INVESTIGATION INTO THE DEGRADATION OF MORTAR LININGS AND CONCRETE BY MICROORGANISMS IN INDUSTRIAL WATER SYSTEMS

by

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EXECUTIVE SUMMARY

1. Background and motivation

In the past mild steel, covered with organic coatings, has been used extensively for the fabrication of pipework in industrial water systems. Microbially influenced corrosion (MIC) has, however, caused numerous failures with consequent down-time for repair and maintenance.

Replacement materials, such as austenitic stainless steel, have proved to be too expensive for industrial water systems. From an economic viewpoint cement and mortar lining of mild steel pipes may prove to be a viable alternative. Various bacteria, which are commonly found in industrial water systems, may, however, degrade such cement-based lining materials.

This study evaluated the effects of micro-organisms and the concentration of aggressive chemical species on the mortar linings and concrete used to protect the mild steel pipework.

The dramatic increase in MIC in recent years has been directly attributed to the recent drought and subsequent deterioration in water quality experienced in this country. Under drought conditions, industrial water users are forced to operate systems at extremely high cycles of concentration. The effects of the concentration of aggressive species, eg. chlorides and sulphates, on concrete and mortar linings remain to be investigated in those industrial systems where the water is recycled.

Most of the work carried out to date both by local and overseas researchers on concrete and mortar linings has been conducted on sewage systems and marine environments. Very limited information is available relating to industrial cooling systems or fire-water systems.

It has been widely reported that in an aqueous system, microorganisms will attach themselves to available surfaces, forming biofilms or biofouling deposits. Discrete colonies within the biofilm or biofouling deposits on metal or concrete structures can result in material degradation. It was therefore considered important to assess the effects of these bacteria on concrete and mortar linings prior to specifying these materials for use in industrial water systems.

2. Aims of the project

The proposed project was divided into two phases. The first phase was designed to investigate the effects of the bacteria on concrete and mortar linings. Should any deleterious effects be observed as a result of microbiological activity, a second phase of the project would be initiated to examine the possible methods of mitigation, for example the use of biodispersant dosing programmes.

3. Main findings and conclusions

Active microbiologically influenced corrosion occurred in the test rigs as demonstrated by the metal loss determined on the control mild steel samples. The materials evaluation showed no deleterious effects on the concrete and mortar samples under the test conditions.

Uniform microbiological attachment occurred on all the materials evaluated and although complete sterility was not achieved in the sterile rig, the microbiological activity was nevertheless appreciably reduced. The addition of a biodispersant to the non-sterile rig resulted in a significant reduction in the numbers of attached bacteria.

Mortar linings and concrete were therefore considered to be suitable alternative materials for the corrosion protection of industrial water systems with similar water chemistry to that used in this investigation.

4. Recommendations

It was recommended that caution be exercised in specifying concrete or mortar linings for industrial water systems with a significantly different water chemistry to that studied and that the choice between mortar linings and concrete be determined by the mechanical engineering aspects of that system.

It was further recommended that the results of this investigation be published in *Water SA* and the report be distributed to all interested parties in industry.

ABSTRACT

The object of this project was to determine the effects of microorganisms, commonly found in industrial water systems, on mortar linings and concrete. Two test rigs were constructed, one of which was maintained under sterile conditions for the duration of the testing. This allowed for comparison between the chemical and microbiological effects on the materials. Samples of commercially available mortar linings and concrete, obtained from local suppliers, were evaluated. Mild steel panels were used for the measurement of corrosion rates under the test conditions. Mild steel panels, coated with the standard Eskom specified epoxy pipe coating were also included to allow comparison of the respective materials.

Active Microbiologically Influenced Corrosion occurred in the test rigs as demonstrated by the metal loss determined on the mild steel samples. Evaluation of the materials showed no deleterious effects on the concrete and mortar samples under the test conditions, while uniform microbiological attachment was identified on all the materials evaluated. Although complete sterility was not achieved in the sterile rig, the microbiological activity was nevertheless appreciably reduced.

In the second phase of the investigation the addition of a biodispersant to the non-sterile rig resulted in a significant reduction in the numbers of attached bacteria.

Mortar linings and concrete are therefore considered to be suitable alternative materials for the corrosion protection of industrial water systems with similar water chemistry to that used in this investigation. However it is recommended that caution be exercised in specifying mortar linings and/or concrete for an industrial water system with a significantly different water chemistry to that used here.

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1. INTRODUCTION

Historically, mild steel protected with thin-film organic coatings, has been used as the material of fabrication for pipework in industrial water systems. Not only have numerous failures and severe metal loss been experienced as a result of Microbiologically Influenced Corrosion (MIC), but the organic coatings require considerable downtime for repair and maintenance. It has been estimated that the direct costs of MIC in South African industry, i.e. material replacement and chemical treatment, is approximately R400 million per annum (Reference 1). These direct costs do not include consequential downtime/outage costs.

Research work carried out on alternative materials has shown that the austenitic stainless steels, while being more resistant to MIC than mild steel, are nevertheless still prone to fairly severe attack. The high nickel-containing alloys, e.g. 2 RE 10, 2 RK 65 and SANICRO 28, appear to be resistant to MIC (Reference 2). These materials are, however, extremely expensive and are therefore cost prohibitive for general engineering applications, i.e. industrial water systems.

Mortar linings and concrete require considerably less downtime for repairs and maintenance than do organic coatings and are far less costly than the high nickel alloys. From an economic point of view therefore, providing these materials are not prone to MIC, they would provide a cheaper alternative.

The dramatic increase in MIC in recent years has been directly attributed to the recent drought and subsequent deterioration in water quality experienced in this country (Reference 3). Under drought conditions, industrial users are forced to operate systems at extremely high cycles of concentration (Reference 4). The effects of the concentration of aggressive species, e.g. chlorides and sulphates, on concrete and mortar linings have to be investigated in those industrial systems where the water is recycled. It is considered that possibly these species will not have any deleterious effects on concrete and mortar linings at the commonly used concentrations. It is then possible that these materials could be used in systems operating at even higher cycles of concentration, thus reducing water consumption and permitting such systems to operate under zero effluent discharge conditions.

The major portion of the work carried out to date both by local and overseas researchers on concrete and mortar linings has been conducted on sewage systems and marine environments (References 5 and 6). Very limited information is available relating to industrial cooling systems or fire-water systems. The literature, as well as one Eskom case study, have identified bacteria which degrade concrete (References 7 and 8), for example *Thiobacillus spp* and the Anaerobic Sulphate Reducing Bacteria (ASRBs). These bacteria are commonly found in industrial water systems throughout South Africa (Reference 9).

It has been widely reported that in an aqueous system, microorganisms will attach to available surfaces by means of extracellular polysaccharide polymers, forming biofilms or biofouling deposits (References 10 and 11). The physical presence of such deposits in cooling water systems can result in frictional resistance (Reference 12). In addition, discrete colonies within

the biofilm or biofouling deposits on metal or concrete structures can result in material degradation. It was therefore considered important to assess the effects of these bacteria on concrete and mortar linings prior to specifying these materials for use in industrial water systems.

The project was divided into two phases. The first phase was designed to investigate the effects of the previously mentioned bacteria on concrete and mortar linings. Should any deleterious effects be observed as a result of microbiological activity, a second phase of the project would be initiated. The second phase would examine the possible methods of mitigation, for example the use of biodispersant dosing programmes.

2. MATERIALS AND METHODS

2.1 Test Materials

The materials evaluated were:

-concrete

-mortar

-mild steel

-epoxy coated mild steel

2.1.1 Concrete

ASTM-C1012 for the testing of length changes in hydraulic mortars (Reference 13) specifies a prism size of 60mm x 10mm x 10mm. The size of the aggregate used in the concrete mix for standard production water pipes is generally of the order of 20mm in diameter. The use of the specified prisms is precluded as a uniform composition of all sample prisms would not be guaranteed.

On the recommendation of a leading concrete manufacturer, Rochla Pipes, prisms were cut to a size of 50mm x 50mm x 5mm, from 150mm cubes, using a wet cutting technique. The cubes are standard, production line quality control samples and are thus considered to be representative of mass produced concrete water pipes. Dimensional measurements were taken at a number of points on each prism, as illustrated in Figure 1.

2.1.2 Mortar

The mortar samples were prepared by a commercial mortar lining applicator (Magnaflux), spraying the mortar into wooden moulds. This is a standard mortar lining application technique. Various compositions of mortar were used, but are typically mixtures used for the lining of water pipes. The details of the various compositions are listed in Table 1.

The dimension of these prisms was 50mm x 50mm x 20mm. The prism thickness (20mm) was dictated by the application technique.

2.1.3 Mild Steel

The mild steel coupons, 50mm x 50mm x 2mm, were included in these tests as the corrosion rates of mild steel in cooling water, both as a result of chemical and microbiological corrosion, are well documented (Reference 14). These coupons can thus be regarded as controls in these tests by measuring the corrosion rates under these specific test conditions. The thickness of these coupons (2mm) was selected to enable accurate mass loss measurement.

2.1.4 Epoxy Coated Mild Steel

Mild steel coupons, 50mm x 50mm x 2mm, were coated with the standard Eskom pipe coating, a polyamide cured epoxy (Copon EP2300). This is the specified coating for the corrosion protection of cooling water systems on Eskom power stations. These samples were included to allow comparison of the performance of the respective materials. The dry film thicknesses of the coating on the test samples were to specification, i.e. average 250µm.

In order to evaluate any visible or microstructural changes in the test materials, unexposed samples of all the test materials were retained.

2.2 Test Rigs

Two identical rigs were constructed. The material of fabrication was Poly Vinyl Chloride (PVC), as this material is considered to be relatively inert. The test rigs are illustrated in Figure 2.

Water was pumped through each rig at a flowrate of 0,8 metres per second. This flowrate is representative of flow conditions generally experienced in power station cooling systems. During the commissioning of the rigs, severe overheating problems necessitated the retrofitting of a cooling system.

Any localised turbulent flow in the test sections of the rigs could give erroneous results in terms of the biofilm build-up. To avoid any localised flow conditions, the inlet and outlet of the test section of each rig was fitted with a waterbox. These waterboxes were flared at an angle of 12 to these test sections. This angle has been proven to reduce localised flow turbulence.

In addition the concrete and mortar prisms, being respectively approximately 5mm and 20mm in thickness, were arranged in a staggered 3-4-3-4 arrangement to eliminate any localised turbulence in the flow around the prisms. The mild steel and epoxy coated coupons, were only 2mm in thickness and thus localised flow patterns should not occur (see Figure 3).

Each sample was held in position in the test sections by means of PVC slides, on the lower cross members and PVC slides and nylon screws on the upper cross members, as illustrated in Figures 4 and 5.

2.3 Rig Operation

2.3.1 Sterile Control

It is imperative that the distinction between chemical and microbiological degradation be made. Microbiological effects will thus be negated in one of the test rigs, by operating it under sterile conditions. Heating the water to 75°C to achieve sterilsation was found to be impractical. Leakage occurred due to distortion of the PVC.

Therefore, growth of microorganisms in the control rig was inhibited by addition of the biocide isothazolin, at 5ppm, on a weekly basis.

2.3.2 Cooling System

The overheating of the rigs can be directly attributed to the poor heat transfer characteristics of the PVC material. Numerous problems were experienced with the optimisation of the cooling system.

The required temperature of the circulating water under operating conditions was 35°C, this being the average temperature in power station cooling water systems.

2.3.3 Circulating Water

The circulating (test) water was obtained from the North-side cooling water system at Duvha Power Station. The chemical composition of the water is detailed in Table 2. This water contains those microorganisms which are known to be aggressive with respect to the test materials.

On a monthly basis, immediately prior to sterilisation of the control rig, 25 litres (approximately one third) of the circulating water was drained from each rig and replaced with fresh cooling water from Duvha Power Station. This was done to ensure that major changes in the chemical composition of the water would not occur as a result of microbiological activity.

It was originally planned that, should any deleterious effects, as a result of microbiological activity be observed on any of the test materials, possible methods of mitigation would be investigated. No deleterious effects were observed. However, where cooling water systems are operated at high cycles of concentration, the addition of a biodispersant may be necessary for algal control. The second phase of the project therefore involved the weakly addition of a widely used biodispersant, at 20ppm, to the non-sterile rig.

Microbiological analysis was carried out on the circulating water in both rigs on a weekly basis and chemical analysis was carried out fortnightly, for both phases of the investigation.

2.4 Analyses

2.4.1 Sampling Procedures

In the first phase of the project both rigs were run for a period of six months. Every two months the rigs were opened and four samples of each test material removed under sterile conditions. Microbiological analyses and material evaluations were carried out on all the samples.

Localised flow patterns could be created by the removal of the concrete and mortar samples. Their vacant positions in the sample holders were therefore filled with inert PVC blanks.

On completion of the first phase of the investigation, both rigs were drained and refilled with water, which was again obtained from the North side cooling water system at Duvha Power Station. Four samples of each material type were then placed in each rig. In order to avoid any localised flow patterns, the spare sample holders were filled with PVC blanks.

Both rigs were run for a period of one month, with weekly slug dosing of a biodispersant into the non-sterile rig and weekly dosing of a biocide into the sterile rig. Microbiological analyses and material evaluations were then carried out.

2.4.2 Microbiological Analyses

Three of the four samples removed, at each sampling, from each rig were placed in sterile Ringer solution containing 20ppm of a biodispersant and shaken for thirty minutes. The resultant suspension of microorganisms was analysed for the presence of the following:

- total aerobic and anaerobic bacteria

- ASRB's

- aerobic and anaerobic acid producing bacteria

The samples were removed from the Ringer solution and the materials evaluation (see Paragraph 2.4.3) carried out. The remaining sample was processed for viewing under the Scanning Electron Microscope (SEM) to determine the extent of biofilm formation.

2.4.3 Material Evaluation

Visual Examination

As soon as the samples were removed from the rigs, prior to being immersed in the Ringer solution, a detailed visual examination was carried out. All details of the visual appearance of the samples were recorded and photographed.

After the biofilm removal, as detailed in Paragraph 2.4.2, the samples were washed with potable water and carefully dried using clean cotton cloths. The visual appearance of the cleaned samples was compared with the unexposed retained samples and any differences in the appearance of the samples recorded.

Dimensional Measurements

The dimensions of the removed samples were carefully measured at the points detailed in Figure 1 in accordance with ASTM-C1012. These measurements were compared with the measurements of the prisms prior to exposure.

Mass Loss Measurements

After the details of the visual appearance of the mild steel samples were recorded, the samples were cleaned again, using a standard cathodic cleaning method ASTM-G1 (Reference 15). The samples were weighed and the mass losses calculated.

Microscopy

The concrete and mortar samples were sectioned and the exposed cross sections examined under a stereo microscope and a scanning electron microscope. These examinations determine whether the microstructure of the material was altered in any way as a result of chemical effects or microbiological activity. For comparison, the unexposed samples were also examined.

Chemical Analysis of Corrosion Products

It has been shown that the activity of the *Thiobacillus* spp. on the surface of concrete produces two different corrosion products. (Reference 16). These products are gypsum and ettringite, with the gypsum being produced on the surface of the concrete at low pH and the ettringite within cracks at high pHs.

Any corrosion products observed on the surface of the test samples, were analysed using either X-ray Diffraction (XRD) or Energy Dispersive X-ray Analysis Techniques.

3. RESULTS AND DISCUSSION

3.1 Visual Examination

The four samples of each test material removed from the rigs, at two monthly intervals during the first phase of the project, were visually examined for indications of degradation. There were no visible differences between the sterile and non-sterile samples. A fine brown deposit was observed on all the samples. This deposit, which was determined as being iron oxide, the corrosion product from the mild steel samples, was easily removed with a bristle brush and potable water.

The mild steel samples which were removed after 2, 4 and 6 months' exposure, were the only samples in the first phase displaying signs of MIC. The attack was more severe in the areas located under the sample holders (Figure 6). This can be explained as these crevice areas would be anaerobic, thus encouraging the growth of ASRB's. These localised effects were also observed on the sterile samples. The biocide added to the sterile rig would have been excluded from these crevices.

Blistering was observed on a number of the epoxy coated mild steel samples (Figure 7). This blistering was, however, localised and on every sample where blistering was noted, this occurred diagonally across one corner of the panel. During the preparation of the epoxy coated samples, for ease of application of the successive coats of the epoxy material, the samples were suspended by means of a small clamp to allow the coating to cure. This clamp was applied to one corner of the sample. The localised failure of the coating is therefore considered to be due to the contamination of the substrate by these clamps. No colour change of the epoxy coatings, as was observed in a previous study, was noted on any of the samples (Reference 17).

The samples from the second phase of the investigation were similar in appearance to those sampled during the first phase. Here again, a fine brown deposit was observed on all the samples, which was easily removed and localised attack of the mild steel samples was evident. No blisters were observed on the epoxy coated mild steel samples. The clamps were thoroughly cleaned and degreased prior to use, proving that the blisters in the first set of samples were due to an application problem. Again, no colour change of the epoxy coating was observed.

3.2 Microbiological Analysis

The bulk water in both the sterile and non-sterile rigs was microbiologically analysed once a week for the duration of the first phase. Total aerobic and anaerobic bacteria as well as H_2S producing bacteria were quantified. The results are shown in Figure 8. The number of planktonic bacteria in the bulk water remained fairly constant during the first phase of the investigation. However, the anaerobic bacteria increased in the last month of operation. The SRB's in the non-sterile rig were too numerous to count for the duration of the test. The numbers of bacteria in the sterile rig were significantly lower than in the non-sterile rig. However, large fluctuations in the numbers of bacteria were noted. SRB's were either not detected in the sterile rig or present in extremely low numbers.

The chemical analyses of the bulk water in both rigs showed that there was little variation in the chemical composition of the water.

The results of the numbers of sessile bacteria, quantified on the samples of each material type, removed during the first phase of the investigation are illustrated in Figure 9. No aerobic or anaerobic acid producing bacteria were detected on any of the test materials, or in the bulk water. There was, however, attachment of the other groups of bacteria on all the test materials. It was noted that the number of bacteria quantified on the concrete samples was generally lower than on the other material types. This could have been due to the fact that the dispersion of attached bacteria from the surface of the concrete samples may not have been complete, due to the rough surface. The number of sessile bacteria on the other test materials remained relatively constant over the test period.

Although the bulk water in the sterile rig was found to be almost free of bacteria, sessile bacteria were enumerated on the samples removed from this rig. However, the number of attached bacteria was considerably less than on the samples removed from the non-sterile rig. Thus, although complete sterility was not achieved, microbiological activity was appreciably reduced.

The second phase of the work involved the addition of a biodispersant into the non-sterile rig. The results obtained are shown in Figure 10. Again complete sterility was not achieved in the non-sterile rig and the number of bacteria enumerated on the concrete samples was lower than on the other test materials. The biodispersant significantly reduced the number of sessile bacteria attached to the test materials in the non-sterile rig. A reduction of an average of one log number of bacteria per square centimetre was recorded.

On examination under the SEM, no visible differences in the attachment of bacteria on the various sample surfaces was observed (Figure 11). Bacterial attachment also occurred in the non-sterile rig. The SEM technique cannot be used to determine biofilm thickness. Therefore, no variances in the extent of bacterial attachment were distinguished.

3.3 Material Evaluation

3.3.1 Dimensional Measurements

The dimensions of all the concrete and mortar samples, from Phase 1 and Phase 2, together with their dimensions prior to exposure, are provided in Tables 3 to 7. No significant changes in the dimensions were observed. The minor differences in individual readings are considered to fall within the limits of accuracy of the measuring technique.

3.3.2 Mass Loss Measurements

After the exposed mild steel panels had been cleaned using the cathodic cleaning technique prescribed in ASTM G1, the panels were re-weighed. The corrosion rates, expressed in millimetres per year were calculated according to the following formula:

corrosion rate in mm/yr =

$$\frac{\text{mass loss} \times 8760000}{\text{Metal Density (g/cm}^3\text{)} \times \text{area of panel (mm}^2\text{)} \times \text{hours exposed}}$$

The corrosion rates of the panels removed in Phase 1 are illustrated in Figure 12. It can be clearly seen, that in all cases the corrosion rates are higher in the non-sterile samples than in the sterile samples. The difference in these rates can be attributed to MIC, although a small proportion of the corrosion rates on the sterile samples may be due to MIC as complete sterility was not achieved.

The corrosion rates of the mild steel panels, removed after the second phase, are illustrated in Figure 13. The corrosion rates are higher in the non-sterile samples, i.e the samples that were in the rig that was treated with the biodispersant, than in the sterile samples. The corrosion rates, after one month's exposure are higher than those after 4 months' exposure in phase 1. This phenomena has been described previously (Reference 18) and can be explained by the fact that the biodispersant does not remove the biofilm uniformly from the metal surface. This leads to the formation of numerous active anodic areas on the surface which contribute to an increase in the measured corrosion rate.

3.3.3 Microscopy

The concrete and mortar samples, from both the first and second phase of the investigation, as well as duplicates of unexposed samples were sectioned and examined under the stereo microscope (see Figures 14 and 15). No changes in the microstructure were observed. A few representative samples were also examined under the Scanning Electron Microscope. Here again no changes in the micro-structure were observed.

3.3.4 Chemical Analysis

As mentioned in paragraph 2.4.3, it has been shown that the activity of the *Thiobaciillus spp*, on the surface of cementitious materials, produces two different corrosion products viz gypsum and ettringite. No corrosion products were observed on the surface of any of the concrete or mortar samples. This can, however, be explained by the fact that no acid forming bacteria were identified in the microbiological analyses.

4. CONCLUSIONS

From the results obtained it can be concluded that:

- Active microbiologically influenced corrosion occurred in the test rigs as demonstrated by the metal loss determined on the control mild steel samples.
- The materials evaluation showed no deleterious effects on the concrete and mortar samples under the test conditions.
- Uniform microbiological attachment occurred on all the materials evaluated.
- Although complete sterility was not achieved in the sterile rig, the microbiological activity was nevertheless appreciably reduced.
- The addition of a biodispersant to the non-sterile rig resulted in a significant reduction in the numbers of attached bacteria.

Mortar linings and concrete are therefore considered to be suitable alternative materials for the corrosion protection of industrial water systems with similar water chemistry to that used in this investigation.

5. RECOMMENDATIONS

It is recommended that caution be exercised in specifying concrete and/or mortar linings for an industrial water system with a significantly different water chemistry to that used here. The performance of these materials, in other waters, cannot be guaranteed.

In addition it is recommended that the choice between mortar linings and concrete for any specific system, be determined by the mechanical engineering aspects of that system.

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8. TABLES

TABLE 1

COMPOSITION OF MORTAR SAMPLES

SAMPLE No	COMPOSITION
1A	OPC*
1B	OPC
2A	OPC
2B	OPC
3A	OPC + 15% Fly Ash
3B	OPC + 15% Fly Ash
4A	OPC + 15% Fly Ash
4B	OPC + 15% Fly ash
5A	OPC + 15% Fly Ash
5B	OPC + 15% Fly Ash
6A	OPC + 30% Fly Ash
6B	OPC + 30% Fly Ash
7A	OPC + 30% Fly Ash
7B	OPC + 30% Fly Ash
8A	OPC + 30% Fly Ash
8B	OPC + 305 Fly Ash
9A	OPC + 30% Fly Ash
9B	OPC + 30% Fly Ash
10A	OPC + 15% Fly Ash
10B	OPC + 15% Fly Ash
11A	OPC + 15% Fly Ash
11B	OPC + 15% Fly Ash
12A	OPC + 30% Fly Ash
12B	OPC + 30% Fly Ash

OPC* - Ordinary Portland Cement

TABLE 2

CHEMICAL ANALYSIS OF CIRCULATING WATER (DUVHA NORTH SIDE COOLING WATER)

pH at 25°C	8,43
Conductivity at 25°C	2000 to 2500µS/cm
Total Alkalinity	104mg/l $CaCO_3$
Cl^-	70mg/l
$SO_4^{=}$	500 to 1000mg/l
Total Hardness	690 mg/l $CaCO_3$

TABLE 3

DETAILED DIMENSION MEASUREMENTS - BEFORE AND AFTER EXPOSURE PHASE 1 - CONCRETE SAMPLES - STERILE

(Measurements in Millimetres)

POSITION OF MEASUREMENT	SAMPLE NUMBER											
	1A	2A	3A	4A	5A	6A	7A	8A	9A	10A	11A	12A
a: before	46,0	46,1	47.5	46.1	48,9	47,7	47,2	46,9	48,3	46,5	43,8	46,1
a: after	46,1	46,1	47,4	46,1	48,8	47,6	47,3	46,8	48,2	46,6	43,8	46,0
b: before	48,5	45,8	49,2	45,0	45,0	46,8	46,2	50,2	46,2	45,1	46,7	49,0
b: after	48,5	45,8	49,0	44,9	44,9	46,9	46,2	50,2	46,1	45,1	46,8	49,0
c: before	46,2	46,0	47,9	46,5	50,1	48,1	47,3	47,0	45,1	46,9	44,9	46,2
c: after	46,2	46,0	47,8	46,5	50,0	48,1	47,3	46,8	45,1	46,8	44,8	46,2
d: before	48,0	46,2	49,1	44,0	46,2	46,9	47,0	49,5	47,0	46,2	46,3	49,0
d: after	47,8	46,1	49,2	43,9	46,3	46,8	47,0	49,2	47,1	46,1	46,4	49,0
e: before	6,0	5,6	6,1	5,7	4,5	4,5	5,0	5,2	5,5	6,1	5,3	5,8
e: after	6,0	5,5	6,0	5,7	4,6	4,3	4,9	5,0	5,6	6,1	5,3	5,9
f: before	5,6	5,1	5,3	5,9	5,1	5,0	5,2	5,2	5,6	5,9	5,7	5,9
f: after	5,5	5,0	5,3	6,0	5,0	4,9	5,2	5,2	5,6	5,8	5,6	6,0
g: before	5,9	5,1	5,1	5,8	5,0	5,0	5,2	5,4	5,7	5,2	5,7	5,8
g: after	5,9	5,0	5,2	6,0	5,0	4,9	5,1	5,3	5,7	5,2	5,6	5,9
h: before	5,6	5,1	4,9	6,0	4,1	5,5	5,0	5,6	5,6	4,5	4,9	5,8
h: after	5,7	5,1	5,0	6,0	4,1	5,5	4,9	5,4	5,5	4,5	4,8	5,9
i: before	5,6	5,1	4,9	6,0	4,1	5,5	5,0	5,6	5,5	4,5	5,0	5,9
i: after	5,3	5,2	5,O	6,0	4,0	5,5	5,1	5,6	5,5	4,5	4,9	5,8
j: before	5,6	5,9	5,1	5,8	4,0	4,9	4,3	5,5	5,1	4,0	4,9	5,1
j: after	5,7	5,6	5,1	5,7	4,0	4,9	4,2	5,5	5,1	3,9	4,9	5,1
k: before	5,6	5,9	5,1	5,4	4,0	4,9	4,3	5,3	5,2	4,5	5,0	5,1
k: after	5,6	5,7	5,1	5,4	4,1	4,8	4,4	5,2	5,2	4,5	5,0	5,0
l: before	5,6	5,9	5,8	5,5	4,7	4,7	4,8	5,0	5,2	6,0	5,2	5,8
l: after	5,5	5,8	5,8	5,5	4,7	4,6	4,8	5,0	5,3	6,1	5,4	5,7
m: before	5,6	6,0	5,2	6,0	4,8	4,9	5,1	4,8	5,7	5,8	5,2	5,9
m: after	5,6	6,0	5,0	5,9	4,7	4,9	5,1	5,O	5,8	5,8	5,4	5,9

TABLE 4

DETAILED DIMENSION MEASUREMENTS - BEFORE AND AFTER EXPOSURE PHASE 1- CONCRETE SAMPLES - NON-STERILE

(Measurements in Millimetres)

POSITION OF MEASUREMENT	SAMPLE NUMBER											
	1B	2B	3B	4B	5B	6B	7B	8B	9B	10B	11B	12B
a: before	47,9	47,9	48,0	48,0	48,2	48,7	48,8	49,3	49,8	49,4	52,0	49,7
a: after	47,9	47,8	48,1	48,1	48,2	48,6	48,8	49,3	49,9	49,5	52,0	49,6
b: before	50,7	46,9	50,4	48,7	45,7	46,3	47,7	49,8	49,3	50,0	48,4	45,9
b: after	50,7	46,8	50,5	48,7	45,7	46,4	47,7	49,8	49,2	50,0	48,4	45,9
c: before	47,6	47,6	48,0	48,6	48,4	49,1	48,9	49,2	49,8	49,3	51,8	48,0
c: after	47,5	47,6	47,9	48,4	48,4	49,0	48,9	49,2	49,9	49,3	52,0	47,8
d: before	50,5	47,0	49,6	48,8	46,1	46,5	47,7	50,2	49,5	49,3	48,6	46,1
d: after	50,4	47,1	49,5	48,8	46,2	46,4	47,8	50,1	49,3	49,3	48,7	46,2
e: before	7,7	7,4	7,0	7,3	7,8	7,6	7,7	7,6	7,2	7,5	7,4	7,1
e: after	7,7	7,5	7,0	7,3	7,8	7,6	7,8	7,6	7,1	7,5	7,3	7,0
f: before	7,5	7,4	7,5	7,4	7,6	7,2	7,6	7,1	7,6	6,9	7,6	7,0
f: after	7,4	7,3	7,5	7,4	7,6	7,4	7,6	7,0	7,5	7,0	7,6	7,0
g: before	7,8	7,3	7,5	7,4	7,6	7,3	7,6	7,1	7,7	6,9	7,8	7,0
g: after	7,7	7,2	7,5	7,4	7,6	7,2	7,6	7,1	7,7	6,9	7,9	7,2
h: before	8,0	6,7	7,7	7,0	7,6	6,7	7,7	7,3	7,6	6,8	7,5	7,7
h: after	8,0	6,8	7,7	7,0	7,6	6,7	7,8	7,3	7,5	6,9	7,6	7,7
i: before	8,0	6,7	7,7	7,9	7,7	6,7	7,8	7,4	7,6	6,7	7,4	7,5
i: after	7,9	6,7	7,7	7,8	7,7	7,6	7,8	7,5	7,5	6,7	7,4	7,6
j: before	8,1	6,7	7,1	6,9	8,0	6,6	7,6	8,5	7,6	7,5	7,3	8,1
j: after	8,1	6,7	7,1	6,8	8,1	6,7	7,6	8,4	7,5	7,6	7,4	8,0
k: before	8,2	6,7	7,1	7,0	8,0	6,8	7,6	8,7	7,7	7,5	7,4	8,5
k: after	8,2	6,7	7,1	7,0	7,0	6,9	7,7	8,7	7,5	7,5	7,4	8,5
l: before	7,8	7,3	7,0	7,3	7,9	7,6	7,7	7,8	7,2	7,4	7,3	7,5
l: after	7,7	7,4	7,1	7,5	8,0	7,8	7,7	7,7	7,3	7,4	7,3	7,5
m: before	8,3	7,4	7,3	7,1	8,2	7,0	7,7	7,5	7,8	7,2	7,6	7,9
m: after	8,4	7,4	7,4	7,2	8,3	7,1	7,8	7,6	7,9	7,3	7,7	7,9

TABLE 5

DETAILED DIMENSION MEASUREMENTS - BEFORE AND AFTER EXPOSURE PHASE 1 MORTAR SAMPLES - STERILE

(Measurements in Millimetres)

POSITION OF MEASUREMENT	SAMPLE NUMBER											
	1A	2A	3A	4A	5A	6A	7A	8A	9A	10A	11A	12A
a: before	48,3	48,3	48,1	48,0	47,9	48,2	48,0	48,2	47,1	49,2	49,0	48,9
a: after	48,3	48,3	48,0	48,0	48,0	48,2	49,9	48,1	48,9	47,8	48,5	48,9
b: before	48,5	49,2	49,7	48,2	47,2	48,7	49,9	48,1	48,9	47,8	48,5	48,4
b: after	48,3	49,1	49,8	48,1	47,2	49,0	49,8	48,0	48,8	47,7	48,5	48,5
c: before	48,5	48,0	47,5	49,0	47,9	49,1	47,4	48,2	47,1	48,9	49,2	48,9
c: after	48,5	48,0	47,3	49,0	47,9	49,0	47,2	48,3	47,2	48,9	49,3	48,9
d: before	48,3	48,5	49,4	48,0	47,4	48,3	49,9	48,2	49,2	47,2	48,2	47,9
d: after	48,5	48,6	49,4	48,0	47,5	48,2	49,8	48,1	49,0	47,2	48,3	47,8
e: before	8,7	8,4	8,4	8,2	8,8	8,8	9,9	8,1	9,0	9,1	8,6	9,0
e: after	8,1	8,3	8,3	8,1	8,8	8,8	9,9	8,1	9,0	9,0	8,6	8,9
f: before	8,1	8,3	8,1	8,9	8,5	8,8	9,2	8,0	9,0	10,0	8,9	9,1
f: after	8,0	8,4	8,0	8,9	8,6	8,9	9,1	8,1	9,1	9,9	8,9	9,1
g: before	8,2	8,8	8,3	8,9	8,8	8,9	9,2	8,1	9,1	10,0	8,9	8,7
g: after	8,2	8,8	8,2	8,9	8,8	8,9	9,2	8,0	9,1	9,9	9,0	8,6
h: before	8,6	8,1	8,2	8,1	8,3	8,5	9,0	8,0	9,5	10,0	8,6	9,6
h: after	8,6	8,0	8,2	8,0	8,3	8,5	9,0	8,0	9,6	10,0	8,6	9,6
i: before	8,6	8,2	8,0	8,0	8,3	8,7	9,0	8,1	9,2	10,1	8,9	8,7
i: after	8,7	8,3	8,0	8,0	8,2	8,8	8,0	8,0	9,2	10,0	8,0	8,7
j: before	8,7	8,1	8,0	8,0	8,2	8,8	8,9	8,0	9,0	9,1	8,9	8,9
j: after	8,6	8,1	8,0	8,0	8,2	8,8	8,9	8,1	9,0	9,1	8,8	8,9
k: before	8,8	8,0	8,0	8,1	8,3	8,8	9,0	8,1	9,0	9,1	8,7	8,8
k: after	8,8	8,1	8,0	8,0	8,3	8,8	8,9	8,1	8,9	9,1	8,8	8,8
l: before	8,9	8,7	8,1	8,2	8,3	8,9	9,3	8,2	9,0	9,1	8,5	8,7
l: after	8,8	8,8	8,0	8,0	8,3	8,8	9,2	8,2	8,9	9,0	8,5	8,6
m: before	8,2	8,3	8,1	8,2	8,9	9,0	9,1	8,3	9,2	9,1	8,8	8,9
m: after	8,2	8,2	8,1	8,3	8,9	9,0	9,0	8,3	9,2	9,1	8,7	8,9

TABLE 6

DETAILED DIMENSION MEASUREMENTS - BEFORE AND AFTER EXPOSURE PHASE 1 - MORTAR SAMPLES - NON-STERILE

(Measurements in Millimetres)

POSITION OF MEASUREMENT	SAMPLE NUMBER											
	1B	2B	3B	4B	5B	6B	7B	8B	9B	10B	11B	12B
a: before	48,8	48,6	48,5	47,9	48,0	48,1	47,9	48,8	48,0	48,0	48,0	48,3
a: after	48,8	48,7	48,7	47,9	48,1	48,0	47,8	48,8	47,8	48,0	47,9	48,3
b: before	49,5	48,2	49,1	48,0	47,5	48,7	49,1	48,9	49,2	49,0	49,0	49,1
b: after	49,3	48,2	49,1	48,0	47,5	48,7	49,0	48,8	49,2	49,0	48,8	49,1
c: before	48,2	49,0	48,8	47,8	48,0	49,1	48,2	49,0	48,5	48,2	48,0	48,2
c: after	48,0	49,1	48,6	47,9	47,9	48,2	48,9	48,6	48,3	48,2	48,0	48,2
d: before	49,5	48,1	49,1	48,0	48,0	48,2	49,9	48,5	49,0	49,1	48,8	48,1
d: after	49,3	48,1	49,0	48,1	48,0	48,2	49,9	48,5	49,0	49,2	48,9	48,1
e: before	8,9	8,1	8,3	8,9	8,5	9,0	10,0	8,2	8,9	8,1	8,6	8,6
e: after	8,9	8,0	8,2	8,9	8,6	9,1	9,9	8,2	8,9	8,1	8,6	8,5
f: before	8,5	9,0	8,1	8,2	8,2	8,9	9,9	8,5	8,5	8,3	8,7	8,6
f: after	8,5	9,0	8,0	8,2	8,1	8,9	9,8	8,4	8,5	8,2	8,7	8,7
g: before	8,2	8,5	8,1	8,6	8,9	8,9	9,9	8,3	8,9	8,8	8,9	8,6
g: after	8,2	8,6	8,0	8,5	8,9	8,9	10,9	8,4	8,8	8,8	8,9	8,6
h: before	8,3	8,1	8,0	8,0	8,1	8,2	8,9	8,8	9,0	8,3	8,9	8,8
h: after	8,2	8,2	8,1	8,0	8,0	8,1	8,8	8,8	9,0	8,4	8,9	8,9
i: before	8,8	8,0	8,0	8,6	8,4	8,2	8,9	8,5	9,0	8,7	9,0	9,3
i: after	8,8	8,0	8,2	8,5	8,5	8,3	9,0	8,5	9,0	8,8	8,8	9,3
j: before	8,8	8,0	8,0	8,1	8,3	8,6	9,2	8,2	9,1	8,2	8,9	8,1
j: after	8,7	8,1	8,1	8,0	8,0	8,6	9,2	8,2	9,1	8,2	8,8	8,0
k: before	8,7	8,1	8,2	8,5	8,1	8,8	9,1	8,3	9,0	8,2	9,0	8,5
k: after	8,8	8,1	8,0	8,6	8,2	8,8	9,2	8,2	9,0	8,2	8,9	8,5
l: before	8,8	8,0	8,2	8,3	8,1	8,9	10,0	8,2	9,0	8,1	8,8	8,5
l: after	8,8	8,1	8,1	8,1	8,0	8,9	9,9	8,2	9,0	8,0	8,9	8,6
m: before	8,3	8,4	8,3	8,1	8,2	8,0	8,7	8,5	8,8	9,2	8,6	8,9
m: after	8,3	8,3	8,4	8,0	8,3	8,0	8,7	8,6	8,8	9,1	8,6	8,8

TABLE 7

DETAILED DIMENSION MEASUREMENTS - BEFORE AND AFTER EXPOSURE PHASE 2 - CONCRETE SAMPLES - STERILE

(Measurements in Millimetres)

POSITION OF MEASUREMENT	SAMPLE NUMBER			
	1X	2X	3X	4X
a: before	45,8	47,0	48,1	46,1
a: after	45,7	46,9	48,1	46,1
b: before	47,9	48,8	46,0	46,
b: after	47,9	48,9	46,1	46,0
c: before	45,5	47,3	48,3	46,3
c: after	45,5	47,2	48,3	46,3
d: before	47,9	48,0	47,2	46,2
d: after	47,9	48,1	47,3	46,1
e: before	5,2	5,3	7,1	6,5
e: after	5,2	5,2	7,2	6,5
f: before	5,3	5,5	6,3	6,8
f: after	5,3	5,4	6,4	6,7
g: before	5,3	5,4	6,3	5,6
g: after	5,3	5,4	6,4	5,5
h: before	5,1	5,4	6,4	5,8
h: after	5,0	5,4	6,5	5,8
i: before	5,1	5,4	6,4	5,8
i: after	5,1	5,5	6,5	5,9
j: before	5,3	5,4	7,2	5,8
j: after	5,3	5,4	7,3	5,9
k: before	5,1	5,5	7,2	5,6
k: after	5,0	5,6	7,3	5,6
l: before	5,2	5,3	7,2	5,4
l: after	5,2	5,4	7,3	5,6
m: before	5,3	5,6	7,2	6,2
m: after	5,4	5,6	7,2	6,2

TABLE 8

DETAILED DIMENSION MEASUREMENTS - BEFORE AND AFTER EXPOSURE PHASE 2 - CONCRETE SAMPLES - NON-STERILE

(Measurements in Millimetres)

POSITION OF MEASUREMENT	SAMPLE NUMBER			
	1Y	2Y	3Y	4Y
a: before	41,1	48,0	47,2	44,4
a: after	41,1	47,9	47,1	44,3
b: before	45,1	47,0	48,3	47,1
b: after	45,1	46,9	48,2	47,0
c: before	46,6	48,2	47,2	44,2
c: after	46,6	48,2	47,3	44,3
d: before	45,3	46,6	48,5	47,9
d: after	45,3	46,6	48,3	47,8
e: before	5,9	5,5	7,2	5,7
e: after	5,8	5,5	7,2	5,6
f: before	5,9	5,2	6,6	5,6
f: after	5,9	5,3	6,6	5,6
g: before	5,7	6,1	6,4	5,3
g: after	5,6	6,1	6,4	5,5
h: before	5,3	6,4	6,0	5,2
h: after	5,3	6,4	6,1	5,1
i: before	5,2	6,6	6,1	5,5
i: after	5,1	6,5	6,1	5,6
j: before	6,0	6,8	6,7	5,4
j: after	6,3	6,9	7,6	5,4
k: before	6,0	6,8	6,8	5,1
k: after	6,0	6,8	6,9	5,0
l: before	5,9	6,5	7,1	5,1
l: after	5,9	6,4	7,3	5,1
m: before	6,0	6,8	7,0	5,5
m: after	6,0	6,6	7,2	5,5

TABLE 9

DETAILED DIMENSION MEASUREMENTS - BEFORE AND AFTER EXPOSURE PHASE 2 - MORTAR SAMPLES - STERILE

(Measurements in Millimetres)

POSITION OF MEASUREMENT	SAMPLE NUMBER			
	1X	2X	3X	4X
a: before	48,7	47,8	48,7	47,8
a: after	48,7	47,9	48,8	47,8
b: before	47,8	47,7	48,2	47,8
b: after	47,7	47,7	48,2	47,9
c: before	48,7	47,7	49,0	48,1
c: after	48,8	47,6	49,3	48,1
d: before	48,5	47,2	49,7	48,3
d: after	48,3	47,2	49,7	48,3
e: before	9,0	8,0	9,4	8,4
e: after	9,0	8,1	9,4	8,4
f: before	8,6	8,3	9,3	8,4
f: after	8,6	8,3	9,3	8,6
g: before	8,5	8,6	7,9	8,2
g: after	8,6	8,6	7,9	8,2
h: before	8,3	8,4	8,5	8,4
h: after	8,3	8,4	8,6	8,5
i: before	8,3	8,2	7,6	8,5
i: after	8,3	8,3	7,6	8,6
j: before	8,5	8,0	8,8	8,5
j: after	8,5	8,1	8,9	8,5
k: before	8,6	8,0	8,8	8,0
k: after	8,6	8,1	8,9	8,0
l: before	8,6	8,0	9,3	8,5
l: after	8,5	8,1	9,4	8,5
m: before	8,7	8,0	9,1	8,6
m: after	8,8	8,0	9,0	8,5

TABLE 10

DETAILED DIMENSION MEASUREMENTS - BEFORE AND AFTER EXPOSURE PHASE 2 - MORTAR SAMPLES - NON-STERILE

(Measurements in Millimetres)

POSITION OF MEASUREMENT	SAMPLE NUMBER			
	1Y	2Y	3Y	4Y
a: before	47,8	49,3	47,6	48,7
a: after	47,8	49,2	47,6	48,8
b: before	49,4	48,1	48,3	48,3
b: after	49,4	48,0	48,2	48,3
c: before	48,0	49,6	49,1	48,8
c: after	48,0	49,5	49,3	48,8
d: before	48,7	47,1	48,0	48,0
d: after	48,8	47,2	48,2	48,1
e: before	9,4	8,2	8,1	8,5
e: after	9,4	8,1	8,1	8,4
f: before	9,1	8,2	8,1	8,1
f: after	9,0	8,2	8,2	8,0
g: before	9,3	8,4	8,3	8,2
g: after	9,3	8,5	8,2	8,3
h: before	10,1	8,4	8,3	8,1
h: after	10,1	8,4	8,1	8,1
i: before	10,1	8,3	8,0	8,1
i: after	10,1	8,4	8,1	8,1
j: before	10,2	8,7	7,7	8,1
j: after	10,3	8,9	7,7	8,0
k: before	10,2	8,6	7,7	8,4
k: after	10,2	8,7	7,7	8,4
l: before	9,4	8,5	7,8	8,2
l: after	9,3	8,4	7,8	8,2
m: before	10,0	8,8	7,9	7,4
m: after	9,9	8,8	7,8	7,5

9. FIGURES

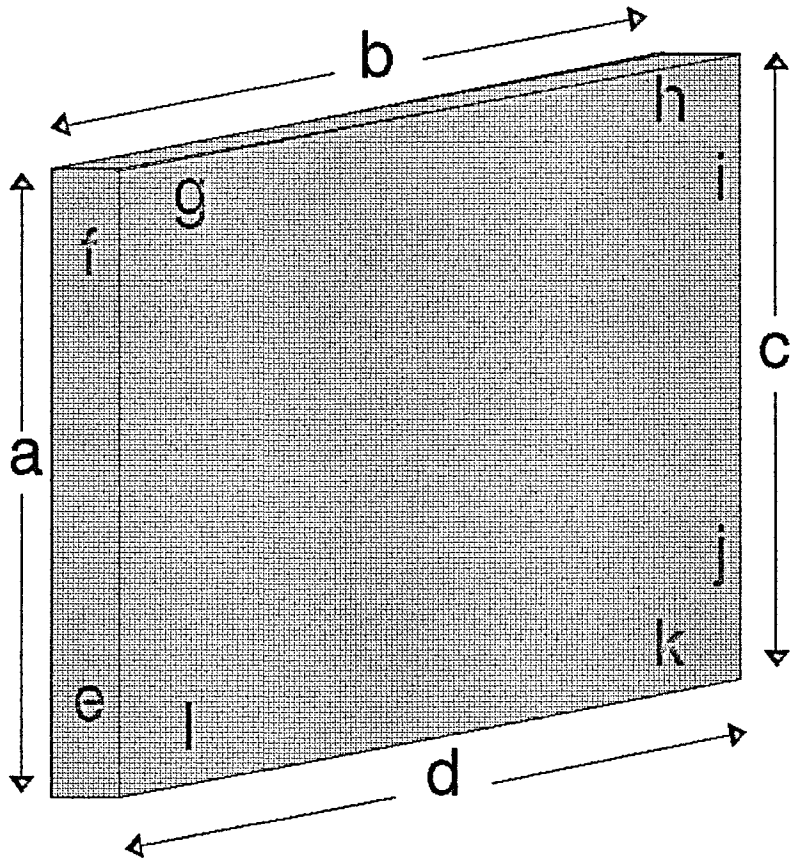

Figure 1 : Measuring points on concrete and mortar prisms

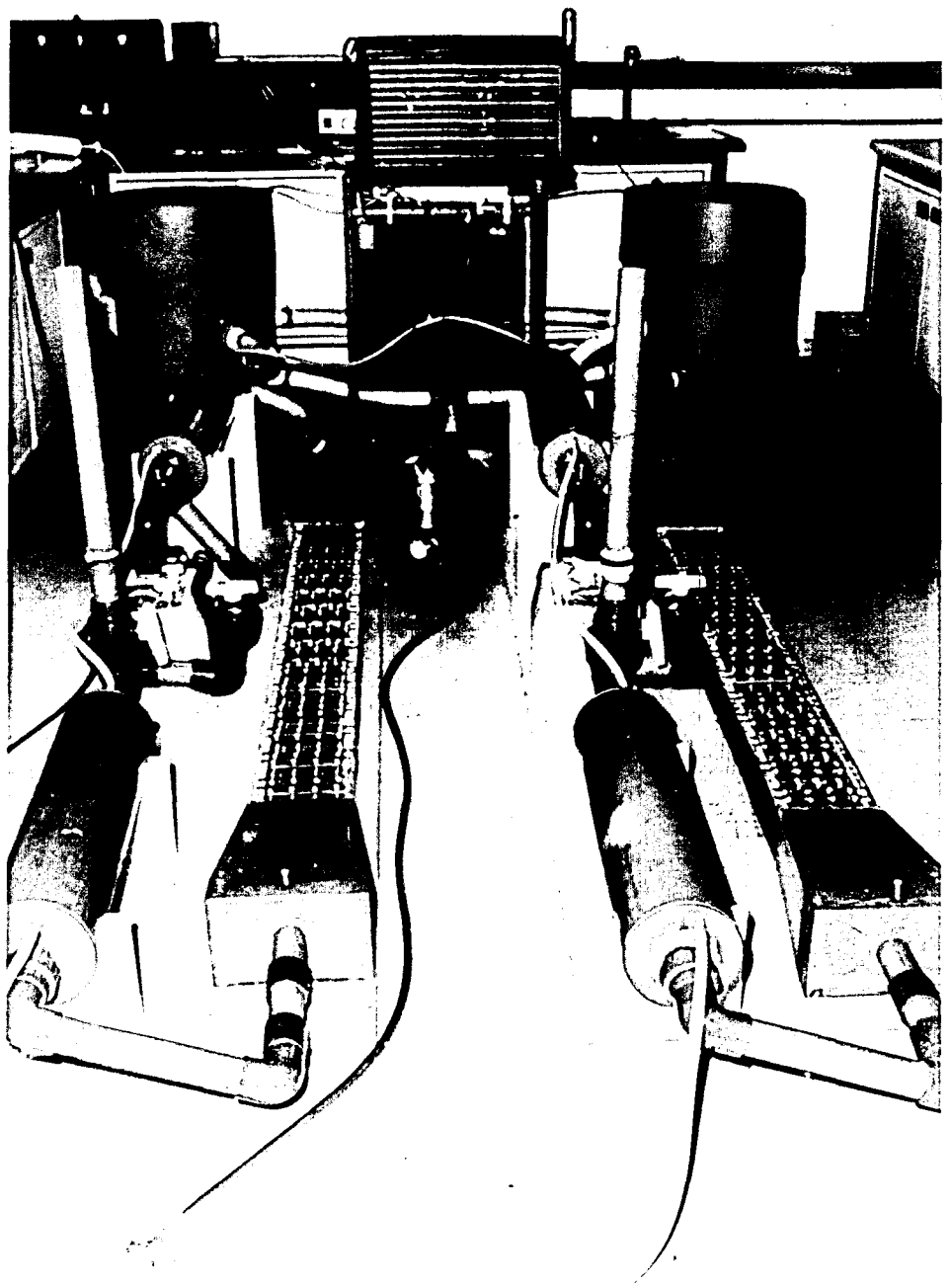

FIGURE 2 STERILE AND NON-STERILE TEST RIGS

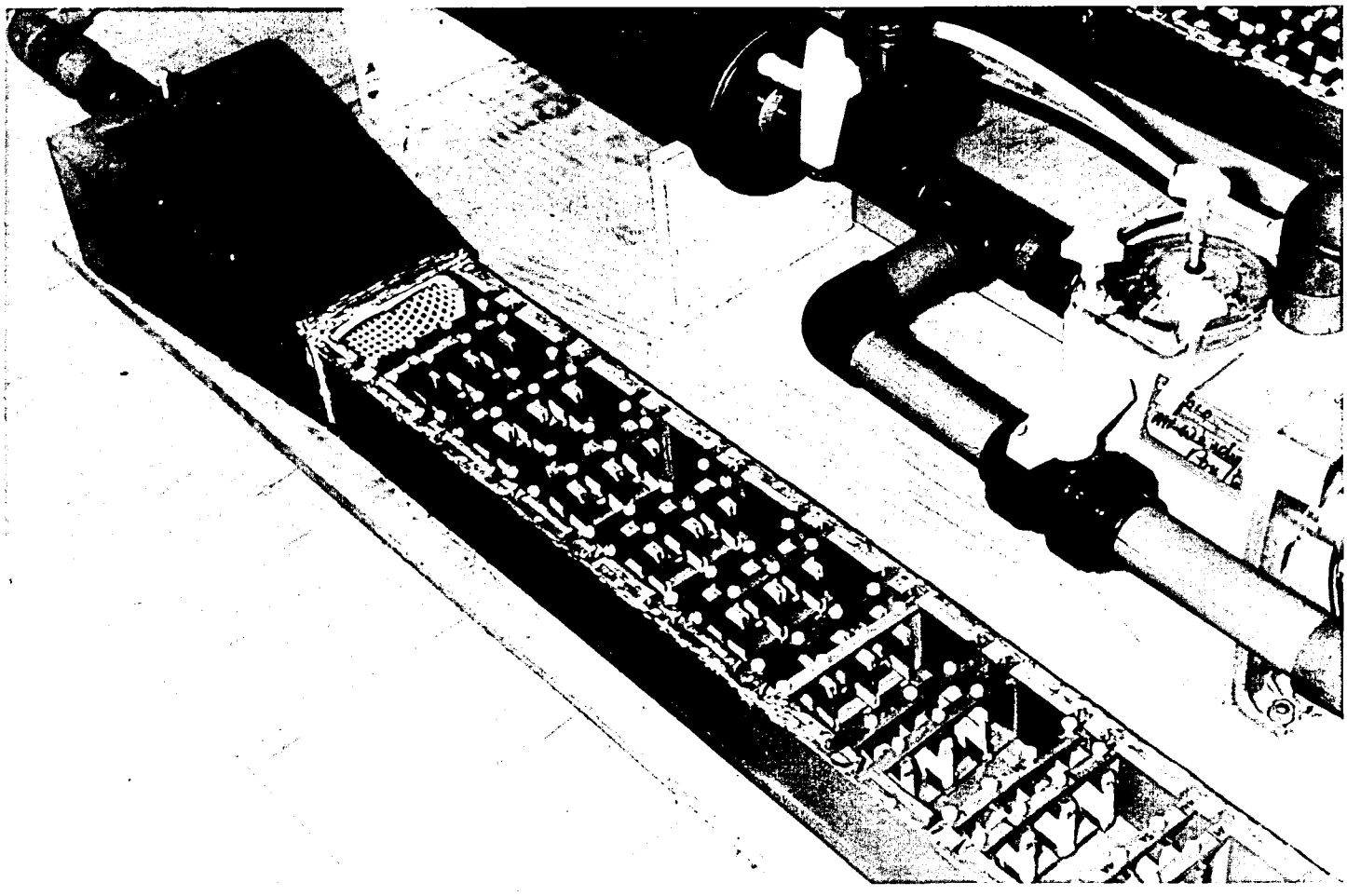

FIGURE 3 SAMPLE CONFIGURATION

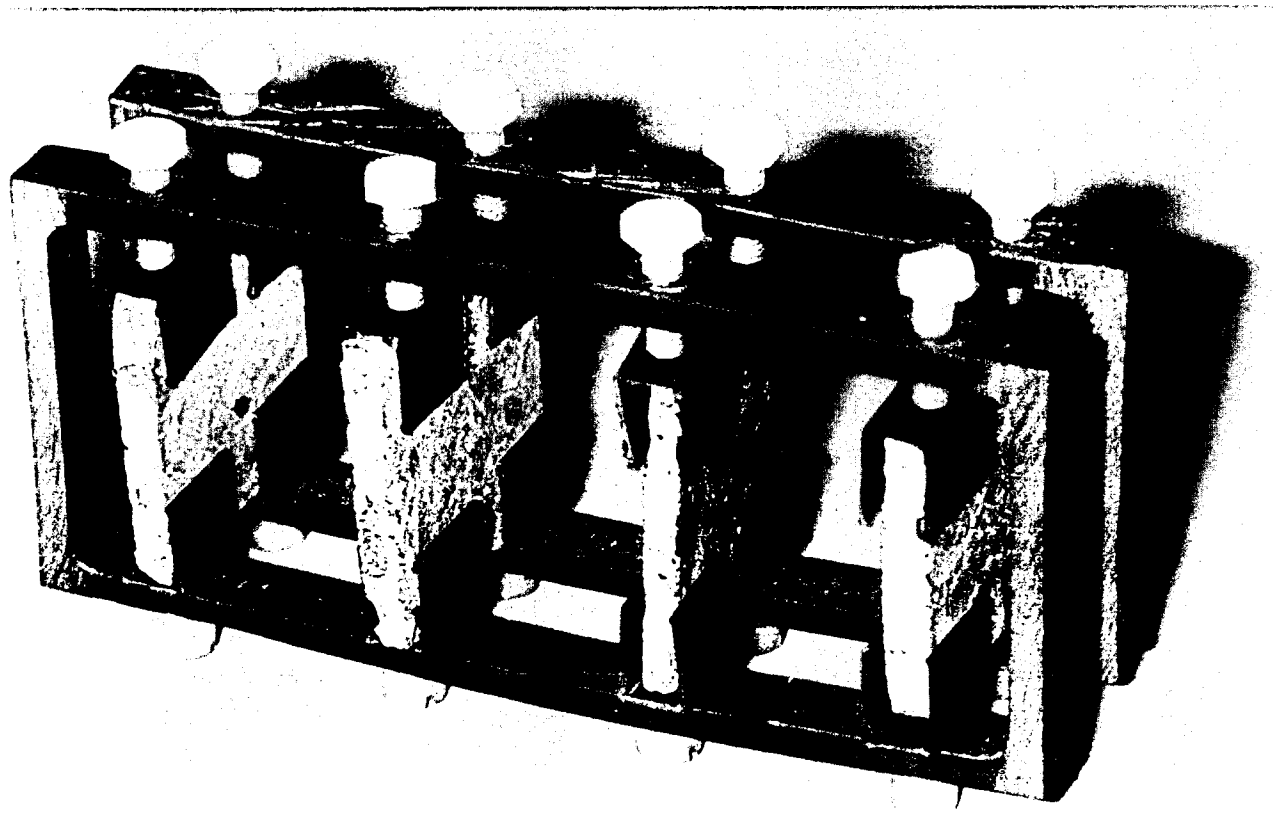

FIGURE 4 HOLDERS FOR CONCRETE AND MORTAR SAMPLES

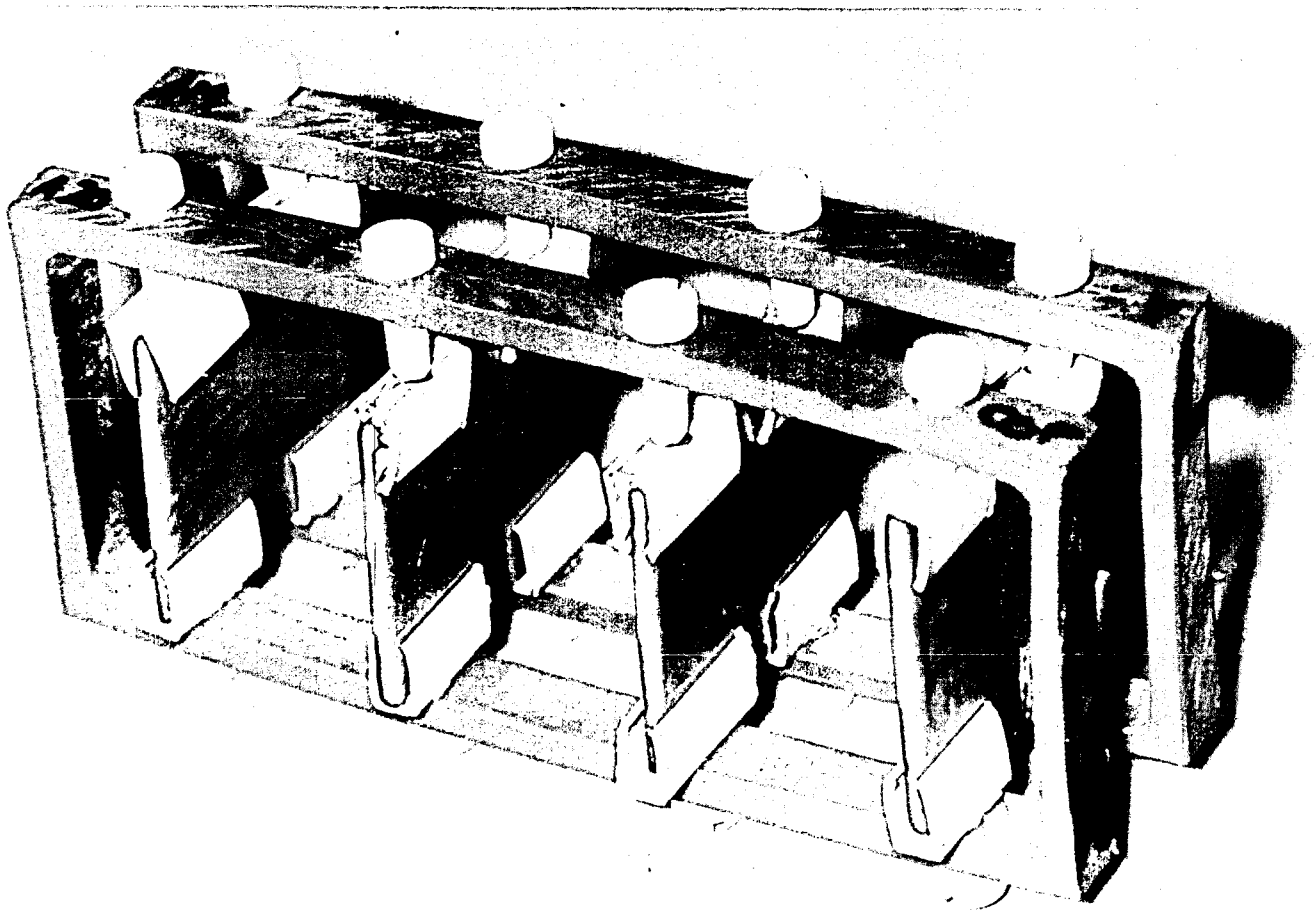

FIGURE 5 HOLDERS FOR MILD STEEL AND
EPOXY COATED MILD STEEL SAMPLES

FIGURE 6 MILD STEEL SAMPLE SHOWING MIC ATTACK

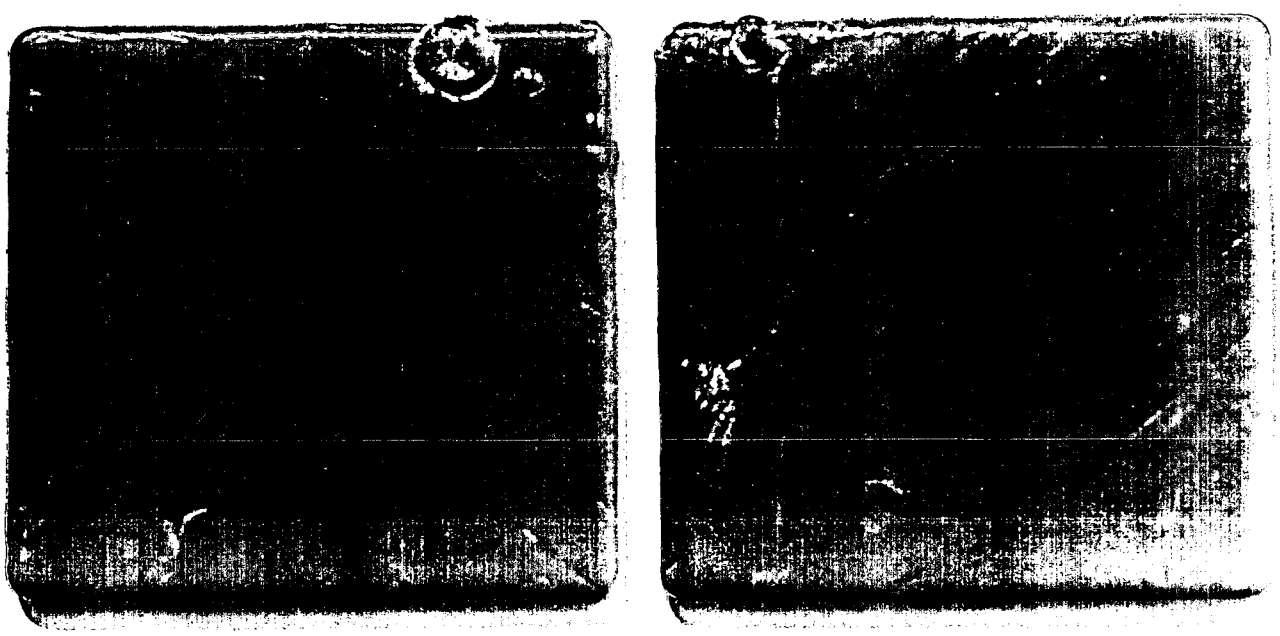

FIGURE 7 BLISTERING ON EPOXY COATED MILD STEEL SAMPLES

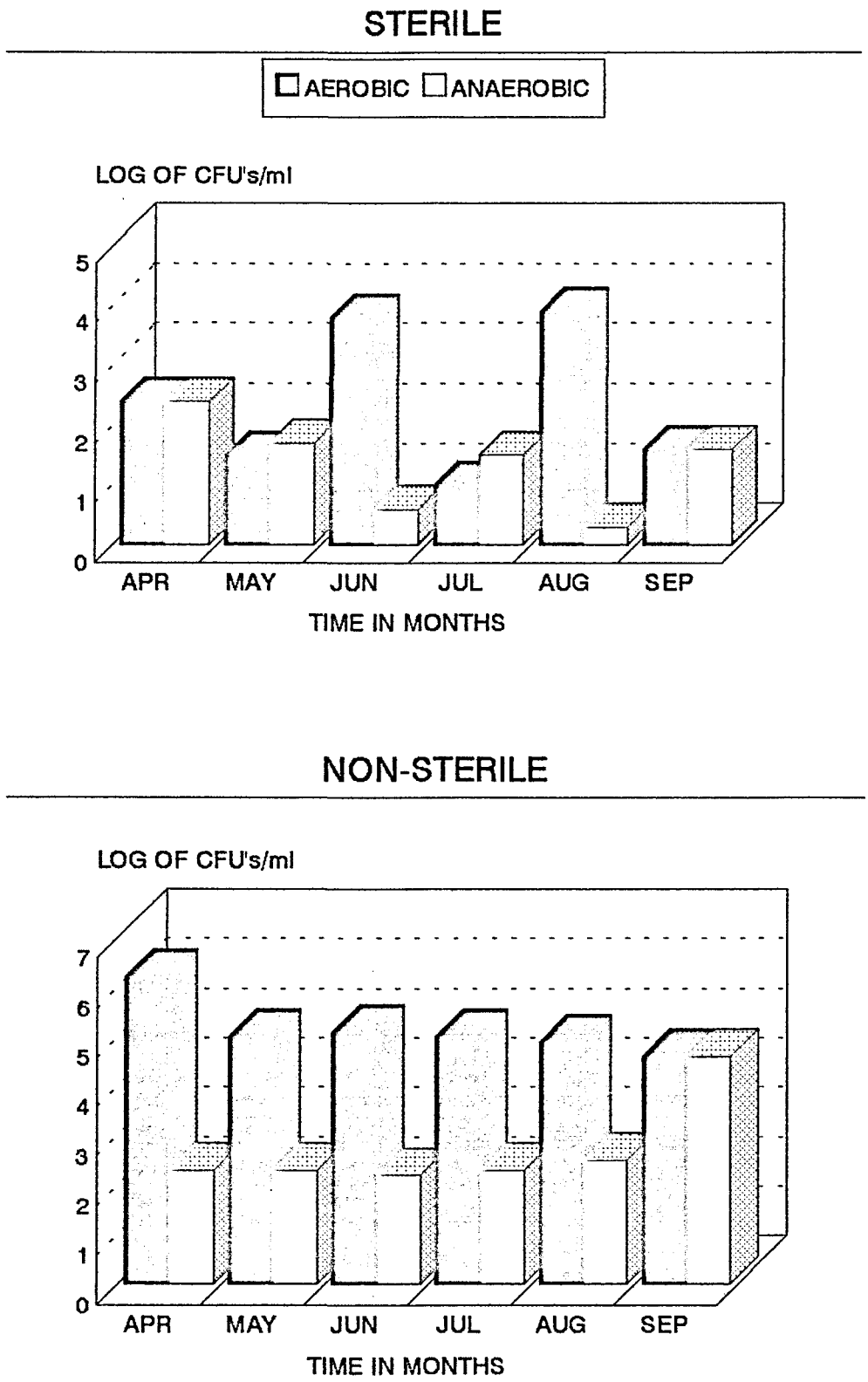

Figure 8 : Microbiological analysis of bulk water during the first phase of the investigation

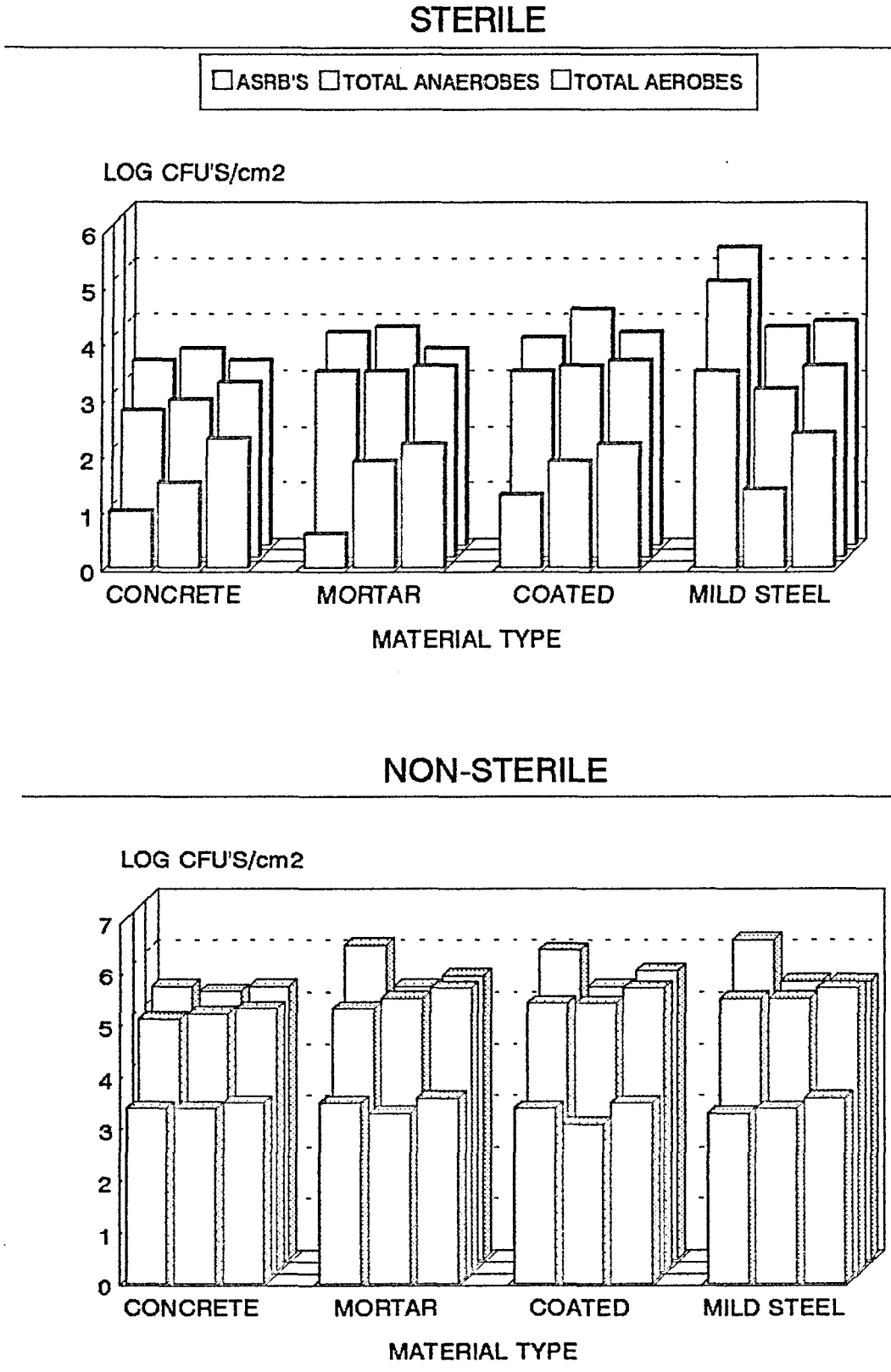

Figure 9 : Bacteria enumerated on the test materials during the first phase of the investigation

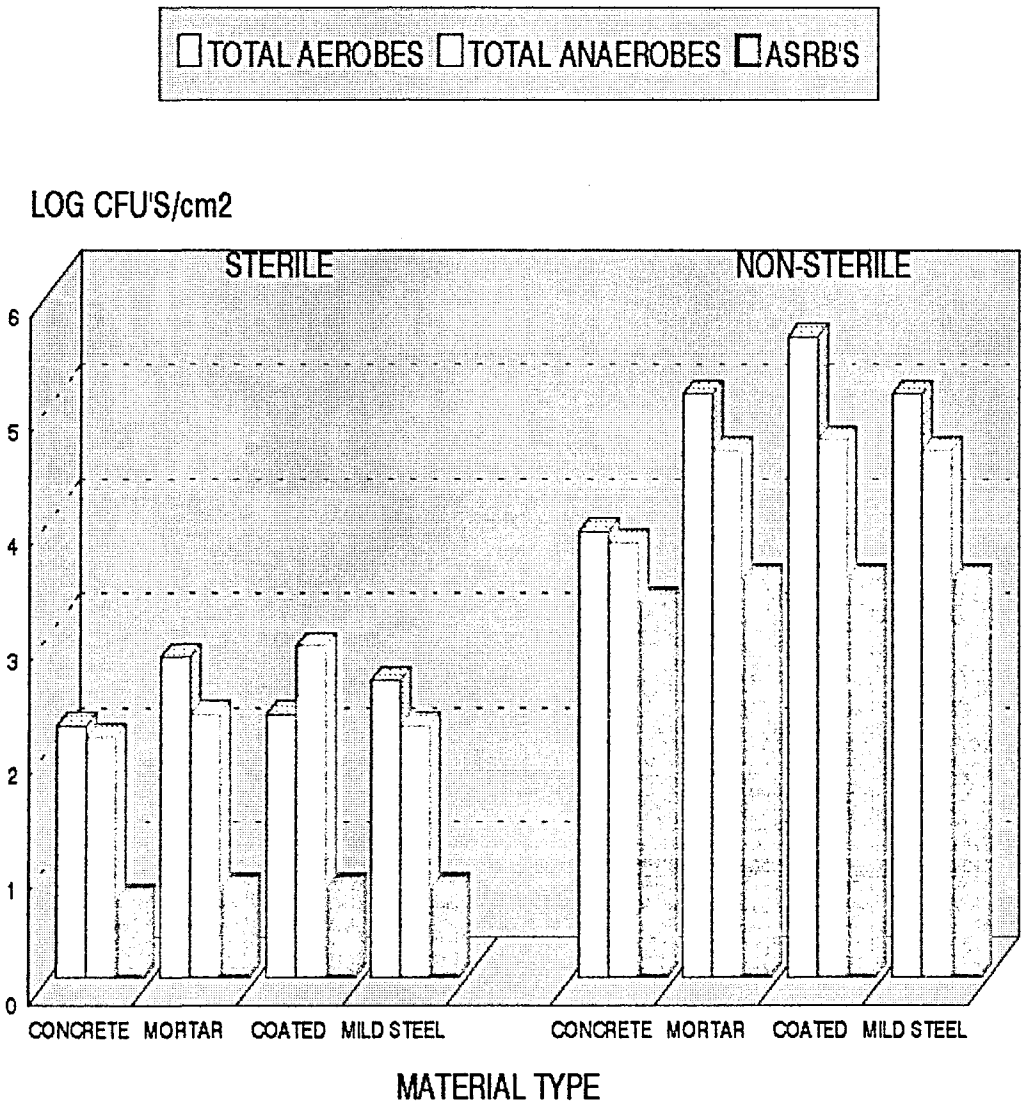

Figure 10: Bacteria enumerated on the test pieces after completion of second phase of the investigation

FIGURE 11 SCANNING ELECTRON MICROGRAPH SHOWING ATTACHED BACTERIA ON THE SURFACE OF A MILD STEEL SAMPLE

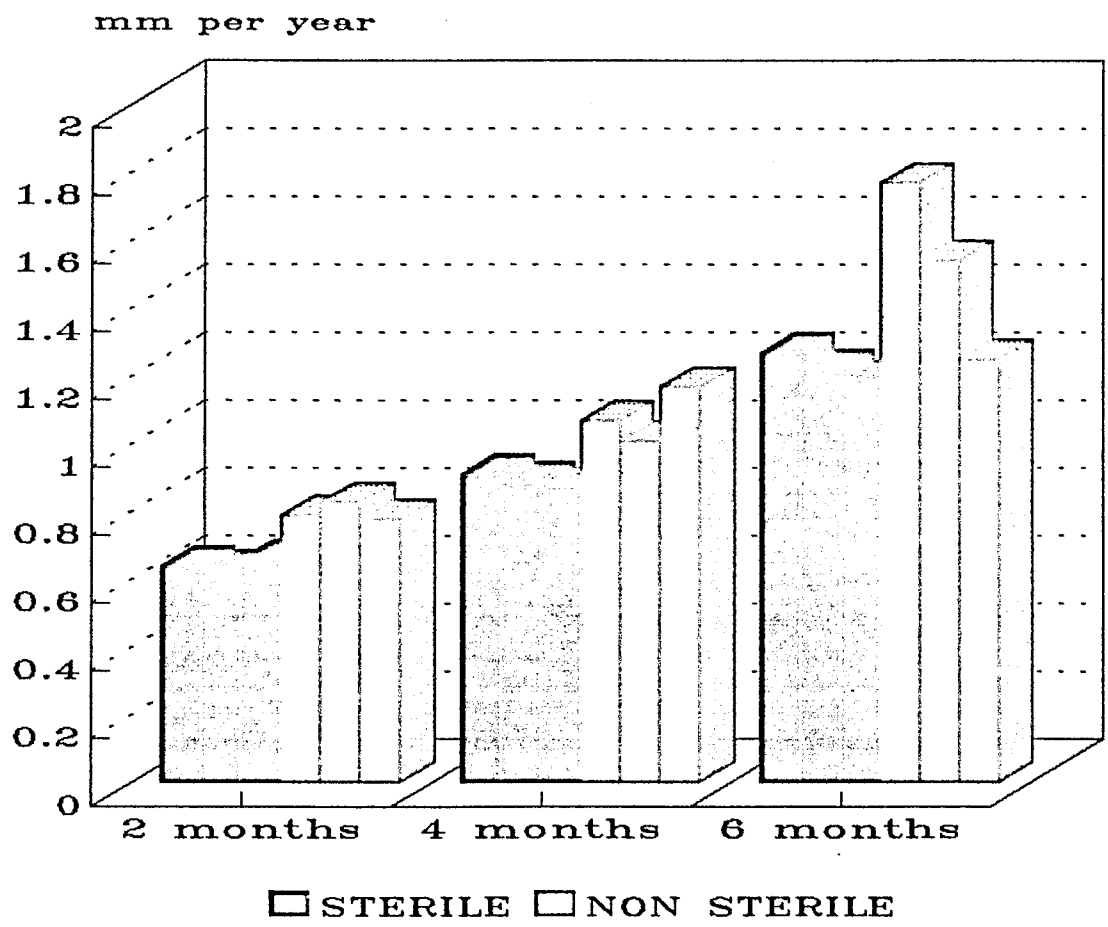

Figure 12 : Corrosion rates on the mild steel panels - Phase 1

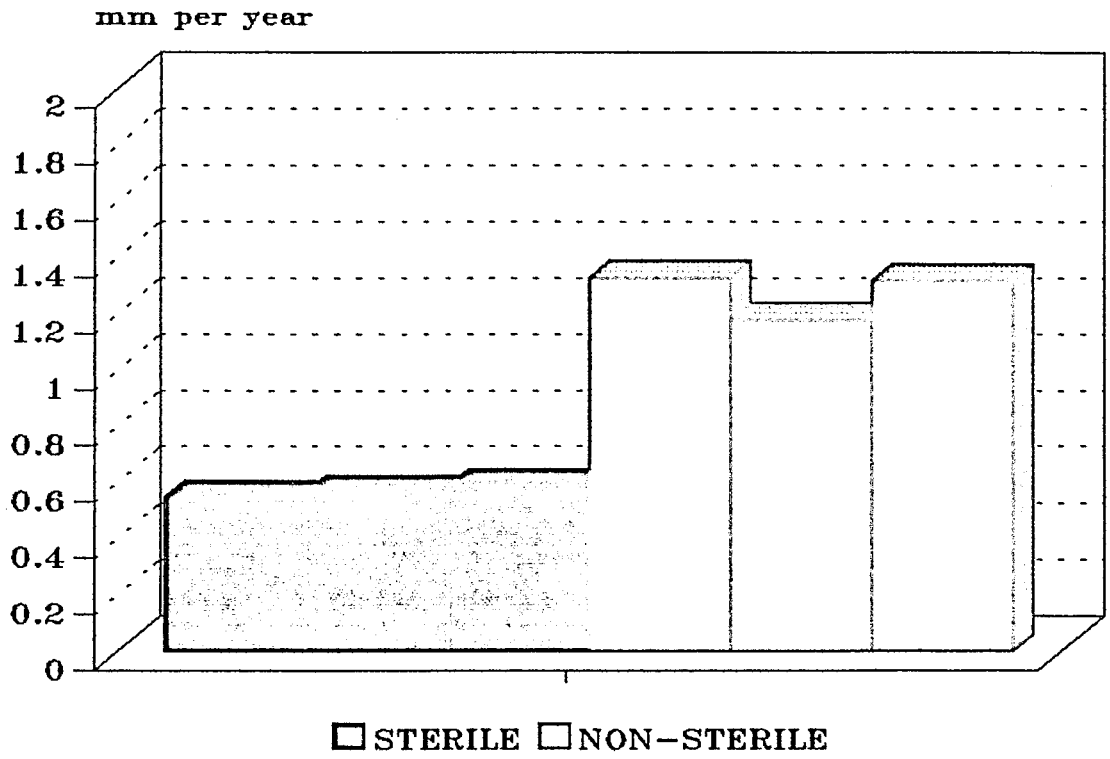

Figure 13 : Corrosion rates on the mild steel panels - Phase 2

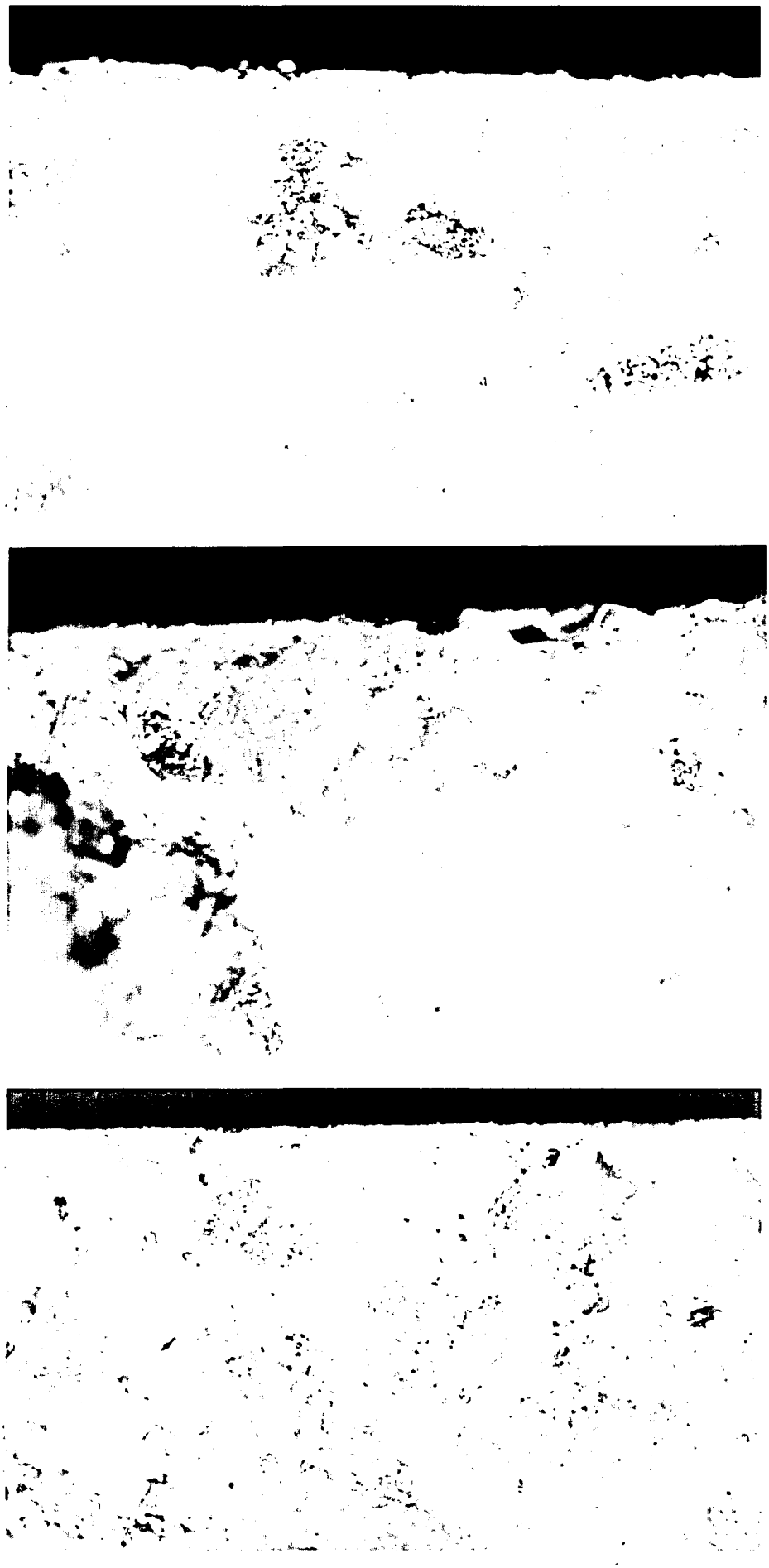

FIGURE 14 MICROGRAPHS OF CROSS-SECTION THROUGH CONCRETE SAMPLES

FIGURE 15 MICROGRAPHS OF CROSS-SECTIONS THROUGH MORTAR SAMPLES