9.5 for a considerable time. This work investigates whether an increase in pH will lead to an increase in plumbosolvency.

III CONCLUSIONS

Initial laboratory studies indicated that at pH levels above 10 the plumbosolvency would increase significantly.

Field trials confirmed that lead concentrations would be increased at high pH levels but if the pH levels were kept below 10.5 the lead concentrations should remain below the current EC directive MAC.

IV RECOMMENDATIONS

To reduce the risk of high lead concentrations after cement mortar lining the pH levels should be kept below 10.5.

Further field trials may be required to determine whether these results are applicable to other water quality areas.

The EC directive MAC relating to lead concentrations is currently being revised. The conclusions of this report may require revision in the light of future changes to the MAC.
Laboratory studies of Humberside College of Higher Education were conducted to determine whether plumbosolvency was increased at high pH levels due to lime. A field trial was then carried out in Birmingham to check whether the laboratory results applied under normal cement mortar lining conditions.
CONTENTS

1. INTRODUCTION 1
2. OBJECTIVE 2
3. PROCEDURE 2
4. RESULTS 3
5. DISCUSSION 4
6. CONCLUSIONS 5
7. RECOMMENDATIONS 5

ACKNOWLEDGEMENTS

REFERENCES

TABLES

FIGURES

APPENDIX A
INCREASES IN LEAD AND pH LEVELS FOLLOWING CEMENT MORTAR LINING IN LOW ALKALINITY WATER AREAS

1. INTRODUCTION

Previous studies have shown that the cement mortar lining of water mains in areas with low alkalinity water can result in the pH levels of the conveyed water being increased\(^1\). The elevated pH levels were found to be highest in small diameter water mains with low flows carrying water with an alkalinity around 10mg/l\(^-1\) (as CaCO\(_3\)). Levels of pH in excess of 12 have been observed, with levels above 10 persisting for many months in some areas.

These high levels of pH caused concern because they exceeded the EC Directive maximum admissible value (MAV) of 9.5\(^2\). However this level is not set because of health reasons\(^3\) and the direct effect of high pH levels with low buffering capacities on health is difficult to quantify\(^4\).

Another reason for high pH levels being of concern was the possibility that increased pH levels may increase plumbosolvency in lead services. Plumbosolvency at low pH levels is well documented and water is treated to provide a pH at which plumbosolvency is at minimum (around pH 8.5)\(^5\).

To investigate plumbosolvency at the higher pH levels encountered following cement mortar lining a series of laboratory studies were carried out at the Humberside College of Higher Education. The experimental procedure and results are presented in their summary report which is attached as Appendix A.

The report concluded that: "the laboratory tests suggest that the cement mortar relining of mains could lead to significant increases in plumbosolvency when pHs above 10 are maintained". Following these results it was necessary to conduct field trials to establish the extent to which these effects occurred in practice.

This report details the field trial carried out to investigate whether lead levels were elevated following the cement mortar relining of a main in the Birmingham area of Severn Trent Water (STW).
2. **OBJECTIVES**

(a) To investigate whether lead levels are increased at the consumer's tap following the cement mortar lining of a 100mm diameter main in an area with very low alkalinity water.

(b) If lead levels are increased, is this related to the elevated pH levels or to the disturbance on the main during the relining procedure (characterised by increases in iron and turbidity following scraping and prior to lining).

3. **PROCEDURE**

The main chosen for the trial was the 100mm diameter main in Garisbrook Road, Birmingham. For the purpose of the trial the main was made into a dead end by inserting a valve halfway along its length. Samples for water quality examination were taken from an outside tap situated at a consumer's house (16 Garisbrook Road) near the dead end. This outside tap was supplied through about 6m of lead service pipe.

The trial consisted of monitoring water quality from the sample point for 3 days prior to scraping. The main was then scraped and returned to service for 3 days, after which it was cement mortar lined with OPC mortar and samples were taken until lead and pH levels were satisfactory.

The timetable of events was as follows:

- **02.02.88** Samples taken 10.00 hours
- **03.02.88** Samples taken 10.00 hours
- **04.02.88** Samples taken 10.00 hours
- **05.02.88** Main scraped and returned to service
- **08.02.88** Sample taken 09.00 hours, then main cement mortar lined
- **09.02.88** Main returned to service and sample taken 13.30 hours
- **10.02.88** Samples taken 10.00 hours
- **11.02.88** Samples taken 10.00 hours
- **12.02.88** Samples taken 10.00 hours
- **15.02.88** Samples taken 10.00 hours
<table>
<thead>
<tr>
<th>Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.02.88</td>
<td>Samples taken</td>
</tr>
<tr>
<td>18.02.88</td>
<td>Samples taken</td>
</tr>
<tr>
<td>22.02.88</td>
<td>Samples taken</td>
</tr>
<tr>
<td>24.02.88</td>
<td>Dead end valve opened to increase flow through main and reduce pH levels</td>
</tr>
<tr>
<td>25.02.88</td>
<td>Samples taken</td>
</tr>
<tr>
<td>01.03.88</td>
<td>Samples taken</td>
</tr>
<tr>
<td>08.03.88</td>
<td>Samples taken</td>
</tr>
</tbody>
</table>

Samples were taken for the following parameters:

- pH — on-site measurement
- Conductivity — on-site measurement
- Lead — first draw off, unfiltered and filtered (0.4μm)
- Lead — flushes sample, unfiltered and filtered (0.4μm)
- Lead — 30 min stagnation sample, unfiltered and filtered (0.4μm)
- Manganese
- Iron
- Turbidity
- Total alkalinity

The turbidity and alkalinity were analysed by STW and the lead, iron and manganese were preserved and analysed at WRc Medmenham.

4. RESULTS

Table 1 shows the complete set of data collected during the trial.

Before scraping and lining took place the pH, total alkalinity, turbidity, manganese and iron levels were fairly constant. The total lead levels for the flushed and 30 minute stagnation samples were also relatively constant and below their EC Directive limits of 50 and 100μg/l respectively.

The sample taken on the 8.02.88 after the main had been scraped and returned to service showed elevated iron (0.41mg/l) and turbidity (1.2 FTU) levels which was to be expected due to the disturbance of the main and the newly exposed iron
surface of the pipe. In addition the pH level was increased slightly but this was probably due to a new cement lining upstream of the test main. Lead levels however were not increased above the levels seen before scraping took place.

On the 8.02.88 the main was lined with cement, allowed to cure overnight and returned to service on the 9.02.88. The sample taken on that day showed very high pH levels (12.3) and increased alkalinity, turbidity and lead levels. The levels of lead seen on this day were around 1300μg/l after a 30 minute stagnation test.

On successive days after lining the pH levels gradually decreased from 12.3 to 11.7 after 13 days. This was coupled with a decrease in lead levels to 258μg/l after a 30 minute stagnation test.

On the 24.02.88 (14 days after lining) the dead end valve in Garisbrook Road was opened to increase the flow through the main and to reduce the pH levels. This proved effective and the pH dropped from 11.7 to 9.9 in the space of two weeks. This was accompanied by a decrease in the lead levels to 24μg/l after a 30 minute stagnation test.

5. DISCUSSION

The results show that before scraping and lining took place the lead concentrations were below the levels laid down in the EC Directive\(^\text{(2)}\). After scraping the main and returning it to service the lead concentrations remained at a similar level to that seen before the main was disturbed.

After lining took place however the pH levels were elevated and all lead levels were increased. This would suggest that the increase in pH gives rise to an increase in lead concentrations. Figures 1, 2 and 3 show lead levels plotted against pH for a 30 minute stagnation sample, a flushed sample and a first draw sample respectively. The graphs show the total lead level and the proportion of that which is made up of soluble lead.
The figures suggest that as pH increases above 10.5 the lead levels increase dramatically. On Figures 1 and 2 the respective EC Directive MACs for lead are indicated. These indicate that if pH levels were kept below 11, the lead concentrations should remain below MAC levels.

6. CONCLUSIONS

1. After cement lining the dead end test main, pH levels were increased to above the EC Directive MAV\(^{(2)}\).

2. After scraping the main lead levels were not increased.

3. After cement lining the main, lead levels were increased to above the EC Directive MAC\(^{(3)}\).

4. The high lead concentrations consisted mainly of soluble lead.

5. Lead levels remained above the current EC Directive MAC whilst the pH remained above 11.

6. The field trials confirmed the earlier laboratory studies (Appendix A) that showed increased pH levels would result in increased lead concentrations.

7. RECOMMENDATIONS

1. To avoid increased lead concentrations following cement relining the pH level should be maintained below 10.5.

2. Field trials in other water quality areas where pH levels are increased after cement mortar lining need to be carried out to determine whether these results are applicable to other areas.

3. The EC directive MAC relating to lead concentrations is currently being reviewed. The conclusions of this report may require revision in the light of future changes to this MAC.
ACKNOWLEDGEMENTS

I would like to acknowledge the assistance given by the staff of Severn Trent Water during the field trials carried out in Birmingham.
REFERENCES


4. ROSE P. Alkaline pH and Health – A review prepared for the Water Research Centre. BIBRA. (Internal distribution only).

| DATE     | TIME | DAYS AFTER | pH | CONDUCTIVITY (μS/cm) | TOTAL ALKALINITY (mg/l CaCO3) | TURBIDITY (FNU) | MANGANESE (mg/l) | IRON (mg/l) | LEAD A (μg/l) | LEAD B (μg/l) | LEAD C (μg/l) | LEAD D (μg/l) | LEAD E (μg/l) | LEAD F (μg/l) |
|----------|------|------------|----|----------------------|-------------------------------|----------------|-----------------|-------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| 2.02.88  | 10.00| 8.68       | 76.3| 12                   | 0.7                           | 0.011           | 0.166           | 34          | 35            | 27            | 36            | 24            |               |               |
| 3.02.88  | 10.00| 8.68       | 88.8| 13                   | 0.8                           | 0.010           | 0.173           | 45          | 16            | 16            | 11            | 32            |               |               |
| 4.02.88  | 10.00| 9.24       | 88.7| 14                   | 0.7                           | 0.010           | 0.160           | 28          | 12            | 20            | 7             | 43            | 26            |               |
| 8.02.88  | 19.00| 10.28      | 84.6| 13                   | 1.2                           | 0.016           | 0.469           | 40          | 35            | 24            | 10            | 49            | 18            |               |
| 9.02.88  | 13.30| 12.31      | 1500.0| 300                  | 2.0                           | 0.011           | 0.161           | 892         | 1190          | 800           | 732           | 1300          | 1100          |               |
| 10.02.88 | 10.00| 1         | 11.78| 432.0                | 110                           | 0.9             | 0.136           | 484         | 472           | 151           | 174           | 410           | 290           |               |
| 11.02.88 | 10.00| 2         | 11.40| 268.0                | 76                            | 0.8             | 0.010           | 0.155        | 164           | 152           | 86            | 40            | 250           | 260           |               |
| 12.02.88 | 10.00| 3         | 11.44| 246.0                | 70                            | 1.2             | 0.010           | 0.138        | 86            | 98            | 58            | 48            | 224           | 207           |               |
| 15.02.88 | 10.00| 6         | 11.56| 258.0                | 71                            | 1.3             | 0.018           | 0.151        | 166           | 114           | 68            | 63            | 221           | 199           |               |
| 16.02.88 | 10.00| 7         | 11.30| 188.0                | 60                            | 4.9             | 0.062           | 0.723        | 158           | 125           | 64            | 34            | 45            | 42            |               |
| 18.02.88 | 10.00| 9         | 11.10| 143.0                | 51                            | 0.7             | 0.009           | 0.142        | 155           | 44            | 33            | 19            | 88            | 74            |               |
| 22.02.88 | 10.30| 13        | 11.72| 383.0                | 100                           | 0.7             | 0.010           | 0.143        | 241           | 253           | 83            | 111           | 258           | 224           |               |
| 25.02.88 | 10.00| 16        | 10.42| 92.6                 | 27                            | 1.0             | 0.010           | 0.140        | 313           | 23            | 18            | 16            | 36            | 25            |               |
| 1.03.88  | 10.00| 21        | 10.24| 89.1                 | 33                            | 1.0             | 0.011           | 0.152        | 44            | 37            | 19            | 12            | 17            | 10            |               |
| 8.03.88  | 10.00| 28        | 9.92 | 90.8                 | 24                            | 0.6             | 0.013           | 0.137        | 21            | 13            | 14            | 7             | 24            | 14            |               |

**KEY:**
- **LEAD A** = FIRST DRAW OFF  - TOTAL
- **LEAD B** = FIRST DRAW OFF  - FILTERED (0.4 um)
- **LEAD C** = FLUSHED SAMPLE  - TOTAL
- **LEAD D** = FLUSHED SAMPLE  - FILTERED (0.4 um)
- **LEAD E** = 30 min. STAGNATION - TOTAL
- **LEAD F** = 30 min. STAGNATION - FILTERED (0.4 um)
FIGURE 1

LEAD vs pH (30 min. stagnation sample)

KEY

<table>
<thead>
<tr>
<th>TOTAL LEAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOLUBLE LEAD</td>
</tr>
</tbody>
</table>

LEAD (ug/L)

PH units

EC MAC

100
FIGURE 3

LEAD vs pH (first draw off)

KEY

TOTAL LEAD

SOLUBLE LEAD

LEAD (µg/l)

pH units

8.5  9   9.5  10  10.5  11  11.5  12  12.5
APPENDIX A

Report by: HUMBERSIDE COLLEGE OF HIGHER EDUCATION,
SCHOOL OF FOOD STUDIES

PLUMBOSOLVENCY PROPENSITY OF SOFT WATERS AT ELEVATED
PHs DUE TO LIME
HUMBERSIDE COLLEGE OF HIGHER EDUCATION

SCHOOL OF FOOD STUDIES

PLUMBOSOLVENCY PROPENSITY OF SOFT WATERS AT ELEVATED pH'S

DUE TO LIME : SUMMARY REPORT FOR WRC

Summary

Laboratory pipe rig experiments using new lead pipes and artificial waters, dosed with lime-water to give pH's up to 12, are reported. The results suggest that lime leached into very soft waters may lead to significant plumbosolvency at pH's in the region of 10 and above, and very high lead levels at higher pH's. For a range of low alkalinity waters, pH has the dominant effect.

Pipes pretreated at pH 8 give similar results to new lead pipes.

1. Background

When cast iron mains have been spray coated with a lining of cement mortar, the leaching of lime into the water produces an appreciable rise in pH, up to 12 in some cases. With soft waters, elevated pH's may be maintained for some time, especially in deadend legs.

These series of experiments, using the standard plumbosolvency propensity test at Humberside College, were to investigate whether a possible plumbosolvency problem exists at these elevated pH's. It was agreed that artificial waters, prepared from distilled water, would be used for these tests, and that the leaching effects would be simulated by lime-water additions.

2. Plumbosolvency Propensity Test

25 litres of the test water is required. It is pumped at a slow flow rate (≈ 30 ml/s/hr) through a 6 inch length of new lead pipe at 25°C. Lead concentrations in the exit water are measured every few days, normally stabilising within 10 days. The residence time of the water in the pipe is about 30 minutes, and the lead levels obtained are generally of comparable magnitude to conventional 30-minute stagnation lead values from lead-plumbed properties.

Scanning electron microscopy of the pipe deposits may reveal different types of crystal structure related to observed lead levels.
3. Experimental: Preparation of Waters and Pipe rig run

5 series of experiments were completed, each consisting of 5 waters. In all cases, the containers were protected from CO₂ ingress by soda-lime absorption tubca.

Lime-water prepared at room temperature (saturated solution) contains 0.16 g/100 mls of Ca (OH)₂. Thus it was calculated that 115 mls of lime-water in 25 litres should produce a calculated alkalinity of 10 (mg/l CaCO₃). When the first series was prepared, it was found that the distilled water had a pH of about 5½. 115 mls of lime-water only increased the pH to 6.5, later increasing to 7.0.

1st Series: Minimum alkalinity. Lime-water additions of 115 mls, 270 mls, 750 mls, 2½ litres and 7½ litres were made to distilled water to give initial pH's of 6.5, 9, 10, 11 and 12. (Pipes W1-W5)

2nd Series: Initial alkalinity higher (Sodium carbonate and carbon dioxide). 2.6 g of Na₂CO₃.10 H₂O were added to each 25 litres of distilled water and the pH reduced to 7.0 with CO₂. Lime water additions of 30 mls, 90 mls, 270 mls, 810 mls and 2430 mls were made. (Pipes W6-W10)

3rd Series: Initial alkalinity higher (Lime-water and carbon dioxide). 1250 mls of lime-water were added to 24 litres of distilled water and the pH reduced to 7.0 with CO₂ to prepare 5 nominally identical waters. Fixed lime-water additions were made as in the second series. (Pipes W11-W15)

4th Series: Minimum alkalinity target. Lime-water additions were made to target pH's of 9, 10, 10½, 11 and 12.

5th Series: Pretreated pipes and minimum alkalinity. Pipes reconditioned at pH 8 for two months (in 2½ ft. lengths) were used. Initially sections of these pipes were re-run on waters at pH 8 (distilled plus lime-water). After 18 days the lead values were stable, and the containers were switched to one containing waters prepared with target pH's 8, 10, 10½, 11 and 12.

Pipes from the first 3 series (W1-10 and W14 and W15) were cut open and the deposits examined by scanning electron microscopy at SCM Chemicals, Stallingborough.
4. Measurement on Waters and Pipe Rig Results

The results are listed in Table 1 for each series in order of increasing lime-water addition. The pH values quoted are those measured during the run. They do not always correspond exactly to the initial or target values.

The alkalinity measurements were not always as expected. Although they increase generally with lime-water addition, there are exceptions and anomalies. For the last 3 series they were confirmed by repeat measurements at a different time. It is possible that there were some variations in distilled water quality and/or CaCO₃ deposition.

In most cases consistent lead values were quickly obtained, and appropriate means and standard deviations are quoted. In the fifth series the mean values for 3 to 7 days after the change to elevated pH waters are also given. It is clear that even for the pretreated pipes, the major changes in lead level occur very rapidly.

5. Discussion: Lead Level vs pH

The results as a whole suggest that, over the range of calcium concentration/alkalinities tested, the dominant influence on the lead level is the pH. In figure 1, the mean lead levels (on a log scale) are plotted against the pH of the water for all of the results.

As expected, a minimum lead level is reached in the region of pH 8 to 8½. However, above about pH 10 the lead level starts to show a very rapid increase with pH. All series follow the same general relationship, although the pretreated pipes tend to give slightly lower values. Very high lead values are obtained for all the waters of the highest pH's.

The loose pipe deposit observed in the first series at pH 10 (W3) appears to give rise to an untypical lead result; it was not repeated in the other series, although a much smaller amount of solid was present in W10 (at pH 10.4). The presence of variable amounts of loose crystal accounts for the large standard deviation of the measured lead value.
6. **Pipe Deposit: Scanning Electron Microscopy**

Pipes W1 and W2 contained some big crystals and patchy deposit. SEM revealed the thicker deposit and the other areas both to consist of hexagonal plates, interpreted as a form of basic lead carbonate, having relatively low solubility under these conditions.

In W3 some of the deposit was loose. Solid crystal, which was present in appreciable amounts in the corresponding tubing, was collected and examined by EDS on the electron microscope. As with the pipe deposit, it contained no calcium or other heavy element, apart from lead. SEM indicated that the surface of the loose granules consisted of thin plate-like crystals, and the background surface was also hexagonal plates. The high lead level obtained in this case must be due to particulate basic lead carbonate.

The deposits in pipes W6–W10 (second series) all consisted of hexagonal plate-like crystals, although they differed in detail. Thus the deposit was very thin in W10 and thickest in W8, the hexagonal plates were very thin in W9 and relatively thin in W6, W7 and W8, and were largest in W9 and W6, of variable sizes in W8 and smallest in W10. No element other that lead was detected by EDS in either thick or thin crystals. Pipe W14 (Third series) was similar to W6.

In W4 and W5 (high lead levels) the deposit was thick and powdery, slightly yellow in W4, and yellow in W5. There was no sign of any definite crystals by SEM nor any loose particulate material. Again no heavy element other than lead was present. This deposit could contain lead hydroxide, formed because of shortage of carbonate. The solubility of lead hydroxide is such that lead levels as high as those observed could easily be achieved. Pipe W15 had an appearance very similar to W4, which had a similar lead level.

7. **Conclusions**

1. The effect of pH is deominate with artificial low alkalinity waters. Pipes pretreated at pH 8 give similar results to new lead pipes.

   (a) As expected, the solubility of the basic lead carbonate deposit decreased as the pH increases up to about pH 8.5.

   (b) With further increase in pH, the solubility of the basic lead carbonate increases again so that significant plumbosolvency might be expected around and above pH 10.

   (c) This is a tendency for loose deposit to be produced leading to the possibility of increased lead levels from particulate basic lead carbonate.

   (d) At higher pH's very high lead levels are observed, probably due to lead hydroxide formation.

2. Hence the laboratory tests suggest that cement-mortar re-lining of mains could lead to significant increases in plumbosolvency when pH's above 10 are maintained. Field trials will be necessary to establish the extent to which these effects occur in practice.
### Table 1: Results

<table>
<thead>
<tr>
<th>Pipe No.</th>
<th>pH During run</th>
<th>Alkalinity (mg/l CaCO₃)</th>
<th>Conductivity (µhos/cm@25°C)</th>
<th>Lead Level (µg/l Pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td><strong>First Series</strong></td>
<td></td>
<td></td>
<td></td>
<td>9-20 Days (5 meas.)</td>
</tr>
<tr>
<td>W1</td>
<td>7.0</td>
<td>28</td>
<td>-</td>
<td>57</td>
</tr>
<tr>
<td>W2</td>
<td>8.7</td>
<td>22</td>
<td>-</td>
<td>32</td>
</tr>
<tr>
<td>W3</td>
<td>10</td>
<td>20</td>
<td>-</td>
<td>2,100</td>
</tr>
<tr>
<td>W4</td>
<td>11</td>
<td>83</td>
<td>-</td>
<td>5,300</td>
</tr>
<tr>
<td>W5</td>
<td>12</td>
<td>170</td>
<td>-</td>
<td>30,000</td>
</tr>
<tr>
<td><strong>Second Series</strong></td>
<td></td>
<td></td>
<td></td>
<td>12-29 Days (4 meas.)</td>
</tr>
<tr>
<td>W6</td>
<td>7.5</td>
<td></td>
<td>-</td>
<td>37</td>
</tr>
<tr>
<td>W7</td>
<td>8.2</td>
<td></td>
<td>-</td>
<td>38</td>
</tr>
<tr>
<td>W8</td>
<td>9.2</td>
<td>40-55</td>
<td>-</td>
<td>54</td>
</tr>
<tr>
<td>W9</td>
<td>9.8</td>
<td></td>
<td>-</td>
<td>70</td>
</tr>
<tr>
<td>W10</td>
<td>10.4</td>
<td></td>
<td>-</td>
<td>214*</td>
</tr>
<tr>
<td><strong>Third Series</strong></td>
<td></td>
<td></td>
<td></td>
<td>11-22 Days (4 meas.)</td>
</tr>
<tr>
<td>W11</td>
<td>7.5</td>
<td>56</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>W12</td>
<td>7.9</td>
<td>66</td>
<td>114</td>
<td>25</td>
</tr>
<tr>
<td>W13</td>
<td>8.4</td>
<td>59</td>
<td>102</td>
<td>41</td>
</tr>
<tr>
<td>W14</td>
<td>9.3</td>
<td>19</td>
<td>54</td>
<td>34</td>
</tr>
<tr>
<td>W15</td>
<td>10.8</td>
<td>104</td>
<td>370</td>
<td>5,600</td>
</tr>
<tr>
<td><strong>Fourth Series</strong></td>
<td></td>
<td></td>
<td></td>
<td>5-23 Days (5-7 meas.)</td>
</tr>
<tr>
<td>W19</td>
<td>9.0</td>
<td>12</td>
<td>260</td>
<td>57</td>
</tr>
<tr>
<td>W16</td>
<td>9.9</td>
<td>24</td>
<td>780</td>
<td>65</td>
</tr>
<tr>
<td>W17</td>
<td>10.5</td>
<td>35</td>
<td>1,440</td>
<td>243</td>
</tr>
<tr>
<td>W18</td>
<td>11.1</td>
<td>76</td>
<td>3,800</td>
<td>2,800</td>
</tr>
<tr>
<td>W20</td>
<td>11.9</td>
<td>455</td>
<td>18,000</td>
<td>35,000</td>
</tr>
</tbody>
</table>

**F**: Measured on retained samples after completion of run

**S**: Unsifted. Filtered measurements 110 and 111 µg/l. Some solid crystal clearly present.

**E**: Appreciable amounts of solid crystal present.
Fig 1: PIPE RIG MEAN LEAD LEVEL vs PH OF WATER

- 1st SERIES: lime-water addition only; new lead pipes
- 2nd SERIES: higher initial alkalinity: \( \text{Na}_2\text{CO}_3 + \text{CO}_2 \)
- 3rd SERIES: higher initial alkalinity: lime-water + \( \text{CO}_2 \)
- 4th SERIES: lime-water addition only
- 5th SERIES: pretreatment

\( \text{Pb (µg/L)} \)

- 1st SERIES: lime-water addition only; new lead pipes
- 2nd SERIES: higher initial alkalinity: \( \text{Na}_2\text{CO}_3 + \text{CO}_2 \)
- 3rd SERIES: higher initial alkalinity: lime-water + \( \text{CO}_2 \)
- 4th SERIES: lime-water addition only
- 5th SERIES: pretreatment

- Lime-water addition only; pipes pretreated at pH 6.