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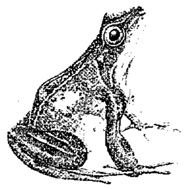

DoE 0001-SW/1

DETERIORATION OF ASBESTOS CEMENT WATER MAINS (MSP 9731 SLD)

Final report to the Department of the Environment

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September 1988

DoE Contract Reference: PECD 7/7/117
Contract Duration: May 1984 to December 1987

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PREFACE

In May 1984 the Department of the Environment placed a contract (Ref PECD 7/7/117) with the Water Research centre to investigate and report on the deterioration of asbestos cement water mains in the the United Kingdom. This contract ended on 31 December 1987. An interim report "Usage and Performance of Asbestos Cement Pressure Pipe" was provided and issued to the Water Industry in March 1986. This final contract report, whose objectives are presented in the Summary, includes the interim report as Section 1.

SUMMARY

I OBJECTIVE

The objectives of the investigation are:

(i) To determine the amount, size, age and geographical distribution of asbestos cement pressure pipe conveying potable water in the UK water supply system.

(ii) To estimate the population supplied by water which has been conveyed through asbestos cement mains.

(iii) To determine the rates of deterioration of asbestos cement pipe occurring in UK waters and the potential for release of asbestos fibres into the water supply.

(iv) To assess the efficacy of measures which could be taken to reduce the deterioration of asbestos cement pipes or prevent further release of fibres.

II REASON

The recent interest in asbestos in the environment has resulted in questions being raised over the suitability of asbestos cement pipes for conveying potable water. A recent study commissioned by the Department of the Environment has concluded that asbestos cement pipes may contribute to the numbers of asbestos fibres in the conveyed water in the distribution system, and suggests that the aggressiveness of the water and the length and age of the pipes are contributory factors.

III CONCLUSIONS

(i) Asbestos cement usage

- Asbestos cement (AC) pipes account for approximately 11% (37,000kms) of the total length of mains in the United Kingdom water supply system.

- Approximately 22% of the population (12 million people) receive water which has passed through asbestos cement pipes.

(ii) Deterioration

- Low pH, low alkalinity waters are aggressive to asbestos cement pipes.

- Of the asbestos cement pipe laid approximately half is in locations where the conveyed water may be aggressive.

- The most reliable method of assessing the depth of degradation incurred was by elemental analysis through sections of the pipe. Phenolphthalein staining showed a very good correlation with elemental analysis. None of the other techniques assessed proved suitable.

(iii) Failures/Degradation rate

- In areas of aggressive conveyed and groundwaters corrosion related failures have been reported from pipes less than 20 years old.

- In less aggressive environments the failure rate of asbestos cement pipes has been seen to increase linearly with age.

- Prediction of rates of attack are very difficult in the UK as most of the pipes are bitumen coated, and the pipe degradation is thus very localised around defects in the coating.

- The maximum internal degradation observed was 8mm in a period of 40 years.

(iv) Protection

- Both epoxy resin and cement mortar can be successfully applied to the inside of new and degraded pipes to provide enhanced protection, or to renovate the pipes.

- Cement mortar lining may only be a temporary solution to internal degradation as the mortar itself deteriorates by the same mechanisms as asbestos cement.

- Epoxy resin lining prevented any further degradation of the inside of the pipe.

- Acceleration factors of approximately 10 have been achieved in the accelerated corrosion rig when compared to the most severe degradation observed in service.

- Rates of deterioration of asbestos cement can be reduced by chemically treating the conveyed water to increase its buffering capacity. However chemical treatment cannot prevent release of fibres from pipes which are already degraded.

IV **RESUME**

Water utility records have been examined to determine the amount of asbestos cement pipe in use in the UK water supply system. The data has been analysed to identify the size, age and geographical distribution of AC pipes. An assessment of the population served has been made. Failure data from four selected areas were analysed and show a failure rate below the national average for all pipe materials. Various trends have been identified in the failures from each of the areas, and possible reasons for these trends have been proposed.

Examination of pipes exhumed from a wide variety of environments showed attack to be non uniform due to the presence of a bitumen coating. Because of this non-uniform attack no simple model could be determined to explain the deterioration, although reasonably good correlations could be made for low pH, low alkalinity waters. It is thus not possible to accurately predict potential rates of release of fibres into the water supply.

Cement mortar and epoxy resin protective linings were successfully applied to asbestos cement pipes in various conditions of degradation. Accelerated corrosion tests were developed to determine the efficacy of these protective linings. The tests provided an acceleration of approximately 10 compared to the most severe degradation observed from exhumed pipe samples, thus 12 months exposure to the accelerated tests approximates to a 10 year service exposure.

Short term tests examining the effect of modifications to the chemical characteristics of the water were undertaken to assess whether protection could be afforded by treatment of the conveyed waters.

CONTENTS

INTRODUCTION

Asbestos cement (AC) pressure pipes were first manufactured in the United Kingdom in the late 1920's and have been used in the water supply system since the 1930's. Use of AC pipe became widespread during the 1950's and 1960's, particularly in the smaller diameter distribution sizes. It's popularity was a result of being cheaper and easier to handle than cast iron, and its claimed resistance to corrosion attack.

The recent interest in asbestos in the environment has raised questions[1] on the suitability of asbestos cement pipes for conveying potable water, particularly with regard to its effect on the water quality. Concern has been expressed over the possibility of asbestos fibres being released into the water supply by deteriorating pipework.

A recent study commissioned by the Department of the Environment (DoE)[2] has shown that asbestos cement pipes may contribute to asbestos levels in water in the distribution system. The report suggests that the aggressiveness of the water, and the length and age of the pipes probably contribute to the concentration of fibres found.

Asbestos cement pipes are known to deteriorate in certain environments, but the parameters controlling the rate of degradation, and their effect on pipe performance are not fully understood. Hence the DoE commissioned the Water Research Centre (WRc) to investigate the deterioration of AC pressure pipes in the UK.

The objectives of the project are:

(i) To determine the scale and conditions of use of asbestos cement pipes in the UK water supply, and the population receiving water which has passed through AC mains.

(ii) To determine the mechanism and rate of deterioration of asbestos cement pipes in a range of potable water environments. From this information the potential for fibre release will be assessed.

(iii) To evaluate suitable lining materials and water treatment techniques to minimise fibre release.

SECTION 1

USAGE AND PERFORMANCE OF ASBESTOS CEMENT PRESSURE PIPE

1.1 SCOPE OF SECTION 1

To meet the first objective of determining the scale and conditions of use of asbestos cement pipes in the UK water supply and the population receiving water conveyed through AC pipes the Water Industry's records were examined to:

(a) quantify the usage of AC pipe with respect to age and conveyed water quality,

(b) assess the population receiving water supplied through AC mains,

(c) determine the performance of AC pipe and the parameters which affect its failure rate.

1.2 USAGE OF ASBESTOS CEMENT PIPE

1.2.1 DATA COLLECTION

(i) Length

Various approaches were adopted to collating data from the Water Utilities depending on the quality and form of the records. Much of the data was derived directly from mains laying records or from distribution plans. When records of this nature were unavailable estimates based on the known mains laying practice, or measurement of mains identified as AC by the Utilities staff were used. In those instances where complete material information was not available, only that which was positively identified as AC was measured. Hence the amount recorded represents a minimum length in the ground.

(ii) **Diameter**

The diameters of the mains were generally identified on the plans or mains laying records. In some areas the data provided was limited to size ranges, often split between small diameter, distribution mains ≤6", and large diameter trunk mains, >6".

(iii) **Ages**

When available, most of the data gave only approximate age distributions for the pipe laid. However, accurate information was available from a limited number of areas, which enabled the production of precise age profiles.

(iv) **Population served**

An estimate of the population receiving water supplied through AC pipes was generally made by determining which towns and villages are supplied by AC trunk mains. The populations of these towns was obtained from recent census records generally held by the appropriate water undertaking. In some instances detailed numbers of consumers connected to AC distribution mains were available, but generally only for short lengths of pipe. Where no population figure was available, estimates were based on the proportion of distribution size mains which were AC, with an enhanced proportion for large diameter trunk mains. However, as many of the distribution systems are networked, and consumers may receive water from various sources, accurate population data is impossible to obtain.

(v) **Water Quality**

Water quality data was obtained from a WRc data base which contains information on water hardness, alkalinity and pH. These were used to identify the areas where the conveyed water is potentially aggressive to AC.

1.2.2 RESULTS

1.2.2.1 Length of Asbestos Cement Pipe

Data on the length of asbestos cement pipe in use has been obtained from water utilities which operate 98% of the UK water mains. Of the 347,669 kms of main in the ground[3, 4] over 37,500 kms, or approximately 11% of the system, is asbestos cement. Some 12.1 million people, or approximately 22% of the population receive water which has been conveyed through AC pipe. The data is summarised in Table 1.1, which also shows the breakdown in usage between the Water Authorities, Water Companies, Scottish Regional Councils and the Department of the Environment for Northern Ireland.

Table 1.2 presents a detailed breakdown of the usage and population served for each Water Authority, and for the Companies within each Authority's boundary.

A wide variation in AC pipe usage is evident between different Water Authority areas ranging from 3% in Thames Water area to 22% in Anglian. Within the Scottish Regional Councils (RC's) the variation is wider, from 3% in Central and Lothian RC's to 70% in the Western Isles Island Council. The data is presented graphically in Figures 1.1A and 1.1B and shows more clearly the pattern of usage around the country. There is a clear relationship between the use of AC mains and population density. Those areas with a low population density i.e. large rural areas, contain a relatively large proportion of AC mains, whereas those with a high population density, ie containing large urban areas, have a small proportion of AC.

1.2.2.2 Diameters

Over 60% of the data recorded identified specific AC pipe diameters.

The remaining data generally combined two or more pipe sizes, and these were apportioned between diameters in the ratios obtained from the more detailed data. This allowed the total length of AC pipe of each diameter to be estimated. Figure 1.2 presents the proportions and lengths of pipe in several diameter bands and shows that over 80% of the AC mains laid are 6" or less in diameter, which generally relates to distribution main sizes.

Variations in the usage of the different diameters exist between the Water Authorities, the Scottish Regional Councils, and the Water Companies. Small diameter mains up to 3", account for a higher proportion of AC laid in the Scottish Regional Councils than the Water Authorities, which in turn are higher than the Water Companies see Figure 1.3. This trend also correlates with the population densities of the supply areas, those with a low population density using large proportions of small diameter mains.

1.2.2.3 Age profiles

The majority of the Water Undertakings provided approximate age data. Complete and accurate age data was available from only a limited number of Water Utilities which contained approximately 12% of the total length of asbestos cement mains. This sample had a diameter breakdown similar to the total national usage.

The age pattern from the detailed information and from the areas where only approximate data was available were broadly equivalent. Since the detailed study was compiled from Water

Authority areas, Water Companies and Scottish Regional Councils the data can be considered representative of the national mains laying pattern.

From an initially low rate of laying of AC mains in the 1930's, use of the material gained in popularity, reaching a peak of 1250km/yr in the 1950's and 1960's see Figure 1.4. The rate of mains laying has since continuously decreased to the current rate of approximately 200km/yr.

Figures 1.5 and 1.6 show the age distribution for the diameter ranges used. In Figure 1.5 the age profile for the AC mains is presented in terms of the percentage of the total mains laid, and shows a gradual move away from laying small diameters, with the use of 3" and below reaching a maximum in the 1950's, 4" to 10" reaching a maximum in the 1960's and 12" and above reaching a maximum in the 1970's.

Presenting the age/diameter data as a proportion of the mains laid during each decade, Figure 1.6 shows the trend towards the use of larger diameters. Until the 1950's over 50% of the asbestos cement mains laid were 3" or less in diameter, whereas in the 1980's this figure had fallen to 2%. Conversely the use of 12" and above has increased from none during the 1930's and 1940's, to 20% during the 1980's.

These trends in the mains laying can be attributed to several factors.

Manufacture of asbestos cement pipe started in the UK in the late 1920's, when it provided the only practical alternative to cast iron in the smaller diameters. With the lower cost, and the claimed chemical stability it proved an attractive material. The use of AC increased sharply during the 1940's and 1950's as the passing of the 1944 Rural Water Supplies Act placed an obligation on the Water Undertakings to supply water to communities, providing certain conditions were met.

The advent of uPVC in the 1960s provided a cheap alternative to cast iron and asbestos cement, and thus the market share of small diameter (<6") AC pipe dropped, and continued to decline during the 1970s and 1980s.

1.2.2.4 Asbestos cement and corrosive environments

Asbestos cement pipes are known to deteriorate when conveying certain aggressive waters[5,6,7]. Deterioration of AC is generally caused by either soft water leaching of the cementitious matrix, or by acid or sulphate attack. Various attempts have been made to classify the aggressiveness of water to AC, with the two most commonly used parameters being the Langelier Index[8] which is a measure of the level of carbonate saturation, and the AWWA Aggressiveness Index[9] which is a simplification of the Langelier Index (see Appendix 1).

As most water distribution systems are networked and often convey blended waters it has not been possible to relate AC mains directly to their conveyed water quality. Thus an arbitrary parameter was used defining areas with aggressive waters as those where most of the conveyed water was considered to be "soft" (i.e. total hardness <75mg/l). In these areas some internal deterioration of the AC mains is possible and can be anticipated. The areas with the most aggressive water are in the north and the west, where the water is derived from moorland sources, or from areas of hard igneous and metamorphic rock (Figure 1.7). Within these areas of potentially aggressive water approximately 18,500km of asbestos cement pipes have been laid serving a population of approximately 5.5 million. This represents approximately 48% of the asbestos cement mains, and 10% of the population of the UK.

1.2.3 SUMMARY OF MAINS LAYING DATA

(i) Of the 347,669 kms of potable water mains in the United Kingdom water supply system, approximately 11% or 37,542 kms are asbestos cement.

(ii) 22% or 12.1 million of the United Kingdom's population receives water which has been conveyed through AC.

(iii) The utilities with the largest percentage of AC are those with a high proportion of rural areas and a low population density

(iv) Much of the AC laid during the 1950's and 1960's was for rural water supply, and hence was laid in the areas of low population density. Many of these areas coincide with regions with soft conveyed and groundwater which can be considered to be aggressive to AC. It is therefore estimated that approximately 50% of the asbestos cement mains laid may be deteriorating and these supply some 10% of the population.

1.3. PERFORMANCE OF ASBESTOS CEMENT MAINS

To assess the in-service performance of asbestos cement pipes, failure records have been examined from four areas identified as having laid large lengths of AC, and having maintained good mainlaying and burst records[10]. The data was also used to determine whether the presence of soft conveyed water and soft groundwaters cause structural deterioration of the pipe material.

The operators of one of the areas selected considered AC mains to perform well. In this area both the conveyed water and the groundwater are hard, and the soils are generally cohesive clays.

The other three areas were selected as they have generally soft conveyed water and soft groundwaters, and have reported deterioration of AC pipes.

Table 1.3 summarises the extent of the data available for each area, with a broad assessment of the conditions of use.

1.3.1 AREA 1

1.3.1.1 Quality of Records

Detailed mainslaying records have been maintained over the whole period of asbestos cement pipe usage, with accurate information recorded on the year laid, the diameter, and the class of pipe. Some limited information is available on the position in which the pipes have been laid, ie field, path, road.

Burst records have been maintained since 1952, and the information recorded for each failure has generally been very detailed.

The only parameters unrecorded are the presence of a pipe coating, the operating pressure and the cause of failure.

The total hardness of the conveyed water in the area varies between 150 and 500mg/l as $CaCO_3$, and most of the water has a total hardness of 300mg/l as $CaCO_3$. The soils are generally cohesive clays which are not chemically aggressive to AC, with a hard groundwater, producing a non aggressive external environment.

1.3.1.2 Analysis

Figure 1.8A shows the length of asbestos cement laid in Area 1, with a histogram of the percentage laid during each decade presented in Figure 1.8B. Comparison with the National laying pattern of Figure 1.4 shows a similar increase in use during the 1950's and 1960's with a subsequent decline in recent years. However, due to the satisfactory performance of AC in this area it continued to be used at a significant rate during the 1970's and 1980's, in contrast to the National usage which declined more severely. There is a trend towards the use of larger diameter AC, as shown in Figure 1.9, which is consistent with the National trend shown in Figure 1.6.

In 1956 the use of class B asbestos cement pipe for water mains was discontinued, with class C pipe for the smaller diameters becoming standard.

The number of failures occurring on AC mains has increased since records started in 1952 (Figure 1.10A). However, when the length in service is taken into account the trend is reversed, with a relatively constant, low failure rate since 1957 (Figure 1.10B). Two peaks in the failure rate are evident in 1959 and 1976, which correspond to two hot summers with long dry periods. The influence of climatic conditions on the failure rate can be seen in Figure 1.11, where the occurrence of failures through the year is presented. In this study area, over 60% of the failures have occurred during July, August and September when the soil moisture deficit is at a maximum. This results in shrinkage of the cohesive clay soils which are predominant within the area, and causes loading of the buried pipes. Additionally the drying of the clays reduces the attenuation of imposed traffic loads leading to higher loads transmitted to the pipes. The high incidence of ring fracture failures, and the large proportion of failures on small diameter mains, Table 1.4, are consistent with such external loading imposing bending stresses on the pipes[11].

The apparent reduced failure rate after 1957 is coincident with the introduction of class C pipes, which having a thicker pipe wall, see Appendix 2, can withstand higher bending stresses. Indeed, when separate failure rates are calculated for each of the two classes of pipe, the class C pipes have an average failure rate an order of magnitude lower than the class B pipes; 0.026 failures/km yr compared with 0.264 failures/km yr respectively.

Two factors could distort the real difference, enhancing the apparent class C performance:

(i) the larger diameter pipes, which have a higher bending moment resistance, account for an increasing proportion of the AC pipe laid. Thus different diameter distributions exist for class B and class C pipe, which could be expected to affect their overall failure rates.

(ii) the class B pipes tend to be older, and thus could be expected to exhibit a higher failure rate.

To examine the effect of diameter, the failure rate for each size of pipe was calculated for both class B and class C pipes. The results plotted in Figure 1.12 show that the failure rate decreases with increasing diameter, reflecting the increased resistance to beam loading. Comparison of the failure rate of a given diameter for each class of pipe, shows the failure rate for class C to be significantly lower than class B pipe.

Variations in the age profile of the two classes can be eliminated by considering the age of the pipes at failure, and relating to the length exposed. The resulting failure rates are plotted against age in Figures 1.13 and 1.14 for class B and class C pipes respectively. Using the least squares method a best fit line has been determined, and a linear relationship was identified between failure rate and age for both classes of material.

The equations of the two best fit lines are:

for class B pipe $f = 0.0070a + 0.12$

for class C pipe $f = 0.0022a + 0.002$

where f = failure rate (No/km)

a = age (years)

Thus the predicted overall failure rate at 50 years is

0.47 failures/km yr for class B pipe

0.11 failures/km yr for class C pipe

A similar analysis has been performed on 4" pipe of each class, and it can be seen from Figures 1.15 and 1.16 that the same linear relationship between failure rate and age exists. The failure rate for 4" class C AC pipe is lower than the failure rate for 4" class B AC pipe.

The predicted failure rates at 50 years being

0.46 failures/km yr for 4" class B AC pipe

0.12 failures/km yr for 4" class C AC pipe

There is however a substantial scatter evident at the larger ages due to the short lengths of pipe exposed for that time, see Figures 1.13 and 1.14.

1.3.2 AREA 2

1.3.2.1 Quality of Records

Although the only details available on mains laying were from distribution plans, and failure records have only been maintained since 1979, this area was included in the survey as it had reported problems with degradation of asbestos cement pipes. The limited data available precludes any accurate analysis of failure trends and relationships, but does enable comparison of failure rates with other areas.

The conveyed water is generally soft with total hardness values between 35 and 90 mg/l as $CaCO_3$. The conveyed waters are therefore considered aggressive towards AC and some degradation of the pipe material can be anticipated. Sandy/gravel soils cover most of the region and enable rapid percolation of the soft groundwaters.

1.3.2.2 **Analysis**

Annual failure rates for area 2 have been calculated for pipes of >3" diameter, and are presented in Figure 1.17, with the average non-accidental failure rate for the six years of records 0.10 failures/km yr. These failures have occurred fairly uniformly through the year (Figure 1.11) suggesting the failures are not attributable either directly or indirectly to the climatic conditions. As accurate age data for laying of the mains is not readily available, the effect of age on failure rate cannot be analysed. However, approximate ages at failure are available enabling general trends to be viewed in ten year age bands. Over 90% of the failures recorded on pipes 50 or more years old have been attributed to corrosion (Figure 1.18), with corrosion cited as the cause of failure on a few pipes which are less than 20 years old. It can be seen from Figure 1.18 that the proportion of failures attributed to corrosion progressively increases with pipe age, and thus can be expected to become more prevalent.

The effect of diameter on failure rate is comparable to that seen in area 1 (Figure 1.12) with the failure rate decreasing with increasing diameter. However, as the class of pipe has not been recorded, it is not possible to determine whether this lower failure rate is related to class or diameter.

A summary of the failure data together with the total mains laid is presented in Table 1.5, where the high incidence of longitudinal fractures and the high proportion of failures occurring in sand and gravel are prominent.

A longitudinal fracture is consistent with an effective over-pressurisation of the pipe, which may be caused by surge pressures, by loss of strength due to degradation of the pipe material or by a combination of these effects. This diagnosis is confirmed by the cause of some 60% of the failures being attributed to either surge or corrosion.

1.3.3 AREA 3

1.3.3.1 Quality of Records

Mainslaying records have been maintained since asbestos cement was first laid although the data on pipe ages is not precise. Various classes of pipe have been laid, but have not always been recorded.

Burst records have been maintained since 1972, and have recorded most information. However, the limited period covered by the records precludes an accurate analysis of failure trends.

The conveyed water is generally soft with the total hardness commonly less than 50mg/l as $CaCO_3$. Much of the soil is sandy/gravel with some areas of peat and clay.

1.3.3.2 Analysis

Annual failure rates, excluding failures due to accidental damage, for the eleven years of records are presented in Figure 1.19, with the average failure rate 0.026 failures/km yr. There is very little variation from this value with increasing age, although the cause and type of failure changes. In Figure 1.20 the number of failures for each five year period is presented with the numbers of corrosion induced and longitudinal failures. In the early life of the pipes there are very few corrosion or longitudinal failures.

After approximately 15 years corrosion induced failures become increasingly significant, with 35% of the failures of 25 - 30 year old pipe attributed to corrosion, and 75% recorded as longitudinal fractures. Thus the pipes are progressively deteriorating in the soft conveyed and groundwaters, but in this operating environment have a minimum life of 15 - 20 years before corrosion causes failure.

Figure 1.21A presents the failure rate for each diameter of AC pipe laid within this area. However, the small number of failures recorded may be masking any trends in the failure rate.

Table 1.6 presents a summary of the failure data and shows that the types of failure are evenly divided between longitudinal fractures, ring fractures and joints, indicating failure is not caused by a single mechanism.

Climatic conditions do not appear to significantly affect the failure rate, as the recorded failures have occurred relatively uniformly through the year (Figure 1.11).

1.3.4 AREA 4

1.3.4.1 Quality of Records

Detailed mainslaying records have been maintained since asbestos cement was first laid, and the pattern of use is similar to the National usage, with a majority of the AC laid during the 1950's and 1960's (Figure 1.22). All the pipe laid in this area has been class C.

Burst records were initiated in 1971, and have been maintained in good detail since. Again the limited period for which records are available precludes accurate analysis of failure trends.

The conveyed water is generally soft, with a total hardness of less than 50ppm as $CaCO_3$, and would thus be considered moderately aggressive to AC. Much of the soil in the area is sandy/gravel with limited areas of clay.

1.3.4.2 Analysis

During the 11 years of available burst records there have been 135 failures which are not attributed to accidental damage. This gives an average failure rate of 0.047 failures/km yr; the annual rates are plotted in Figure 1.23. Analysis of the failure rate with respect to age shows a very high failure rate (0.95 fails/km yr) during the first year of service (Figure 1.24). Of these failures 90% are ring fractures indicating the application of a bending load. When a cause of failure has been recorded 55% are attributed to subsidence and 41% to loading. Failures of this type early in the life of a pipeline may be caused by several factors, either individually, or in combination.

(i) the use of contractors vehicles in development areas on unmade ground, thus severely overloading the buried pipes.

(ii) general ground settlement

(iii) poorly laid pipe

(iv) poor quality pipe

After the first year the failure rate drops to a constant low level of 0.04 failures/km yr (Figure 1.24).

Although most of the failures are ring fractures, Table 1.7, which are characteristic of beam loading, there does not appear to be the expected relationship between diameter and failure rate Figure 1.21B. However, this may be due to the limited data available.

Few corrosion related failures have been reported despite the soft conveyed water, with few related longitudinal fractures.

There appears to be little effect of climatic conditions, with the failures fairly evenly distributed through the year (Figure 1.11).

1.3.5 COMPARISON OF THE FOUR AREAS EXAMINED

In each of the four areas selected, the mains laying pattern is broadly similar, with a majority of the asbestos cement pipe laid during the 1950's and 1960's. Much of the pipe in use is small diameter, although there is a trend away from the use of AC for small diameter mains.

Comparison of the failures in area 1 which was selected as its water and environments are non-aggressive with areas 2, 3 and 4, where soft water, aggressive environments exist shows several important factors.

(i) The non-accidental failure rate of class C AC pipe in area 1 is comparable to that of areas 3 and 4, but is considerably lower than area 2 where the class of main is unknown.

(ii) Class B pipes in area 1 have a significantly higher failure rate than the class C pipe, and higher than the overall failure rates of areas 2, 3 and 4.

(iii) Area 2 shows a high incidence of corrosion related failures, which account for an increasing proportion of the total failures of older pipes.

(iv) Ring fractures, which are commonly caused by bending stresses, are the predominant type of failure in area 1. Area 2 features a high incidence of longitudinal fractures which are consistent with an effective over-pressurisation of the pipe. Corrosion of the pipe wall may contribute to the incidence of longitudinal fractures caused by overpressurisation by effectively reducing the strength of the pipes.

(v) The distribution of failures through the year is fairly random for areas 2, 3 and 4 where sandy/gravel soils commonly occur, whereas in area 1, with cohesive clay soils, most of the failures occur during the dry summer months.

This is also reflected in the high failure rate in area 1 during years with hot dry summers.

(vi) Although no degradation of the material is reported in area 1, the failure rate increases linearly with age for both class B and class C pipe, suggesting either deterioration of the material properties is occurring or the influence of external factors is increasing.

(vii) In areas 2 and 3, which have aggressive waters, the proportion of failures attributed to corrosion increases with age, with corrosion related failures first occurring at around 20 years. Longitudinal failures, which are commonly associated with corrosion, follow a similar trend although at a higher rate. However, Area 4, which has a similarly aggressive conveyed water has recorded very few corrosion related failures.

(viii) For the four areas examined, the overall non-accidental failure rate of AC is 0.10 failures/km yr, with the highest rate 0.11/km yr. This compares with 0.139 fails/km yr for non-accidental failures of 3" and 4" uPVC mains and 0.14 fails/km yr for cast iron mains in London[12].

1.4 RELATIONSHIP BETWEEN FAILURE DATA AND MAINLAYING

In the four areas selected for analysis of failure data a majority of the AC mains were laid during the 1950's and 1960's and in later years an increasing proportion of the AC laid has been for larger diameter mains. Thus the mainslaying pattern is similar to the national pattern of use suggesting that the failure trends of each area may be related to other comparable environments without undue distortion due to different age and diameter profiles. However variations in the failure rates may occur due to different surface usage since no information is available on the position of laying.

Analysis of the failure records from Area 1 shows the failure rate to increase linearly with age. The relationship has been determined to be:

$$F = 0.00697A + 0.122 \text{ for class B pipes}$$
$$F = 0.00217A + 0.00225 \text{ for class C pipe}$$

where F = failure rate failures/km yr
A = age years

The reason for this trend is not known, but assuming that it continues, according to the relationships shown above, then at 50 years a failure rate of 0.47 failures/km yr can be anticipated for class B pipe and 0.11 failures/km yr for class C pipe. Or alternatively the national average failure rate of 0.22 failure/km yr[13] will be reached after:

14 years service for class B pipe
100 years service for class C pipe

In areas 2, 3 and 4 (with more aggressive environments of soft conveyed and groundwater) the information on ages was not accurate enough to allow a trend analysis. However, an increasing proportion of the failures after about 20 years service are attributed to corrosion. The cause of the corrosion and whether internal or external corrosion, a combination of the two or some other parameter control the failure rate is currently unknown.

Nationally the majority of the AC pipe was laid during the 1950's and 1960's and is thus 15 to 35 years old. Approximately 50% of the AC has been laid in soft water areas. Corrosion is a time dependent phenomenon and with corrosion related failures reported from about 20 years it is anticipated that corrosion will become an increasing cause of failure, unless steps can be taken to prevent or minimise any further deterioration.

1.5 CONCLUSIONS

1. Asbestos cement pipes account for approximately 11% (37,000kms) of the total length of mains in the United Kingdom water supply system.

2. Approximately 22% of the population (12 million people) receive water which has passed through asbestos cement pipes.

3. Of the AC pipe laid approximately half is in locations where the conveyed water may be aggressive.

4. In areas of aggressive conveyed and groundwaters corrosion related failures have been reported from pipes less than 20 years old.

5. In less aggressive environments the failure rate of asbestos cement pipes has been seen to increase linearly with age.

Table 1.1 - Use of asbestos cement for water mains

	Population Density	Length of Mains Total*	Asbestos Cement		Population Total*	Served via AC	
	/km^2	kms	kms	%	000's	000's	%
Water Authorities	357	219,255	22,043	10	37,071	7,444	20
Companies Water	451	68,166	6,884	10	12,508	3,404	27
Scottish Regional Councils	67	42,267	6,624	16	5,020	1,184	24
DoE Northern Ireland	110	17,981	1,991	11	1,562	116	7
TOTAL		347,669	37,542	11	56,161	12,148	22

* Data from references

(3) Water Services Yearbook 1984

(4) Water Services Yearbook 1985

(14) Water Authorities Association 1984

(15) Strathclyde RC Private Communications

Table 1.2 - National usage of asbestos cement pipe and population served

Water Authority	Mains Length Total[4]	Asbestos Cement		Population TOTAL[4]	Served by Asbestos Cement	
	km	km	%	1000's	1000's	%
Anglian Water	28,094	5,441	19	3,539	1,295	37
Water Companies within Authority Boundary	10,404	2,931	28	1,982	1,458	74
Total for Anglian	38,498	8,372	22	5,521	2,753	50
Northumbrian Water	8,281[3]	550	7	1,219[3]	340	28
Water Companies within Authority Boundary	7,959	222	3	1,413	182	13
Total for Northumbrian	16,240	772	5	2,632	522	20
North West Water	36,200[14]	3,213	8	6,788	1,737	26
Severn Trent Water	37,044	3,599	10	6,800	870	13
Water Companies within Authority Boundary	6,781	754	11	1,430	254	18
Total for Severn Trent	43,825	4,353	10	8,230	1,124	14

Table 1.2 (cont)

Water Authority	Mains Length			Population		
	Total (4)	ASBESTOS CEMENT		TOTAL (4)	SERVED BY ASBESTOS CEMENT	
	km	km	%	1000's	1000's	%
Southern Water	11,124	343	3	2,018	168	8
Water Companies within Authority Boundary	11,965	764	6	1,837	390	21
Total for Southern	23,089	1,107	5	3,855	558	14
South West Water	13,800 (14)	982	7	1,422 (14)	461	32
Thames Water	26,691 (14)	992	4	7,179 (3)	773	11
Water Companies within Authority Boundary	20,009	308	2	3,995	177	4
Total for Thames	46,700 (14)	1,300	3	11,174	950	9
Welsh Water	22,320	3,934	18	2,694	840	31
Water Companies within Authority Boundary	1,816	541	30	259	132	51
Total for Welsh	24,136	4,475	19	2,953	972	33

Table 1.2 (cont)

Water Authority	Mains Length			Population		
	Total[4]	ASBESTOS CEMENT		TOTAL[4]	SERVED BY ASBESTOS CEMENT	
	km	km	%	1000's	1000's	%
Wessex Water	9,200	991	11	1,013	329	32
Water Companies within Authority Boundary	8,333	1,358	16	1,421	810	57
Total for Wessex	17,533	2,349	13	2,434	1,139	47
Yorkshire Water	26,501[14]	1,998	8	4,399[3]	631	15
Water Companies within Authority Boundary	899	6	<1	171	1	<1
Total for Yorkshire	27,400	2,004	7	4,570	632	14
DoE Northern Ireland	17,981	1,991	11	1,562	110	7

Table 1.2 (cont)

Water Authority	Mains Length			Population		
	Total[4]	ASBESTOS CEMENT		TOTAL[4]	SERVED BY ASBESTOS CEMENT	
	km	km	%	1000's	1000's	%
Borders RC	1,380	302	22	90	22	24
Central RC	2,249	58	3	379	50	13
Dumfries & Galloway RC	3,029	800	26	135	75	56
Fife RC	2,407[15]	198	8	351	135	38
Grampian RC	4,941	526	11	435	122	28
Highland RC	4,639	1,684	36	187	80	43
Lothian RC	5,336	163	3	738	84	11
Strathclyde RC	13,441[15]	1,150	9	2,280	400	18
Tayside RC	3,855	1,055	28	395	186	47
Western Isles IC	990	688	69	30	30	100

Table 1.3 - Summary of asbestos cement mains and failures data

	Area 1	Area 2	Area 3	Area 4
Conveyed water total hardness as $CaCO_3$ mg/l	300	20 - 50	22	28
Groundwater	Hard	Soft	Soft	Soft
Soil type	Cohesive clay	Sand/Gravel	Sand/Gravel	Sand/Gravel
Pipes laid	1938 - 1984	1935 - 1968	1942 - 1982	1935 - 1981
Failure records	1952 - 1984	1979 - 1984	1972 - 1982	1971 - 1982
Total AC length kms	927	492	389	230
Failure rate /km yr	0.11	0.10	0.026	0.047

TABLE 1.4

Data Summary: Area 1

Total failures (1952 - 1984) = 1571

Length by Diameter

1.5"	-
2"	-
3"	7.4%
4"	48.1%
5"	-
6"	25.1%
7"	-
8"	-
9"	13.2%
10"	-
12"	3.9%
>12"	2.3%

Diameter of Failures

1.5"	-
2"	-
3"	14.5%
4"	74.5%
5"	-
6"	9.5%
7"	-
8"	-
9"	1.2%
10"	-
12"	0.3%
>12"	-

Ground type for Failures

"No information"	0.1%
"Rock"	0.0%
"Sand & Gravel"	0.1%
"Clay"	99.5%
"Silt"	0.0%
"Fill"	0.0%
"Ballast"	0.1%
"Other"	0.3%

Failure Type

"No information"	0.8%
"Long fracture"	1.0%
"Ring fracture"	96.8%
"Ring fracture & ferrule"	0.5%
"Joint"	0.1%
"Blow out"	0.6%
"Ferrule"	0.2%
"Corrosion"	0.0%
"Other"	0.0%

Cause of Failures

"No information"	100.0%
"Accidental"	0.0%
"Surge"	0.0%
"Subsidence"	0.0%
"Corrosion"	0.0%
"Loading"	0.0%
"Other"	0.0%

Position of Failures

"No information"	13.5%
"Carriageway"	0.3%
"Lt Tarmac Road"	7.3%
"Unmade Road"	26.6%
"Verge/Footpath"	50.3%
"Field"	0.6%
"Other"	1.4%

TABLE 1.5

Data Summary: Area 2

Total failures of pipe >3" (1979 - 1984) = 306

Length by Diameter

1.5"	NA
2"	NA
3"	33.9%
4"	24.1%
5"	9.7%
6"	15.5%
7"	4.1%
8"	1.5%
9"	3.8%
10"	0.7%
12"	2.8%
15"	3.7%

Diameter of Failures

1.5"	NA
2"	NA
3"	47.7%
4"	37.6%
5"	10.5%
6"	1.0%
7"	2.3%
8"	0.7%
9"	0.3%
10"	0.0%
12"	0.3%
15"	0.0%

Ground type for Failures

"No information"	0.3%
"Rock"	1.3%
"Sand & Gravel"	45.0%
"Clay"	50.3%
"Silt"	0.0%
"Fill"	0.0%
"Ballast"	0.3%
"Other"	2.6%

Failure Type

"No information"	0.3%
"Long fracture"	66.3%
"Ring fracture"	10.1%
"Ring fracture & ferrule"	2.0%
"Joint"	12.1%
"Blow out"	0.7%
"Ferrule"	0.0%
"Corrosion"	1.6%
"Other"	6.9%

Cause of Failures

"No information"	8.2%
"Accidental"	0.0%
"Surge"	23.5%
"Subsidence"	14.7%
"Corrosion"	34.6%
"Loading"	1.6%
"Other"	17.3%

Position of Failures

"No information"	0.7%
"Carriageway"	16.3%
"Lt Tarmac Road"	4.2%
"Unmade Road"	0.0%
"Verge/Footpath"	69.9%
"Field"	8.2%
"Other"	0.7%

TABLE 1.6

Data Summary: Area 3

Total failures >2" (1971 - 1982) = 153

Length by Diameter

1.5"	NA
2"	NA
3"	40.9%
4"	26.6%
5"	1.1%
6"	21.3%
7"	3.0%
8"	-
9"	5.4%
10"	-
12"	1.7%
>12"	-

Diameter of Failures

1.5"	NA
2"	NA
3"	66.8%
4"	10.6%
5"	0.7%
6"	7.5%
7"	2.7%
8"	-
9"	8.6%
10"	-
12"	2.7%
>12"	-

Ground type for Failures

"No information"	12.8%
"Rock"	4.5%
"Sand & Gravel"	23.1%
"Clay"	47.5%
"Silt"	0.0%
"Fill"	1.9%
"Ballast"	1.9%
"Other"	8.3%

Failure Type

"No information"	3.8%
"Long fracture"	34.6%
"Ring fracture"	20.5%
"Ring fracture & ferrule"	0.0%
"Joint"	19.9%
"Blow out"	4.5%
"Ferrule"	0.7%
"Corrosion"	1.3%
"Other"	14.7%

Cause of Failures

"No information"	25.0%
"Accidental"	0.0%
"Surge"	13.5%
"Subsidence"	9.0%
"Corrosion"	12.2%
"Loading"	14.1%
"Other"	26.2%

Position of Failures

"No information"	62.8%
"Carriageway"	3.8%
"Lt Tarmac Road"	3.2%
"Unmade Road"	0.0%
"Verge/Footpath"	18.0%
"Field"	10.3%
"Other"	1.9%

TABLE 1.7

Data Summary: Area 4

Total failures >2" (1971 - 1982) = 153

Length by Diameter

1.5"	-
2"	9.9%
3"	20.1%
4"	35.9%
5"	0.6%
6"	22.9%
7"	0.9%
8"	-
9"	7.4%
10"	1.3%
12"	1.1%
>12"	-

Diameter of Failures

1.5"	-
2"	7.2%
3"	29.3%
4"	35.7%
5"	0.0%
6"	22.1%
7"	0.0%
8"	-
9"	4.3%
10"	1.4%
12"	0.0%
>12"	-

Ground type for Failures

"No information"	0.7%
"Rock"	7.9%
"Sand & Gravel"	38.6%
"Clay"	45.0%
"Silt"	0.0%
"Fill"	5.0%
"Ballast"	0.0%
"Other"	2.8%

Failure Type

"No information"	0.7%
"Long fracture"	4.3%
"Ring fracture"	70.0%
"Ring fracture & ferrule"	0.0%
"Joint"	12.9%
"Blow out"	2.9%
"Ferrule"	0.0%
"Corrosion"	0.7%
"Other"	8.5%

Cause of Failures

"No information"	49.3%
"Accidental"	0.0%
"Surge"	0.0%
"Subsidence"	23.6%
"Corrosion"	0.7%
"Loading"	13.6%
"Other"	12.8%

Position of Failures

"No information"	40.7%
"Carriageway"	11.4%
"Lt Tarmac Road"	2.1%
"Unmade Road"	0.7%
"Verge/Footpath"	35.7%
"Field"	8.6%
"Other"	0.7%

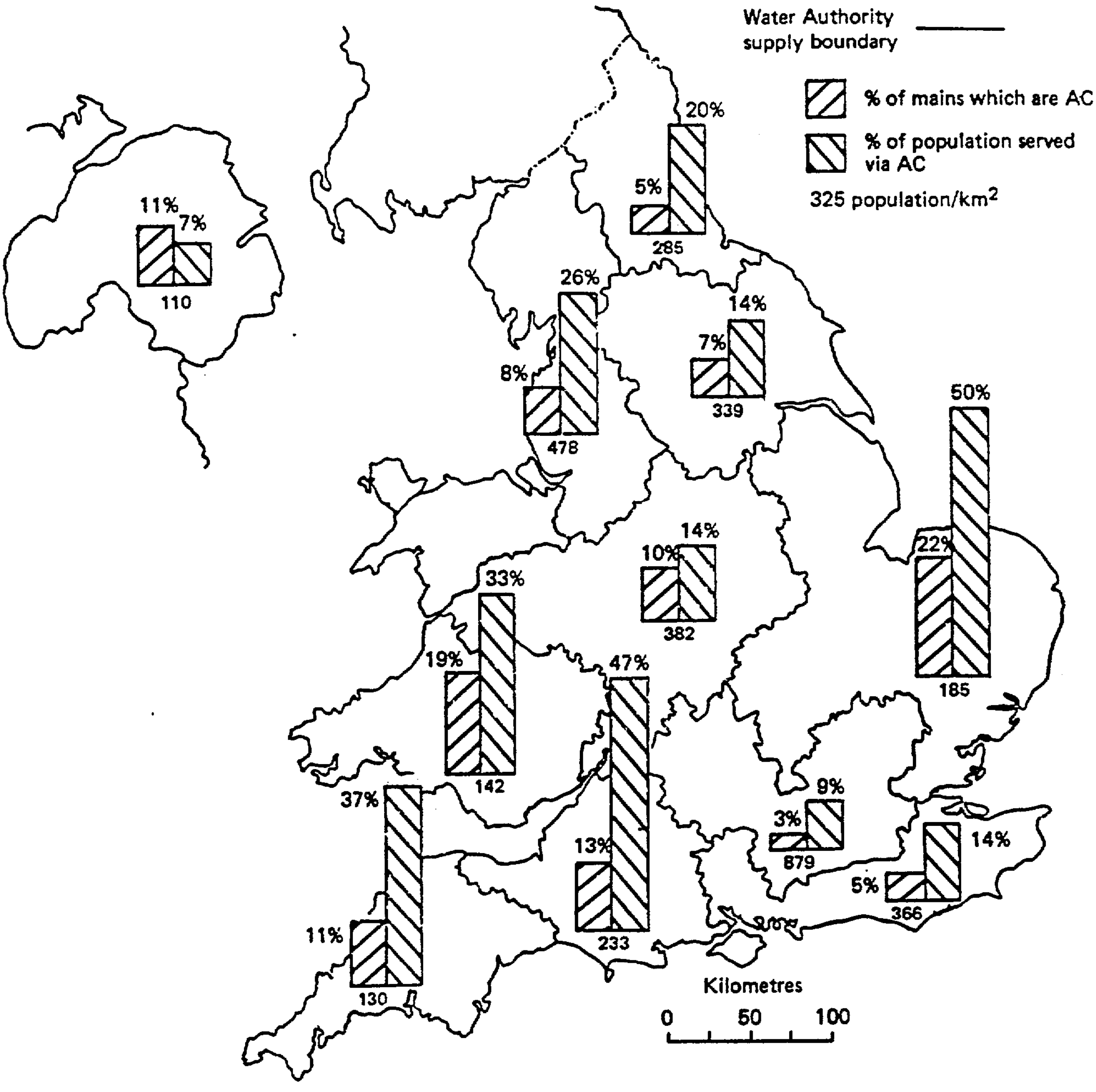


Figure 1.1A National distribution of asbestos cement pressure pipe and population served — England, Wales and N. Ireland

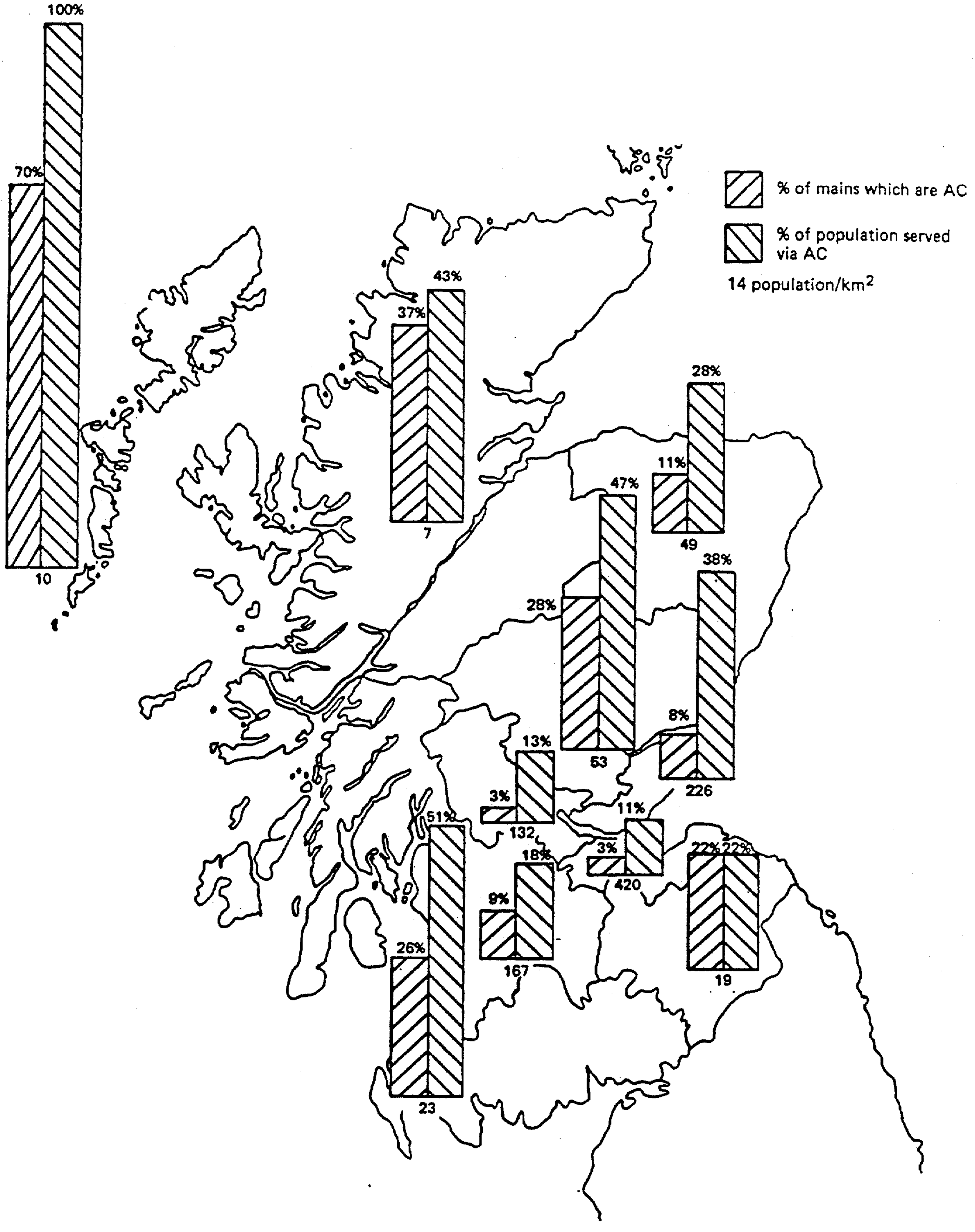


Figure 1.1B National distribution of asbestos cement pressure pipe and population served – Scotland

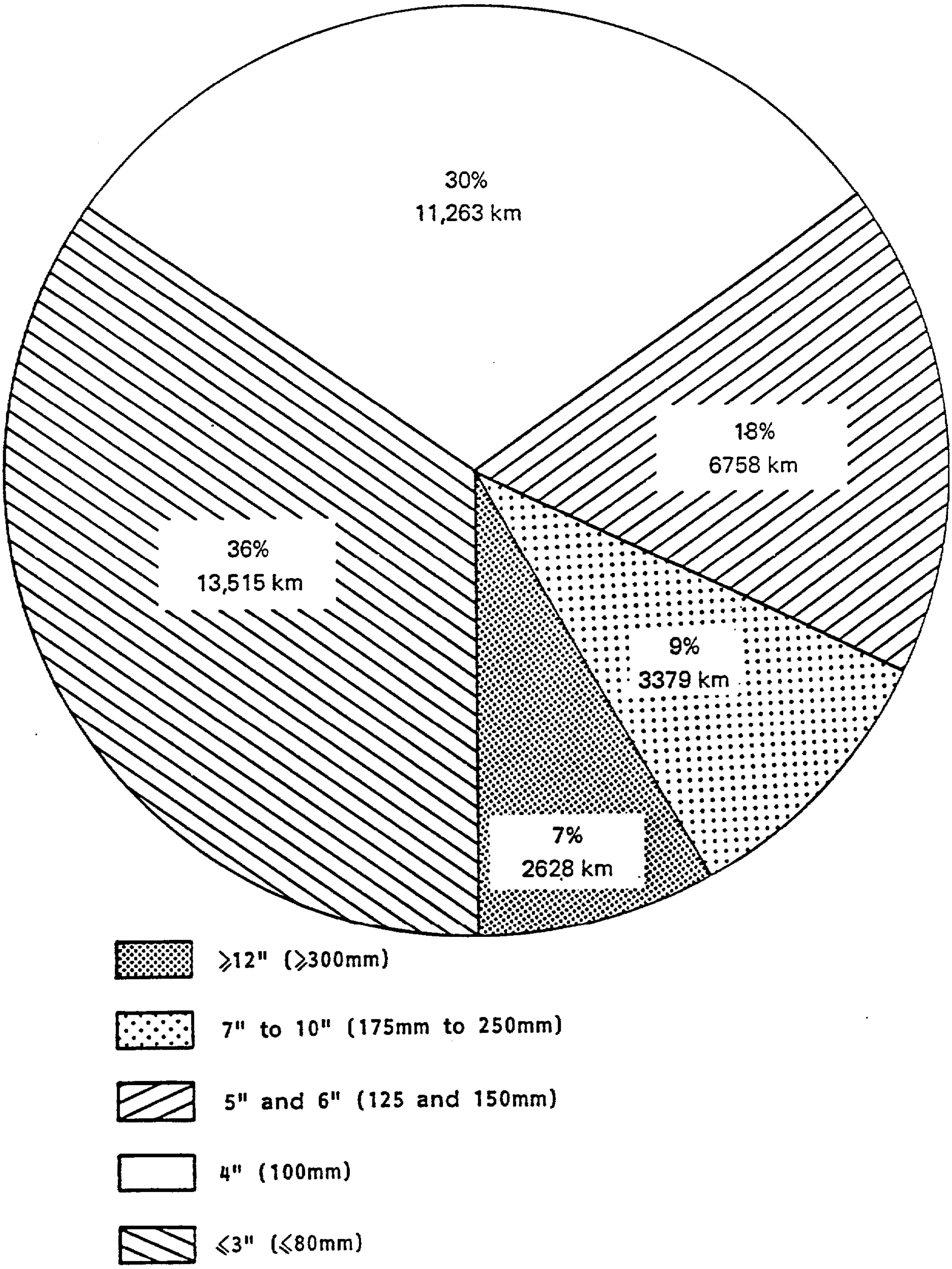


Figure 1.2 National usage of asbestos cement by diameter

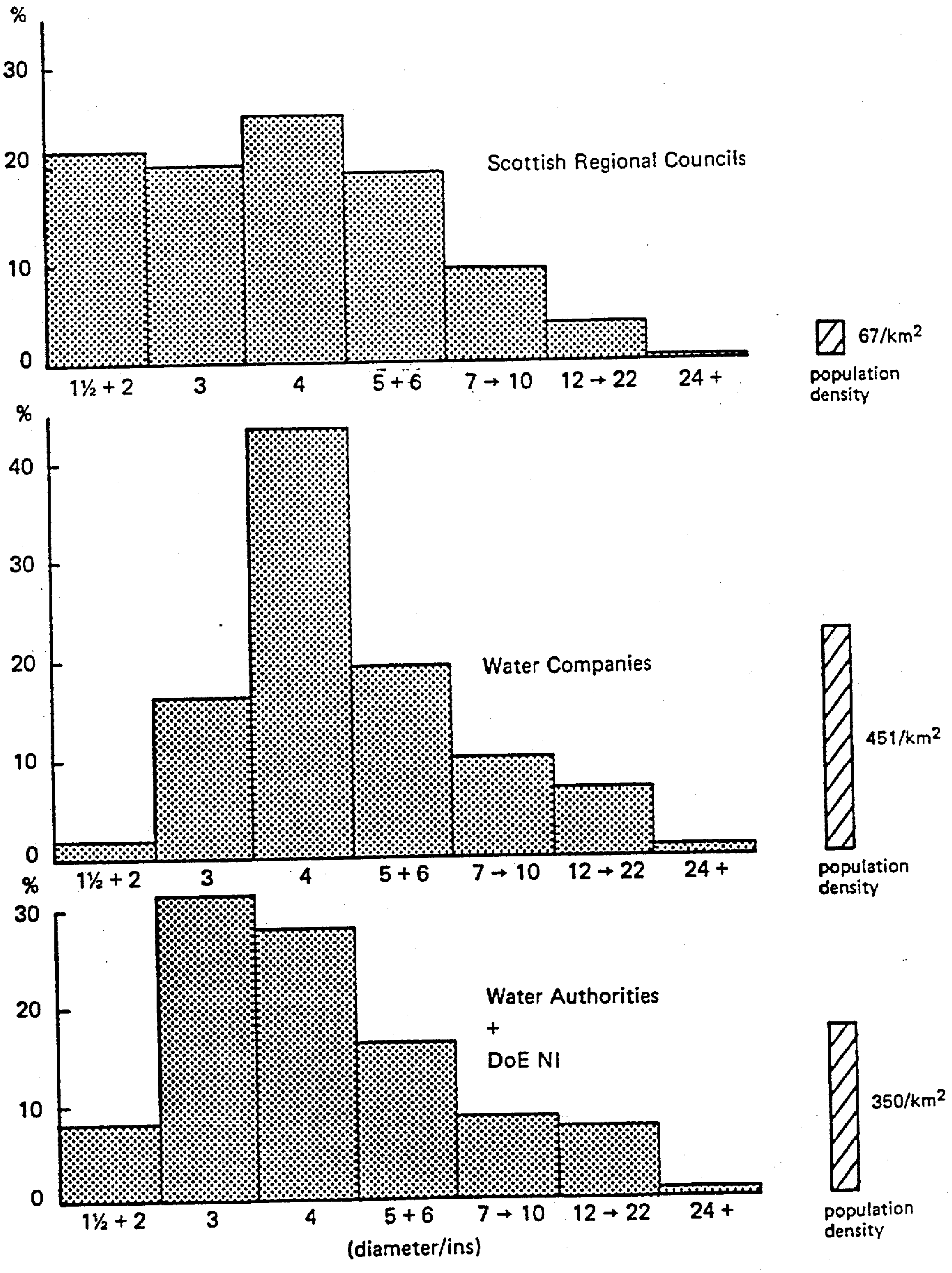


Figure 1.3 Comparison of diameter use between Water Authorities, Water Companies and Scottish Regional Councils

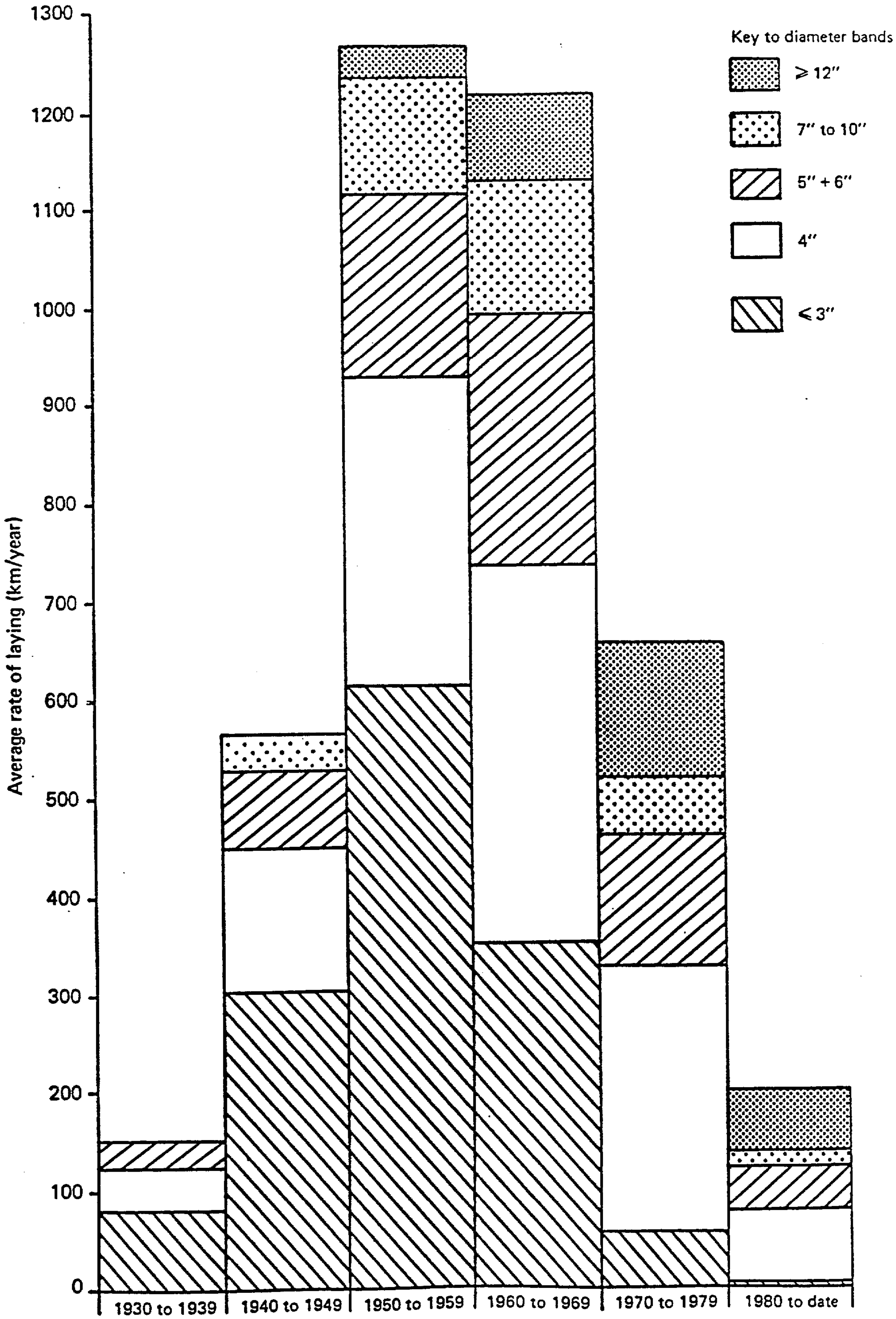


Figure 1.4 Asbestos cement water mains – annual rate of laying by diameter band against period of laying

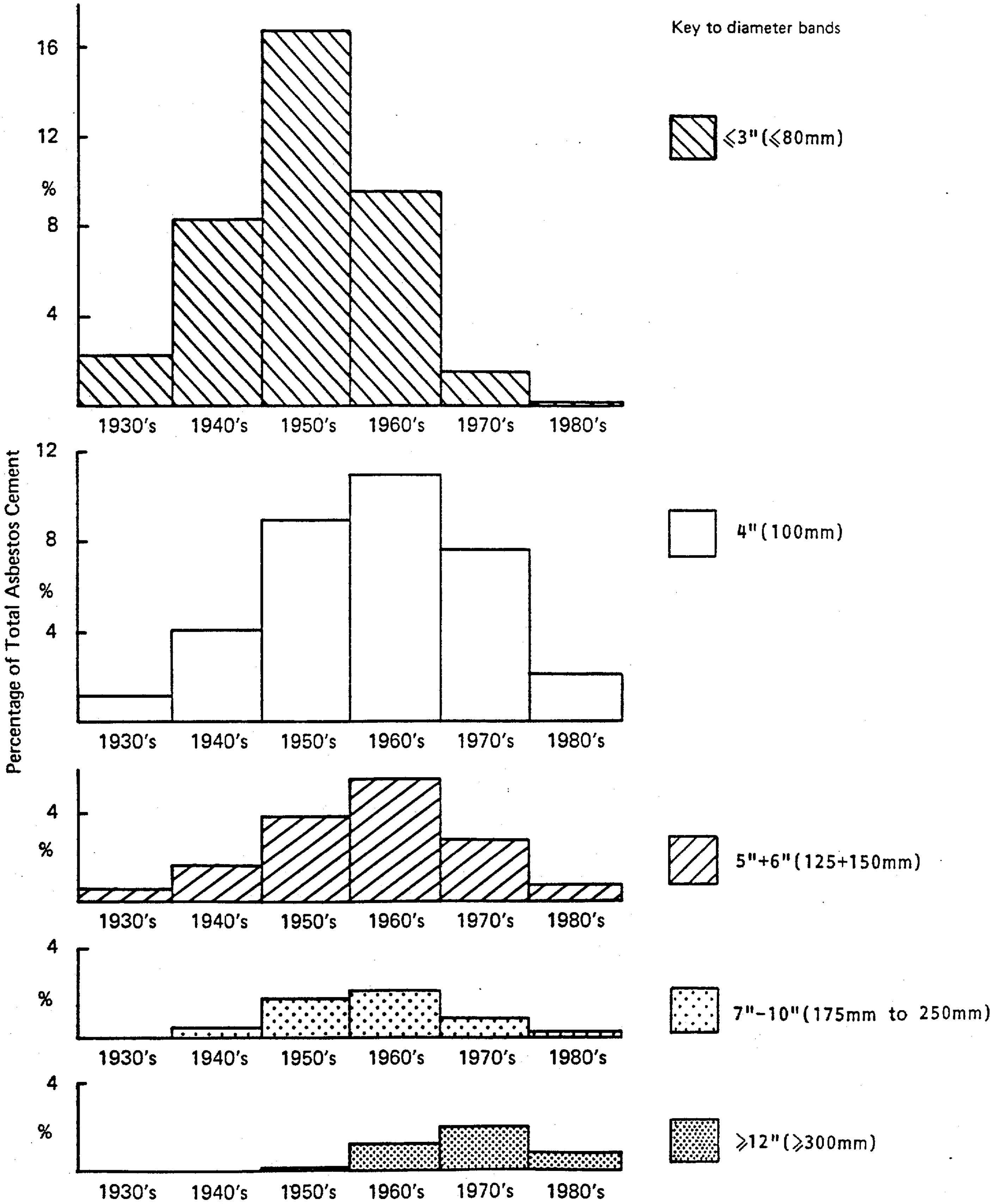


Figure 1.5 Percentage of total asbestos cement laid for each diameter band

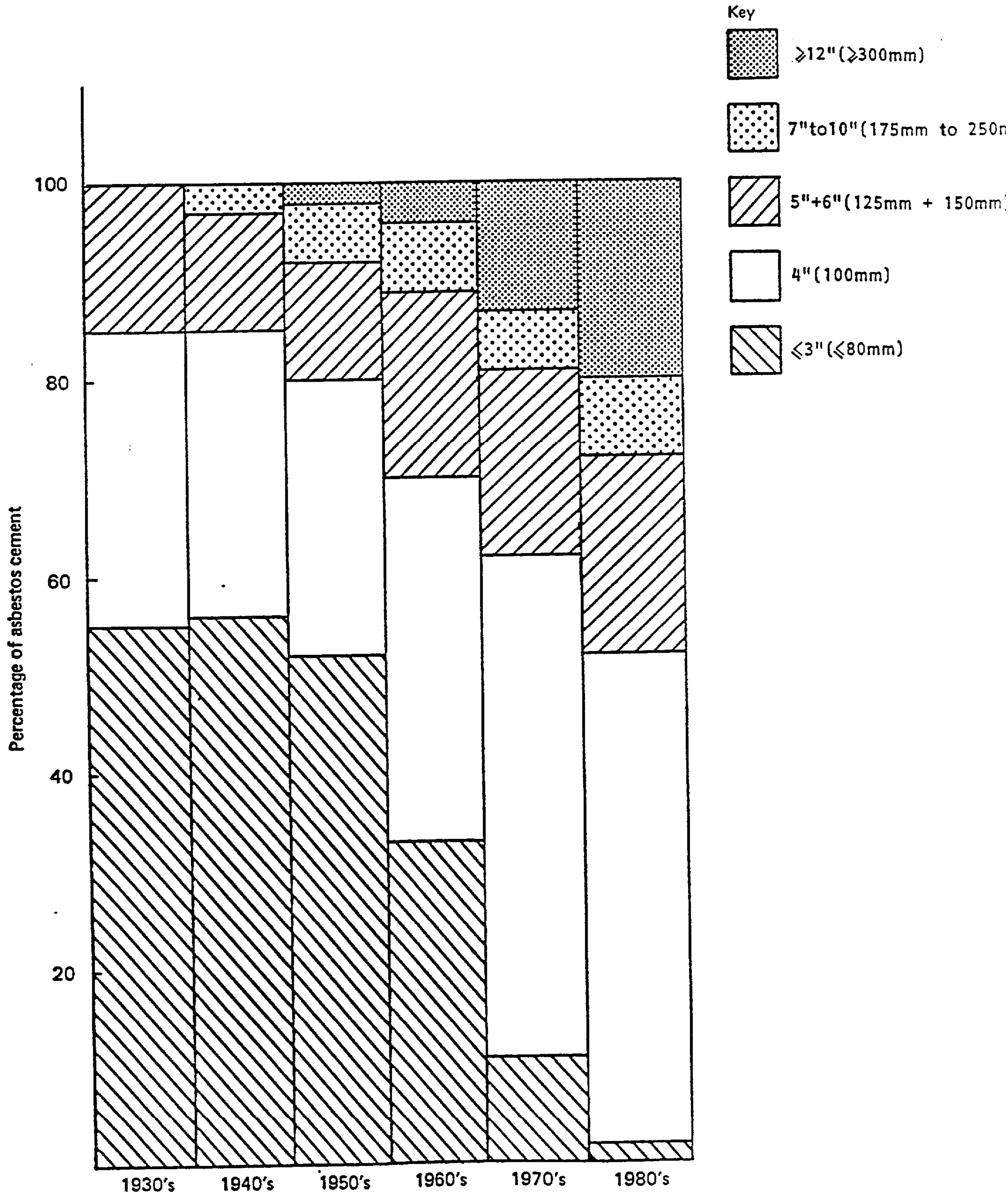


Figure 1.6 Proportion of asbestos cement mains laid in each diameter band

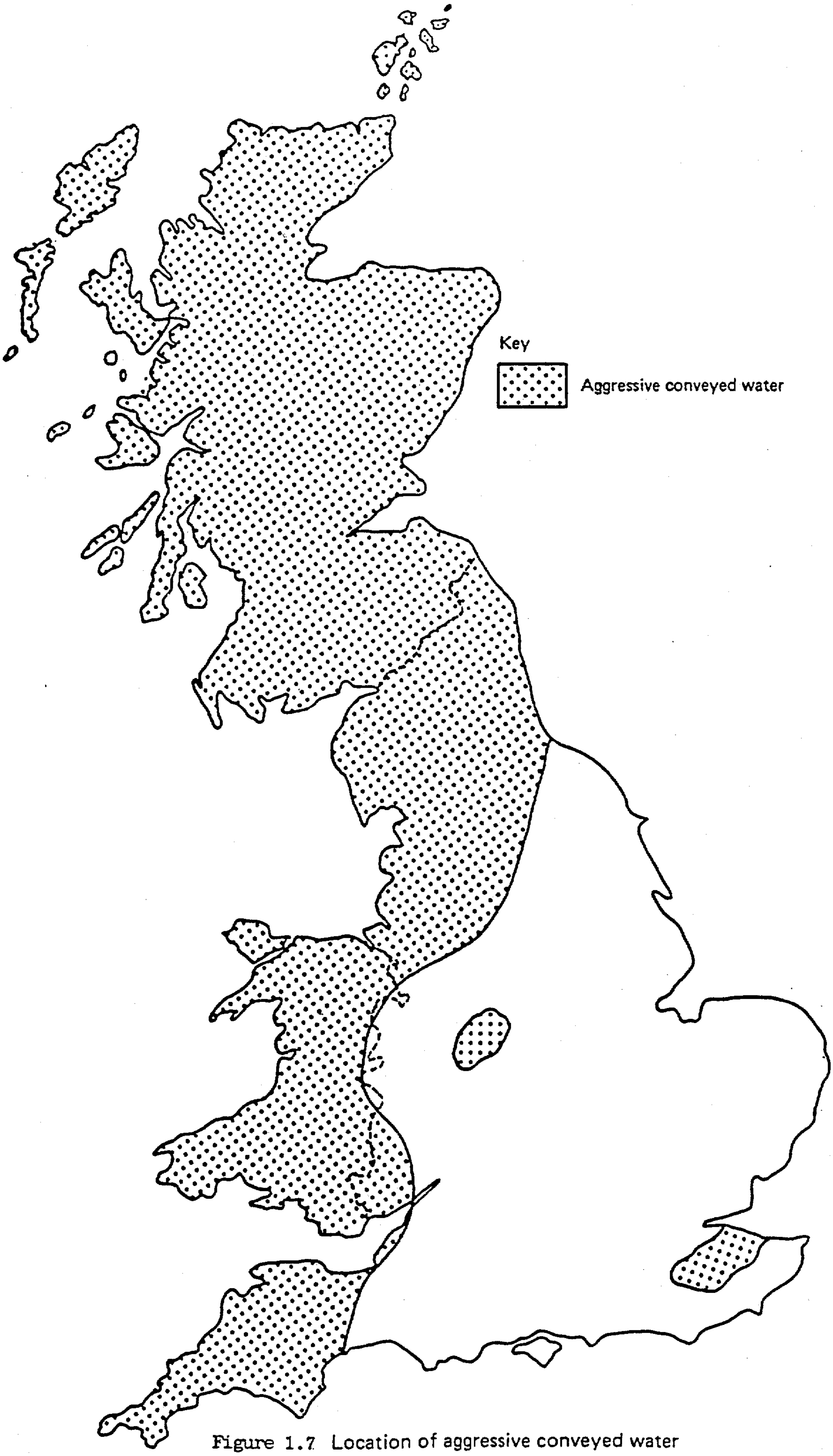


Figure 1.7 Location of aggressive conveyed water

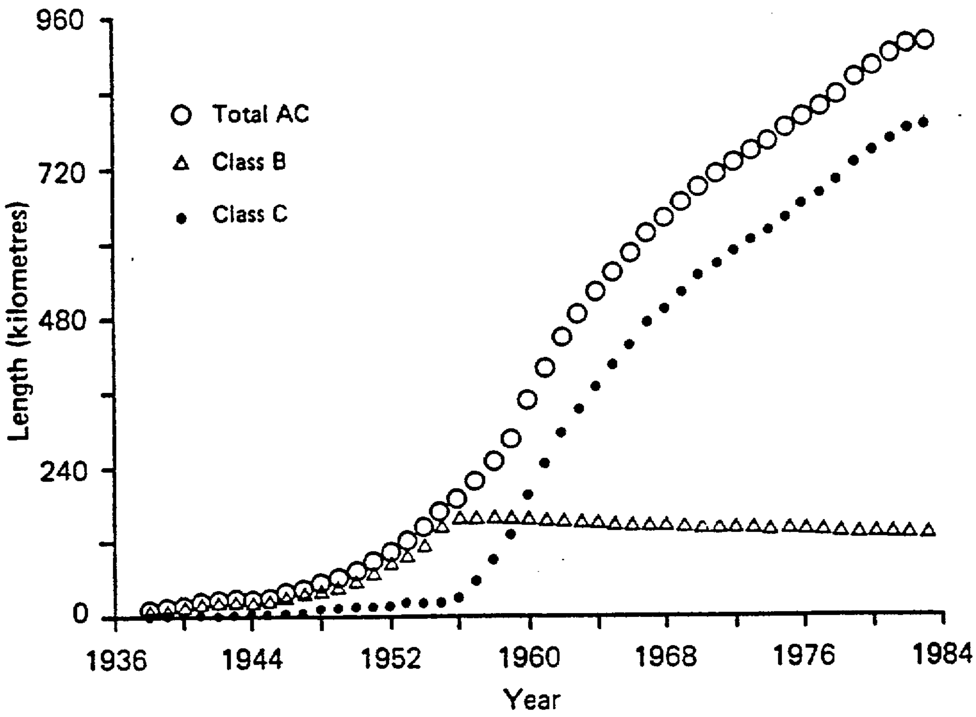


Figure 1.8A Area 1 — Length of AC pipe (kilometres)

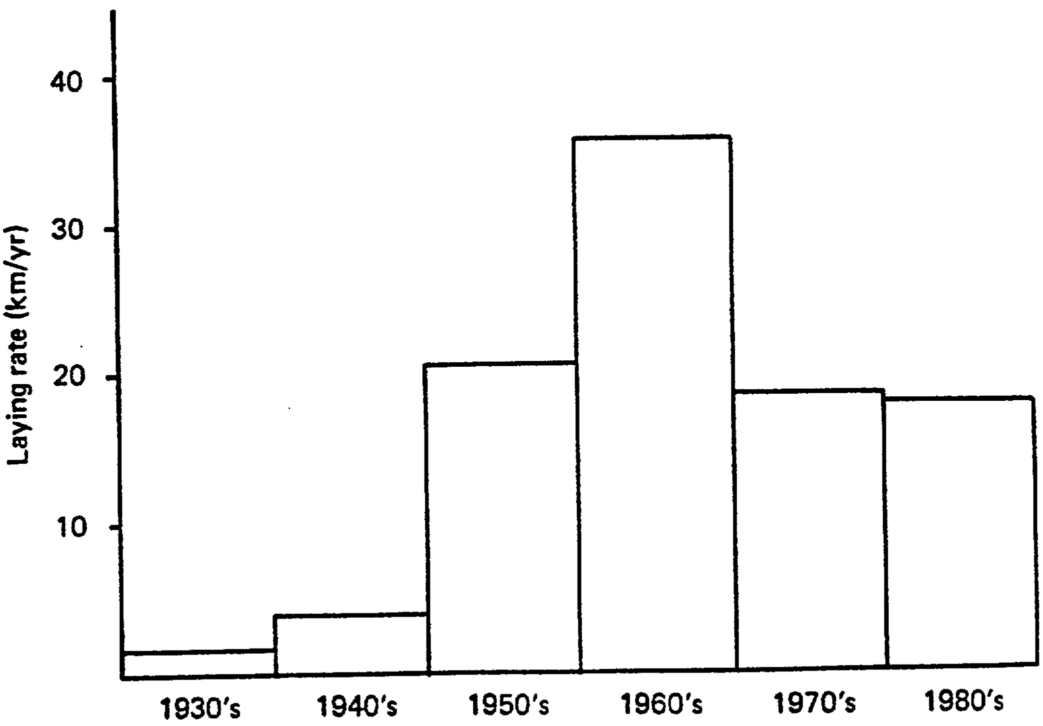


Figure 1.8B Area 1 — Rate of laying asbestos cement

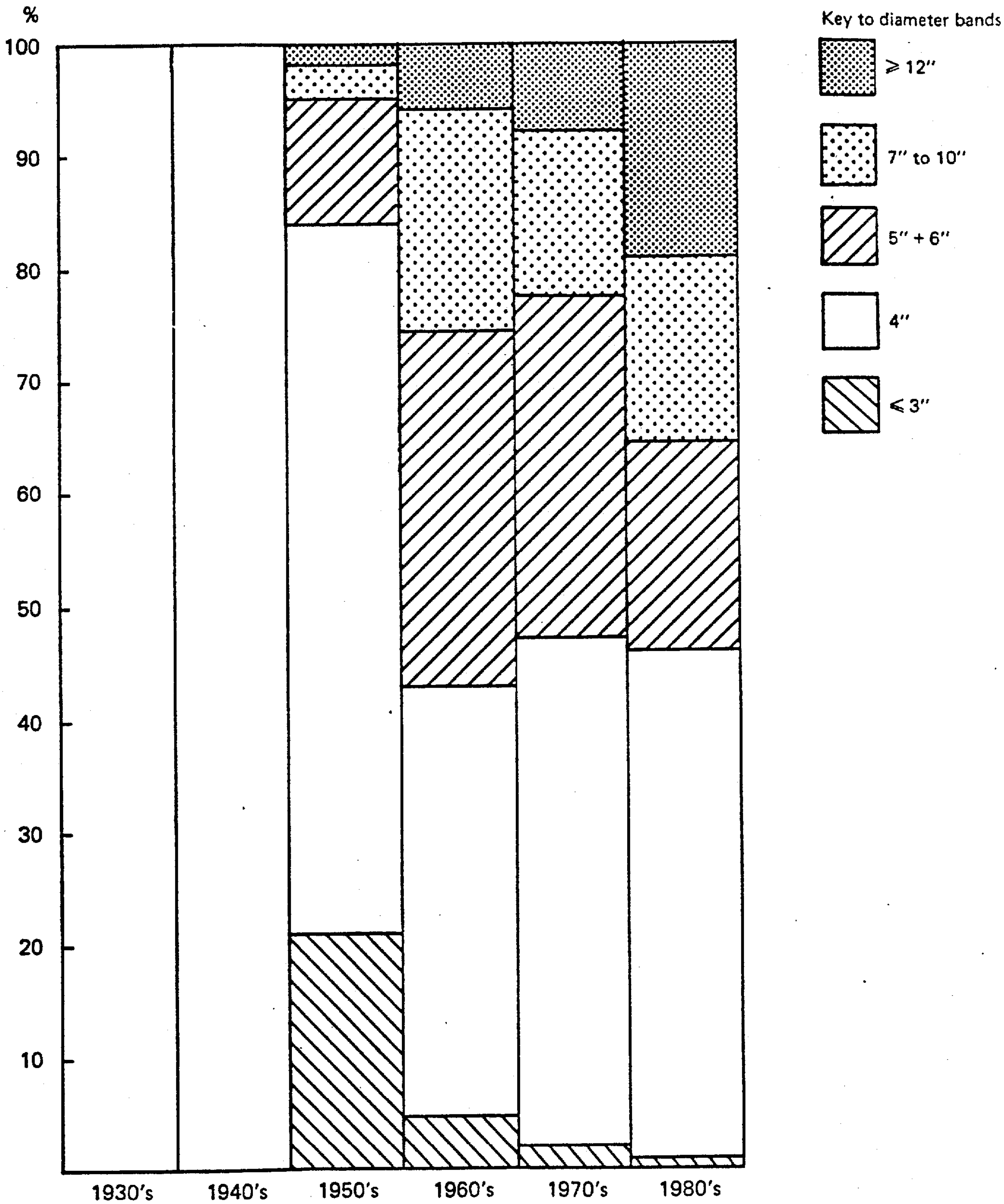


Figure 1.9 Diameter breakdown of asbestos cement mains laying in Area 1

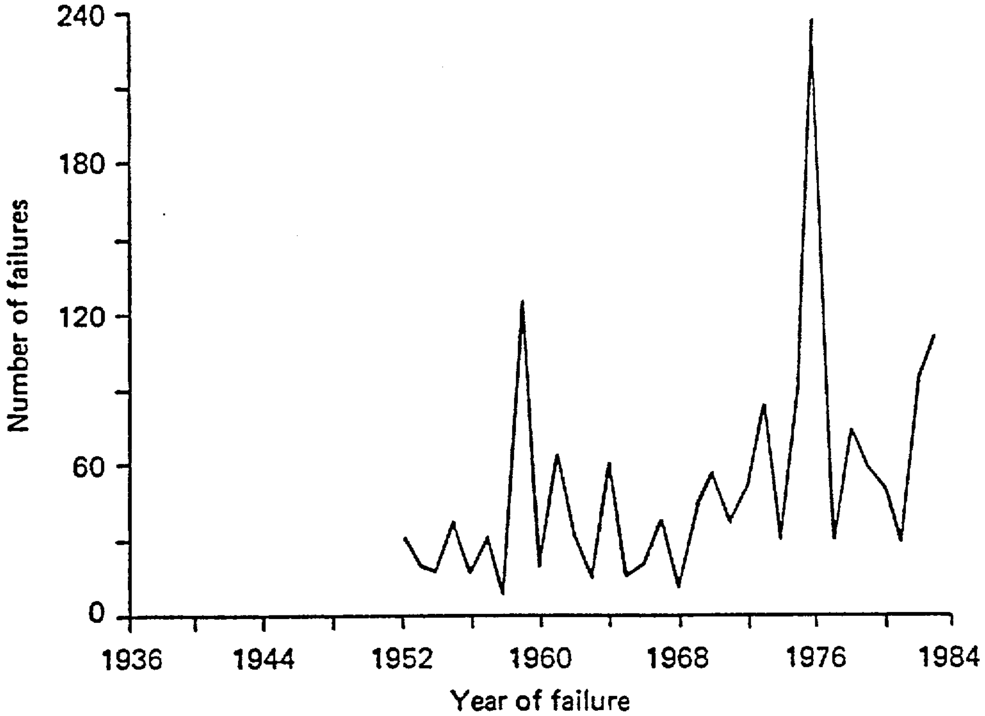


Figure 1.10A Area 1 — Number of failures versus year

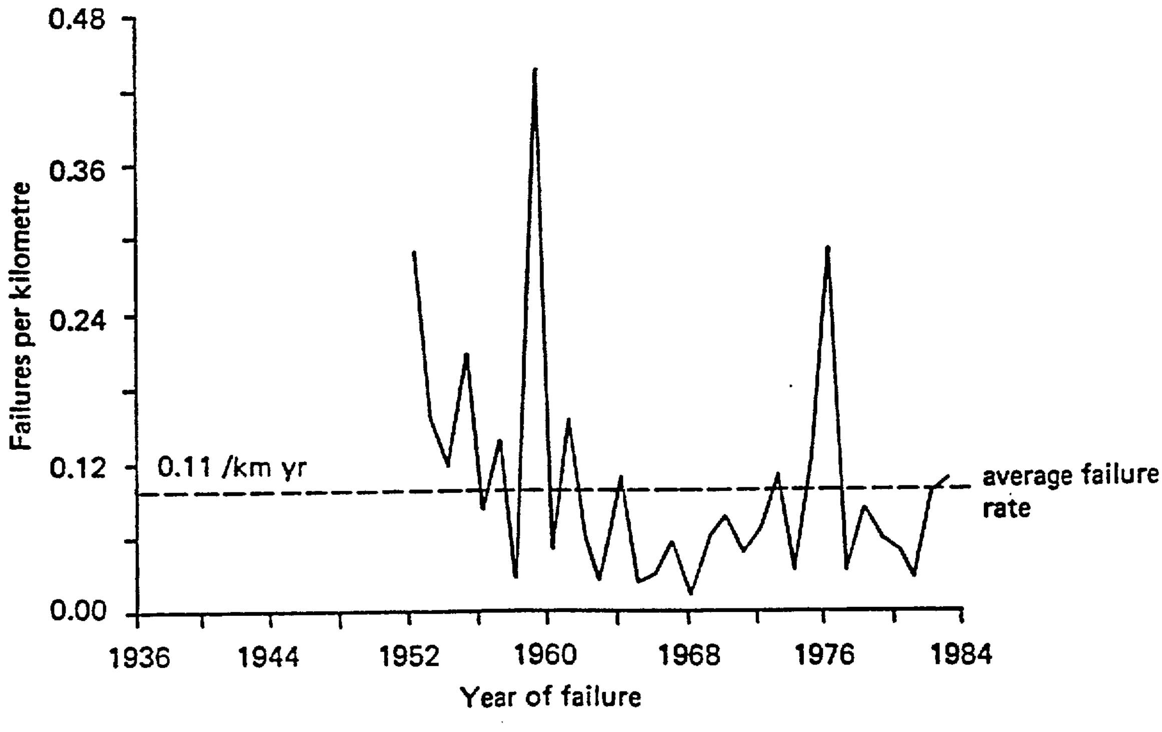


Figure 1.10B Area 1 — Failures per kilometre versus year

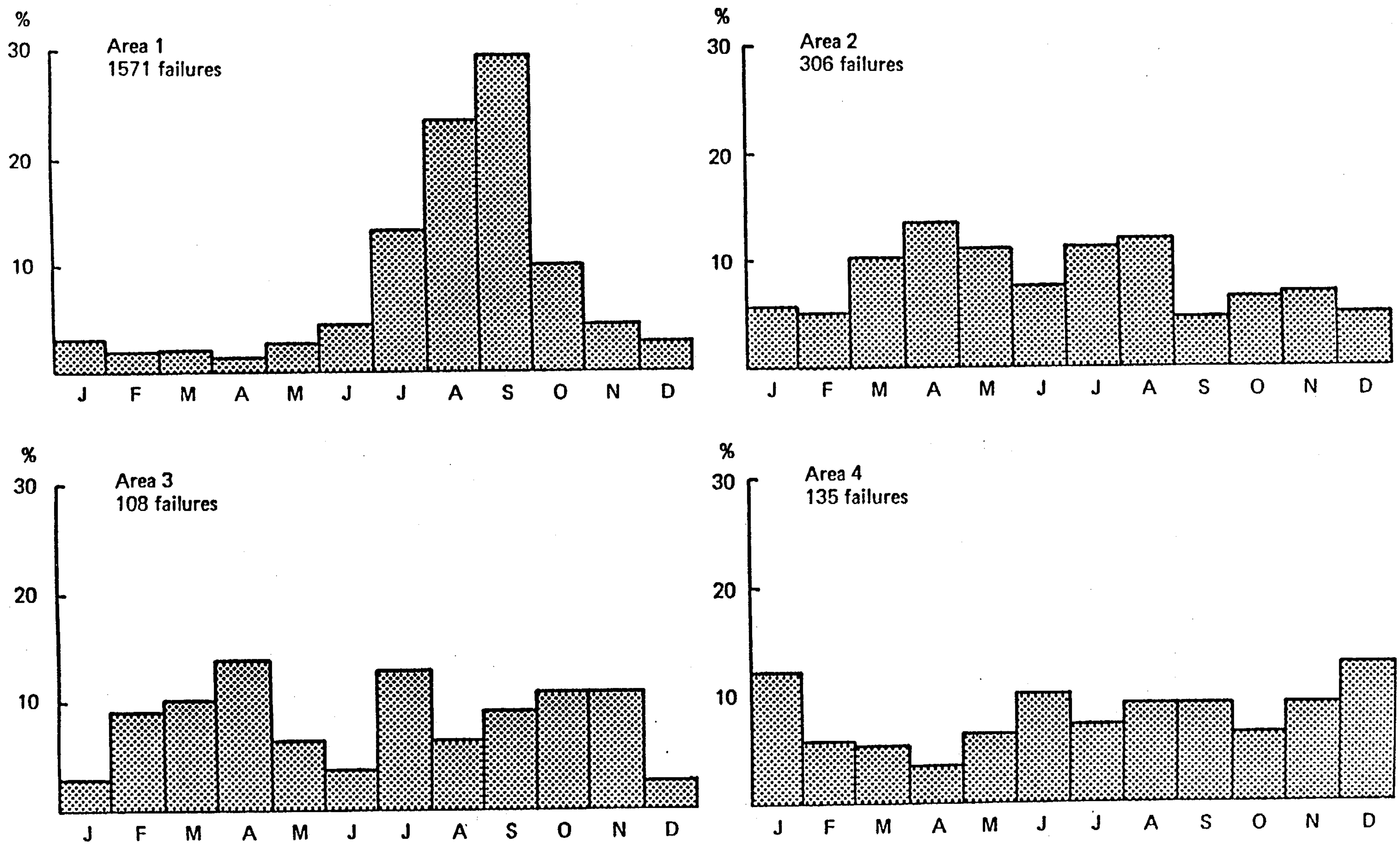
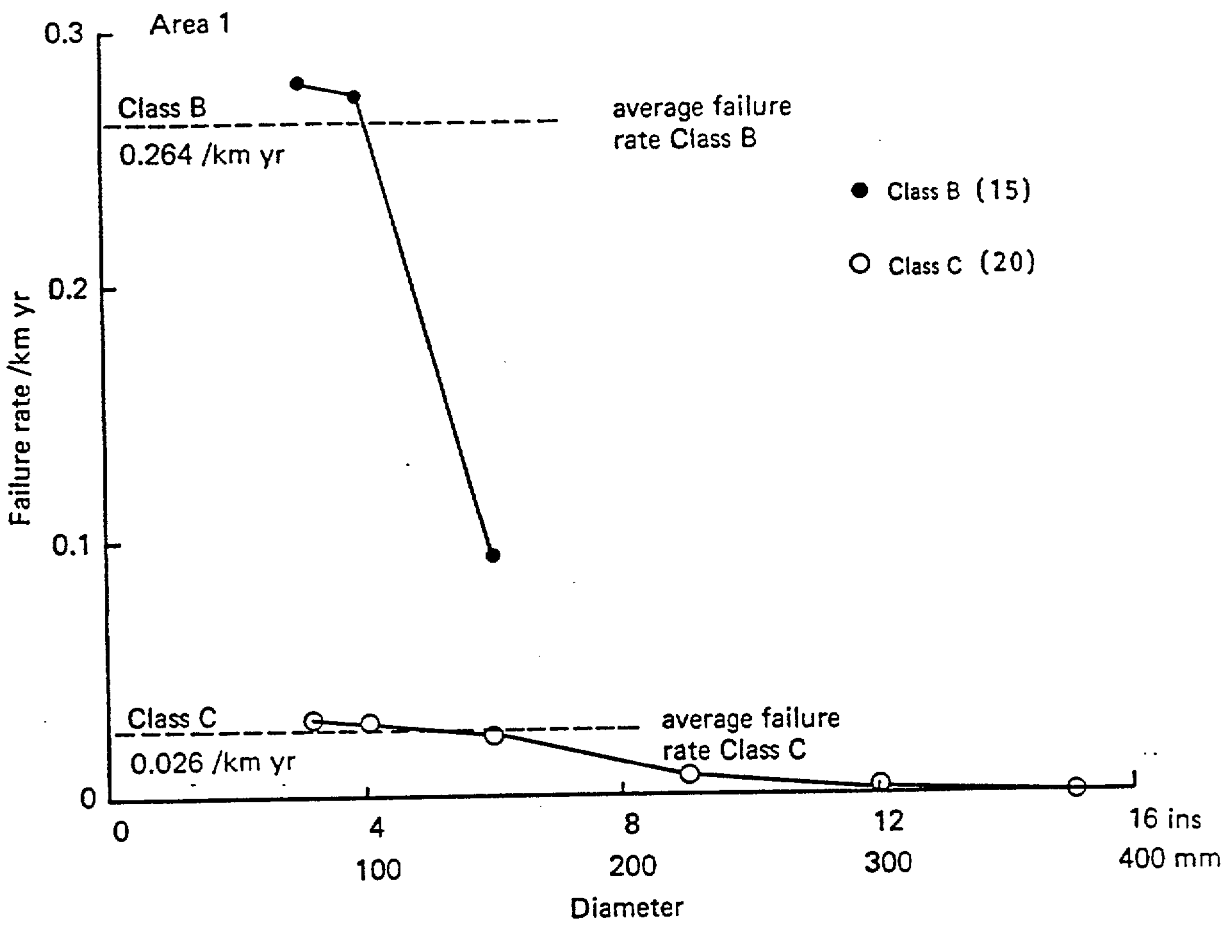


Figure 1.11 Occurrence of asbestos cement pipe failures throughout the year



Failure rate against diameter

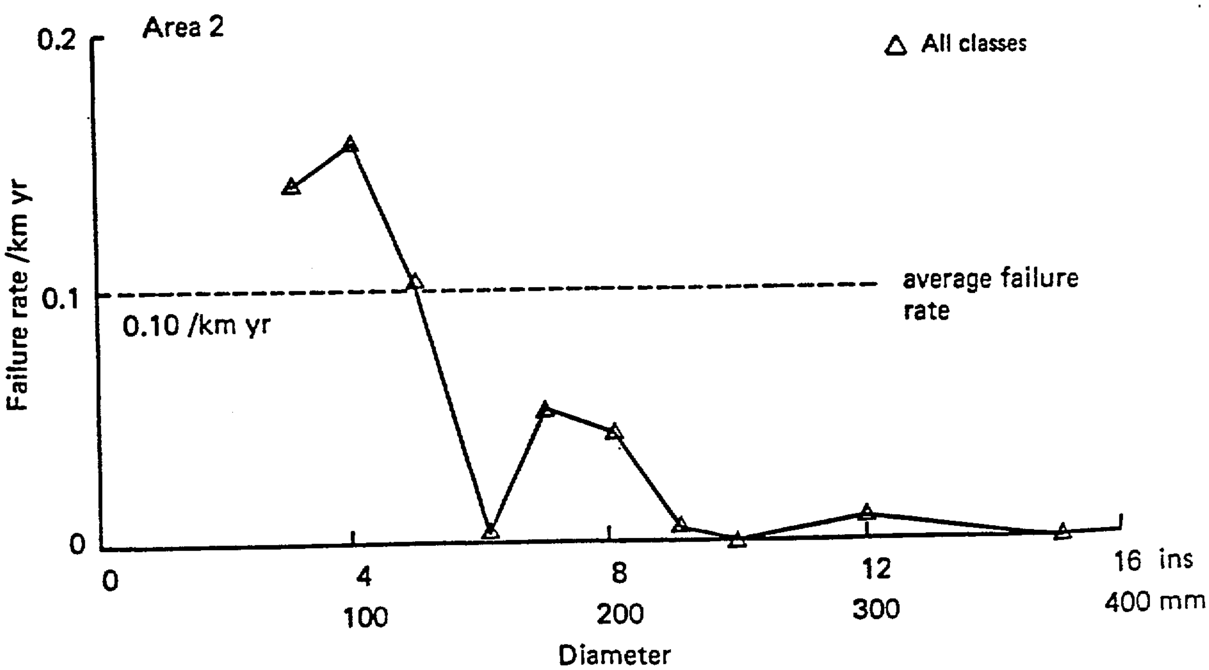


Figure 1.12 Failure rate against diameter

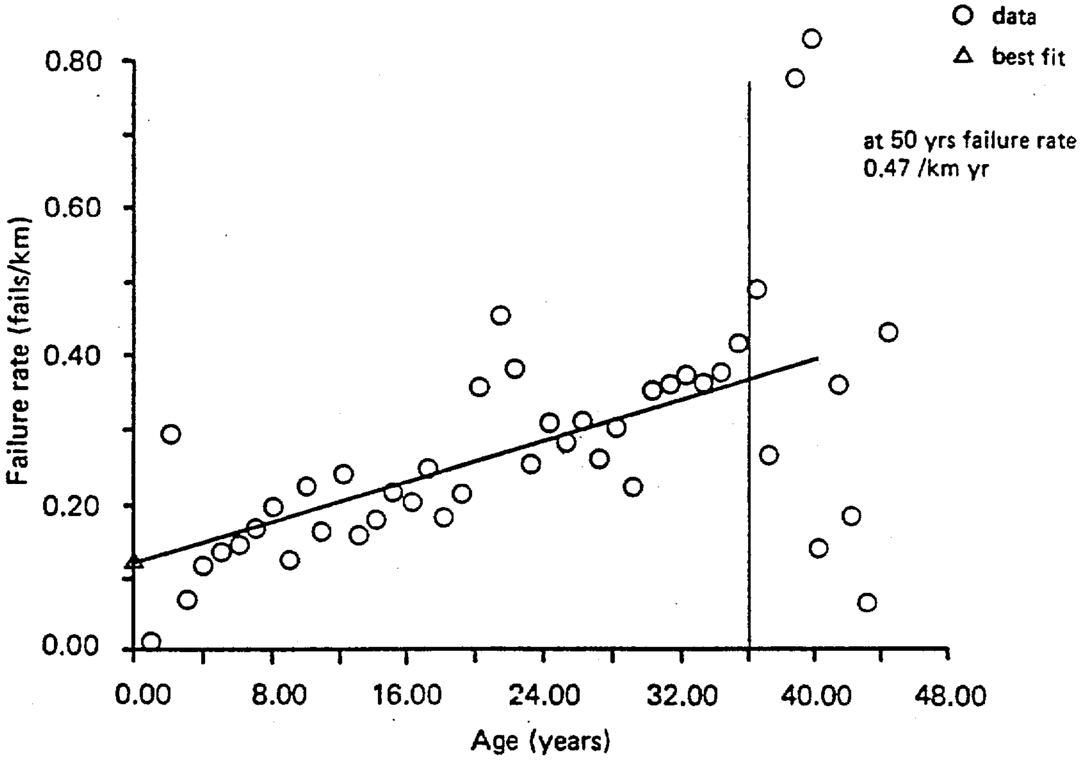


Figure 1.13 Area 1 – Failure rate against age for Class B pipe

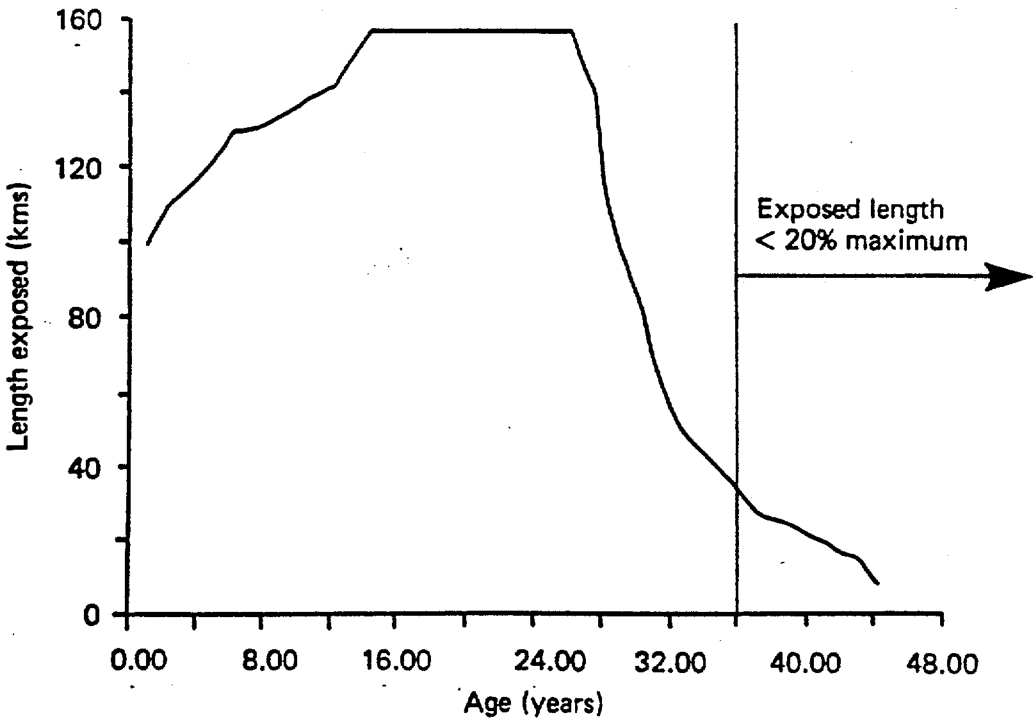


Figure 1.13 Area 1 — Class B — length exposed

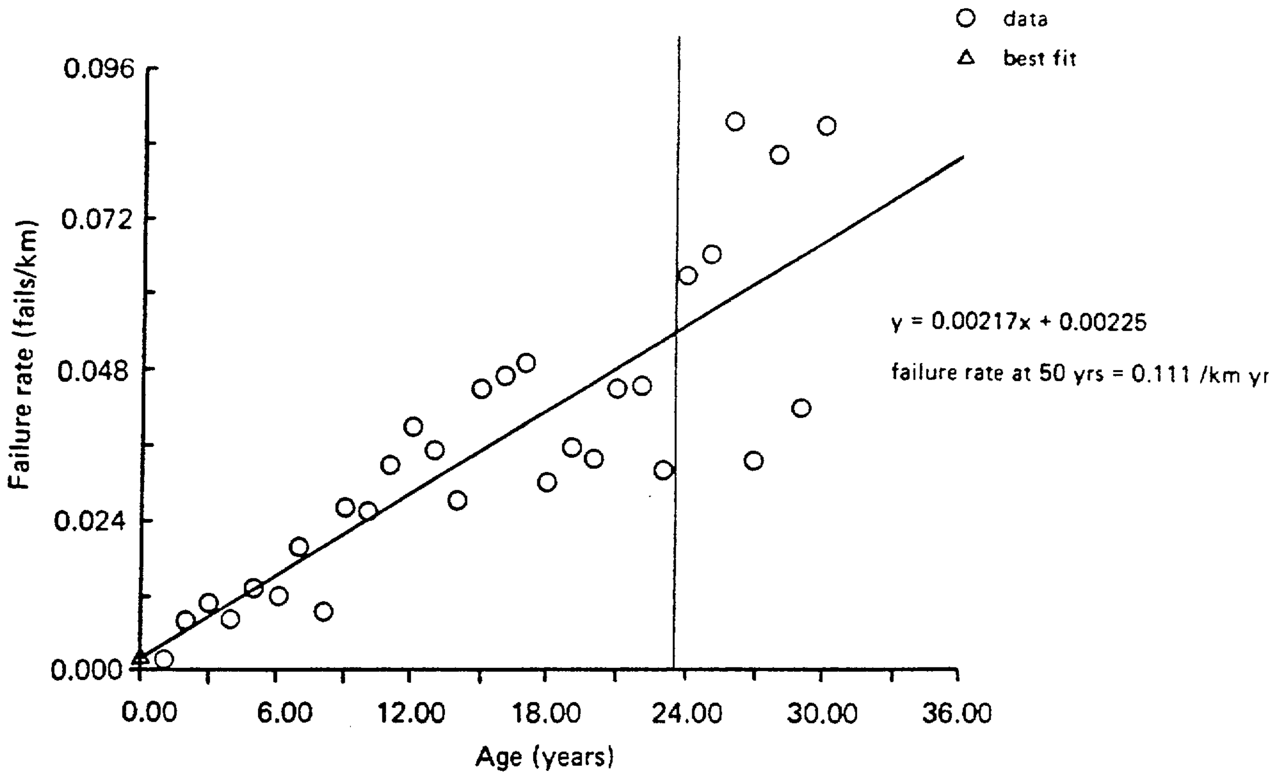


Figure 1.14 Area 1 – Failure rate against age for Class C pipe

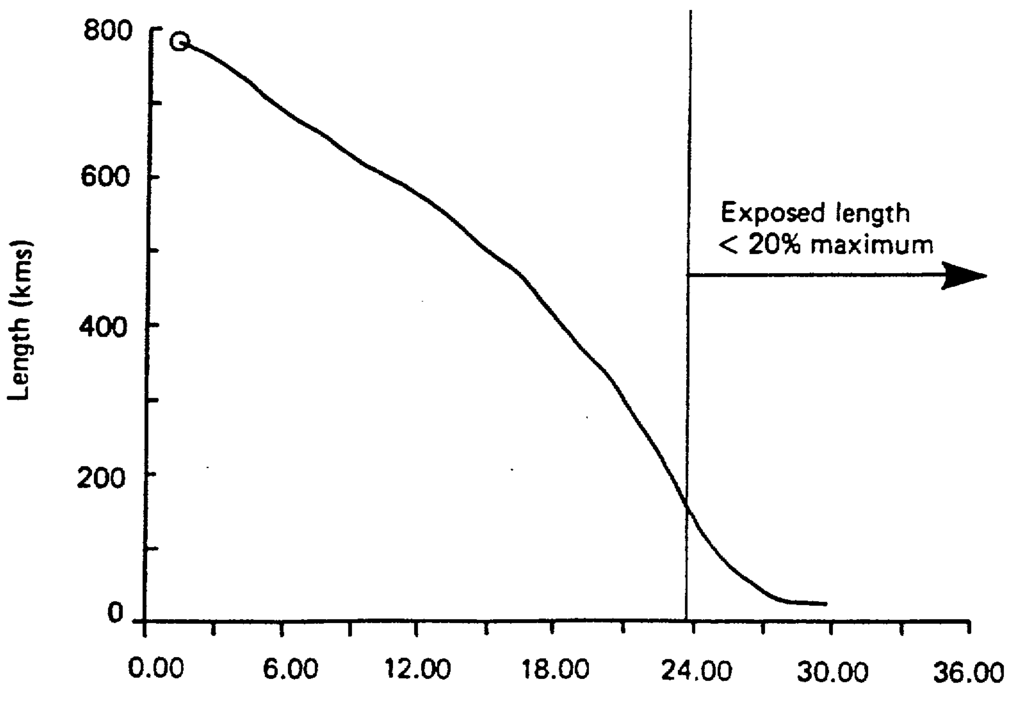


Figure 1.14 Area 1 – Class C – length exposed

Figure 1.15 AREA 1 - FAILURE RATE AGAINST AGE FOR 4" CLASS B

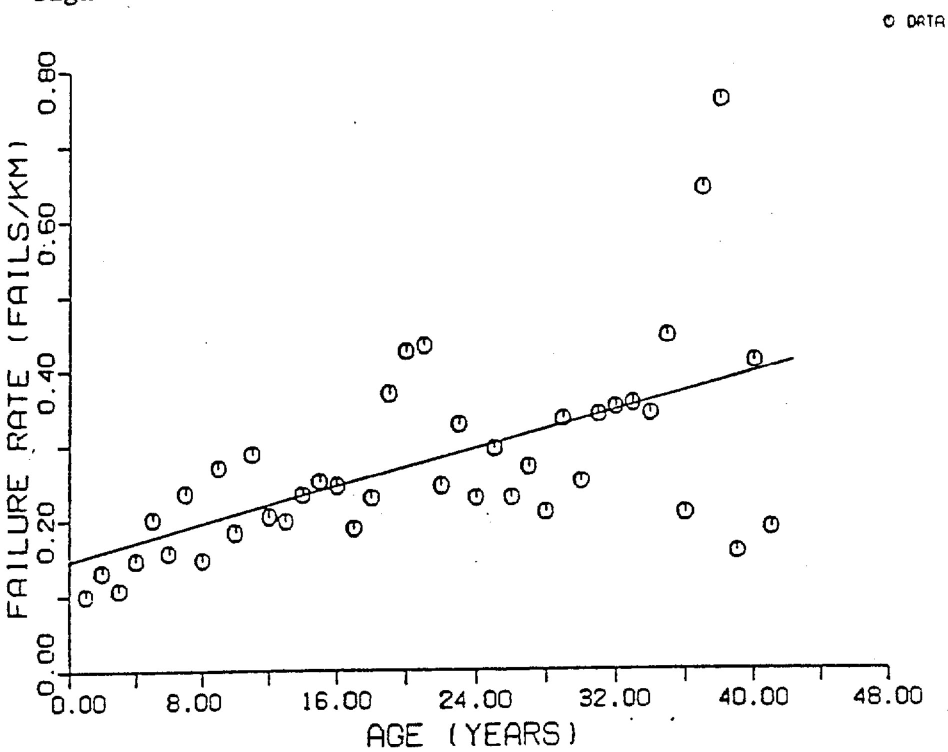


Figure 1.15 AREA 1 - 4" CLASS B - LENGTH EXPOSED

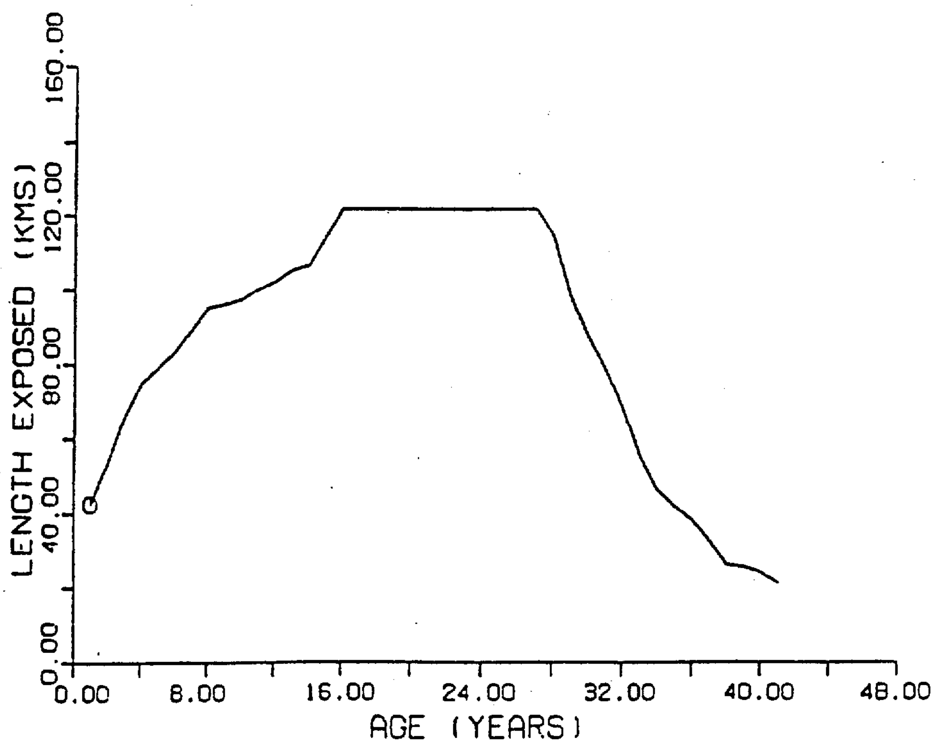


Figure 1.16 AREA 1 - FAILURE RATE AGAINST AGE FOR 4" CLASS C

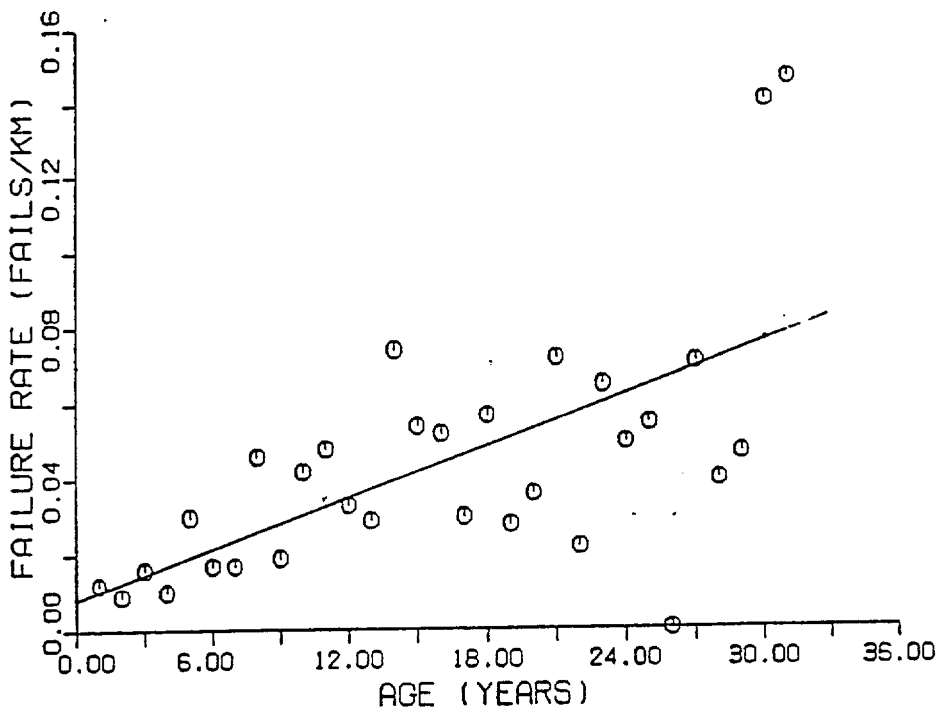
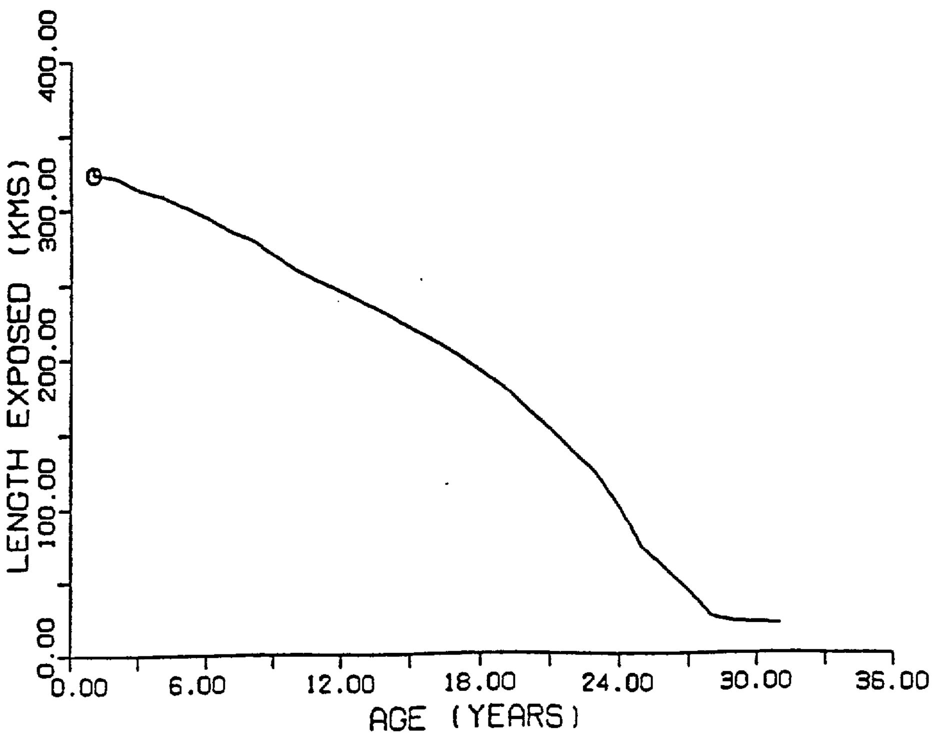


Figure 1.16 AREA 1 - 4" CLASS C - LENGTH EXPOSED



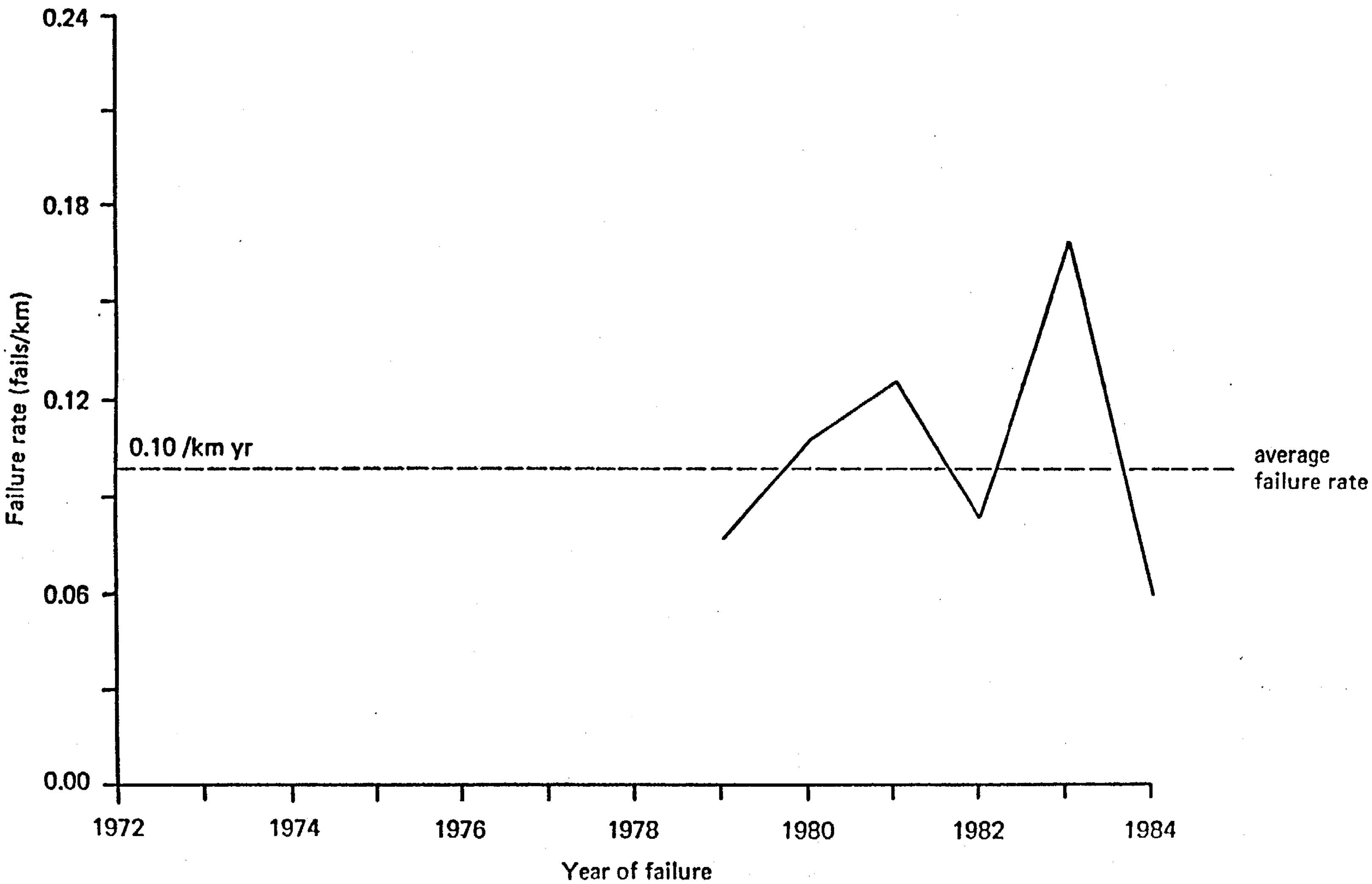


Figure 1.17 Area 2 — Failure rate versus year for ≥ 3″ diameter

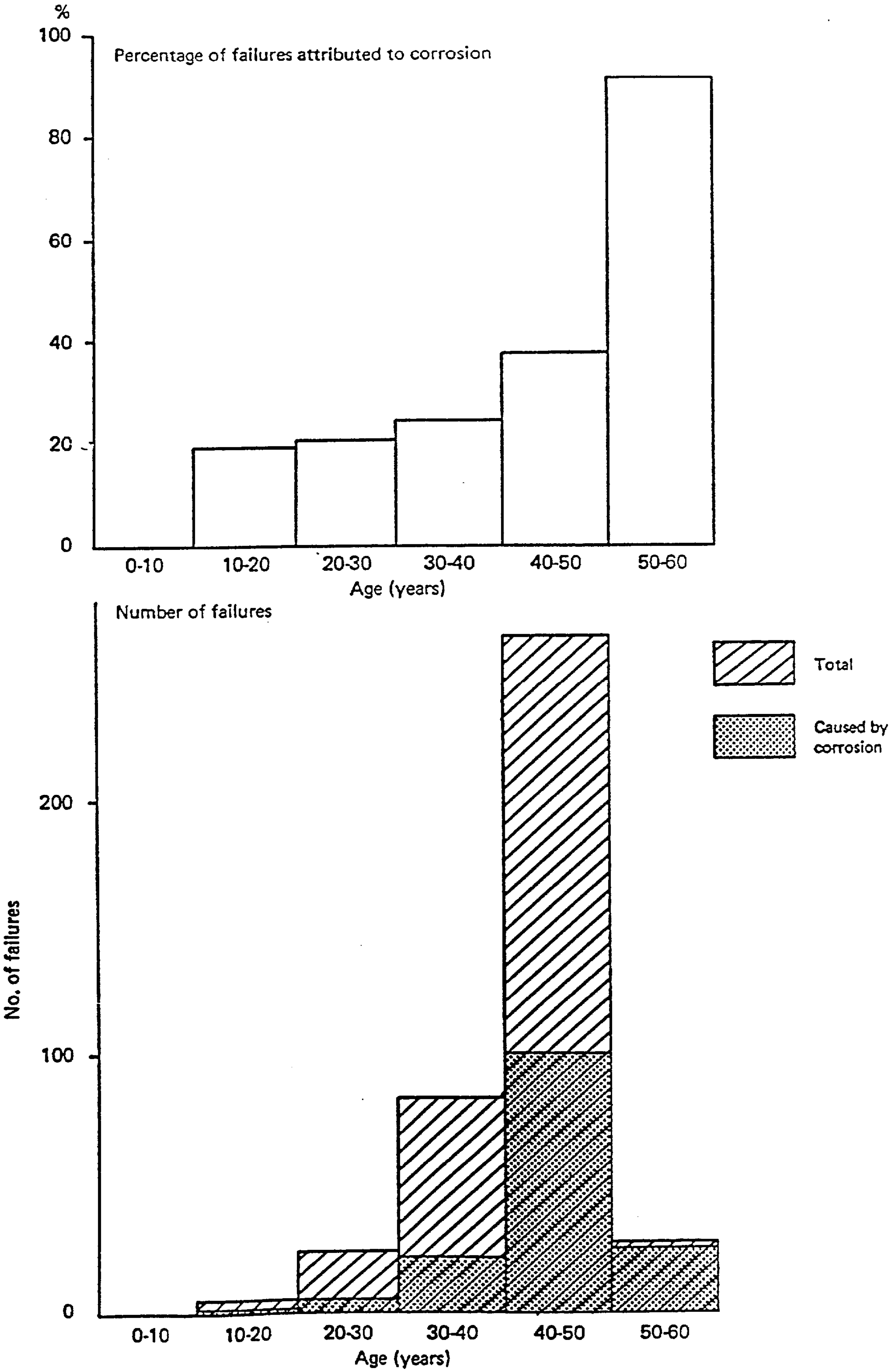


Figure 1.18 Area 2

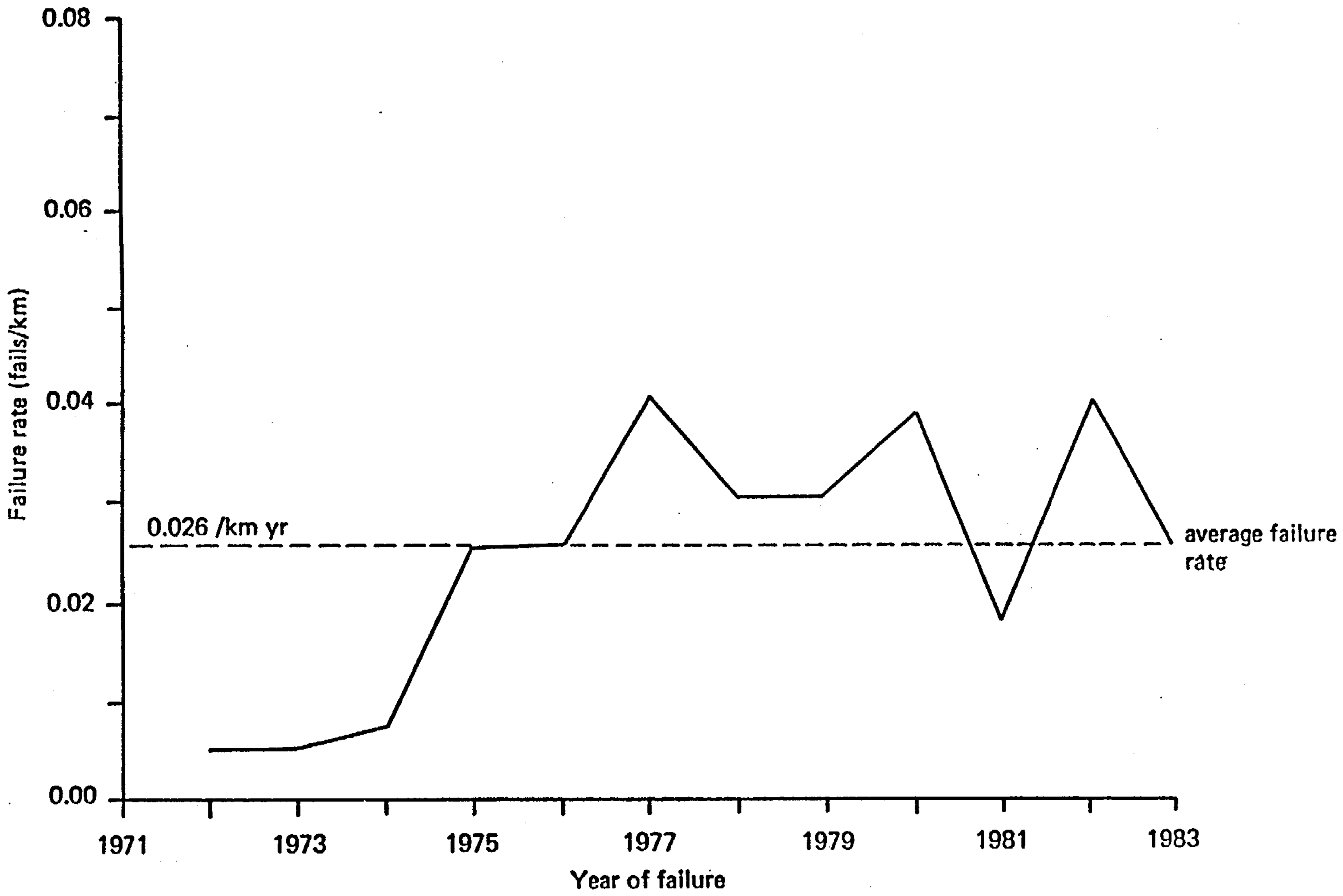


Figure 1.19 Area 3 — Failure rate versus year

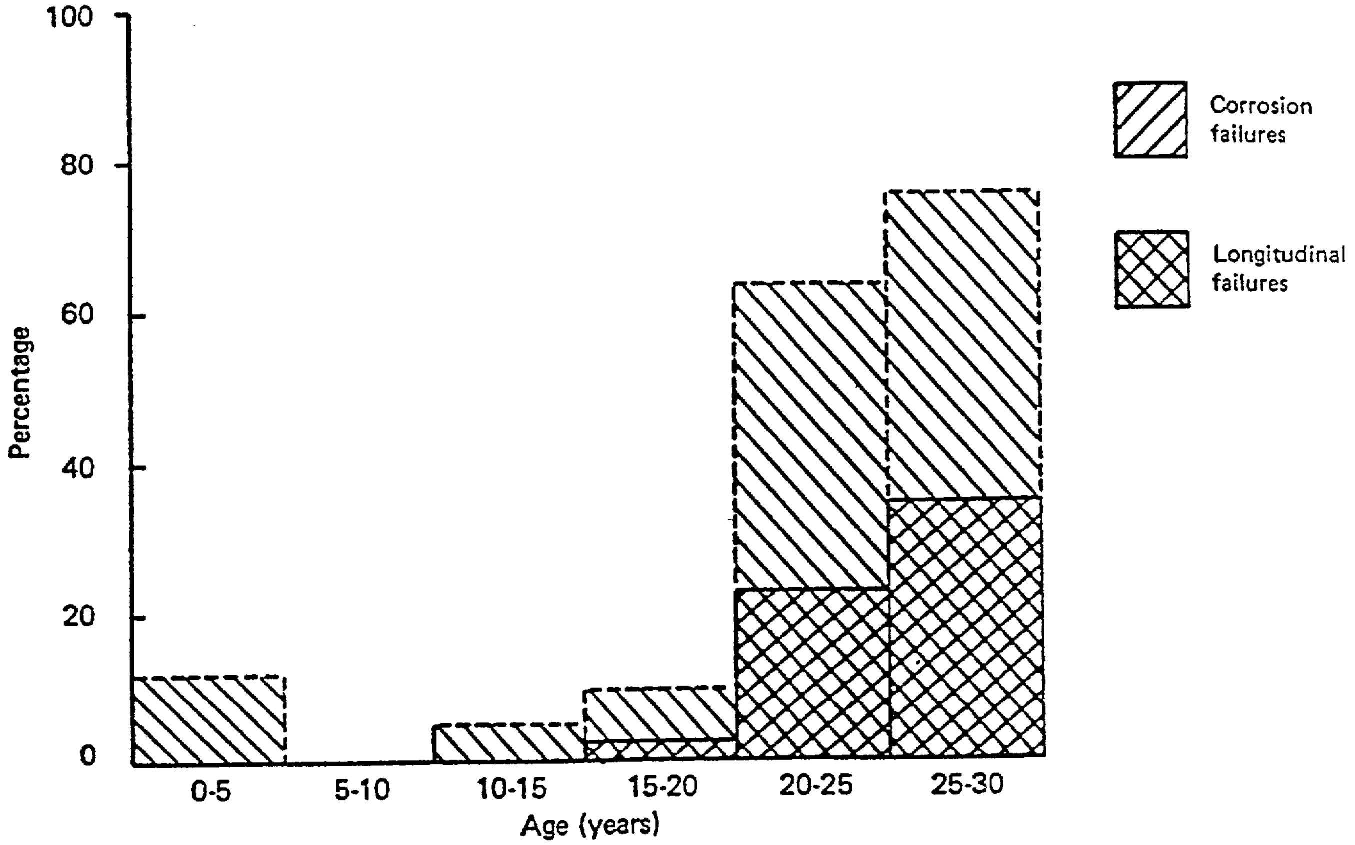


Figure 1.20A Area 3 – Percentage of corrosion induced and longitudinal failures against age

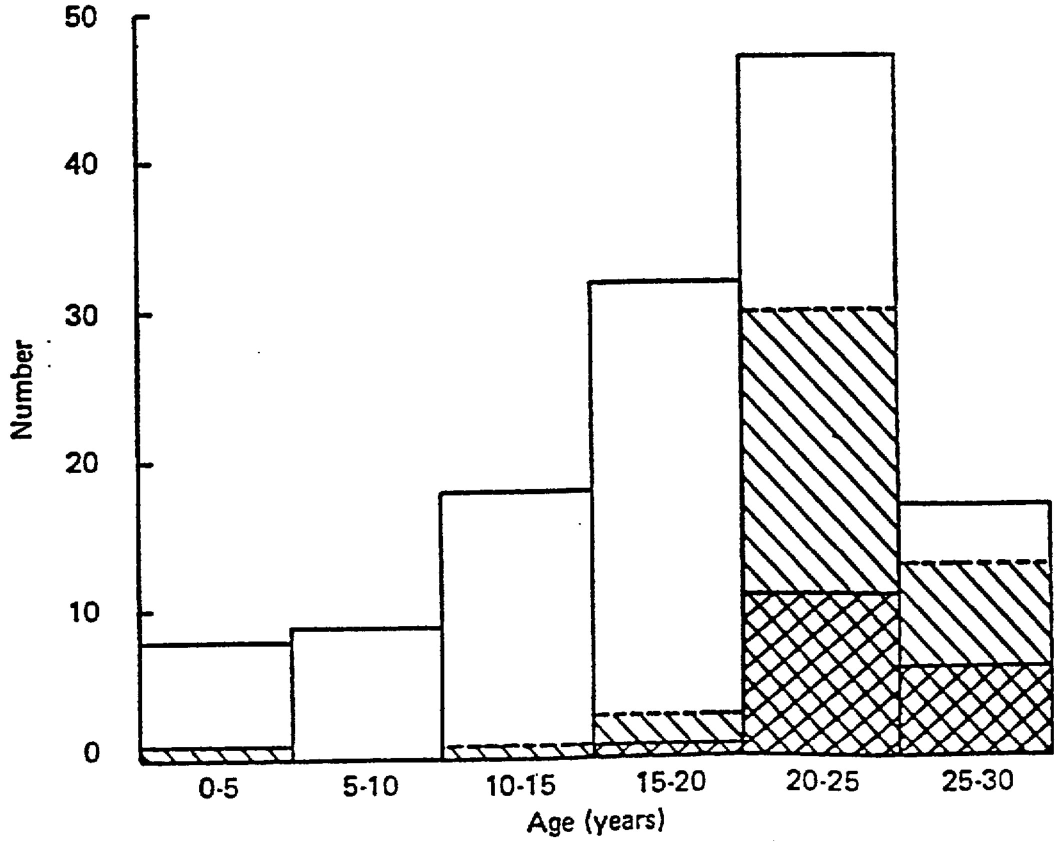


Figure 1.20B Area 3 – Number of failures against age

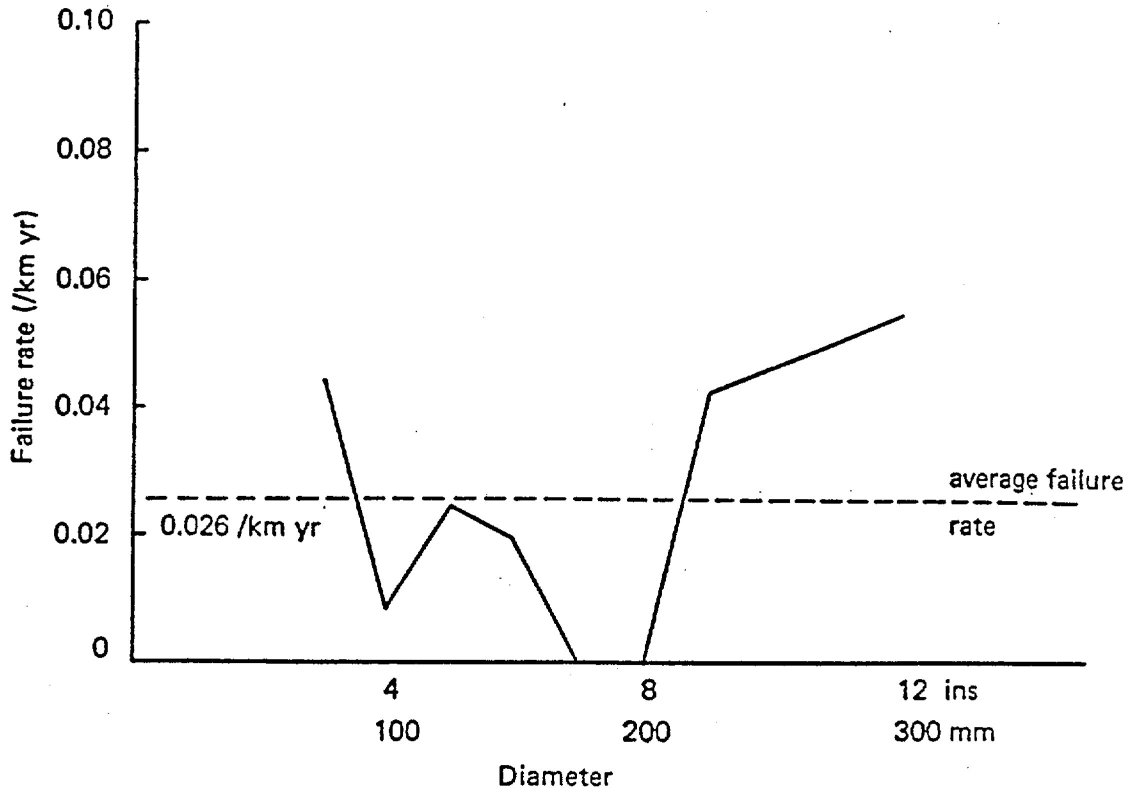


Figure 1.21A Area 3 — Failure rate against diameter

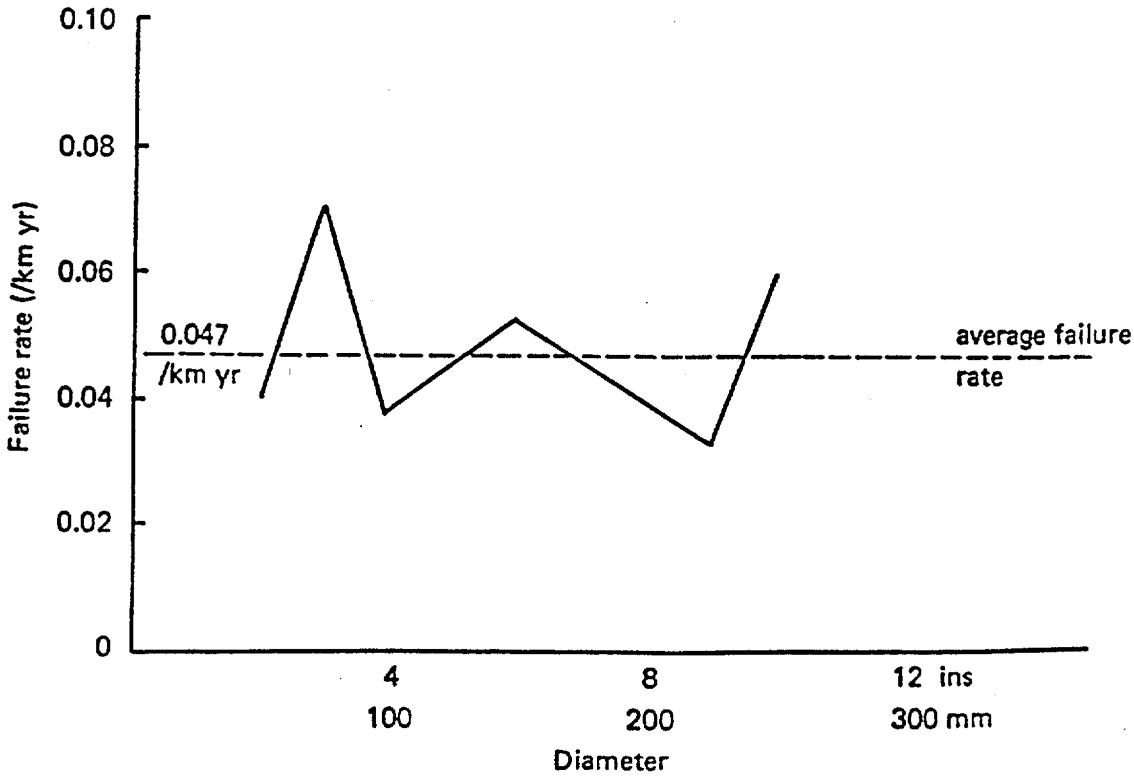


Figure 1.21B Area 4 — Failure rate against diameter

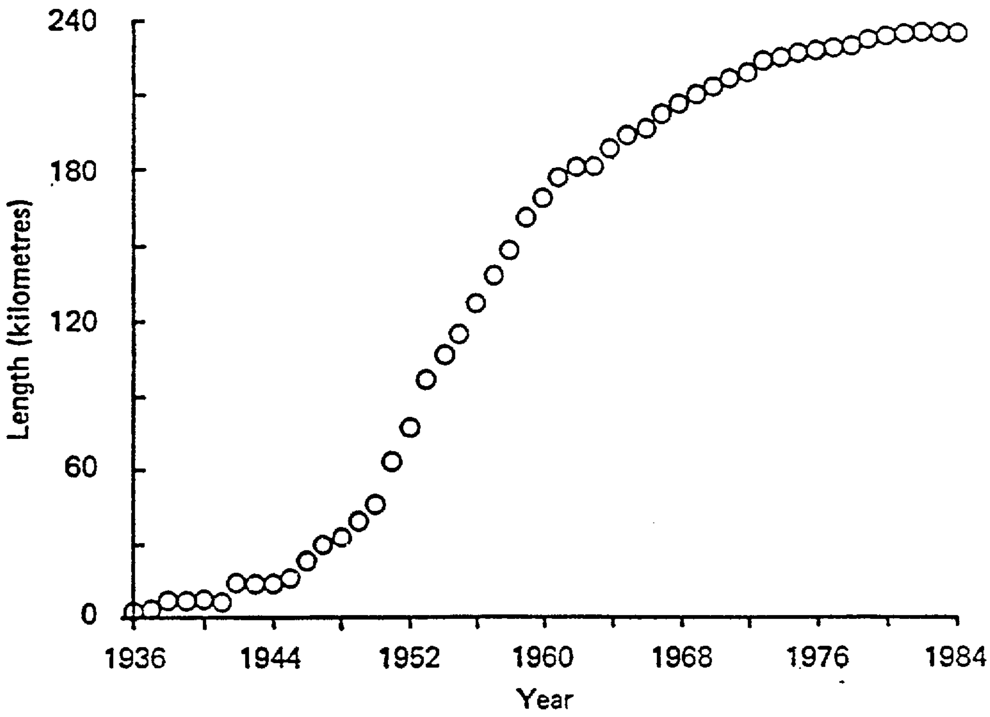


Figure 1.22A Area 4 — Length of asbestos cement laid

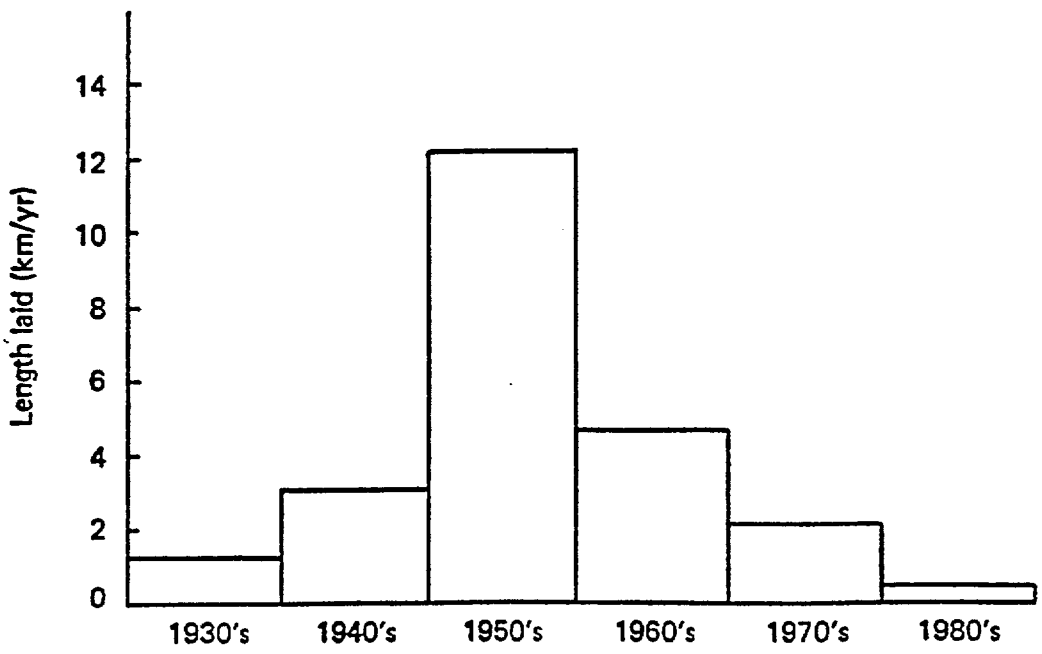


Figure 1.22B Area 4 — Rate of laying of AC

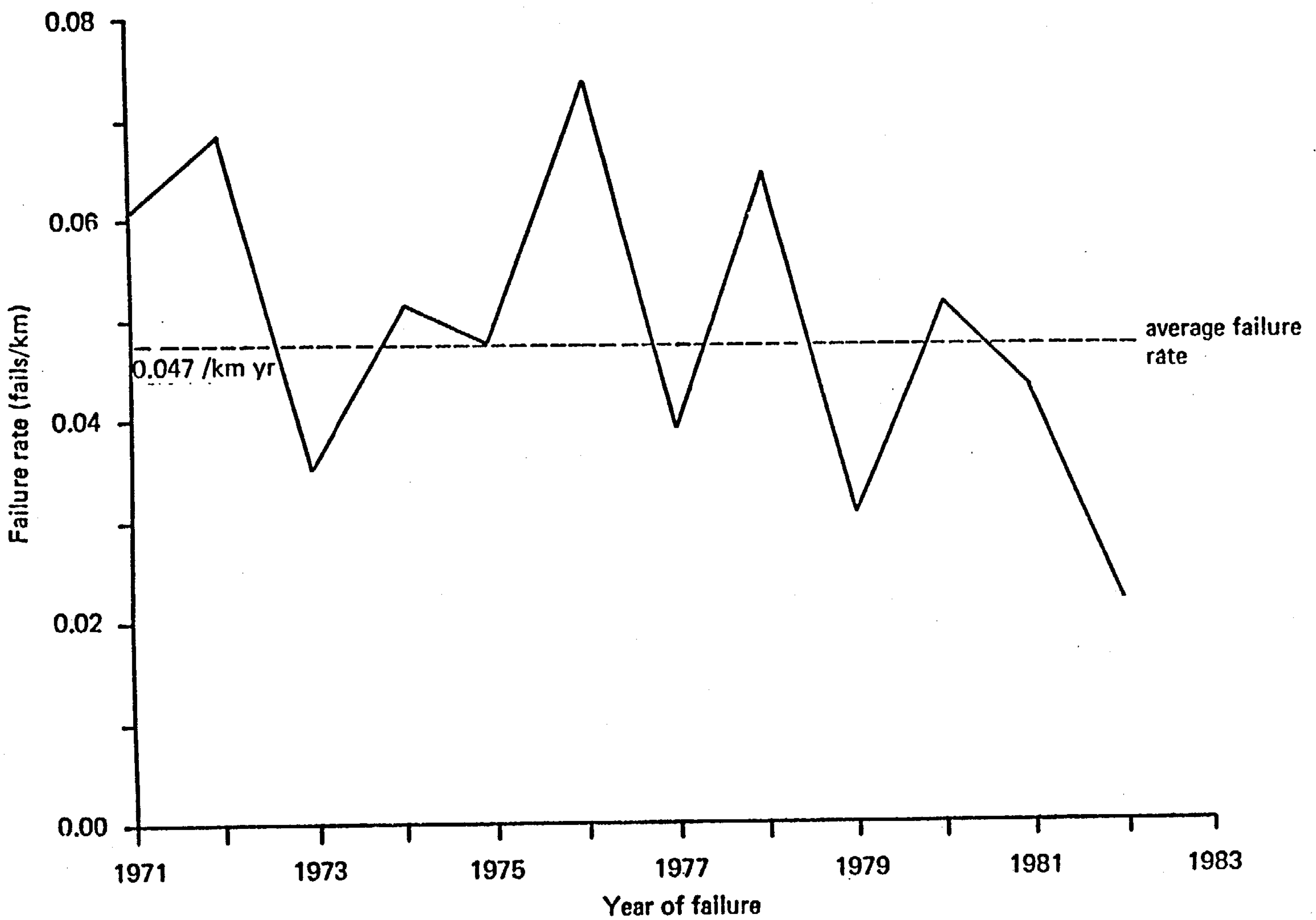


Figure 1.23 Area 4 — Failure rate versus year

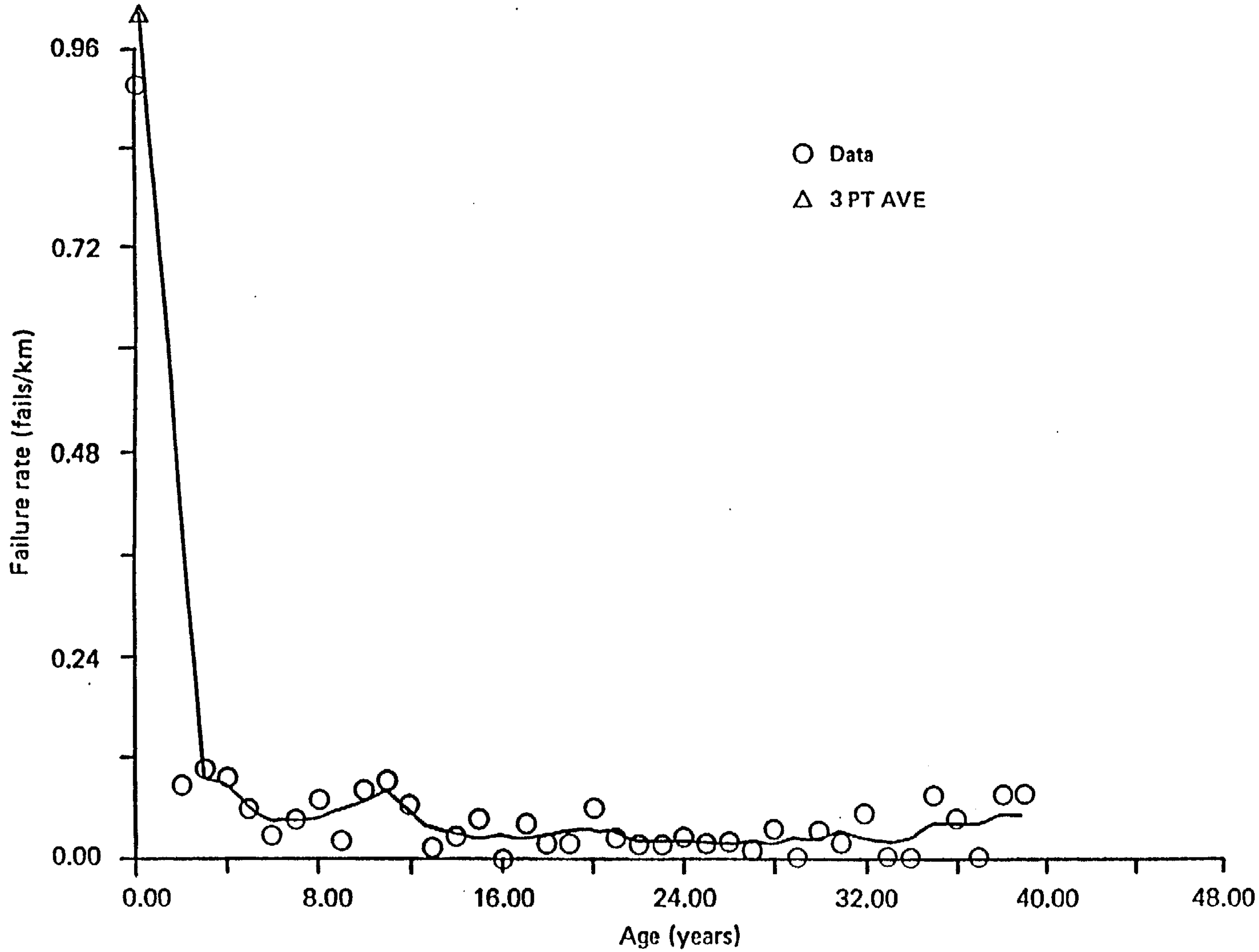


Figure 1.24 Area 4 – Failure rate against age

SECTION 2

DETERIORATION OF ASBESTOS CEMENT MAINS IN THE UK WATER SUPPLY

2.1 INTRODUCTION

Asbestos cement (AC) pipes have been used in the U.K. water supply system for over 50 years. Certain environments have been reported to attack AC, and corrosion related failures have been reported in the U.K. on pipes less than twenty years old. Several investigations of degraded asbestos cement pipe have been reported from the USA[5, 16] and elsewhere [6, 17, 18], and laboratory experiments have been performed to determine the parameters controlling degradation[19, 20, 21]. The results have been compared with various theoretical methods of determining the aggressivity of water to AC, which are based on the carbonate chemistry of the conveyed water. The two most commonly used indices are the Langelier Index[8], and a simplified version - the AWWA Aggressiveness Index[9]. However the correlation between experimental results and the indices is poor.

A more complex model has been devised recently by a CEOCOR committee[22] which is claimed to account for dynamic considerations as well as the static equilibria.

Although much information has been compiled on the theoretical aspects of deterioration of AC pipes there has been no systematic examination of AC pipes which have been in service in the U.K.

This investigation was initiated to examine systematically AC pipes which had been in service in the U.K. to identify the mechanisms and parameters which control the degradation. From this information the potential for fibre release can be assessed, and recommendations on limitations of use can be formulated.

2.2 STATISTICAL APPROACH

The water quality parameters which have been identified previously as contributing to the degradation of AC were selected for the statistical generation of a pipe sampling schedule. Three parameters were used i.e. pH, total hardness and total alkalinity of the conveyed water. Additional parameters used in the statistical design were age, as degradation is time dependant, and pipe diameter, as the average flow regime will vary with size. In general the external environment is isolated from the inside of the pipe and therefore is unlikely to affect the internal degradation. However to produce the maximum amount of information from the limited number of samples which could be examined (i.e. ~150), the statistical design included two external factors namely ground water hardness and soil permeability.

From these seven factors, a pipe sampling schedule was designed to enable an estimation of the linear and quadratic effects of each of the seven factors, together with first order interactions. More details of the principles behind the design are given in Appendix 3, together with the detailed sampling schedule.

2.3 EXHUMATION

From the data compiled for Section 1, areas were identified where significant quantities of AC pipe had been laid. From these areas, distribution systems conveying waters meeting the statistical sampling plan were identified and samples of pipe exhumed. The samples were from random positions on each pipe length and had a minimum length of 0.5m. For each pipe, details of the age, class, diameter etc were provided, together with an analysis of the conveyed water as it leaves the treatment plant or service reservoir supplying the main. In general the samples were taken from either a field or verge location as this minimised both disruption and cost.

A sample of soil was taken from adjacent to the pipe for the majority of pipes exhumed to enable a laboratory assessment of the soil type. Relevant details for all the pipe samples are presented in Table 2.1.

2.3.1 LIMITATIONS IN MEETING STATISTICAL DESIGN

Due to the historical pattern of laying asbestos cement pipes it was impossible to achieve the complete theoretical sampling plan. Additionally the availability of AC pipe samples conveying certain water qualities was sometimes poor. Indeed the water quality measurements used for selecting the samples were generally made at the treatment works before the water was passed into the distribution system. Thus by the time the water was conveyed through the pipes in question its chemical quality may have changed as a result of air contact in service reservoirs, or through contact with any other cementitious materials in the distribution system.

Furthermore, there is generally a variation in the distributed water chemistry on both a daily and a seasonal basis. This may mean that for short periods of time aggressive water is conveyed where the normal type of water would be non-aggressive. In these instances an average water quality has been used. Other problems occur where the water quality conveyed has changed during the lifetime of the pipe, due to either a change in source or in treatment. When these locations were unavoidable the analysis has taken two courses, one where the water conveyed for the longest period was used, and one where the most aggressive conveyed water was used.

The problem over accurate details is particularly significant for the older pipes where, due to changes in the organisation of the water industry, records have either not been maintained, or have been lost. Thus estimates, particularly of age often had to be made.

2.3.2 PIPE SAMPLING

Each pipe was uniquely labelled and samples cut out for analysis and examination. One end of the pipe was cut back 50mm beyond any obvious damage and a 10mm wide ring removed for chemical analysis. Where possible a further 200mm long pipe sample was cut for mechanical and physical testing. In each case the samples were removed from the barrel portion of the pipe, avoiding the tapered joint ends.

The age and diameter distributions for the exhumed pipe samples are presented in Figures 2.1a and 2.1b.

2.4 EXAMINATION AND TESTING

In addition to visual examination both physical and chemical tests were performed on the pipe samples to quantify the amount of degradation which had occurred. The physical tests were performed on the 200mm long sample and the chemical tests on the 10mm rings.

2.4.1 VISUAL EXAMINATION

The pipes were inspected both in the as received condition, and following sample preparation. It was observed on the pipes that the bitumen coating when present was generally intact on the inside of the pipe but was more significantly damaged on the external surfaces.

2.4.2 PHYSICAL TESTS

(a) Penetration Tests

As degradation of the pipe results in changes in the material properties, it was considered that the extent of this degradation may be assessed by monitoring the load required to force a penetrator or indentor into the pipe surface. It was anticipated that the shape of the load/penetration curve would show points of inflexion at degradation boundaries. Initial trials were performed using conical penetrators of various diameters and point angles on an Instron testing machine. The equipment was assembled as shown in Figure 2.2.

Work previously reported[7] had recommended the use of a specially modified Shore D hardness durometer to quantify the degree to which AC pipe had been attacked. The readings from the Shore durometer are inversly related to the depth a needle will penetrate under a given load, and may be related to the modulus and elastic behaviour of the material. The Barcol hardness tester used in this investigation operates on the same principle.

Measurements of 'hardness' were made at ten equally spaced points along the length of the 200mm samples at each of four equidistant circumferential positions, on both the inside and the outside of the pipe, see Figure 2.3. The values were recorded and maxima, minima and mean hardnesses calculated.

(b) Ring crush tests

An Instron testing machine was used to crush 200mm long pipe samples following the procedure given in BS486[23] - see Appendix 4. Prior to each sample being crushed the internal diameters, external diameters and wall thicknesses were measured. The crush strengths were then calculated using the formula given in BS486. Each of the samples was aligned with marked positions relating to the hardness testing positions at the 12, 3, 6 and 9 o'clock positions.

2.4.3 CHEMICAL TESTS

To assess the chemical changes which had occurred in the pipes, analyses were performed on the 10mm rings. One face of the rings was prepared by grinding and polishing to a 1μm finish to provide a flat face for examination. The freshly ground face was stained with phenolphthalein to highlight those areas where maximum degradation had occurred[24].

The areas of maximum internal and external degradation were identified, and through wall slices approximately 2mm thick cut from these areas for more detailed analysis (see Figure 2.4). These were mounted in blocks of ten in resin and polished to a 1μm finish.

(i) Elemental analysis

A conducting carbon coat was vacuum sputtered onto the polished surface of the mounted samples. The concentration of five elements was measured along the slices (i.e. through the pipe wall) using X-ray energy dispersive spectroscopy (EDS) on an electron-microprobe analyser. Details of the facility used, and the operating conditions are presented in Appendix 5. Measurements were made every 50μm on areas 50μm square for calcium (Ca), silicon (Si), aluminium (Al), magnesium (Mg) and iron (Fe).

The concentrations were recorded digitally, to enable subsequent computer processing of the data, and a plot of the concentration of each element against position in the sample was produced - see example in Figure 2.5.

(ii) Phenolphthalein tests

The blocks of ten slices used for the elemental analysis were repolished, to remove the carbon coating, and stained with phenolphthalein. Degradation depths, shown by the unstained areas, were measured using a microscope and a calibrated graticule eyepiece.

2.5 RESULTS

2.5.1 VISUAL EXAMINATION

Degradation was apparent on some of the pipe samples and was generally most severe at defects in the bitumen coatings. Where degradation had occurred there were obvious differences in the structure of the pipe. Two levels of degradation were sometimes apparent. Most commonly an area of moderate degradation was present adjacent to the unaltered pipe material which was visible by colour differences. For cases with more severe degradation a second area, contained within the first was apparent, where the matrix had been completely removed, leaving a very soft fibrous area see Figure 2.6.

2.5.2 PHYSICAL TESTS

Penetration tests

Typical load/penetration curves through a severely degraded pipe and through an unattacked pipe are shown in Figure 2.2b.

The anticipated changes in the gradient of this curve were not observed for any of the indentors, and greater penetration was observed on the new pipe than on the degraded pipe. Therefore as the technique could not detect the most severe cases of degradation it was decided not to pursue this test.

Barcol Hardness

The maximum and minimum Barcol hardness readings for each sample are presented in Figure 2.7. It can be seen that large differences often exist between the maximum and minimum readings on a pipe sample. However the maximum values are in general relatively constant, indicating most of the pipes have some practically undegraded areas. This, combined with the generally large differences between maximum and minimum readings, shows that the degradation when present is non-uniform.

It was also apparent that the presence of the bitumen coating affected the measurements. Indeed, measurements on a sample of new pipe with a bitumen coating, and with the coating removed showed a difference of ~10%. Thus for bitumen coated pipes, which represented the majority of pipes examined, an allowance must be made for penetration of the bitumen.

Ring Crush Tests

The loaded pipes generally failed at the 12 and 6 o'clock positions first, followed almost immediately by cracking at the 3 and 9 o'clock positions. Figure 2.8 shows a pipe section in the test machine both before and after crushing.

For each of the pipe samples crushed, the load at failure was recorded. The value of this load is related to the pipe diameter and wall thickness. The formula given in BS486 (see Appendix 4) incorporates the geometrical parameters to give a value of the unit transverse crushing strength. The values of transverse crush strength against degradation for each pipe diameter are presented in Figure 2.9 where it can be seen that a wide variation exists.

Most of the measured crush strengths of the pipes fall below the BS486 minimum value of $44Nmm^{-2}$ although little or no degradation was measured in many of the pipes. Thus either the initial strengths of the pipes vary considerably, or during service the pipes are weakened by a mechanism which is not revealed by the elemental or phenolphthalein tests.

2.5.3 CHEMICAL TESTS

Elemental Analysis

Elemental analysis along sections through the pipe wall showed how the concentration of various elements varied. For new, undegraded pipe it can be seen from Figure 2.5 that the concentrations of each element, although oscillating, remain relatively constant through the pipe wall. The calcium concentration remains around 25% and the silicon concentration around 8%. The oscillations in the concentrations are due to the basic inhomogeneity of the AC pipe, with peaks in calcium occurring in cement rich areas, and troughs in the asbestos rich areas. This inhomogeneity is confirmed by optical microscopy of pipe sections Figure 2.10. Application of a moving average to smooth these oscillations shows the trends more clearly (Figure 2.11) but reduces the resolution of the measurements.

Figure 2.12 shows the elemental profile for a degraded pipe, with the smoothed version in Figure 2.13.

From these traces it can be seen that the elemental changes are generally gradual, thus making definition of degradation depth difficult. It has been suggested[7] that the ratio of calcium to silicon (Ca/Si) in the material gives a good indication of the degradation. For undegraded pipes the Ca/Si ratio is approximately 3.5 and this decreases with the progression of degradation. Thus smoothed traces of the Ca/Si ratios were produced for examination, see Figure 2.14. However the same gradual transition is still apparent. It was decided that the changes in calcium concentration, which are a direct result of the chemical leaching provided the most appropriate parameter to use to determine degradation depths.

To enable repeatable measurement of the depths of degradation, an arbitrary calcium concentration reduction was defined, below which degradation was deemed to have occurred. The value chosen was when the calcium concentration had consistently dropped to below 90% of the nominally unaltered matrix. This generally corresponded to a Ca/Si ratio below approximately 3.0.

Phenolphthalein tests

Staining the cement mortar samples with phenolphthalein highlights those areas with a pH >~9.5[24] i.e. where the matrix alkalinity is high due to the presence of free lime. In most cases the staining produced a well defined cut-off between the degraded and undegraded areas, (Figure 2.15) enabling accurate measurement of the depths of degradation.

To examine the relationship between the elemental analyses and the phenolphthalein stain tests the two measurements have been plotted against each other. As can be seen from Figure 2.16 the measurements are in good agreement.

2.6 STATISTICAL ANALYSIS

Before performing a regression analysis on the raw data, the predictor determinands, i.e. those parameters such as age, pH, hardness, and alkalinity were examined to determine whether any correlations exist. With the exception of alkalinity and hardness, which had a correlation coefficient of 0.9, all the variables were poorly correlated thus justifying the care taken in designing the sampling schedule. This independance of the variables enables regression analysis to be performed without confounding the results.

Examination of the correlation matrix revealed that all the predictor variables were poorly correlated with the dependant variables, i.e. the two measures of degradation by phenolphthalein staining and elemental analysis. The best correlation was between pH of the water and the phenolphthalein measure of degradation, but even this was not statistically significant at the 5% level.

Several different linear models were used to fit multiple regressions to the degradation. The best fit in terms of reducing the residual variance included age, pH, hardness and alkalinity although hardness may be dropped from the model due to its high correlation, with alkalinity. Diameter did not affect the fit of any of the models.

The regression coefficients and the associated analysis of the variance are presented in Appendix 6. Although the model

$$\text{Degradation} = a \cdot \text{Age} + b.\ \text{pH} + C.\ \text{Alkalinity} + k$$

is statistically significant at the 5% level, there is a great deal of the variation in degradation which is unaccounted for.

Following the poor fit achieved with fitting a linear model to the full data set two modifications were introduced. The first was to split the data set at some meaningful intermediate point. Two subsets were produced for analysis by splitting the data at each of the following thresholds.

(i) at pH of 7.5 to produce two subsets with pH <7.5 and pH >7.5

(ii) at alkalinity of 75

(iii)at an Aggressiveness Index of 10.5.

The second modification was to introduce quadratic terms.

Significant correlations were found for each of the lower subsets, with no significant relationships apparent for the higher subsets. See Appendix 7.

2.7 DISCUSSION

Analysis of the results shows that there is no simple model to explain degradation measured by elemental analysis or phenolphthalein staining of the asbestos cement. This may be due to one of several interfering factors.

Firstly, most of the pipes examined were bitumen lined. The relative performance of bitumen and non-bitumen coated pipes could not be examined, as the mains records did not identify the original presence of linings. Consequently it was impossible to select samples from both coated and uncoated pipes. The presence of bitumen on the pipes confounds any straightforward relationship between degradation and water quality as the bitumen coating provides protection for an indeterminate period and may itself degrade. Additionally defects may have been present in the coating when the pipe was installed due to manufacturing problems or handling, and the type of bitumen coating has changed over the years. The rate of degradation of the bitumen may be affected by water quality parameters not considered for asbestos cement degradation, thus the time required before attack of the underlying asbestos cement commences may vary significantly for apparently similar water qualities.

Secondly, the rate of attack of asbestos cement may be affected by minor or trace constituents in the water not considered in the analysis. There is limited evidence from America[19] that the presence of iron and other metals in the water may result in reduced rates of attack.

Additional factors which may affect the correlation are the place of manufacture of the pipes, the cement used, the formulation of the bitumen coatings, the extent of damage incurred during installation, the abrasive characteristics of the water, particularly suspended solids which may remove any protective coating, and changes in treatment/water source during the life of the pipe.

Unfortunately in the majority of cases none of those parameters is quantifiable and may interfere with the statistical analysis.

However a general trend is apparent which shows degradation is more severe for conveyed waters of low pH, and low alkalinity. A bitumen coating cannot be relied on to permanently protect the asbestos cement pipe in aggressive waters, thus it is apparent that AC pipes are vulnerable to attack where the conveyed water alkalinity is below 75mg/l or the pH below 7.5.

Estimating the potential rate of fibre release into the water supply is therefore extremely difficult, and would require examination of pipe samples from individual areas. In this way estimates could be made of the extent of degradation (the surface area of the pipes affected), and the effects of pipe diameter could be included in the calculations. The potential for fibre release will be related to the internal surface area of the pipe suffering degradation as well as the rate at which the degradation is proceeding. As the pipe contains approximately 12% asbestos fibres which are relatively uniformly distributed through the pipe wall, estimates of the fibres available for release can be made. However the pipe flow conditions which may cause removal of the fibres have not been studied and are most probably transient in nature, thus making any predictions unreliable. The distribution of fibres within the mains and supply pipe system will be affected by the overall hydraulic characteristics of the pipe system.

2.8 CONCLUSIONS

1. Low pH, low alkalinity waters are aggressive to asbestos cement pipes.

2. The maximum internal degradation observed was 8mm in a period of 40 years.

3. The most reliable method of assessing the depth of degradation incurred was by elemental analysis through sections of the pipe. Phenolphthalein staining showed a very good correlation with elemental analysis. None of the other techniques assessed proved suitable.

4. Prediction of rates of attack are very difficult in the UK as most of the pipes are bitumen coated, and the pipe degradation is thus very localised around defects in the coating.

TABLE 2.1 DETAILS OF ALL EXHUMED SAMPLES

				<---- WATER QUALITY	---->			PHENOLPHTHALIEN STAIN		ELEMENTAL	
PIPE NO	DIAM mm	CLASS	AGE yrs	PH	HARDNESS mg/l	ALKALINITY mg/l	STRENGTH N/mm2	INTERNAL mm	EXTERNAL mm	INTERNAL mm	EXTERNAL mm
0001	100	20	025	7.30	265	187	051	0.27	0.20	0.11	0.41
0002	080	20	025	7.30	262	197	029	0.00	0.40	0.00	0.83
0003	150	20	001	7.30	251	185	028	0.45	0.00	1.17	0.00
0004	050	20	025	7.30	265	187	058	0.00	0.00	0.00	0.00
0005	100	20	024	7.55	261	165	031	0.40	0.00	0.00	0.00
0006	100	00	019	8.60	038	021	051	0.58	0.00	0.34	0.66
0007	100	00	019	8.90	030	010	078	0.00	0.50	0.00	0.77
0008	050	00	050	8.90	030	010	000	3.80	1.10	4.77	1.45
0009	100	20	012	7.20	133	175	000	0.00	1.70	0.00	2.39
0010	075	20	030	7.80	050	021	000	0.00	0.00	0.40	0.00
0011	050	00	035	8.10	044	012	036	0.15	1.18	0.35	1.32
0012	037	20	030	6.40	035	018	051	0.10	1.24	0.32	1.65
0013	075	20	049	7.30	248	227	021	0.00	0.25	0.20	0.43
0014	075	20	050	6.80	071	051	047	0.00	1.40	1.20	1.40
0015	100	15	043	7.70	089	054	033	2.80	1.32	2.89	1.68
0016	075	00	037	7.80	166	091	000	2.00	0.25	2.01	0.00
0017	100	00	026	7.30	209	093	038	0.00	1.10	0.20	2.03
0018	100	00	023	8.90	018	011	040	0.00	0.10	0.00	0.00
0019	075	00	047	7.40	275	194	028	4.00	0.00	5.10	0.00
0020	075	00	022	6.10	062	040	017	5.20	5.80	5.22	5.90
0021	075	00	025	7.50	201	120	039	0.00	2.05	0.00	2.04
0022	050	00	037	7.40	225	130	043	1.90	3.60	2.06	3.65
0023	200	00	045	7.70	275	190	000	8.00	0.50	7.91	0.31
0024	075	00	049	8.90	022	011	034	0.00	0.05	0.00	0.00
0025	150	00	023	8.90	022	011	023	0.30	0.00	0.37	0.00
0026	100	20	040	7.00	026	019	034	0.00	4.50	0.00	5.15
0027	100	00	040	0.00	000	000	040	0.10	0.52	0.15	0.00
0028	125	20	040	7.00	026	019	052	0.00	3.50	0.00	3.91
0029	150	00	028	7.70	340	276	026	0.00	3.60	0.00	3.77
0030	075	00	050	7.30	318	282	034	0.00	3.70	0.00	3.74
0031	125	00	045	7.90	144	318	023	0.00	0.27	0.00	0.00
0032	075	00	050	8.00	075	047	026	0.00	7.60	0.00	8.14
0033	300	15	013	8.10	099	065	000	0.00	0.90	0.00	0.78
0034	375	20	025	8.10	099	065	000	0.00	1.50	0.00	1.39
0035	075	20	040	8.00	075	047	040	0.00	0.40	0.00	1.00
0036	037	20	040	7.00	026	019	000	2.60	2.50	2.91	3.15
0037	075	00	035	7.30	318	282	035	3.70	0.20	3.71	0.00
0038	075	00	035	7.30	318	282	043	0.40	3.40	0.00	3.56
0039	100	00	016	7.90	000	000	055	0.00	0.00	0.00	0.00
0040	100	00	047	7.40	362	243	034	0.20	0.10	0.37	0.38
0041	075	00	020	8.20	047	030	030	0.60	0.00	0.71	0.00
0042	100	25	004	8.70	075	028	000	0.00	0.00	0.00	0.00
0043	075	00	050	7.60	433	243	000	0.00	2.10	0.00	2.02
0044	150	20	008	8.70	075	028	043	0.00	1.00	0.00	1.22
0045	075	00	025	7.08	042	024	032	3.80	4.30	4.48	4.22
0046	150	20	024	7.20	064	034	029	0.00	0.00	0.00	0.00
0047	075	00	010	7.50	394	202	032	0.20	0.00	0.40	0.00
0048	050	25	025	7.30	131	115	043	1.70	0.50	2.57	1.12
0049	050	00	035	7.50	394	202	040	0.00	2.60	0.00	2.21
0050	100	00	026	8.40	023	016	040	0.70	0.20	0.70	0.55
0051	100	00	008	6.90	019	012	045	0.20	0.60	0.23	0.89
0052	050	00	031	7.70	340	276	034	0.00	3.60	0.00	3.46
0053	100	20	030	8.20	031	019	041	5.40	6.10	5.56	6.43
0054	100	20	008	8.20	031	019	062	0.00	0.00	0.00	0.00
0055	050	20	046	8.10	026	019	035	0.60	0.60	0.64	0.00

PIPE NO	DIAM mm	CLASS	AGE yrs	PH	HARDNESS mg/1	ALKALINITY mg/1	STRENGTH N/mm2	PHENOLPHTHALIEN STAIN INTERNAL mm	PHENOLPHTHALIEN STAIN EXTERNAL mm	ELEMENTAL INTERNAL mm	ELEMENTAL EXTERNAL mm
				<---- WATER QUALITY ---->							
0056	150	20	006	8.10	026	019	030	0.00	0.60	0.42	0.57
0057	150	20	030	8.10	026	019	000	0.40	0.30	0.29	0.15
0058	050	00	025	7.60	027	015	035	0.20	3.12	0.29	3.12
0059	100	00	015	7.60	027	015	019	1.80	5.60	1.97	5.56
0060	150	00	015	7.60	027	015	011	0.00	5.20	0.00	5.36
0061	150	00	025	5.50	013	010	000	0.00	5.50	0.00	5.36
0062	175	20	040	7.00	026	019	054	0.20	2.40	0.25	2.60
0063	150	20	031	8.70	075	028	000	0.00	2.40	0.00	2.60
0064	075	20	025	6.90	031	009	033	2.10	2.80	1.64	3.03
0065	075	20	000	6.90	031	009	000	4.60	1.20	4.68	1.34
0066	150	00	040	7.00	026	019	000	6.00	3.50	5.34	3.73
0067	150	20	024	7.20	064	034	000	0.00	3.50	0.00	3.73
0068	100	00	040	8.00	160	140	015	0.60	6.00	0.60	4.50
0069	050	00	030	8.00	160	140	045	0.00	0.10	0.00	0.20
0070	075	00	035	8.00	160	140	040	0.00	6.40	0.00	6.07
0071	075	00	030	7.30	198	150	062	1.30	1.81	0.98	1.76
0072	150	00	025	8.00	160	140	025	0.00	2.00	0.00	2.14
0073	150	00	000	5.90	050	033	036	0.20	0.70	0.28	0.75
0074	100	00	000	9.00	060	028	037	0.00	0.25	0.00	0.00
0075	150	00	030	6.90	415	251	036	0.00	0.20	0.00	0.24
0076	075	00	030	6.80	050	030	029	2.90	1.10	2.93	1.45
0077	050	00	055	6.80	050	030	051	4.00	0.15	3.89	0.14
0078	200	00	015	6.80	050	030	000	4.30	0.00	4.50	0.00
0079	075	00	030	7.60	241	149	030	5.00	0.10	5.20	0.00
0080	150	00	019	8.20	317	183	033	3.70	1.00	3.76	0.00
0081	150	00	036	8.20	317	183	029	0.00	0.20	0.00	0.33
0082	100	00	047	8.10	320	234	041	0.00	0.80	0.16	1.01
0083	100	00	018	8.20	317	183	037	0.40	0.00	0.83	0.00
0084	100	00	009	8.10	320	234	000	0.00	0.80	0.00	0.91
0085	100	00	028	7.60	170	084	023	0.30	5.20	0.31	5.93
0086	150	15	033	8.10	076	032	019	0.00	6.80	0.10	7.40
0087	075	20	027	8.10	076	032	028	0.30	3.70	0.40	3.74
0088	050	20	027	8.50	072	092	071	0.00	3.60	0.10	3.78
0089	150	20	016	8.10	076	032	038	0.10	0.50	0.10	0.50
0090	100	20	020	8.50	072	092	023	0.20	2.00	0.37	2.26
0091	150	00	024	6.00	010	002	016	0.00	4.50	0.00	4.50
0092	100	00	033	6.10	012	006	031	2.20	0.00	2.20	0.00
0093	075	00	035	7.60	035	019	040	2.90	0.00	2.84	0.00
0094	075	00	036	7.35	081	040	037	0.00	0.80	0.00	0.82
0095	075	00	035	7.10	018	017	025	0.40	2.80	0.37	2.76
0096	150	25	014	6.70	006	011	051	0.00	4.00	0.00	4.37
0097	075	25	030	6.70	006	011	038	0.30	2.90	0.28	2.84
0098	050	25	026	6.70	006	011	028	0.10	4.90	0.30	4.96
0099	075	00	023	8.70	044	015	037	0.00	0.25	0.00	0.00
0100	150	00	021	8.60	066	025	040	0.00	0.20	0.00	0.25
0101	075	00	027	8.60	066	025	025	0.30	0.00	0.10	0.00
0102	100	00	032	8.80	044	016	039	0.00	0.00	0.00	0.00
0103	100	00	010	8.50	013	009	033	1.50	0.10	1.71	0.18
0104	150	00	000	8.50	013	009	042	1.30	0.10	1.13	0.19
0105	150	20	035	8.50	013	009	045	0.60	2.20	0.53	3.25
0106	100	00	025	8.50	013	009	024	1.70	0.00	1.94	0.00
0107	100	00	030	8.50	013	009	033	2.90	0.10	2.91	0.17
0108	075	00	045	8.40	010	008	022	0.00	5.95	0.00	4.48
0109	075	00	045	7.50	011	006	051	0.00	0.00	0.00	0.00
0110	050	00	045	8.20	024	030	030	0.70	3.20	0.16	3.43

PIPE NO	DIAM mm	CLASS	AGE yrs	<---- WATER QUALITY ----> PH	HARDNESS mg/l	ALKALINITY mg/l	STRENGTH N/mm2	PHENOLPHTHALIEN STAIN INTERNAL mm	EXTERNAL mm	ELEMENTAL INTERNAL mm	EXTERNAL mm
0111	150	00	000	0.00	000	000	042	0.00	4.20	0.34	4.38
0112	150	00	037	7.27	009	005	020	2.70	1.70	2.85	1.56
0113	075	20	028	7.25	023	008	026	0.40	1.20	0.00	1.34
0114	100	00	029	7.38	248	181	034	0.40	0.20	0.41	0.00
0115	100	00	027	7.40	010	004	033	1.80	1.00	0.54	0.00
0116	075	00	025	7.33	012	005	028	0.00	1.50	0.00	1.85
0117	050	00	024	7.40	010	004	052	0.80	4.50	0.90	4.66
0118	075	00	000	7.46	205	178	031	0.30	0.40	0.00	0.56
0119	075	00	030	7.20	346	271	013	2.20	4.50	1.70	3.91
0120	100	00	015	7.60	231	183	031	0.00	1.10	0.00	1.13
0121	150	00	000	0.00	000	000	000	1.25	0.52	1.25	0.52
0122	100	00	040	7.46	205	178	029	0.00	0.10	0.00	0.00
0123	600	00	035	7.40	320	240	000	0.00	0.00	0.00	0.00
0124	075	00	000	0.00	000	000	020	0.00	1.00	0.00	1.34
0125	075	00	035	7.40	320	240	046	0.10	0.00	0.25	0.00
0126	150	00	034	7.30	360	270	024	0.10	0.25	0.12	0.26
0127	150	00	034	7.30	360	270	018	0.10	0.00	0.20	0.00
0128	075	00	030	7.40	440	245	026	0.10	1.10	0.00	1.52
0129	075	00	030	7.40	440	245	031	0.00	0.00	0.00	0.00
0130	100	00	055	7.40	440	245	000	0.00	0.00	0.00	0.00
0131	150	00	055	7.40	440	245	024	0.30	0.00	0.00	0.00
0132	150	20	027	7.30	556	280	024	0.10	0.00	0.20	0.00
0133	075	20	037	0.00	000	000	021	0.30	1.20	0.00	1.80
0134	100	20	026	7.30	556	280	023	0.00	0.00	0.00	0.00
0135	075	00	010	7.30	556	280	000	0.00	0.00	0.00	0.00
0136	100	25	999	0.00	000	000	027	0.00	0.00	0.00	0.00
0137	075	00	000	0.00	000	000	000	0.00	1.40	0.00	1.76
0138	100	00	000	0.00	000	000	034	0.40	0.30	0.32	0.29
0139	100	00	000	7.50	116	063	034	0.30	7.20	0.23	7.24

Figure 2.1a Age Distribution of Samples

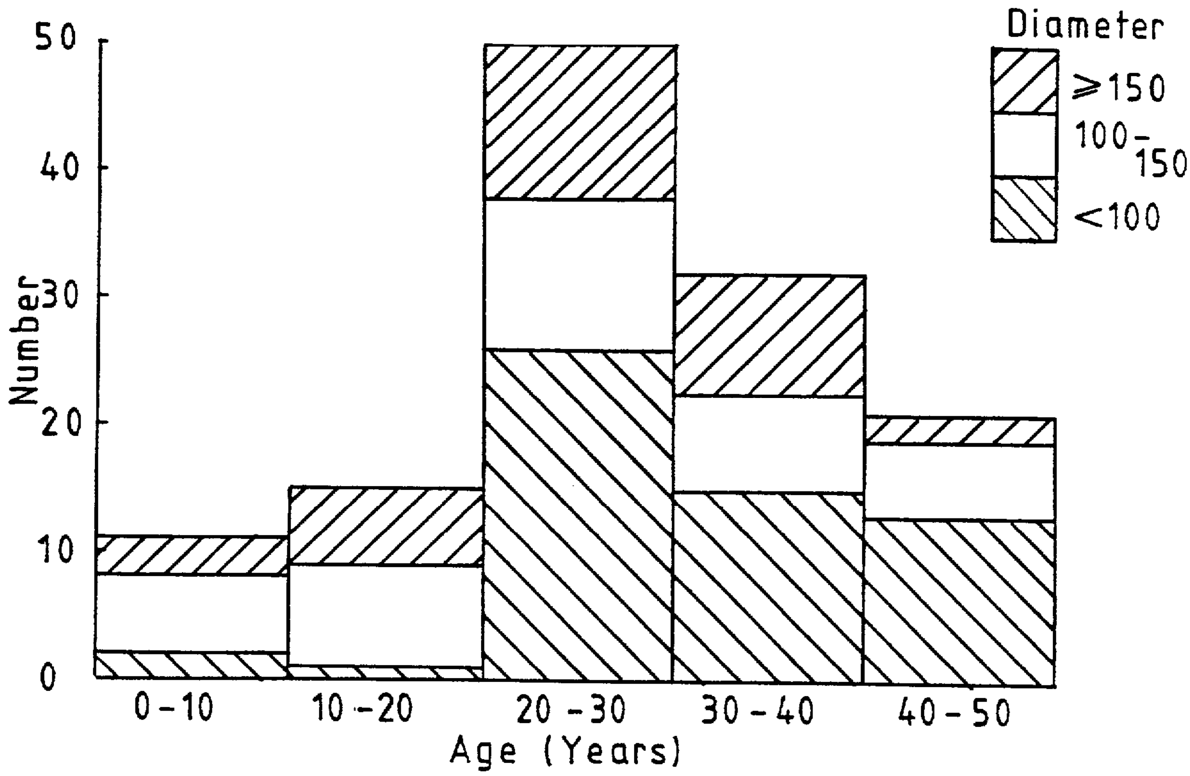


Figure 2.1b Diameter Distribution of Samples

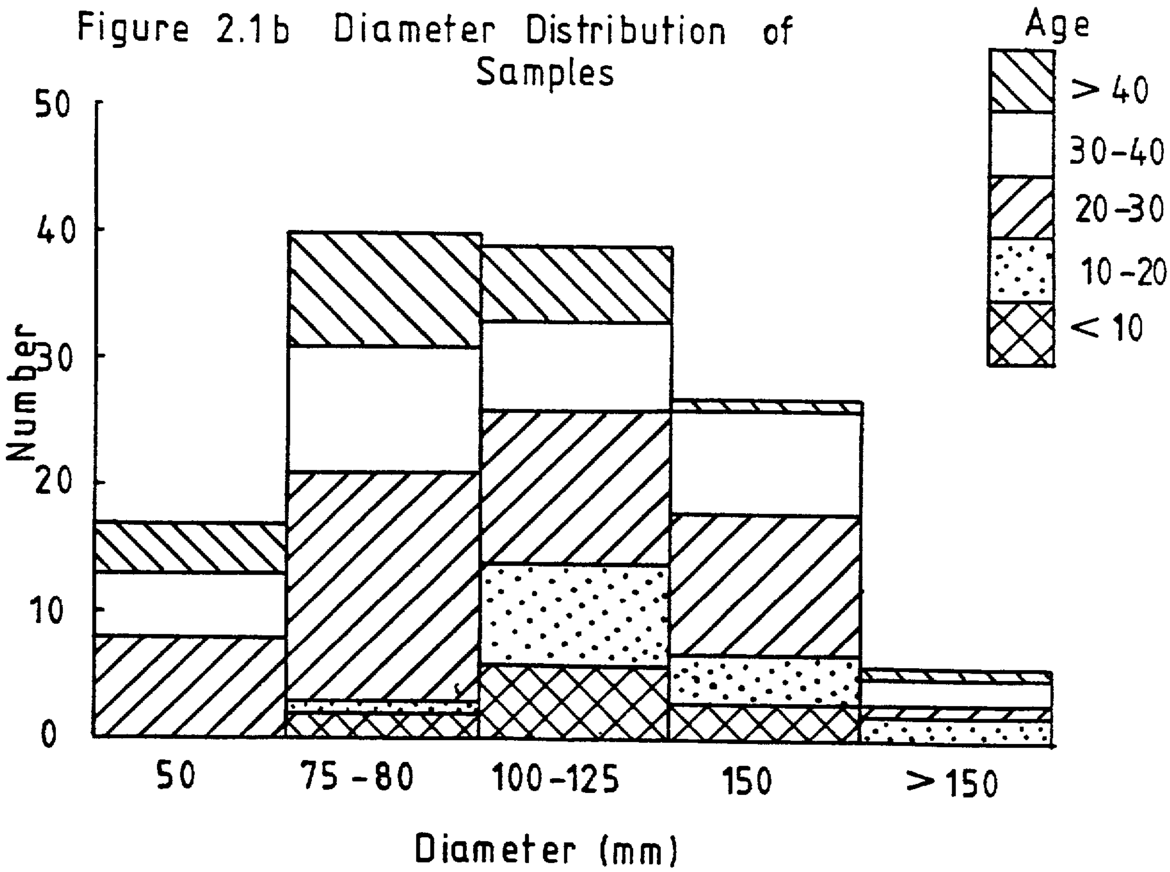


Figure 2.2a Schematic Diagram of Penetration Tests

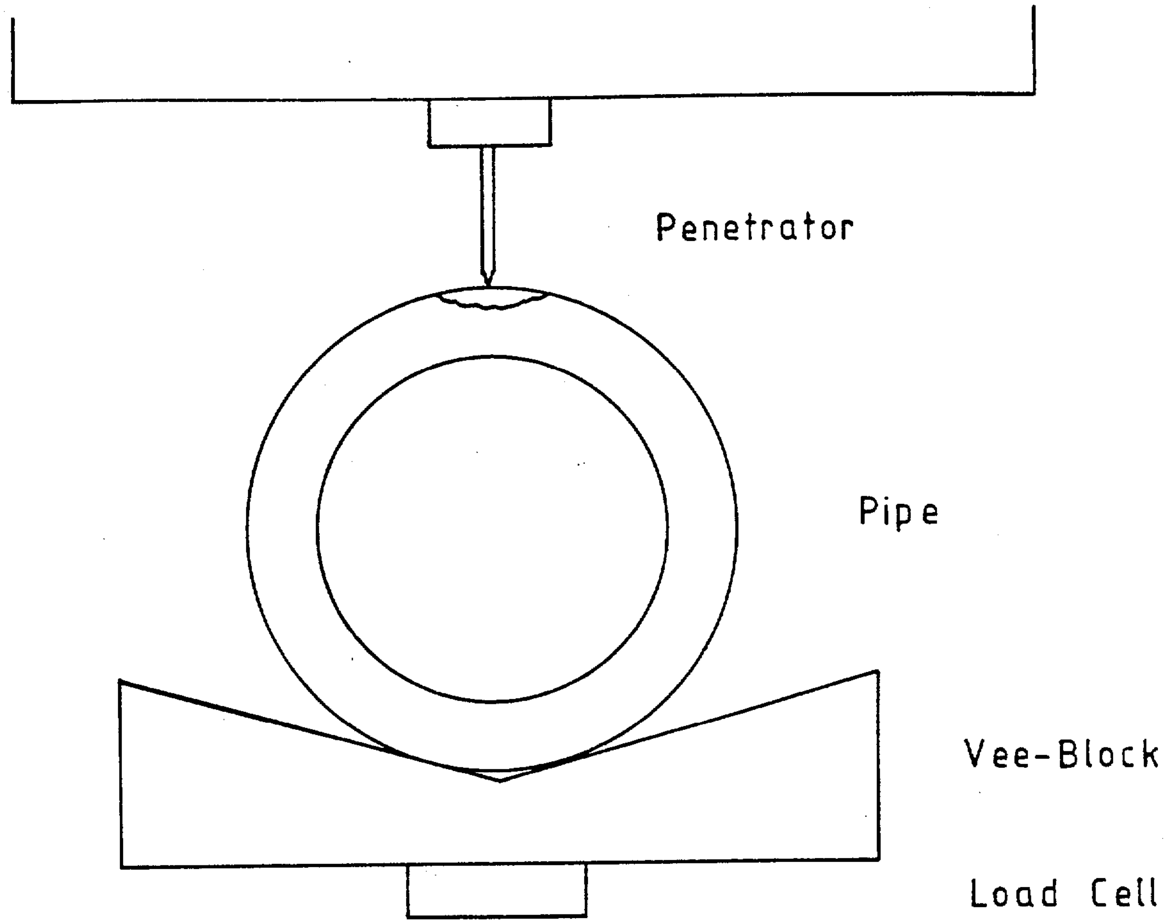


Figure 2.2b Load-Penetration Curve

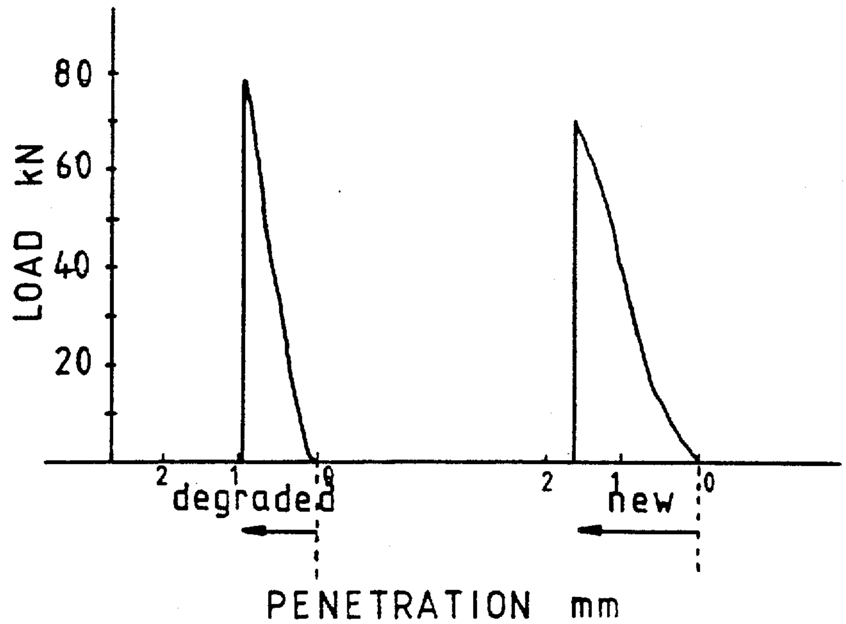


Figure 2.3 Positions for Barcol Hardness Measurements

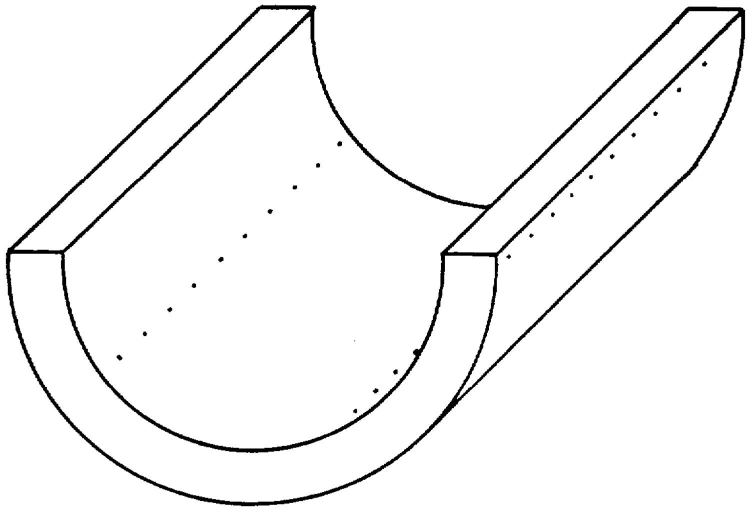


Figure 2.4 Sampling of rings for Chemical Analysis

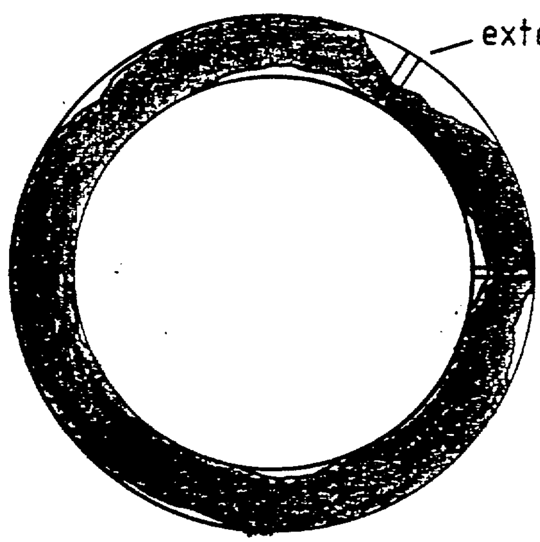


FIGURE 2.5 ELEMENTAL PLOT THROUGH UNDEGRADED PIPE

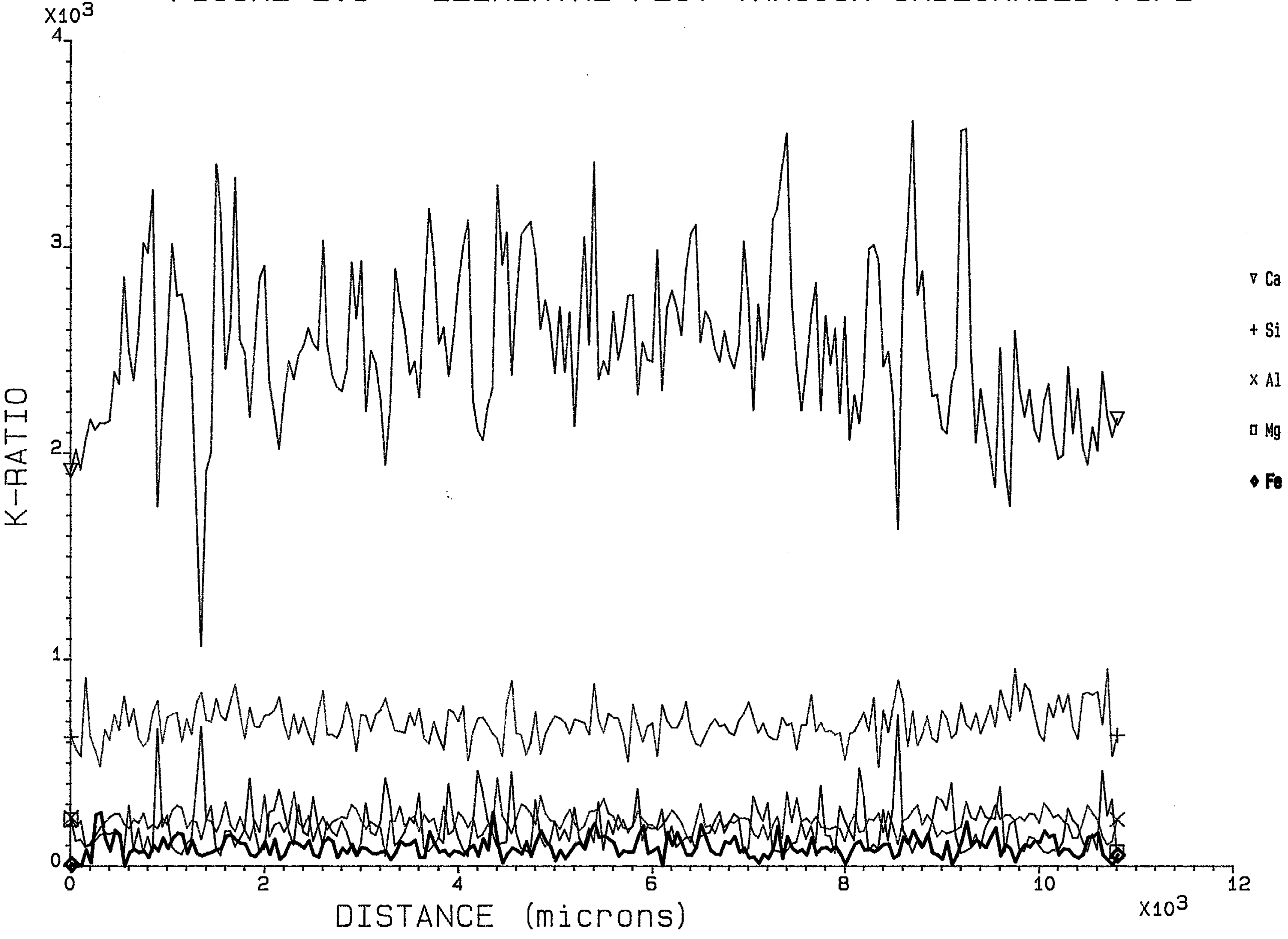
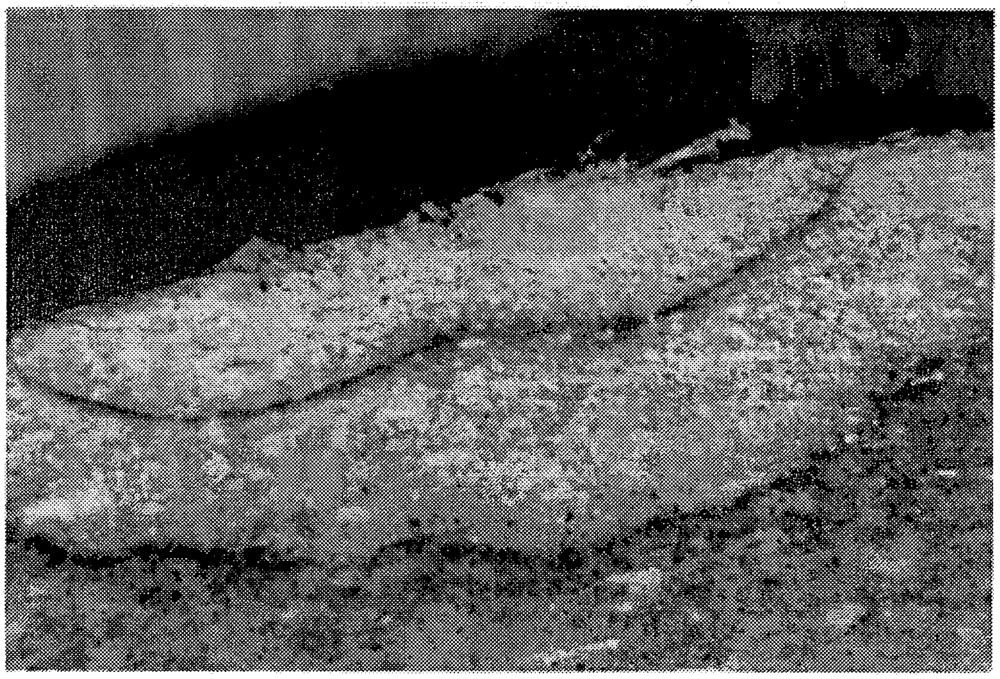


Figure 2.6



Photograph of section through degraded pipe showing the two areas of degradation

FIGURE 2.7   PLOT OF HARDNESS AGAINST SAMPLE

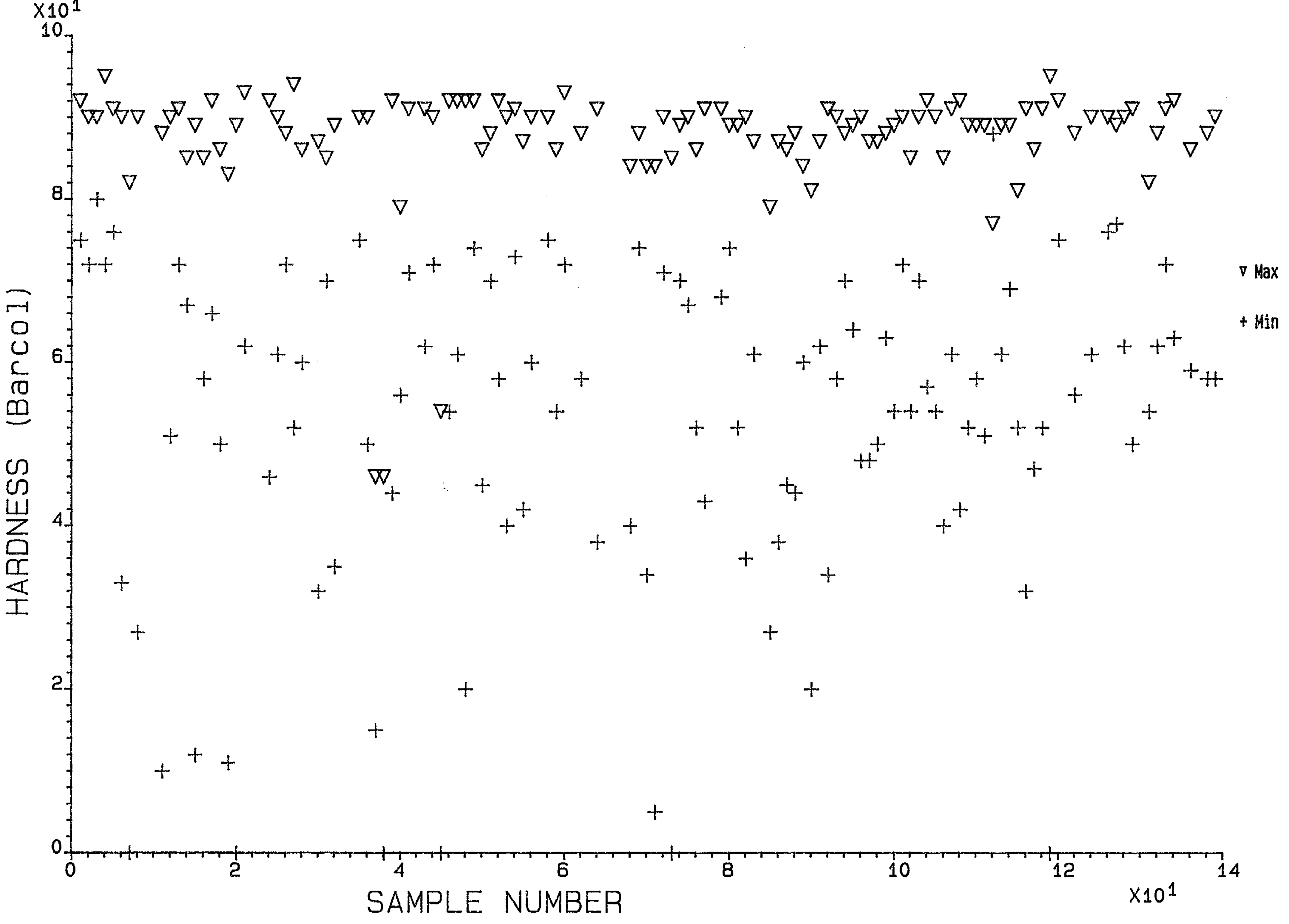
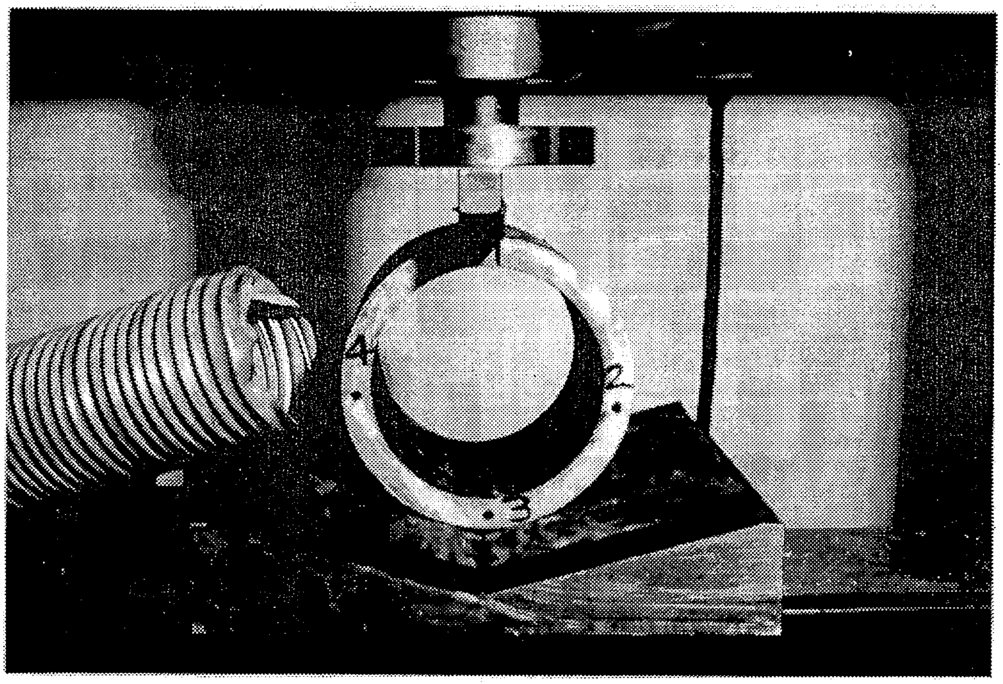
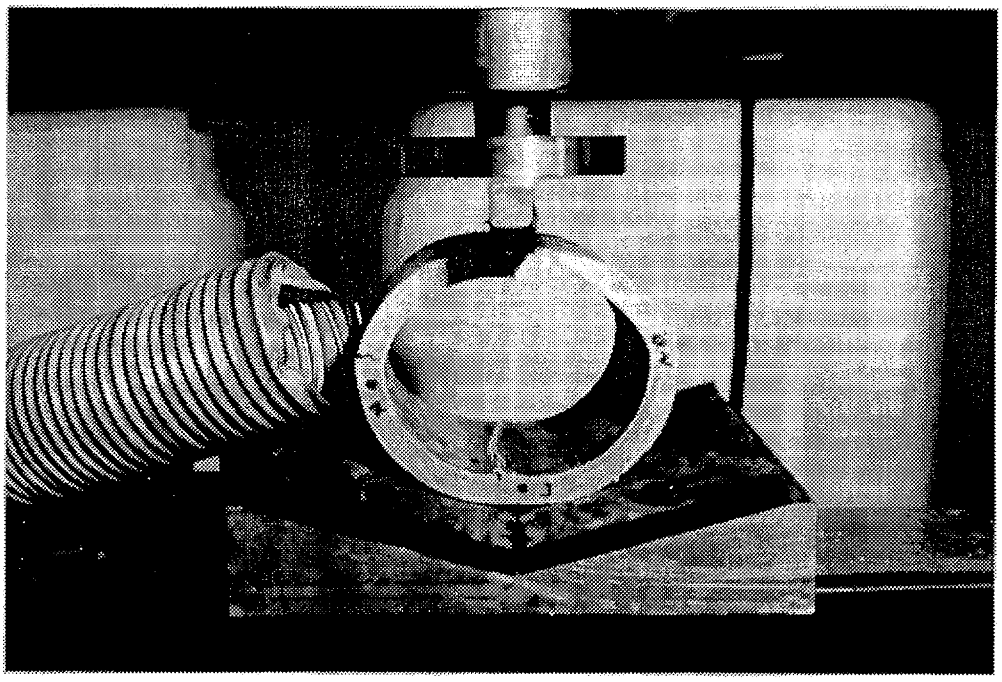


Figure 2.8



Before

200mm pipe samples under transverse crush



After

FIGURE 2.9 STRENGTH AGAINST TOTAL DEGRADATION

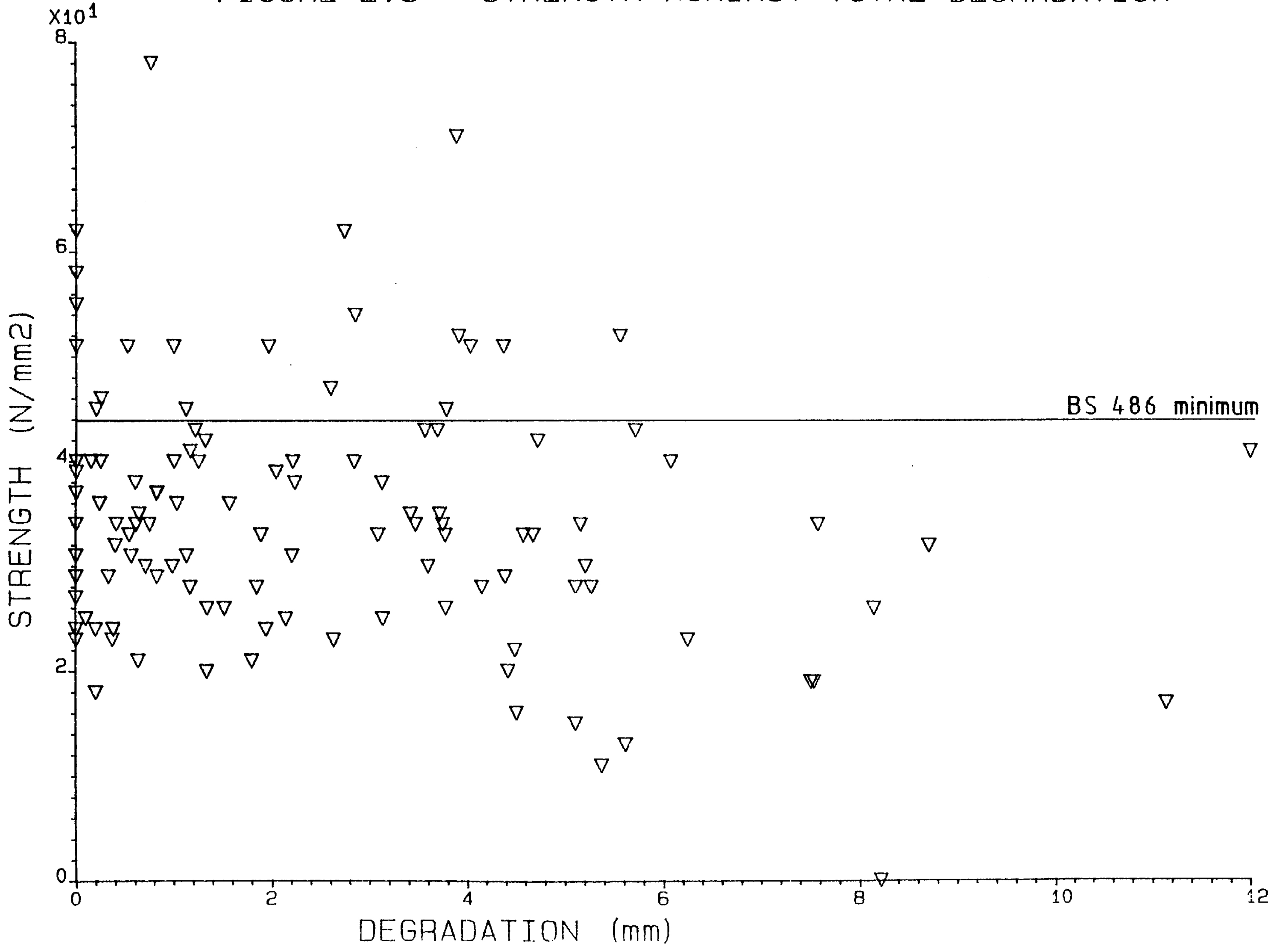
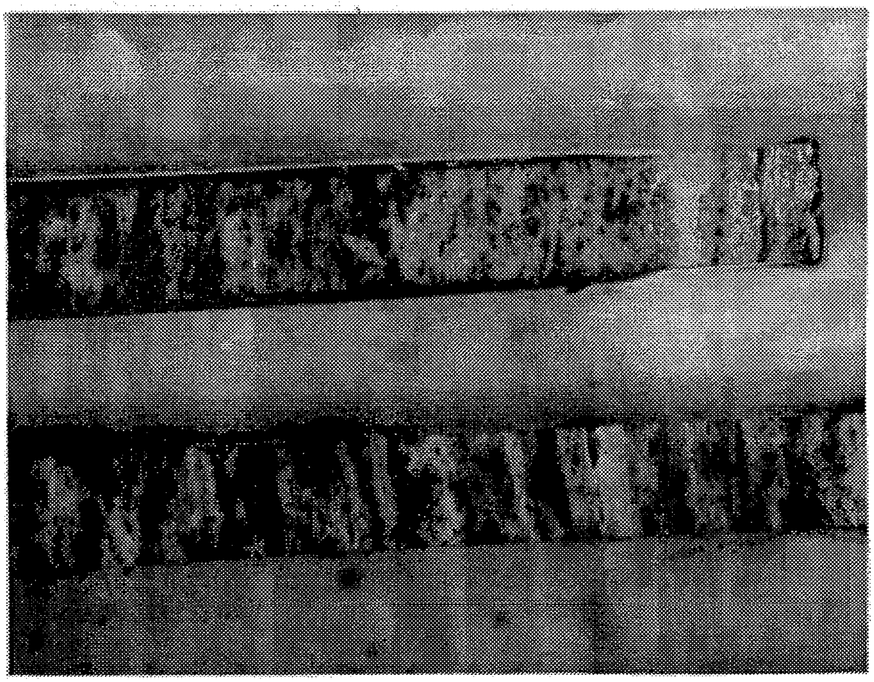


Figure 2.10



Micrographs of sections through pipe wall

FIGURE 2.11 SMOOTHED ELEMENTAL PLOT THROUGH NEW PIPE

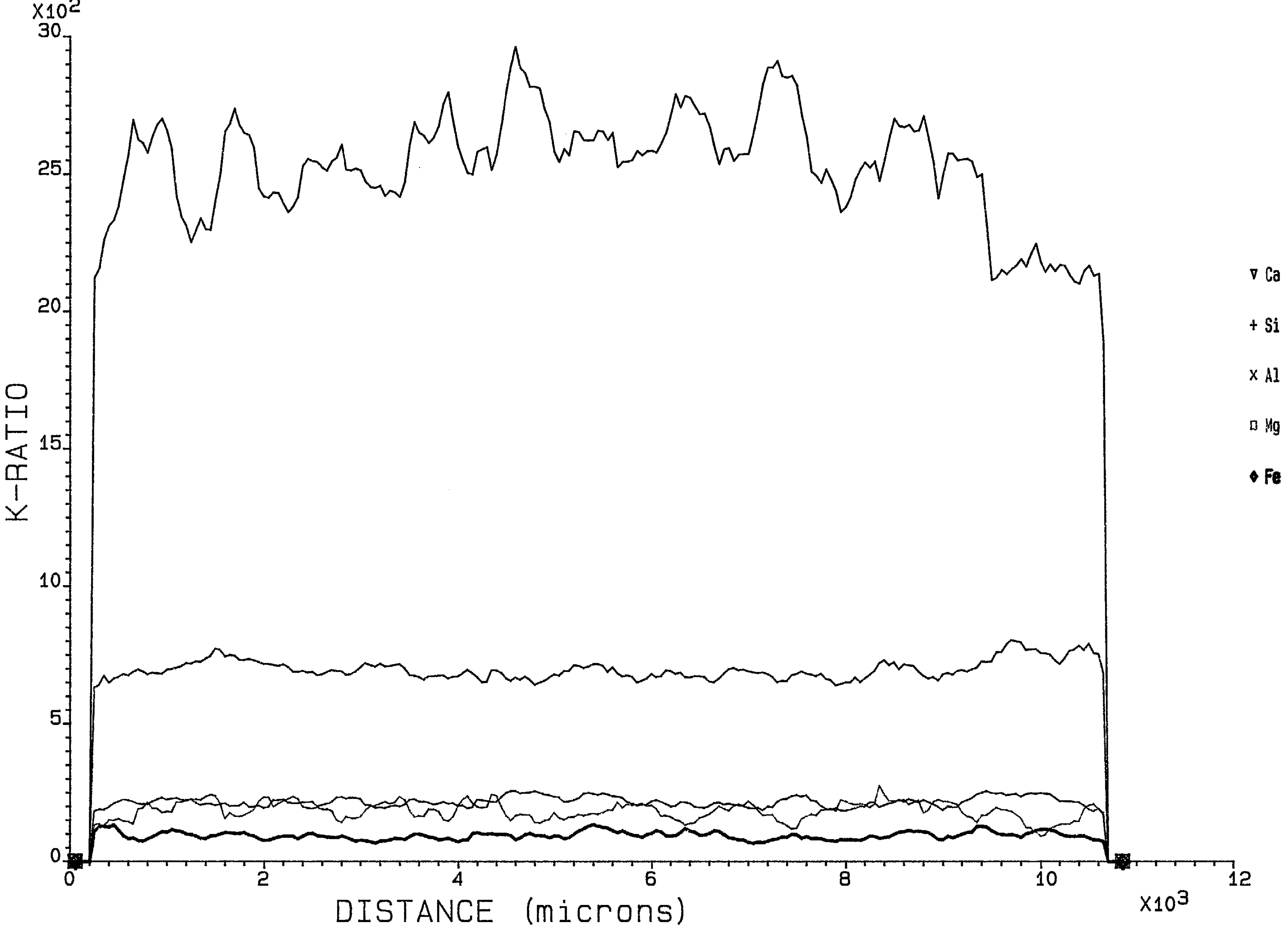


FIGURE 2.12 ELEMENTAL PLOT THROUGH DEGRADED PIPE

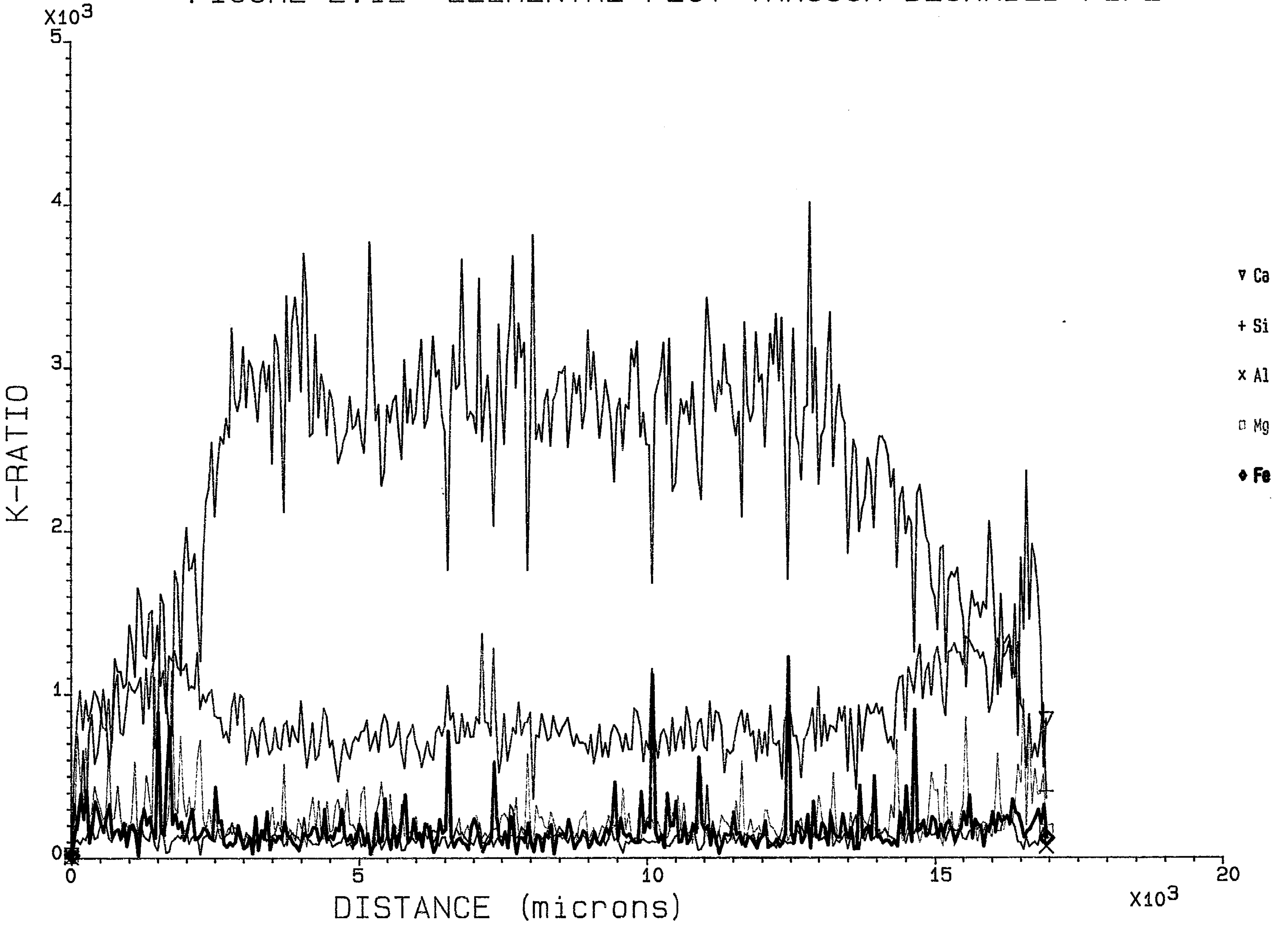


FIGURE 2.13 SMOOTHED ELEMENTAL PLOT THROUGH DEGRADED PIPE

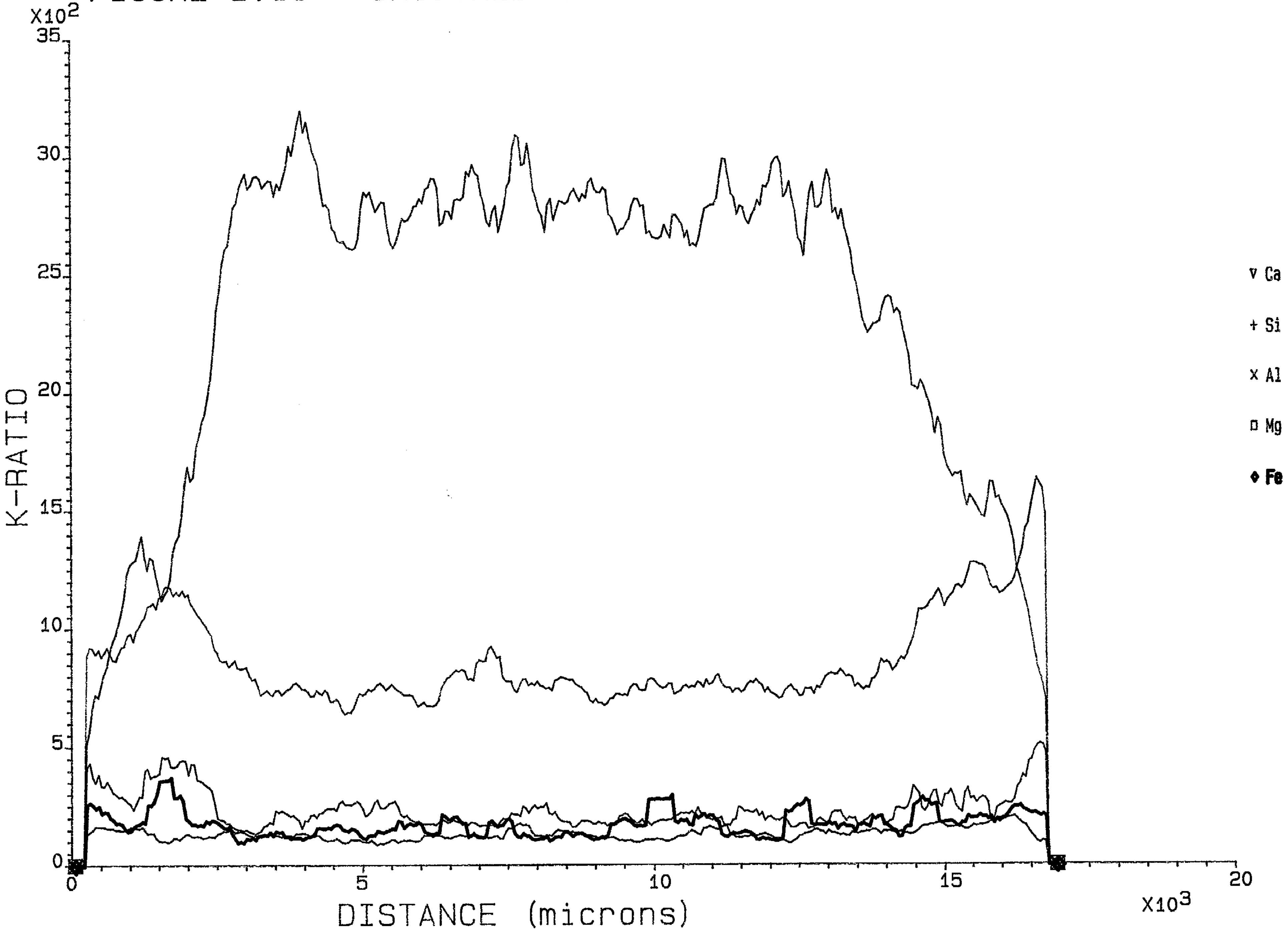


FIGURE 2.14 SMOOTHED CALCIUM/SILICON PLOT OF DEGRADED PIPE

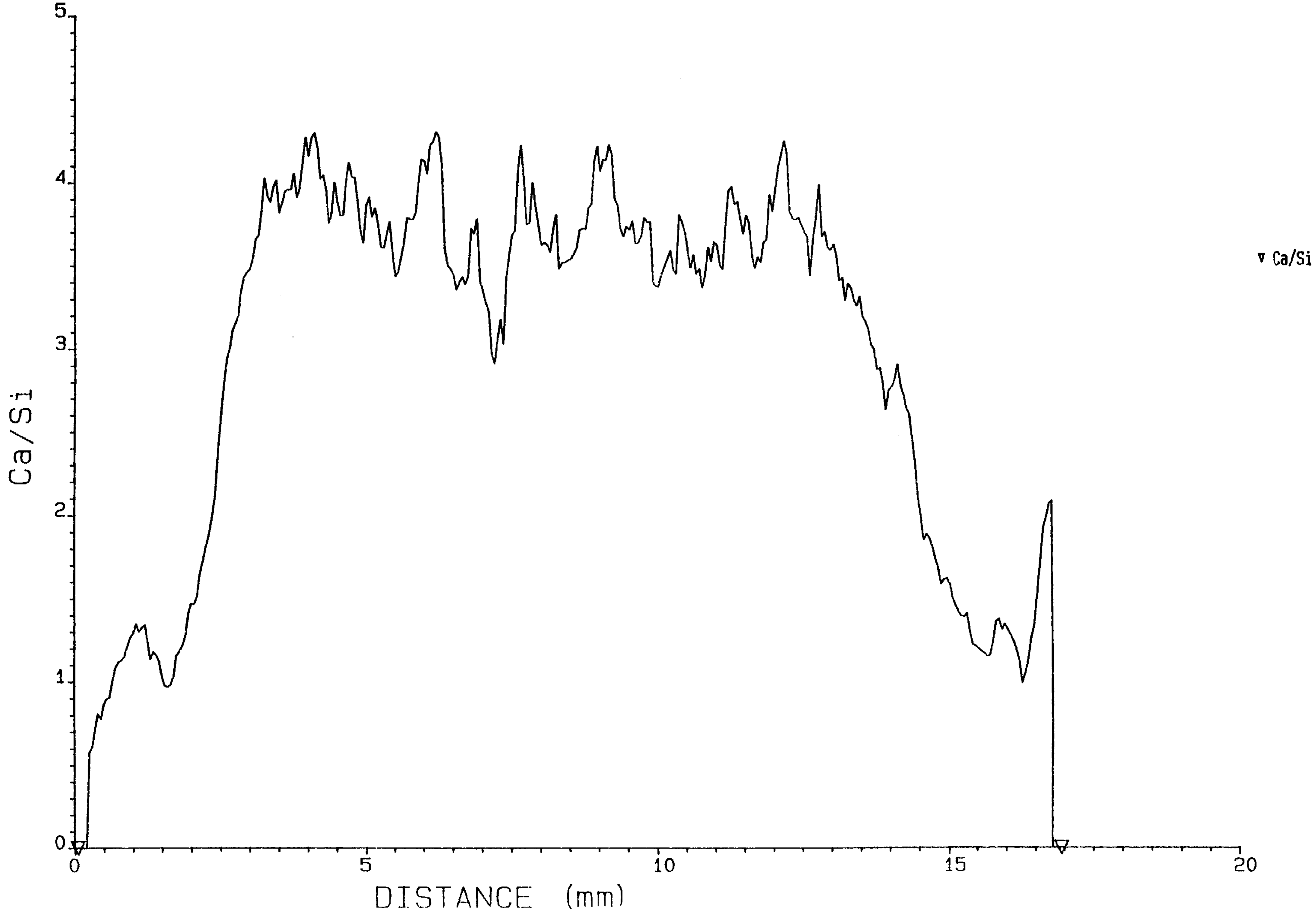
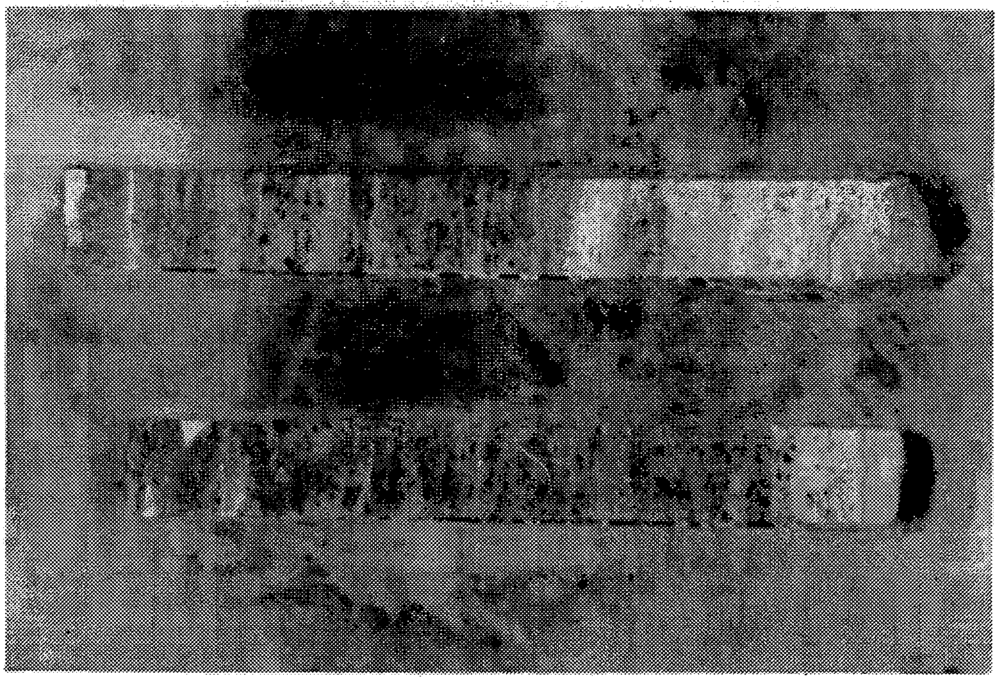


Figure 2.15



Micrographs of stained sections showing well defined boundary of degradation

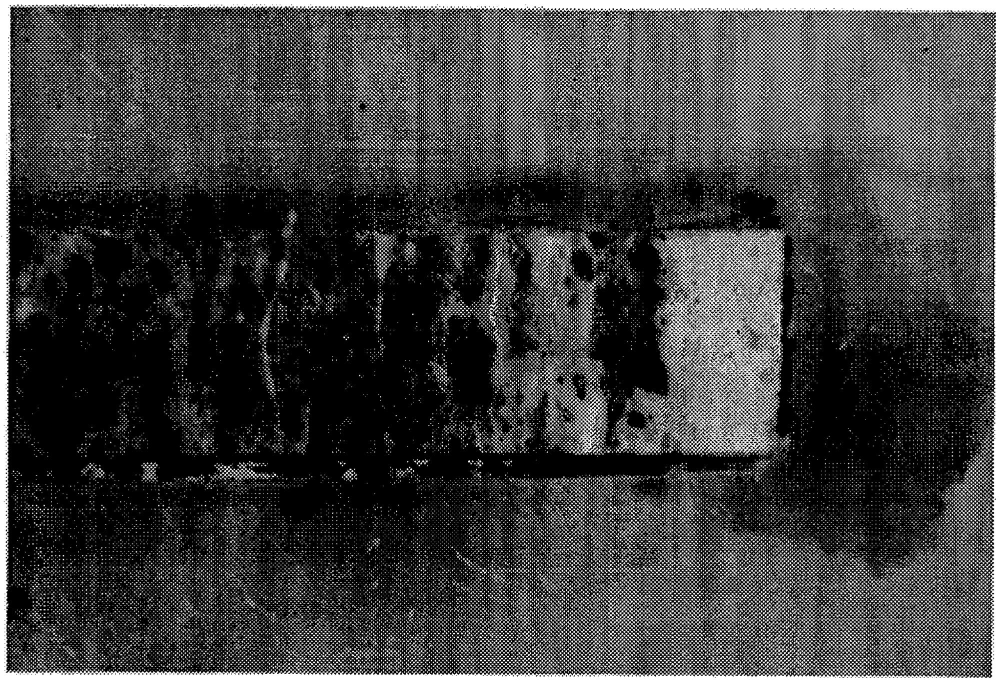
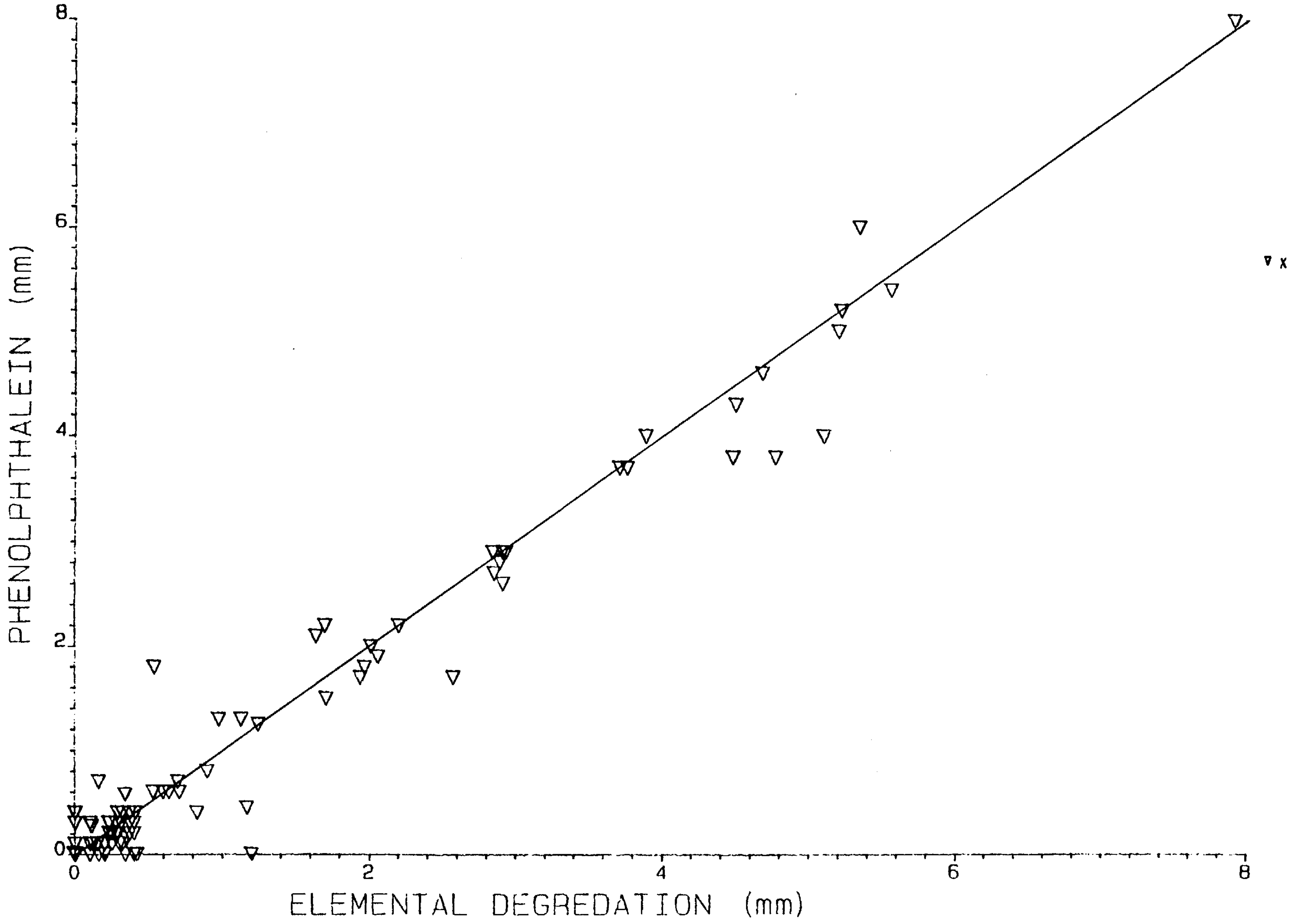


FIGURE 2.16 INTERNAL DEGREDATION PHENOLPHTHALEIN v SEM



SECTION 3

SUITABILITY OF RELINING TECHNIQUES FOR ASBESTOS CEMENT MAINS

3.1 INTRODUCTION

It has been demonstrated in the previous sections that significant degradation of asbestos cement pipes does and has occurred in certain water chemistries. This can cause the release of asbestos fibres into the water supply and, if severe, can result in impairment of the physical performance of the pipe, possibly leading to failure. In areas where degradation of the pipe wall has occurred or where AC is being considered for conveying potentially aggressive waters, it may be necessary to line the internal surface of the pipe. Such a lining would isolate any loose asbestos fibres from the water supply and would stop any further deterioration of the pipe occurring, thus preventing the release of fibres into the water supply.

In situ lining of AC pipes by epoxy resin has been undertaken in the USA(25), however, because of the particular formulation used, it resulted in the release of organic tetrachloroethylene into the water supply. Cement mortar was subsequently applied over the epoxy resin to isolate it from the conveyed water. AC pipe manufacturers also recognise the need in certain circumstances for high performance coatings and offer epoxy resin lined new pipes(26), although currently these do not have the relevant approval for use in UK potable water supplies.

This investigation has considered two main coatings: organic (epoxy resins); and cementitious (cement mortar lining) and accelerated corrosion tests have been developed to determine their potential efficacy for protecting AC pipes. Further consideration has also been given to possible future coatings which may be applicable.

Some limited trials have been performed on chemical dosing of the conveyed water as a means of preventing deterioration.

3.2 PREPARATION OF SAMPLES

As the renovation or treatment of the asbestos cement will be applied to deteriorated pipes, it was considered necessary to experiment with linings applied to degraded pipes. To ensure repeatability of the subsequent tests, an artificially degraded pipe was produced. (Details of the methodologies used are presented in Appendix 8.) After numerous trials, pipes with a degradation depth similar to that commonly seen in the field in areas of severe attack were produced. However, their visual appearance was very different to the naturally degraded pipes previously examined, presumably due to the direct chemical attack employed. These differences between a naturally and an artificially degraded pipe can be seen in Figures 3.1 and 3.2 respectively.

In view of the differences seen it was decided to use both naturally deteriorated pipe, and artificially degraded pipe in the experimental work.

From the previous phase of the project, locations were identified where the internal degradation of the pipe had occurred relatively uniformly around the circumference of the pipe bore, (see Figure 3.3). The available details of the histories of the pipes are presented in Table 3.1. Prior to any treatment or analysis the exhumed pipes were swabbed to remove any internal debris or deposits.

Two lengths of new pipe were incorporated into the coating trials to act as controls. One length was as supplied by the manufacturer with a factory applied bitumen coating, and the other was in the uncoated "grey" pipe condition, and was achieved by dissolving the factory applied bitumen coating with solvents.

3.2.1 RELINING

Abrasive cleaning methods such as power boring or drag scraping as used on corroded cast iron pipes were not employed as they were considered inappropriate.

Such cleaning techniques potentially disturb the deteriorated surface causing release of fibres, and leaving a very rough surface for application of a lining. Sections of pipe from each condition were coupled together using standard Viking-Johnson couplers. The lining was then applied in a single pass. Sections of pipe in each of the test conditions were lined with the two materials commonly used for relining cast iron water mains using the standard application procedures and equipment. Table 3.2 shows the combinations of coating and substrate pipe condition which were available for testing.

The two materials applied were:

i) EPOXY RESIN

Geopox GX014 manufactured and applied by Mercol Descaling Ltd of Bolsover, Nottinghamshire. The coating was applied to give a nominal 1mm thickness. Visually the lining appeared very uniform with very few pinholes or defects apparent. It was not possible to non- destructively test for the continuity of the lining due to the substrate being non- conducting.

ii) CEMENT MORTAR

A mortar comprising a 1:1 mix of ordinary Portland cement (OPC) and Buckland FG50 sand was used with a water:cement ratio of approximately 0.4. The lining was applied by Galliford Pipeline Services following the procedures detailed in the Water Mains Rehabilitation Manual[27] to provide a nominal 4mm thickness. Following an overnight air cure the mortar lined pipes were transported to the laboratory and immersed in water to fully cure prior to sample preparation.

For each material the lining was applied by pumping either the mixed mortar or the separate components of the epoxy resin along pressure hoses to a rotating application head. (In the case of the epoxy resin, the two components are intimately mixed in a static in-line mixer just prior to application.) The material is airlessly sprayed onto the inside wall of the pipe. The thickness is controlled by balancing the rate of pumping the material down the pressure hoses with the rate at which the applicator is drawn through the pipe.

Both of these linings provide a continuous physical barrier which should prevent the release of asbestos fibres from the pipe wall into the water supply. Additionally they isolate the pipe from the conveyed water and should therefore prevent, delay or substantially reduce further degradation of the pipe wall.

3.2.2 WATER TREATMENT

Treating the conveyed water to render it less aggressive to asbestos cement may prevent further degradation of the pipe. Where new AC pipe is being installed, water treatment may prevent the onset of deterioration. However, for AC pipes which have already suffered corrosion attack, water treatment does not generally consolidate the loose fibres, and hence they will still be available for release. However it has been reported[28] that deposition of a calcite layer may be achieved by circulating a mixture of chemicals in the pipeline whilst it is out of service.

Limited experiments were performed to investigate the possible benefits of water treatment in reducing the rates of deterioration.

3.3 EXPERIMENTAL TESTS

To determine the suitability of applying a lining to protect AC pipes, the quality of the as-applied lining was assessed, and accelerated degradation tests were developed to determine the potential long term durability of the protection. Laboratory experiments were also performed to determine the potential efficacy of water treatment. In each set of experiments, new and unprotected degraded pipes were included to act as controls.

3.3.1 LINING QUALITY

After allowing the applied coating to cure samples were cut from the pipe for inspection to assess whether any defects were present. A simple pull-off test was performed on the coatings to assess the degree of bond to the substrate pipe. The results of this test were purely qualitative, but give an indication of the adherence to the various conditions of substrate.

3.3.2 ASSESSMENT OF DEGRADATION

The depths of degradation were assessed by measuring the extent of unstained material following the application of phenolphthalein. This technique provides a good indication of any chemical leaching which has occurred. The strong correlation of degradation depth shown by phenolphthalein stain with elemental profiles produced by microprobe analysis, (see Section 2 and Figure 2.16) give confidence in the use of this technique.

Measurements of the depth of unstained AC were made using a microscope and graticule eyepiece. Comparison of this measurement both before and after exposure to the accelerated corrosion test would indicate whether coatings prevent further degradation of the substrate.

3.3.3 ACCELERATED CORROSION TEST

To examine the level of protection afforded by the application of cement mortar and epoxy resin linings, samples from the coated pipes were subjected to accelerated degradation tests.

3.3.3.1 PRINCIPLES OF THE TESTS

The principal mechanism of internal degradation in asbestos cement water mains is chemical leaching of the cementitious matrix by low pH soft waters. The accelerated corrosion tests developed in this investigation were designed to maintain the same degradation mechanism.

To create conditions which are more aggressive to cementitious materials than those occurring naturally, deionised water saturated with free carbon dioxide gas was passed through the samples. This creates water with virtually no alkalinity, and a very low buffering capacity, with a low pH and a high free carbon dioxide content. A continuous flow of fresh test water was maintained to ensure that constant aggressive conditions prevailed and to avoid the build up of hydroxides in the water. The samples were immersed in a temperature controlled water bath at 10°C to ensure the conditions were comparable to those occurring in the field. Significant variations in temperature may result in changes in the solubilities of the various components in the cementitious matrix, and thus alter the degradation mechanisms operating.

The pH of the supplied and effluent water were monitored at regular intervals, to assist in identification of chemical attack of the pipes.

3.3.3.2 EXPERIMENTAL PROCEDURE

Details of the experimental procedure are presented in Appendix 9. The tests are based on exposure of 0.3m lengths of pipe, and small test coupons cut from the pipes. Figure 3.4 shows a diagram of the test rig.

3.3.4 CHEMICAL DOSING

Samples of new and degraded pipe were installed in a continuous flow rig which was designed to enable controlled flows of deionised or chemically dosed water to flow over the samples (Figure 3.5). The pH of the effluent water was monitored and provides a sensitive means of assessing any degradation which is occurring.

3.4 RESULTS

3.4.1 ARTIFICIAL DEGRADATION

The method which produced the most uniform degradation in a relatively short time was the use of 20% nitric acid in water. Immersion for 48 hours produced a degradation depth of 4mm. This technique was utilised to provide lengths of pipe for coating.

3.4.2 ACCELERATED CORROSION

Profiles of the pH from the effluent water for each of the coating/pipe condition combinations are presented in Figures 3.6, 3.7 and 3.8. On each plot the pH of the inlet carbonated water is also included. Thus the change in pH of the contact water can be seen for each coating/pipe condition combination. For the epoxy resin coated pipes, and the uncoated pipes, this gives an indication of the rates of degradation occurring. For the cement mortar lined pipes the pH will be an indication of the rate of attack of the mortar.

After exposure to the accelerated corrosion the depth of attack on the pipes was assessed by staining freshly cut sections with phenolphthalein and measuring the thickness of the unstained portion at eight equally spaced positions around the pipe using a graticule eyepiece in a microscope. Due to the non-uniform attack on the naturally degraded pipes various depths of degradation occur round the pipe. However by taking the mean of eight measurements from the same relative positions before and after exposure the general trends can be identified.

The means and standard deviations of these measurements are presented in Table 3.4 where the samples suffering significant degradation can be identified. The results are also presented graphically in Figure 3.9.

It can be seen from Table 3.4 that the epoxy resin coated samples show no sign of significant degradation. Significant depths of attack of the cement mortar lining were observed although they did prevent any further deterioration of the asbestos cement. The rate of attack of the cement mortar is approximately 3 to 4 times as fast as that seen in the most aggressive distributed waters[29].

Unlined new asbestos cement pipe also suffered a rapid rate of attack, comparable to the rates evident on the cement mortar linings. However the rate of degradation on the artificially degraded pipe was significantly lower with an unmeasurable increase in the depth of degradation on the uncoated naturally degraded pipe. This would suggest that the rate of degradation of AC pipes, even in very aggressive waters reduces significantly as the degradation front advances, probably due to the increased time required for diffusion of the reactant and the reaction products through the already degraded layer.

3.4.3 CHEMICAL DOSING

Figures 3.10 and 3.11 show the pH measurements of the effluent water from the new and degraded pipes for each of the waters investigated. The waters used were (i) deionised water for a control, (ii) deionised water dosed with 25mg/l sodium bicarbonate to increase the buffering capacity and (iii) deionised water with 25mg/l sodium silicate.

Although there were several interruptions to the tests due to equipment failure, it can be seen in general that the pH of the water dosed with sodium bicarbonate showed the lowest rise suggesting the pipes suffered the least attack. Dosing with sodium silicate resulted in little change in pH.

3.5 DISCUSSION

Small scale trials on the relining of asbestos cement mains have been performed and show some promising trends. The original intention of producing a standard degraded pipe which is similar in characteristics to naturally degraded pipe was not entirely achieved, although a suitable deteriorated substrate was produced. Therefore, to ensure conditions as close to a field application as possible, exhumed pipe samples from areas where relatively uniform degradation had occurred were also used. These samples represented the worst internal condition likely to be encountered in the field, as most of the pipes examined in the previous phase of the project suffered from localised patchy degradation, probably initiated at defects in the internal bitumen coating.

The only preliminary treatment of the mains considered suitable was swabbing to remove any loose debris or standing water, and to clean off any surface slimes, etc. As the build up of hard corrosion products such as tuberculation found in cast iron mains does not occur on asbestos cement, both power boring and drag scraping were considered unsuitable. Additionally these cleaning techniques have the effect of disturbing the surface of the material, and thereby increase the possibility of releasing asbestos fibres into the water supply and decreasing the mechanical strength of the pipe.

No problems were encountered with the spray application of an internal coating and both the epoxy resin and cement mortar linings applied were of relatively uniform thickness. During the preparation of small samples for inspection and testing it was observed that in general the linings were relatively well bonded to the substrate. However, the epoxy resin lining on the new, bitumen coated pipe showed no adhesion at all, which may be caused by a chemical reaction between the epoxy resin and the bitumen or due to the smooth surface presented by the bitumen. This lack of bond may not be a problem in water mains where the lining acts as an arch and thus supports itself, although it may allow passage of water down the interface from any unsealed edges or defects.

In the accelerated corrosion tests to date, the coatings have performed well, and have remained intact. The amount of degradation of the pipe wall occurring (for all except the cement mortar lined samples) is indicated by the pH of the conveyed water. It can be seen that both the epoxy resin lined pipe, and the bitumen coated pipe show very limited increases in the pH of the test water, indicating that little attack of the underlying substrate is occurring. A slightly increased change in pH is observed on the water passing through both the artificially and naturally degraded pipe, showing a low level of attack is occurring while a higher pH change is observed on the new uncoated "grey" AC pipe. The cement mortar lined pipes show relatively high increase in the pH of the test water. This however is most probably due to chemical attack of the mortar lining.

Changes in the chemical characteristics of the test water give an indication of whether degradation of the substrate is occurring. However these chemical changes which are indicative of AC degradation are also caused by attack of the cement mortar. Phenolphthalein staining reveals the extent of degradation, and may be used to monitor the efficacy of coating materials.

Relining deteriorated asbestos cement pipes with cement mortar could only be considered to be a palliative, as the cement mortar is subject to the same mechanism of deterioration as the asbestos cement. It will however provide a barrier between loose asbestos fibres and the conveyed water.

Treatment of the conveyed water can result in a reduction of the rate of attack of the pipe, and if controlled correctly may result in the precipitation of a protection layer. It must be emphasised that water treatment will not prevent the release of any fibres into the water supply, but may inhibit further attack. This method of control can be very expensive as it requires the installation of chemical dosing plant in addition to the running and maintenance costs. However, it may be considered viable should new asbestos cement pipes be required in an area with known aggressive waters.

3.6 POTENTIAL DEVELOPMENTS

The area of potential coatings for asbestos cement pipes was explored for both in situ and factory applied applications. Various methods of application are considered for each of the materials with some comment about their potential advantages and disadvantages. It must be emphasised that these proposed materials and techniques are speculative and will require thorough investigation of their durability and suitability in terms of water quality and toxicology before being used. The ideas may open up new avenues to be explored should renovation of asbestos cement be considered worth pursuing further.

3.6.1 NEW PIPE PROTECTION

The protection of asbestos cement pipes against deterioration must rely on isolating the material from the aggresive environment by applying an effectively impermeable barrier. The presence of defects in the impermeable barrier would lead to localised deterioration.

On new pipes, a variety of techniques may be utilised to apply such a protective barrier and therefore there are a wider range of materials available. Additionally the materials may be applied under more easily controlled conditions, thereby ensuring correct application and enabling the use of materials which may be sensitive to the curing enviroment.

External protective coatings may be applied to prevent deterioration due to attack by soft or sulphate bearing groundwater. For these applications the coating must have the following properties:-

i) Resistant to attack by the surrounding soils and groundwater. In some cases, due to contaminated areas such as reclaimed land, the coatings may be subjected to attack by residual organic solvents etc.

ii) Good bond to the pipe substrate. This ensures that the coating provides good protection. Should it become damaged or contain a defect the attack of the substrate will be limited to the immediate area. The degradation will not be able to undermine the adjacent coating, or proceed along the coating substrate interface.

iii) Toughness. During transportation and installation the pipes can be subjected to mishandling. Any external coating system will need to be sufficiently tough to be able to withstand impacts without breaking.

iv) Ultra violet stability. Pipes are frequently stored in open stockyards for indeterminate periods of time and therefore external coatings may suffer from breakdown due to the action of ultraviolet light if not adequately stabilised.

v) Microbiological stability. The coatings should be resistant to attack by micro-organisms.

Alternatively protection could be provided by wrapping a film of inert material around the outside of the pipe. This technique is already used on some ductile iron pipes with polyethylene to provide protection against external corrosion. The technique can be very economical, but the pipe wrap can potentially suffer damage during transportation and installation as it is of necessity very flexible and can be torn on sharp projections.

The properties required for good performance of internal coatings to water mains include:-

i) Resistance to attack by soft aggressive waters. To provide long term protection to the pipes the coating must be able to withstand submerged conditions.

ii) Good bond to the pipe wall. Should there either be a defect in the coating or damage is incurred a well bonded coating will prevent the flowing water channelling along the pipe/coating interface thereby ensuring any attack of the substrate is localised.

iii) Abrasion resistance. This is particularly important for flowing waters containing particulate matter as often occurs in raw water mains, and indeed in many potable water distribution systems.

iv) Chemical stability and non-toxic. Any coatings applied to the bore of the pipe must not adversely affect the water quality by releasing harmful chemicals into the supply, imposing taste and odour, or supporting microbial growth[31].

3.6.2 USED PIPE PROTECTION

Where asbestos cement pipes have already been installed and are subsequently suffering deterioration the application of protective coatings becomes more difficult. For pipes which are suffering external degradation there are no techniques available which can prevent further deterioration. In these situations consideration must be given to replacement of the pipe, either by traditional methods or renovation if the loss of cross section can be hydraulically accommodated, or breaking out the pipe using a 'mole' and putting in a polyethylene pipe. The technology for these techniques is now established and has been used successfully.

In cases of internal degradation, insitu coatings can be applied by the lining techniques currently used on corroding iron pipes. For these applications however the conditions under which the materials are applied are less well controlled. Any material considered for such in-situ application must:-

i) be capable of being pumped along 150m of pressure hose;
ii) be fluid enough to be sprayed onto the pipe;
iii) be viscous enough to stay on the pipe walls without slumping;
iv) be able to cure in 100% relative humidity and ideally in the presence of water;
v) be able to cure at low temperatures, down to approximately 5°C;
vi) fully cure quickly, within approximately 16 hours;
vii) not impair the conveyed water quality.

In addition the coating should ideally be durable and have the properties stated for internal coatings of new pipes.

These requirements make some of the potential materials unsuitable for in-situ lining.

Apart from replacement and internal coatings there are several new systems currently under investigation for lining mains which are based on curing an impregnated fibre reinforced material in-situ. This can have the advantage of improving the strutural capability of the main as well as protecting the substrate material. In general the material with a resin system already impregnated is either drawn or inverted into the pipe and is then cured by either steam, hot water or ultra violet light. Additional methods involve installing a polyethylene pipe inside the existing pipe using the sliplining, roll down or swage down techniques. The result of each of these methods is a continuous lining, which can cause difficulties in distribution mains as each service connection has to be remade.

3.6.3 COATINGS

Of the various coating systems available[32, 33] some are more suited to factory application and some relatively unsuitable for coating cementitious pipes. A summary table of the systems and their properties/characteristics is presented in Table 3.5. From these characteristics the potential suitability of each of the sytems for either factory or in-situ application can be determined, Table 3.6. However, it must be stressed that any of the coating systems listed would have to be carefully formulated to ensure they can be applied, are durable, and for internal lining, do not impair the water quality.

3.6.3.1 SOLVENT FREE EPOXY RESIN

Epoxy resin coatings have been used for many years to provide protection to various substrates against deterioration. They are capable of a wide variety of modifications and curing systems to meet particular requirements. Formulations are currently available which are tolerant of damp cold conditions during curing. In general they can be applied to give a thick coating of >35μm but care must be taken to ensure they are properly cured, particularly for internal coatings prior to their installation in service. Table 3.7 summaries typical properties of the various types of epoxy based coatings.

With the correct formulation they could be used for internal and external factory applied protection or for internal in-situ lining.

3.6.3.2 POLYURETHANES

In general neither the two pack polyurethanes nor the moisture curing polyurethanes are tolerant of damp conditions during application. In addition the systems generally utilise polyisocyanates to effect a cure and hence would be of questionable suitability for use in contact with potable water. However their good abrasion resistance, chemical stability and toughness should render them suitable for external protection of pipes.

3.6.3.3 VINYL COATINGS

Vinyl chloride/vinyl acetate coatings rely on solvent release for application and therefore must be built up of several layers. The solvents generally contain ketones such as methyl ethly ketone. The substrate additionally must be dry to ensure both a good bond and a full cure. They are thus best suited to factory application where the conditions can be more easily controlled, and would be inappropriate for in-situ use.

3.6.3.4 CHLORINATED RUBBER

Chlorinated rubber coatings dry by solvent evaporation and therefore are applied in several coats to build up the required thickness. They are generally non-toxic and therefore potentially suitable for contact with potable water. They show very good moisture resistance but are susceptible to ultra violet degradation. Thus they are potentially suitable for internal factory applied linings.

3.6.3.5 ACRYLICS

A wide variety of acrylic based coatings are available which can be formulated to meet specific requirements. They generally require temperatures above 10°C to dry. Acrylics are resistant to chemicals and generally have good ultra violet stability. In addition they can be formulated to be non-toxic and therefore potentially suitable for use in contact with potable water. Acrylics are suitable for factory application, both internally and externally, and if modifications can be made to enhance their low temperature cure, could be applied in-situ.

3.6.3.6 POLYESTERS

Polyester resin systems contain significant quantities of styrene, some of which is generally unreacted following polymerisation. Thus unless great care is taken they may be available and hence leached out of the coating. They generally prove difficult to apply and are currently unsuitable for internal linings to water pipes.

3.6.3.7 GLASS FLAKE COATINGS

Glass flakes have been incorporated into various of the above resin systems to enhance their abrasion resistance and reduce their permeability. The resultant coatings are generally more expensive than an unfilled system and for the applications under consideration the additional benefits in performance are probably unjustified.

3.6.3.8 BITUMEN COATINGS

Bitumen has been used for many years to coat asbestos cement pipes. There is evidence that it does provide some protection to the pipe but due to its low thickness and poor physical characteristics it is easily damaged. It does however provide a relatively cheap coating although its performance cannot be guaranteed.

3.7 CONCLUSIONS

(1) Deteriorated asbestos cement pipes can be successfully lined using currently available techniques such as spray-on epoxy resin and cement mortar.

(2) In some cases the linings may not bond to the substrate although this is unlikely to impair their performance.

(3) Epoxy resin linings provide a virtually impermeable barrier which both prevents further degradation of the substrate, and stops any release of asbestos fibres from the deteriorated surface into the water supply.

(4) Cement mortar linings suffer degradation in the environments which cause attack of asbestos cement. Thus although cement mortar linings provide a barrier between the loose asbestos fibres and the conveyed water they are likely to suffer rapid deterioration and should only be considered as a palliative.

(5) Water treatment techniques can be employed to reduce or inhibit the rate of attack of asbestos cement. However, loose asbestos fibres are not prevented from being released into the water supply.

(6) A variety of coating materials are available which may be suitable for use on asbestos cement. Of these only cement mortar, epoxy resin and bitumen can currently be used for internal protection of asbestos cement. Prior to the use of any of the materials, it is critical that their durability and effect on potable water quality should be determined.

Table 3.1 - Pipe histories

	Age	Yrs	pH	$CaCO_3$	Alkalinity
Naturally degraded I	40yrs	15yrs	5.9	350	42
		25yrs	7.3	318	282
Naturally degraded II	unknown		6.9	31	9

Artificially degraded - chemical attack by 20% nitric acid for 48 hours.

New - bitumen coated - as supplied by manufacturer.

New - grey - as supplied by manufacturer with bitumen coat removed by xylene.

Table 3.2 - Pipe substrate/coating combinations

	UNLINED	CEMENT MORTAR	EPOXY RESIN
New bitumen dipped			
New "grey"	A, B	A	A
Artificially degraded	A, C	A	A
Naturally degraded (I)	A, B, C	A	A
Naturally degraded (II)			A

A = Accelerated corrosion - pot tests.

B = Accelerated corrosion - tube tests.

C = Chemical dosing.

Table 3.3 - Pull off tests

SUBSTRATE / COATING	EPOXY RESIN	CEMENT MORTAR
Naturally degraded I	fair	f-good
Naturally degraded II	f-good	f-good
Artificially degraded	good	good
New - bitument coated	v poor	poor
New - grey	good	good

Table 3.4 - Degradation observed for each coating/substrate combination

SUBSTRATE	COATING	0 months		3 months		6 months		12 months	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
New	Unlined	0.0	0.0	1.09	0.09	1.66	1.04	2.59	0.33
	Epoxy resin	0.32	0.33	0.2	0.11	0.1		0.55	0.32
	Cement mortar substrate	0.0 0.0	0.0 0.0	1.31 0.0	0.14	N/A		N/A	
Artificially Degraded	Unlined	1.64	0.17	N/A		2.58	0.22	3.08	0.23
	Epoxy resin	1.75	0.43	N/A		1.59	0.25	1.29	0.01
	Cement mortar substrate	0.0 1.72	0.0 0.06	N/A		1.41 1.62	0.29 0.24	2.34 2.46	0.46 0.32
Naturally Degraded (1)	Unlined	3.89	1.07	N/A		3.74	0.69	3.80	0.27
	Epoxy resin	4.02	1.61	N/A		3.63	1.43	3.07	1.50
	Cement mortar substrate	0.0 3.58	0.0 1.43	1.28	0.21	1.52 3.06	0.35 1.75	2.68 3.43	0.69 1.62
Naturally Degraded (2)	Epoxy resin	2.21	1.72	2.52	1.91	2.25	2.11	N/A	

N/A Samples not available

Table 3.5 – Coatings/linings for asbestos cement pipe

	COATING/LINING	SURFACE AND CONDITION	BOND TO SUBSTRATE	TYPICAL COATING THICKNESS	APPLICATION TECHNIQUES	DRY CURE CONDITIONS	SPECIAL CONSIDERATIONS	RATING OF DURABILITY
1. 2. 3.	Solvent free epoxy, 2 pack Solvent free epoxy coal tar Two pack Solvent free polyurethane Two pack	No loose material. Clean pipe to sound substrate by pigging/ scraping. No free water. Can be damp	Good/ excellent primer recom- mended	250 min.	Rotating head spray or spinner disc. Heated, plural component if necessary to reduce	Catalytic, which can be rapid. Tailor form- ulation to suit application	None special flush lines before return to service after full cure only	8 and 10 if applied correctly
4.	Vinyl: single pack	Clean to sound substrate, solvent flush and dry. No	Good, self priming	50 per coat	Airless spray or modified spinner head	Air day solvent release and coalescence	Sovlent borne. Best suited to factory appli- cation on new	4 to 5 very dependent on application conditions
5.	Moisture curing polyurethane, single pack	Clean to sound substrate, must be dry (no moisture)	Good, self primer	Primer 50 over coat 100 coat	Spinner head or spray	Solvent re- lease and moisture cure. Relative humidity >60%. Air dry.	Solvent con- taining, best suited to new pipes	5 to 6, depends on application conditions
6.	Chlorinated rubber. Single pack	Clean to sound substrate. Dry by solvent flush or dry air blow. Touch dry. No free moisture	Good self priming	Primer 50μm over coats, 100 per coat	Airless spray or modified spinner head	Air dry, air blow. Better solvent re- lease of vinyl. Factory and site appli- cation	Solvent con- taining, sol- vents less aggresive than vinyls	6 to 8 good durability to to water, depen- dent on application
7.	Vinyl acrylic Single pack (Haloflex)	Clean and sound flush with water surface can be moist but no free water	As 6	As 6	As 6	Tailor form- lation to suit appli- cation. Air dry and coalesce	Water borne. Heat to cure if necessary T°C >10	6 to 8, limited long term experience
8.	Glass flake/ resin. Two pack	Clean and dry sound substrate	Good	500 can be structural	Spray/spinner head viscosity depends on on resin, flake size	Catalytic cure, fast if heated	Contains styrene, needs water flush after cure. Best suited to new pipe	8 to 9
9.	Bitumen coal tar solutions	Clean to sound substrate. Dry Solvent flush	Variable poor oboslescent coating	50 per coat	Airless spray or spinner head	Air dry. Heat to through dry Hot air blow	Poor flexibility Solvent generally aromatic	2 to 5

Table 3.6

COATING	FACTORY APPLICATION EXTERNAL	FACTORY APPLICATION INTERNAL	IN SITU INTERNAL
Solvent free epoxy	/	/	/
Polyurethanes	/	X	X
Vinyl coatings	/	/?	X
Chlorinated rubber	X	X	X
Acrylics	/	/	Possibly
Polyesters	/	/	/
Glass flake	/	/	/
Bitumen	/	/	/

TABLE 3.7 - COREACTIVE COATINGS: EPOXY

Properties	Aliphatic Amine Cure	Polyamide Cure	Aromatic Amine Cure	Phenolic Epoxy	Coal Tar Epoxy Amine Cure	Coal Tar Epoxy Polyamide Cure	Water Based Epoxy
Physical Property	Hard	Tough	Hard	Hard	Hard	Tough	Tough
Water Resistance	Good	Very Good	Very Good	Excellent	Excellent	Excellent	Fair-Good
Acid Resistance	Good	Fair	Very Good	Excellent	Good	Good	Fair
Alkali Resistance	Good	Very Good	Very Good	Excellent	Good	Very Good	Fair
Salt Resistance	Very Good	Very Good	Very Good	Excellent	Very Good	Very Good	Fair-Good
Solvent Resistance (Hydrocarbons)							
Aromatic	Very Good	Fair	Very Good	Very Good	Poor	Poor	Poor-Fair
Aliphatic	Very Good	Good	Very Good	Very Good	Good	Good	Good
Oxygenated	Fair	Poor	Good	Very Good	Poor	Poor	Poor
Temperature Resistance	95°C	95°C	120°C	120°C	95°C	95°C	95°C
Weather Resistance	Fair, Chalks	Good, Chalks	Good	Fair	Fair	Fair	Good
Best Characteristics	Strong Corrosion Resistance	Water and Alkali Resistance	Chemical Resistance	Chemical Resistance	Water Resistance	Water Resistance	Ease of Application
Poorest Characteristics	Recoatability	Recoatability	Slow Cure	Very Slow Air Cure	Black Colour Recoatability	Poor Recoatability	Proper Coalescence
Recoatability	Difficult	Difficult	Difficult	Difficult	Difficult	Difficult	Difficult
Primary Coating Use	Chemical Resistance	Water Immersion	Chemical Coating	Chemical Lining	Water Immersion	Water Immersion	Atmospheric Corrosion

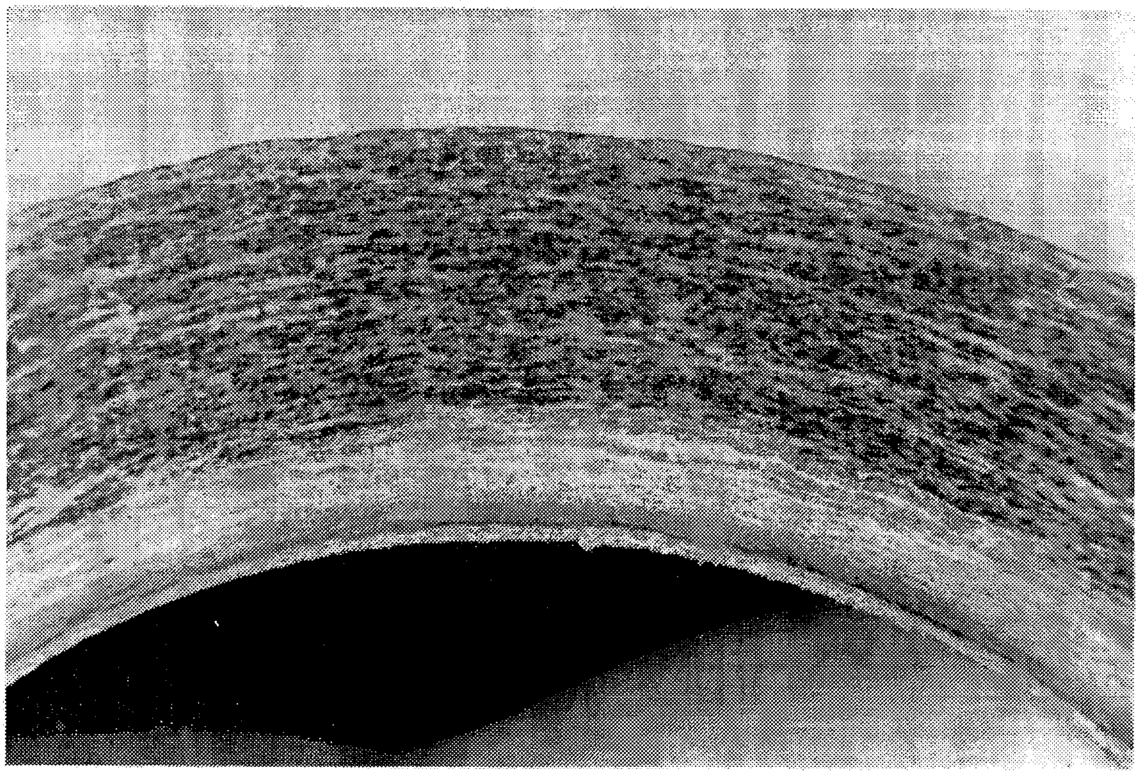


Figure 3.1 Naturally degraded asbestos cement

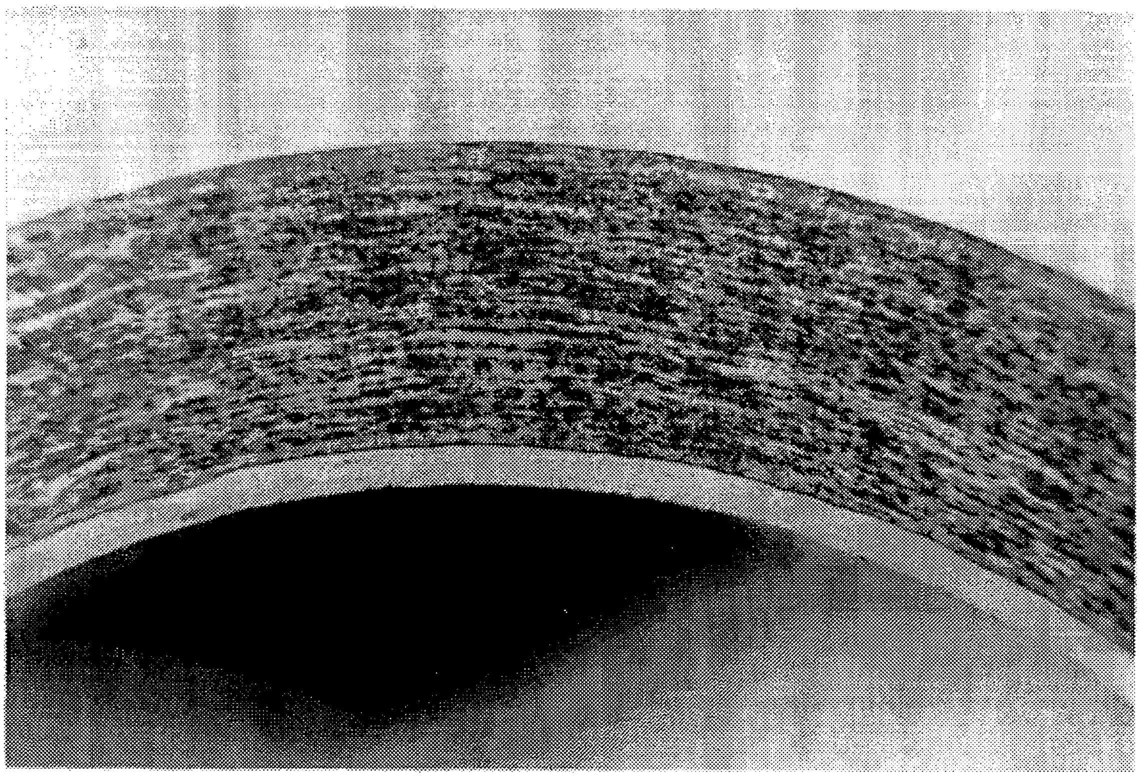


Figure 3.2 Artificially degraded asbestos cement

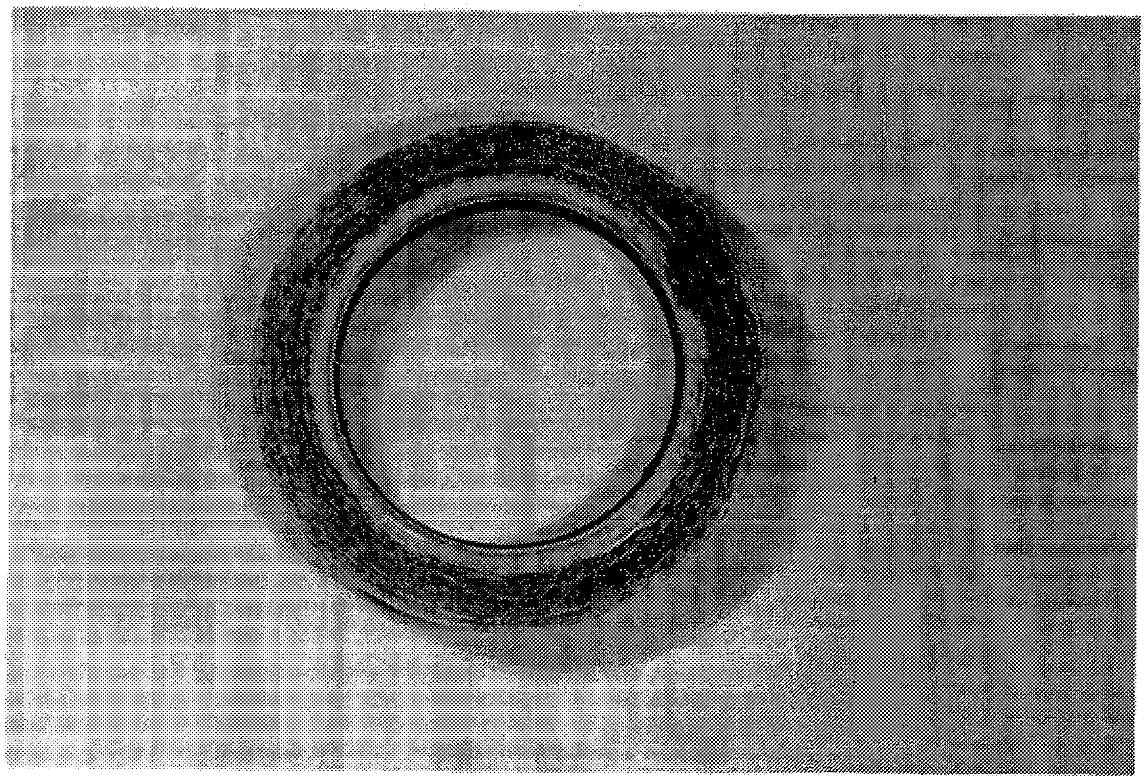


Figure 3.3 Naturally degraded AC pipe

Figure 3.4 Schematic Diagram of Accelerated Degradation Tests

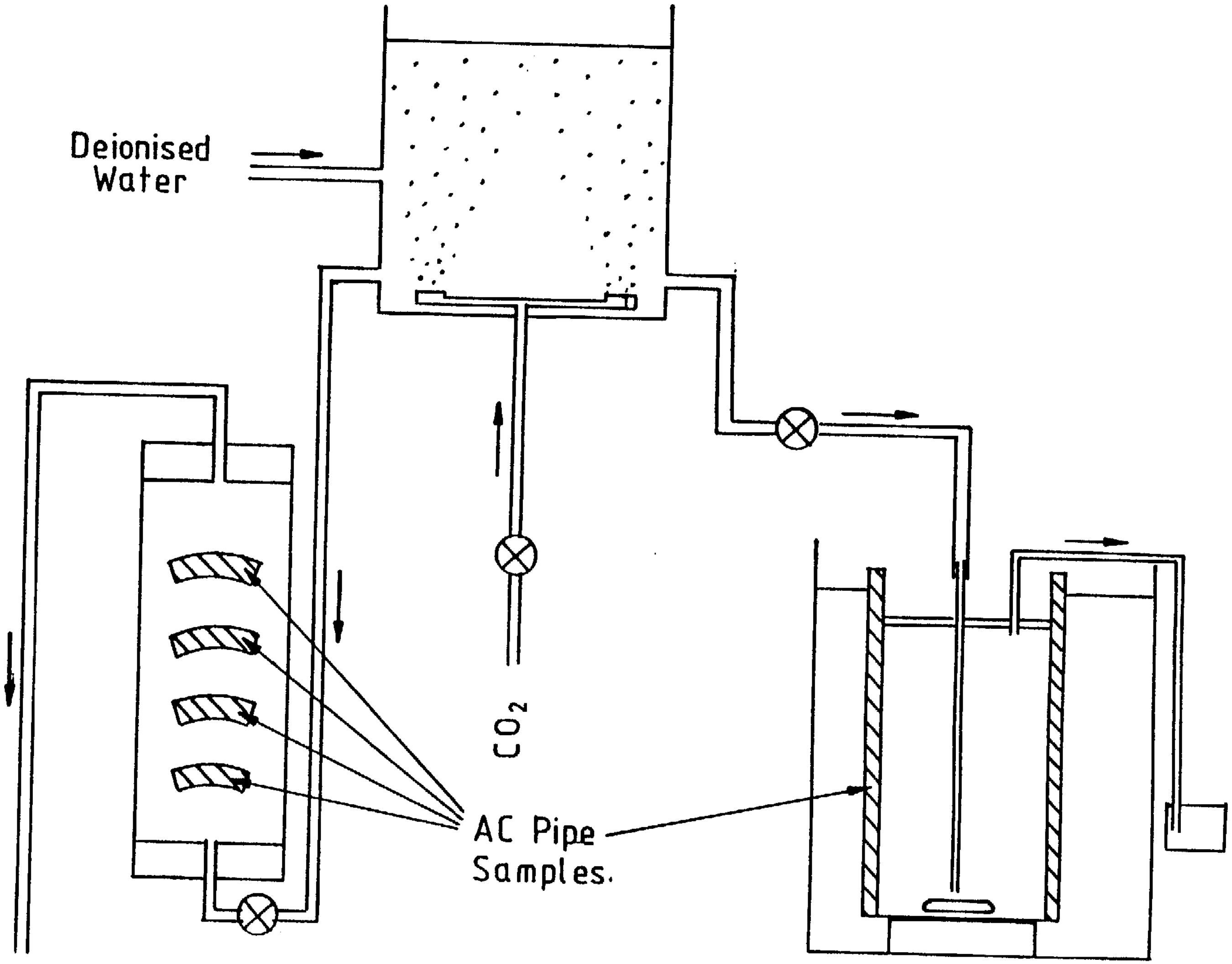


Figure 3.5 Schematic Diagram of Chemical Dosing Tests

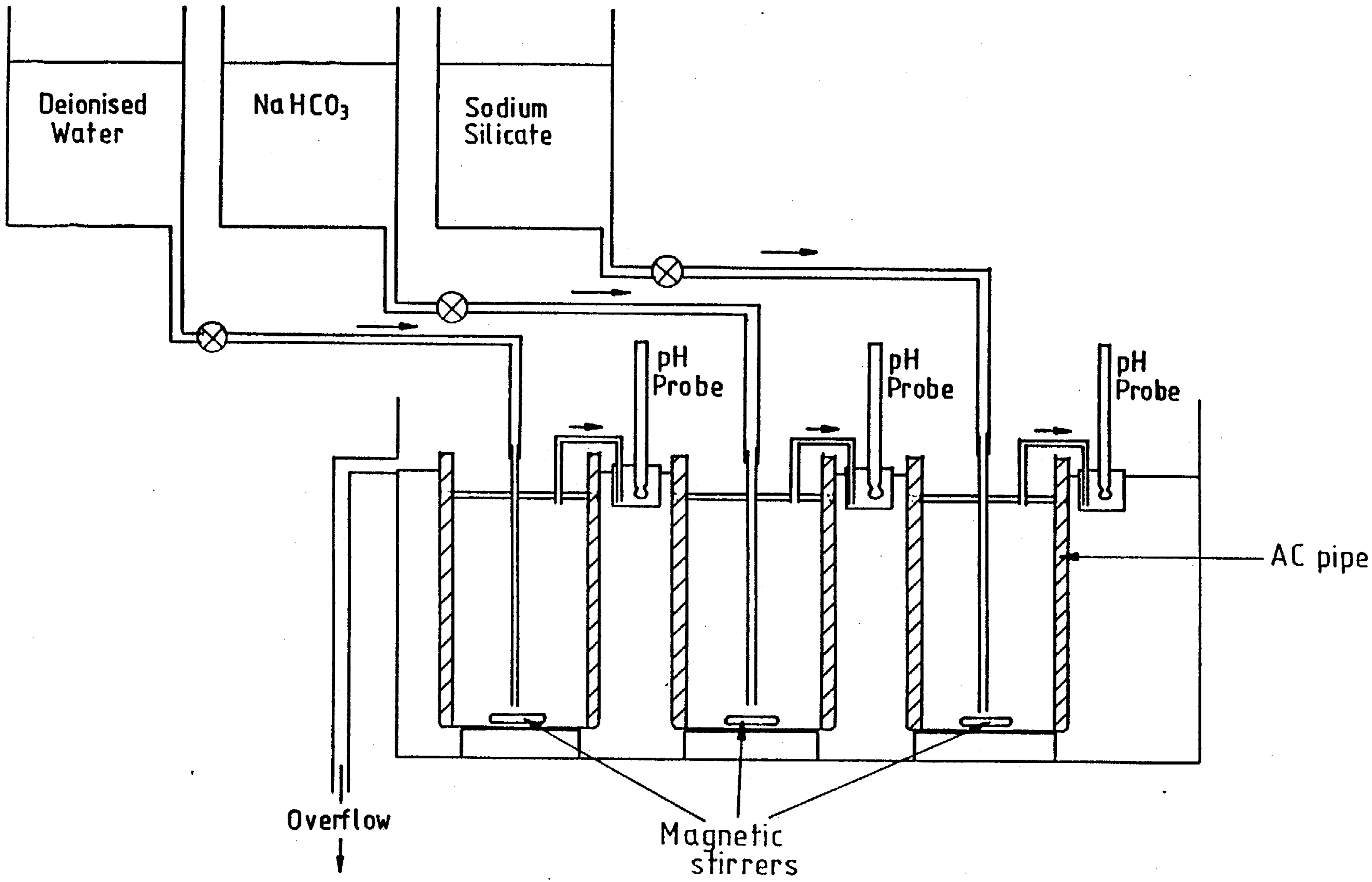


Figure 3.6 Accelerated Degradation - New AC Pipe

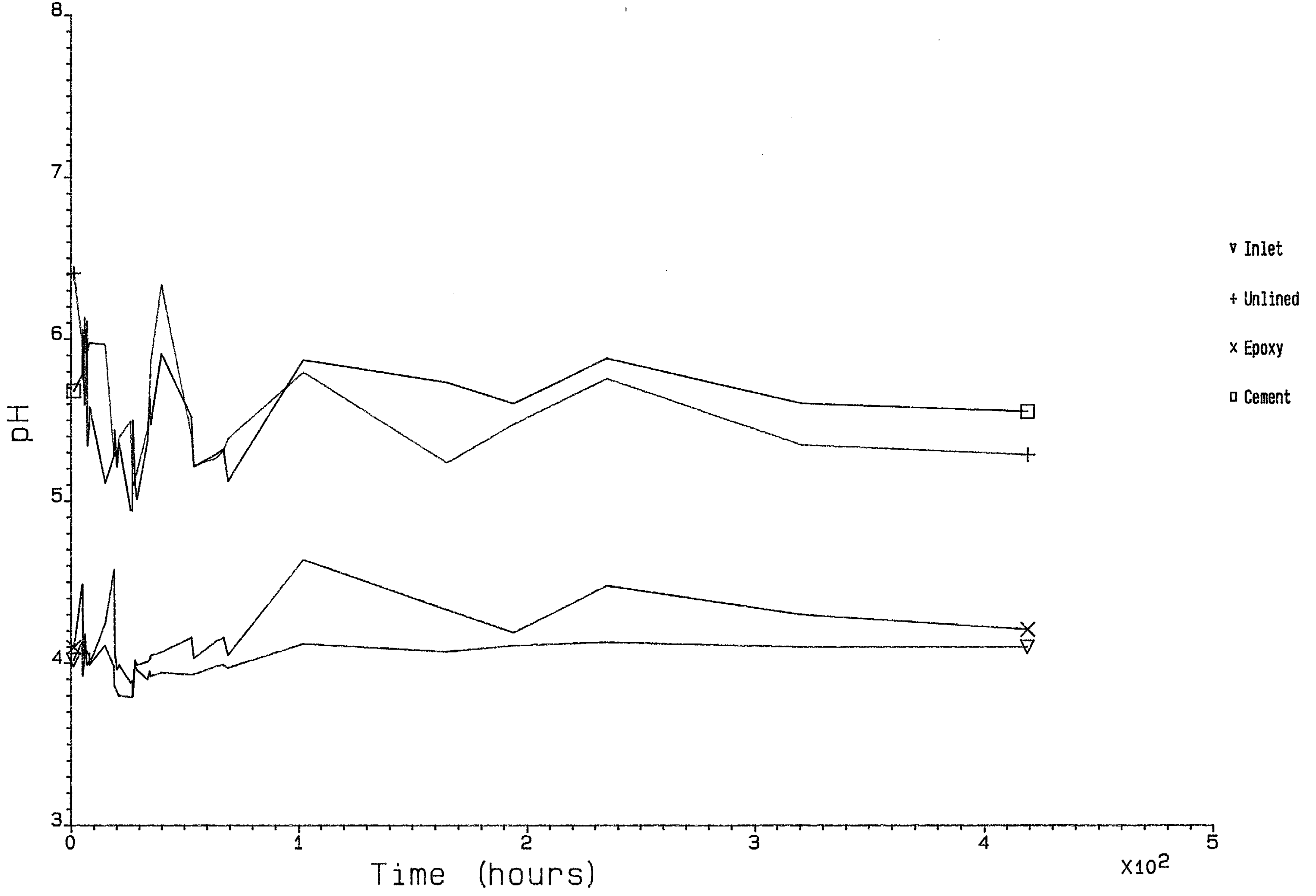


Figure 3.7 Accelerated Degradation - Naturally Degraded

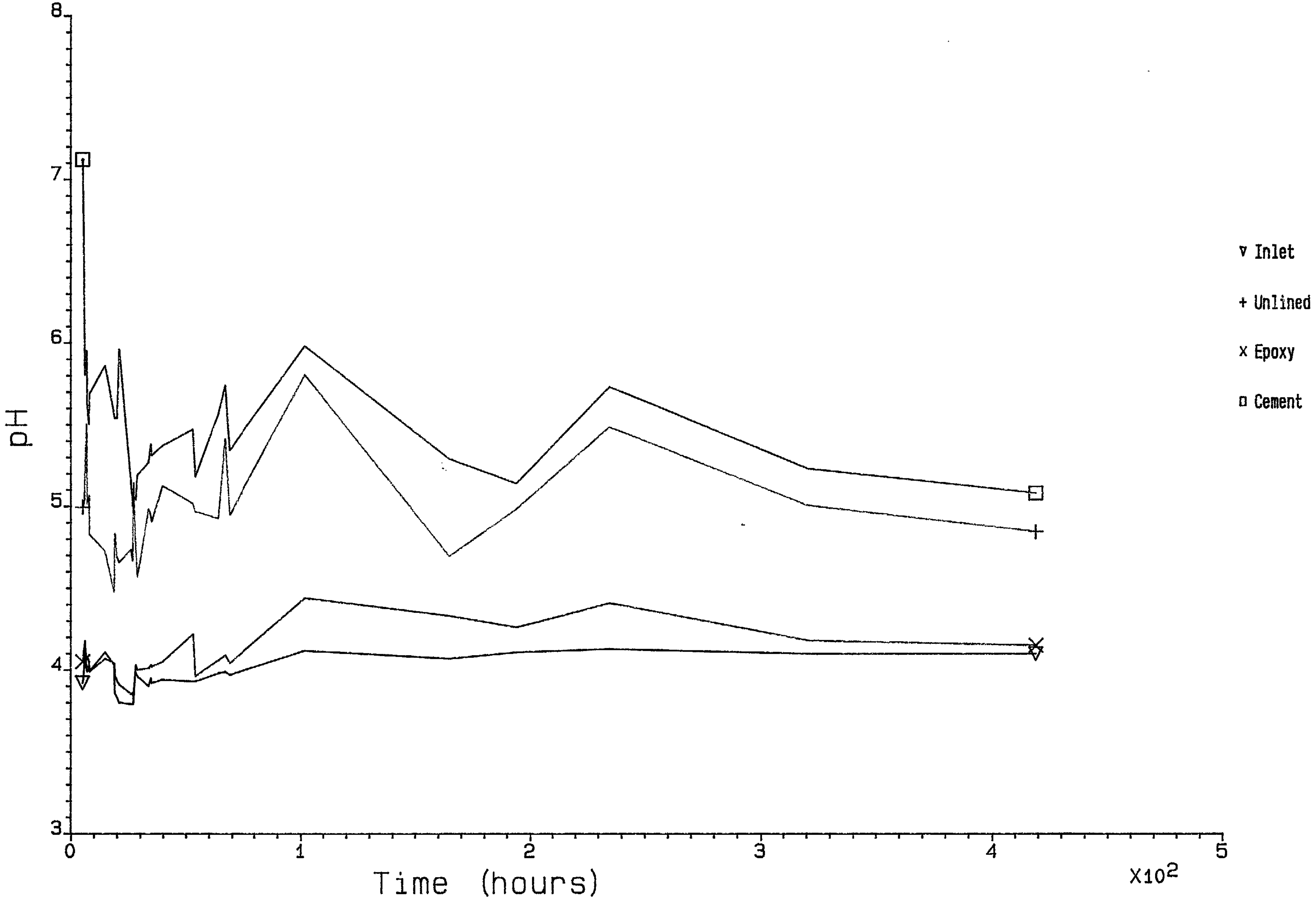


Figure 3.8 Accelerated Degradation - Artificially Degraded

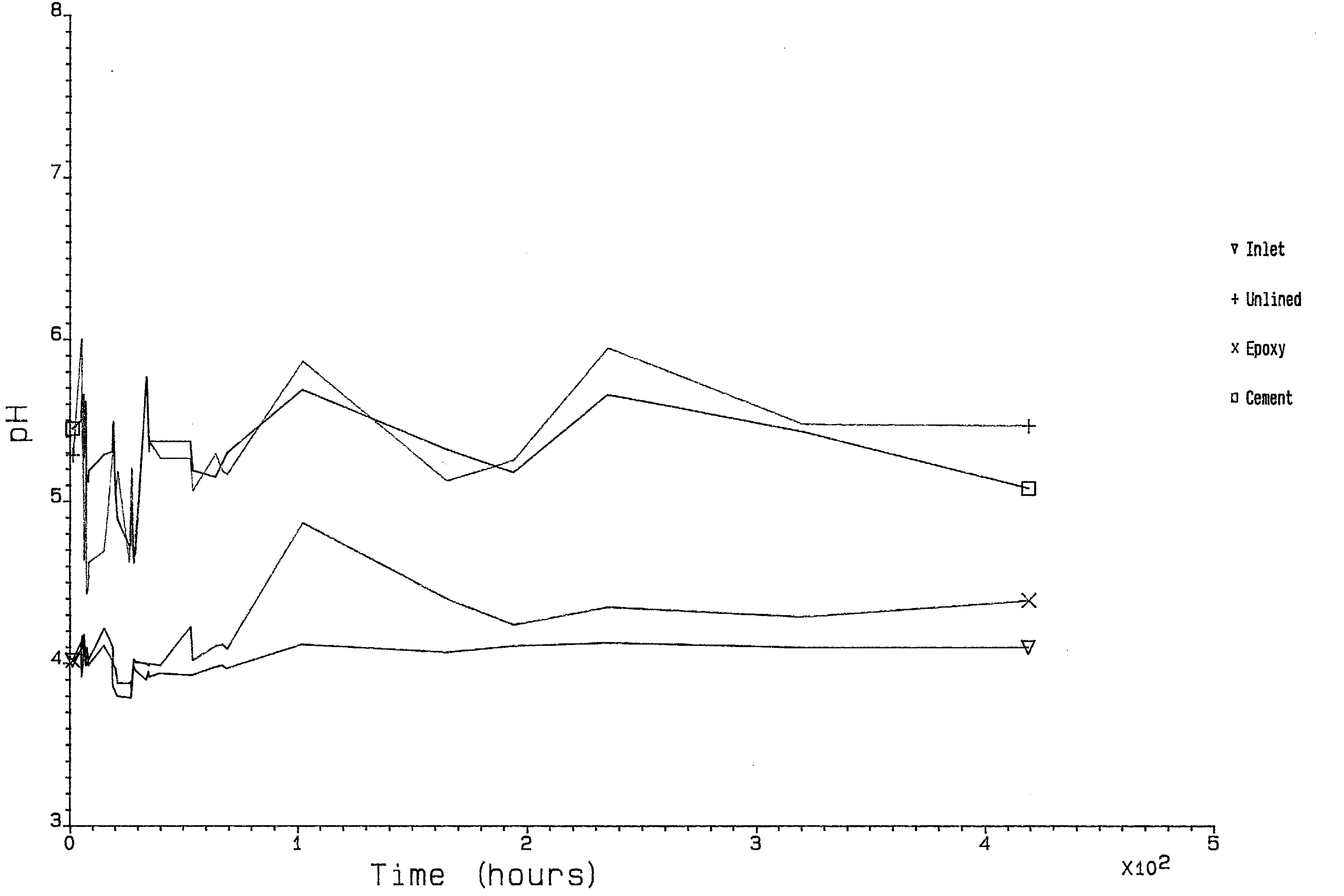


Figure 3.9 Accelerated Degradation Against Time

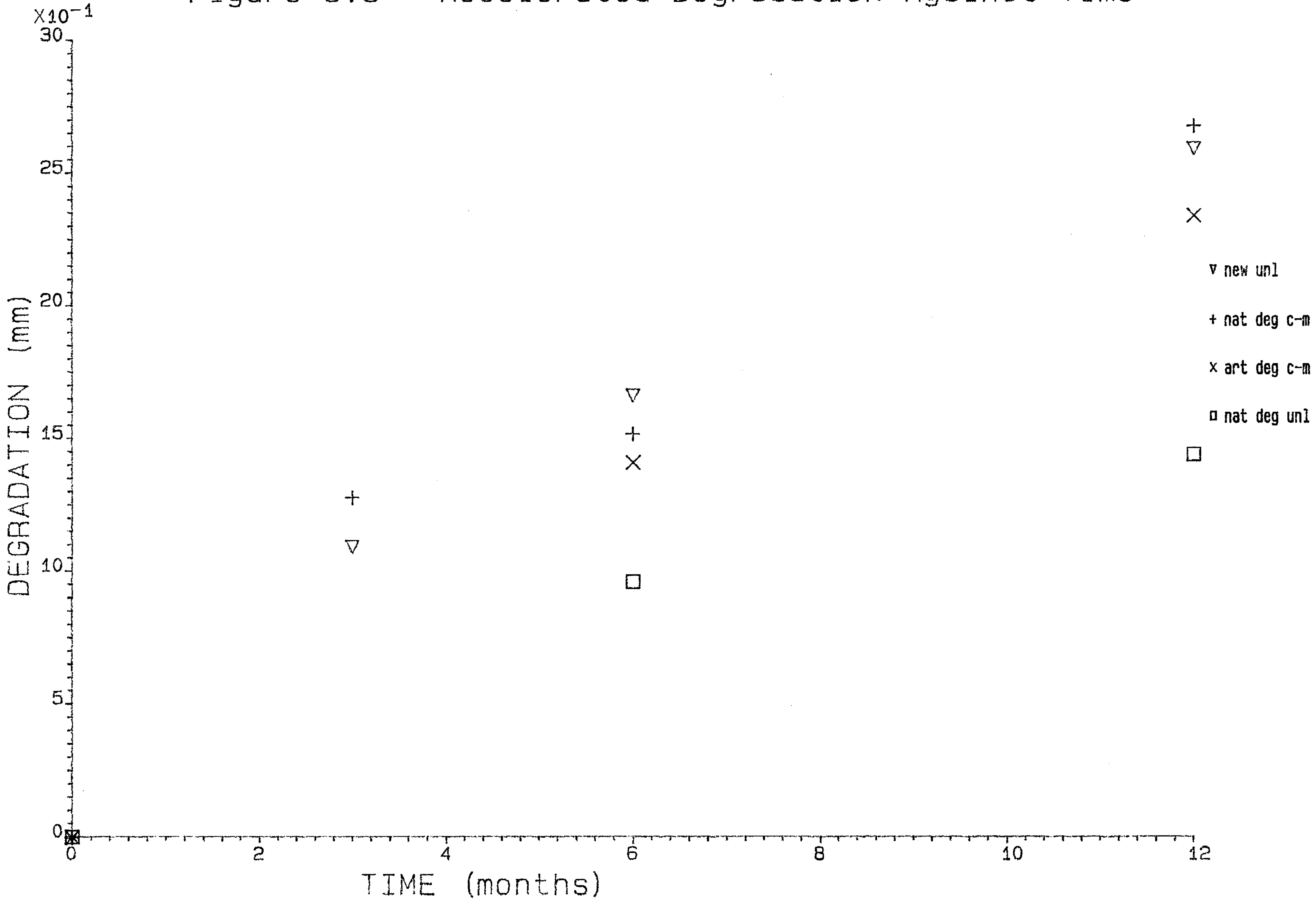


Figure 3.10 Chemical Dosing for New Asbestos Cement

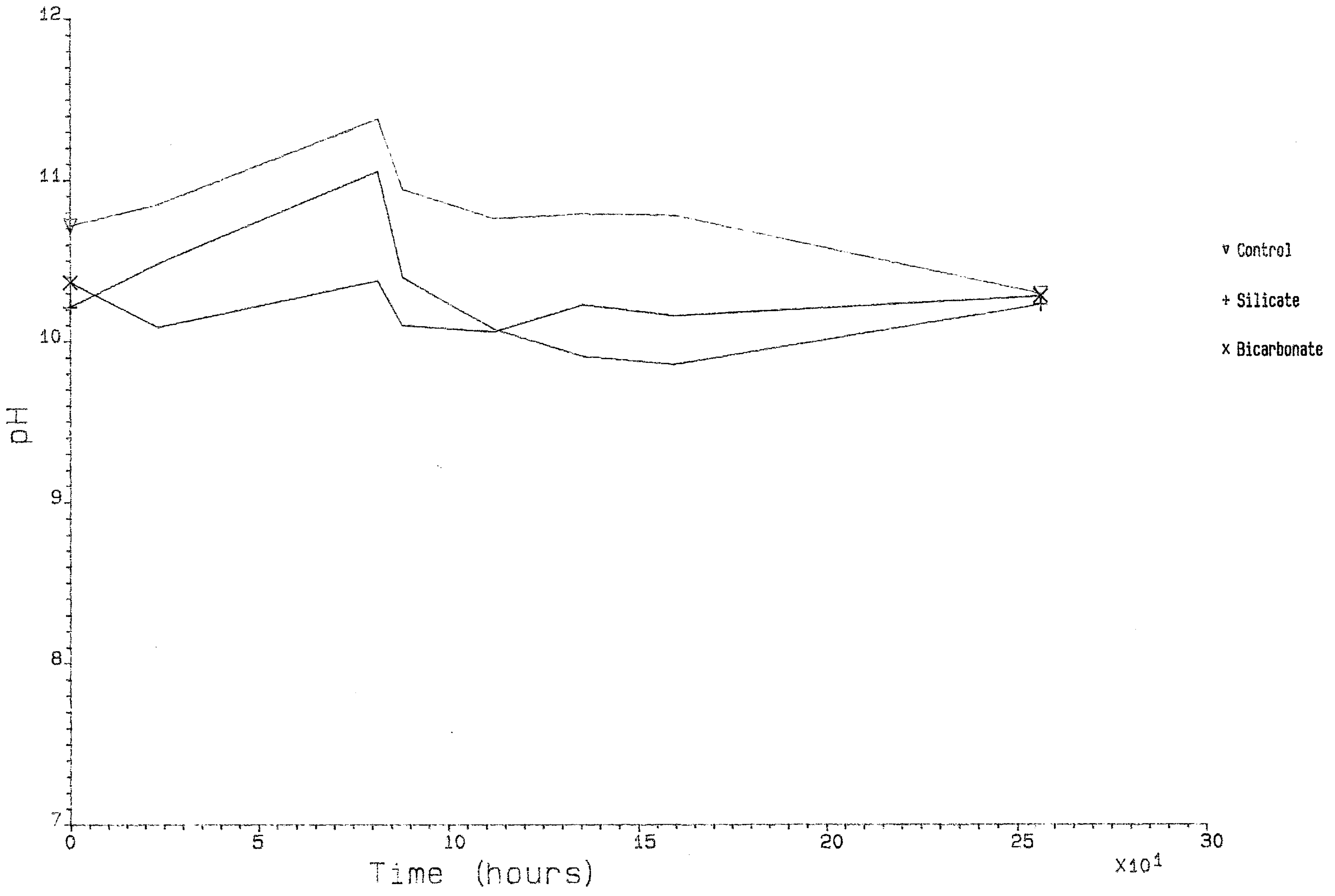
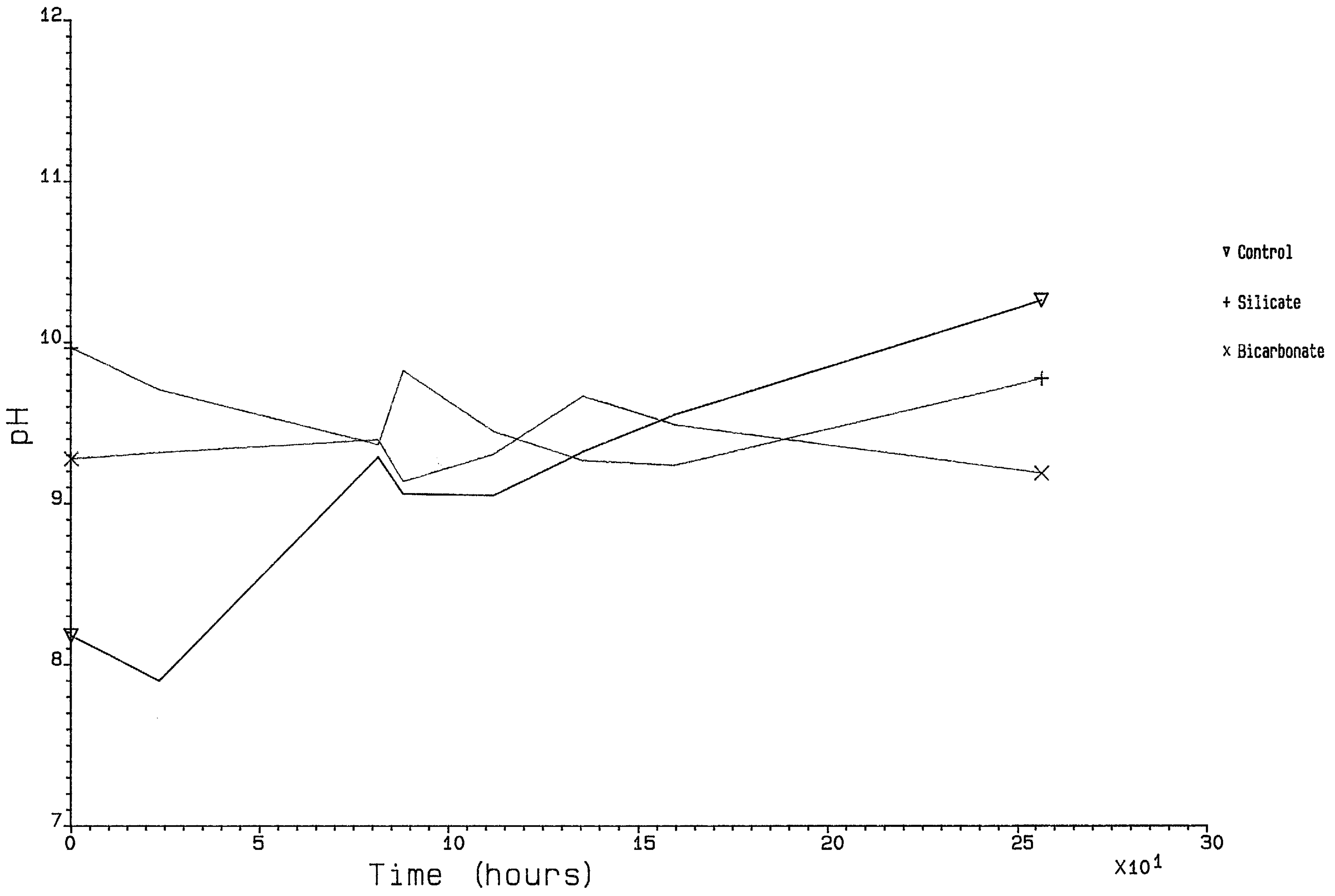


Figure 3.11 Chemical Dosing for Naturally Degraded AC Pipe



SECTION 4

SUMMARY

4.1 SUMMARY OF USAGE

The usage of asbestos cement pipes for conveying potable water in the United Kingdom is relatively widespread, and most utilities own some AC mains. Since its introduction in the 1930's asbestos cement became increasingly popular as an alternative to cast iron as it was claimed to have better corrosion resistance and was easier to handle. The use of AC reached a peak in the 1950's and 1960's when there was extensive mains laying to provide water to rural communities. Indeed this is reflected in the relatively large usage in areas with large rural populations. In the more urban areas AC is generally less common. The use of AC declined in the late 1960's with the introduction of uPVC pipes for small diameter distribution mains and reduced significantly in the late 1970's partly due to the concerns over asbestos. Indeed there has been a sharp trend away from using asbestos cement for small diameter mains, but it is still an attractive material for large diameter trunk mains where it competes with ductile iron, steel, concrete and more recently glass reinforced plastic.

Much of the usage of AC is in rural areas with significant quantities in upland regions conveying relatively low alkalinity waters.

4.2 SUMMARY OF PERFORMANCE

From the four selected ares it was apparent that the failure rate of AC was relatively low and compared favourably with the national average failure rate for all materials (0.1 failures/km year for AC cf 0.2 failures/km year national average). Detailed examination showed AC to be susceptible to beam failures in cohesive clay soils up to 250mm diameter. Interestingly the failure rate of the smaller diameter shows a linear relationship with age. The class B pipe also show a failure rate an order of magnitude higher than the class C pipes.

In the soft water areas there were significantly more longitudinal failures related to effective overpressurisation, and these had been reported as beng related to obvious deterioration of the pipes, in some cases within 20 years of being laid. The proportion of failures attributed to corrosion increased with age. Thus it can be anticipated that corrosion related failures will become more frequent as more of the pipes laid reach 20-30 years old. Much of the corrosion however was external, and a close relationship exists with soil type. Most of the corrosion related failures occurred in the permeable river sand/gravels while in the clay areas there were very few failures reported.

4.3 SUMMARY OF DEGRADATION

Examination of the pipes exhumed from a wide variety of environments showed large differences in their appearances, from those which look virtually unchanged to those suffering extensive deterioration. Most of the pipes exhumed were bitumen coated. In general the deterioration which had occurred was very localised to discontinuities within the bitumen perhaps resulting from defects arising during manufacture, damage incurred during installation or deterioration which has occurred in service.

There was no clear correlation between the various water quality parameters and the degradation measured, possibly as a result of the interference/protective action of the bitumen coatings. There were however general trends apparent which showed there was a greater chance of deterioration occurring in low pH, low alkalinity waters.

However, predicting a rate of fibre release into the water supply was not possible, as the defect area in the bitumen coating could not be predicted, and may vary substantially within a given distribution system. It was apparent however that external degradation is equally significant in terms of limiting the service life of the pipes with relatively extensive deterioration evident.

Transverse crush tests performed on the exhumed pipes showed a wide range of strengths and appeared to correlate very poorly with degradation. Indeed many pipes which did not show any deterioration by elemental analysis had crush strengths well below the current required value in BS 486 of $44Nmm^{-2}$. This suggests that the pipes lose strength with age which is contrary to the manufacturers claims. The results are however compatible with the increased failure rate evident in the area with a non-aggressive environment.

4.4 SUMMARY OF RELINING

Good quality linings can be successfully applied to both new and deteriorated asbestos cement pipes. The presence of a bitumen coating does appear to prevent a good bond between an epoxy coating and the pipe wall.

In accelerated degradation tests the coatings were found to perform well up to a modelled life of ten years. The cement mortar linings however undergo the same mechanism of degradation as the asbestos cement. The epoxy resin linings performed very well and appeared to prevent any further degradation of the asbestos cement pipe.

Water treatment techniques can be employed to reduce or prevent further degradation of the pipes. However this does not provide any barrier to the further release of fibres into the water supply.

Consideration has been given to a variety of other lining materials and techniques which could be employed to prevent further degradation of AC.

4.5 GENERAL

Significant lengths of asbestos cement pipes have been laid in potentially aggressive environments which can lead to either premature failure or progressive release of asbestos fibres into the water supply. The prediction of rates of attack is extremely difficult and it would probably be most effective to take pipe samples from those areas with low pH, low alkalinity waters to quantify the deterioration.

Further deterioraton can be prevented by the application of an internal lining. Of the currently available techniques epoxy resin lining would probably provide the most durable coating.

Some of the developing lining and moling techniques also provide potential solutions, but their suitability would require verification by some practical trials, with detailed assessment of their effects on water quality.

However, as much of the asbestos cement is laid in rural areas, the relining techniques may not be economically viable. Straight replacement by normal open trenching techniques may be cheaper using alternative degradation resistant materials.

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APPENDIX 1

(i) Langelier Index

The Langelier Index[8] (LI) is the difference between the measured pH of a water (pHm) and the theoretical pH at which the water would be saturated with $CaCO_3$ (pH_s) for the existing concentrations of bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), dissolved CO_2 and calcium (Ca^{2+}) ions. Thus

$$LI = pHm - pHs$$

$$pH_s = 12.3 - (\log C + \log A + 0.025T - 0.011\ S)$$

Where C = Calcium hardness mg/l
A = Total alkalinity mg/l
T = Temperature ^oC
S = Total dissolved solids mg/l

For negative values of LI the water tends to dissolve calcium carbonate.

For positive values of LI the water tends to precipitate calcium carbonate.

Therefore, a broad generalisation would be that waters with a negative LI may be considered aggressive to AC, while waters with a positive LI are non-aggressive.

(ii) AWWA Aggressiveness Index

The Aggressiveness Index(AI)[9] is a simplified form of the Langelier Index, notionally modified to account for the temperature dependency of the solubility of calcite, and for the ionic strength of the solution. Although the Index has its critics it is still widely used as a guide to the aggressivity of waters.

The Aggressiveness Index is given as:

$$AI = pH + \log(AH)$$ where pH = pH of the water
A = total alkalinity mg/l $CaCO_3$
H = calcium hardness mg/l $CaCO_3$

with an AI < 10.0 considered highly aggressive
AI 10.0 to 11.9 considered moderately aggressive
AI > 12.0 considered non-aggressive

(iii) **Comparison of AI and LI**

A comparison of the AI and LI is given in AWWA 1977 as:

	AI	**LI**
Highly aggressive	< 10.0	< -2.0
Moderately aggressive	10.0 to 11.9	-2.0 to -0.1
Non aggressive	> 12.0	> 0

APPENDIX 2

Dimensions and Pressure Classifications of AC pipe.

a) Class B, C, D

Nominal dia	CLASS B Test pressure 112m head			CLASS C Test pressure 183m head			CLASS D Test pressure 224m head		
in	Thickness in	Ext dia in	Int dia in	Thickness in	Ext dia in	Int dia in	Thickness in	Ext dia in	Int dia in
1 1/2							.37	2.25	1.50
2							.37	2.72	1.98
3							.40	3.76	2.96
4							.50	4.80	3.80
5							.60	5.90	4.70
6	.45	6.98	6.08	.61	6.98	5.76	.70	6.98	5.58
7	.51	8.06	7.04	.66	8.06	6.74	.80	8.06	6.46
8	.57	9.14	8.00	.72	9.14	7.70	.90	9.14	7.34
9	.60	10.20	9.00	.79	10.20	8.62	.98	10.20	8.24
10	.64	11.26	9.98	.84	11.26	9.53	1.08	11.26	9.10
12	.68	13.14	11.78	1.00	13.60	11.60	1.30	13.60	11.00
15	.84	16.26	14.58	1.24	16.78	14.30			
18	.95	19.38	17.48	1.47	19.96	17.02			
21	1.10	22.50	20.30	1.60	23.12	19.92			
24	1.25	25.60	23.10	1.80	26.26	22.66			
27	1.40	28.70	25.90	2.00	29.40	25.40			
30	1.50	31.78	28.78	2.20	32.52	28.12			
33	1.60	34.88	31.68	2.40	35.66	30.86			
36	1.70	37.96	34.56	2.55	38.76	33.66			
	Test pressure 112m head			Test pressure 183m head			Test pressure 224m head		
mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
38							9.4	57.1	38.3
50							9.4	69.1	50.3
75							10.2	95.6	75.2
100							12.7	121.9	96.5
125							15.3	149.9	119.3
150	11.4	177.3	154.5	15.5	177.3	146.3	17.8	177.3	141.7
175	13.0	204.8	178.8	16.8	204.8	171.2	20.3	204.8	164.2
200	14.5	232.2	203.2	18.3	232.2	195.6	22.9	232.2	186.4
225	15.3	259.1	228.5	20.1	259.1	218.9	24.9	259.1	209.3
250	16.3	286.0	253.4	21.3	286.0	243.4	27.5	286.0	231.0
300	17.3	333.8	299.2	25.4	345.4	294.6	33.0	345.4	279.4
375	21.3	413.0	370.4	31.5	426.2	363.2			
450	24.1	492.2	444.0	37.3	507.0	432.4			
525	27.9	571.5	515.7	40.6	587.2	506.0			
600	31.7	650.2	586.8	45.7	667.0	575.6			
700	35.5	729.0	657.9	50.8	746.8	645.2			
825	40.6	885.9	804.7	66.6	905.8	783.9			
900	43.2	964.2	877.7	70.4	984.5	854.8			

Pipe Dimensions

Nominal dia	Class 15			Class 20			Class 25		
	Int dia	Ext dia	Thickness at ends	Int dia	Ext dia	Thickness at ends	Int dia	Ext dia	Thickness at ends
mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
75	-	-	-	-	-	-	75	96	10.5
100	-	-	-	-	-	-	97	122	12.5
150	154	177	11.5	-	-	-	147	177	16.5
200	203	232	14.5	195	232	18.5	195	240	22.5
225	228	259	15.5	219	259	20.0	219	268	24.5
250	253	286	16.5	243	286	21.5	243	295	26.0
300	296	334	19.0	296	345	24.5	296	356	30.0
350	350	392	21.0	350	405	27.5	350	419	34.5
400	400	448	24.0	400	463	31.5	400	478	39.0
450	445	498	26.5	445	515	35.0	445	532	43.5
500	508	568	30.0	508	586	39.0	508	605	48.5
600	588	654	33.0	588	672	42.0	588	691	51.5
700	687	761	37.0	687	780	46.5	687	801	57.0
750	731	808	38.5	731	830	49.5	731	852	60.5

NOTE: Subject to availability larger diameters can be supplied on request.

APPENDIX 2

Class 15, 20, 25

Pressure Classification

Class	Works test pressure		Maximum allowable sustained working pressure	
	bar	m head	bar	m head
15	15	153	7.5	76.5
20	20	204	10.0	102
25	25	255	12.5	127.5

1 bar = 14.5 lbf/in^2 = 10.197 metres head of water

APPENDIX 3

ASBESTOS CEMENT PIPE DEGRADATION

EXPERIMENTAL DESIGN

SUMMARY

This experimental design, detailed below, has been devised to investigate the effects of seven factors on the degradation of AC pipes. Selecting pipes according to this scheme will provide data for estimating the Linear and Quadratic effects of each of the seven factors, together with First-Order Interactions.

The plan comprises 128 Corner points, 14 Star points and 12 Centre points requiring 154 observations in total.

The Corner points provide a set of points for a "two to the power k" Factorial experiment. They can be considered to be the corners of a hypercube. They also define the region for which the conclusions will be valid. Two levels are needed for each factor, designated [+1,-1]. These two levels represent "high" and "low" values. These should be set so as to have a reasonable chance of occurring with high and low values of the other factors, whilst at the same time delimiting the area of interest.

The Corner points have been modified to allow investigation into four equally spaced levels of the Age factor, represented by [+1,+c,-c,-1] respectively. [c] represents the value [1/3], i.e. one third of the standard age unit.

The centres of the ranges, i.e. midway between the high and low values for each determinand, define the [0] levels in the Star and Centre points.

The Centre points are simply a set of points with all determinands set at their [0] levels, and define the Origin of the design.

The Star points lie on the Principal Axes through this Origin, and preferably also on the hypersphere that passes through the Corner points of the hypercube. Each Star point has value [+a] or [-a] for the relevant factor, and [0] values for the other determinands. To give a Rotatable Design, the Star points and the Corner points should be at the "same distance" from the Origin as measured in standardised units. In the present seven dimensional case, this requires that

$$a = \sqrt{7} = 2.65$$

Thus [+a] = [+2.65] and [-a] = [-2.65], i.e. more extreme than the "high" and "low" values defined above. However, a rotatable design is not essential and we could set [+a] = [+1] and [-a] = [-1].

The Star and Centre points are required for the estimation of quadratic effects. The Centre points will also allow us to test for repeatability, and the experimental observations should be taken from pipes selected from different sites.

TARGET DESIGN

This design provides a set of points, in which, for example, all pipes selected at the high [+1] pH level would have exactly the same value of pH. This represents an ideal which could be achieved precisely only if we could control the factors (as for example in a classical agricultural experiment). However, in this experiment, the required values of the determinands cannot be controlled in this way but have to be taken from the pipes that are available amongst those already laid. Thus pH, to continue our example, will vary from pipe to pipe. Although every effort should be made to get as close to the pre-determined levels as possible, it will not be possible to attain the target design exactly.

As a result, we will not be able to estimate main effects and interactions using standard Factorial Design techniques but will have to use Multiple Regression instead. However, this creates no problems. Both techniques use Least Squares estimation, and, in fact, Factorial Designs are a special case of Multiple Regression theory.

CORRELATIONS

Difficulties arise in Multiple Regression if there exist correlations between the determinands. This plan is designed to eliminate this problem. The nearer we can get to the target levels set by the plan, the smaller will be the correlations. In practise, the data points in the population will tend to be concentrated towards the centre of the design. It may be difficult or impossible to obtain even approximations to some of the Corner or Star points. If the resulting correlations between pairs of factors are very high, it will be impossible to separate their effects.

PROPOSED DESIGN

DETERMINANDS:

A : pH of conveyed water;
B : Hardness of conveyed water;
C : Alkalinity of conveyed water;

D : Hardness of ground water;
E : Soil Permability

F : Diameter of pipe;
G : Age of pipe.

Corner Points

A	B	C	D	E	F	G
+1	+1	+1	+1	+1	+1	+1
+1	+1	+1	+1	+1	+1	-c
+1	+1	+1	+1	+1	-1	+c
+1	+1	+1	+1	+1	-1	-1
+1	+1	+1	+1	-1	+1	+c
+1	+1	+1	+1	-1	+1	-1

+1	+1	+1	+1	-1	-1	+1
+1	+1	+1	+1	-1	-1	-c
+1	+1	+1	-1	+1	+1	+c
+1	+1	+1	-1	+1	+1	-1
+1	+1	+1	-1	+1	-1	+1
+1	+1	+1	-1	+1	-1	-c
+1	+1	+1	-1	-1	+1	+1
+1	+1	+1	-1	-1	+1	-c
+1	+1	+1	-1	-1	-1	+c
+1	+1	+1	-1	-1	-1	-1

(16)

+1	+1	-1	+1	+1	+1	+c
+1	+1	-1	+1	+1	+1	-1
+1	+1	-1	+1	+1	-1	+1
+1	+1	-1	+1	+1	-1	-c
+1	+1	-1	+1	-1	+1	+1
+1	+1	-1	+1	-1	+1	-c
+1	+1	-1	+1	-1	-1	+c
+1	+1	-1	+1	-1	-1	-1
+1	+1	-1	-1	+1	+1	+1
+1	+1	-1	-1	+1	+1	-c
+1	+1	-1	-1	+1	-1	+c
+1	+1	-1	-1	+1	-1	-1
+1	+1	-1	-1	-1	+1	+c
+1	+1	-1	-1	-1	+1	-1
+1	+1	-1	-1	-1	-1	+1
+1	+1	-1	-1	-1	-1	-c

(32)

A	B	C	D	E	F	G
+1	-1	+1	+1	+1	+1	+c
+1	-1	+1	+1	+1	+1	-1
+1	-1	+1	+1	+1	-1	+1
+1	-1	+1	+1	+1	-1	-c

+1	-1	+1	+1	-1	+1	+1
+1	-1	+1	+1	-1	+1	-c
+1	-1	+1	+1	-1	-1	+c
+1	-1	+1	+1	-1	-1	-1
+1	-1	+1	-1	+1	+1	+1
+1	-1	+1	-1	+1	+1	-c
+1	-1	+1	-1	+1	-1	+c
+1	-1	+1	-1	+1	-1	-1
+1	-1	+1	-1	-1	+1	+c
+1	-1	+1	-1	-1	+1	-1
+1	-1	+1	-1	-1	-1	+1
+1	-1	+1	-1	-1	-1	-c

(48)

+1	-1	-1	+1	+1	+1	+1
+1	-1	-1	+1	+1	+1	-c
+1	-1	-1	+1	+1	-1	+c
+1	-1	-1	+1	+1	-1	-1
+1	-1	-1	+1	-1	+1	+c
+1	-1	-1	+1	-1	+1	-1
+1	-1	-1	+1	-1	-1	+1
+1	-1	-1	+1	-1	-1	-c
+1	-1	-1	-1	+1	+1	+c
+1	-1	-1	-1	+1	+1	-1
+1	-1	-1	-1	+1	-1	+1
+1	-1	-1	-1	+1	-1	-c
+1	-1	-1	-1	-1	+1	+1
+1	-1	-1	-1	-1	+1	-c
+1	-1	-1	-1	-1	-1	+c
+1	-1	-1	-1	-1	-1	-1

(64)

A	B	C	D	E	F	G
-1	+1	+1	+1	+1	+1	+c
-1	+1	+1	+1	+1	+1	-1
-1	+1	+1	+1	+1	-1	+1
-1	+1	+1	+1	+1	-1	-c
-1	+1	+1	+1	-1	+1	+1
-1	+1	+1	+1	-1	+1	-c
-1	+1	+1	+1	-1	-1	+c
-1	+1	+1	+1	-1	-1	-1
-1	+1	+1	-1	+1	+1	+1
-1	+1	+1	-1	+1	+1	-c
-1	+1	+1	-1	+1	-1	+c
-1	+1	+1	-1	+1	-1	-1
-1	+1	+1	-1	-1	+1	+c
-1	+1	+1	-1	-1	+1	-1
-1	+1	+1	-1	-1	-1	+1
-1	+1	+1	-1	-1	-1	-c

(80)

-1	+1	-1	+1	+1	+1	+1
-1	+1	-1	+1	+1	+1	-c
-1	+1	-1	+1	+1	-1	+c
-1	+1	-1	+1	+1	-1	-1
-1	+1	-1	+1	-1	+1	+c
-1	+1	-1	+1	-1	+1	-1
-1	+1	-1	+1	-1	-1	+1
-1	+1	-1	+1	-1	-1	-c
-1	+1	-1	-1	+1	+1	+c
-1	+1	-1	-1	+1	+1	-1
-1	+1	-1	-1	+1	-1	+1
-1	+1	-1	-1	+1	-1	-c
-1	+1	-1	-1	-1	+1	+1
-1	+1	-1	-1	-1	+1	-c
-1	+1	-1	-1	-1	-1	+c
-1	+1	-1	-1	-1	-1	-1

(96)

A	B	C	D	E	F	G
-1	-1	+1	+1	+1	+1	+1
-1	-1	+1	+1	+1	+1	-c
-1	-1	+1	+1	+1	-1	+c
-1	-1	+1	+1	+1	-1	-1
-1	-1	+1	+1	-1	+1	+c
-1	-1	+1	+1	-1	+1	-1
-1	-1	+1	+1	-1	-1	+1
-1	-1	+1	+1	-1	-1	-c
-1	-1	+1	-1	+1	+1	+c
-1	-1	+1	-1	+1	+1	-1
-1	-1	+1	-1	+1	-1	+1
-1	-1	+1	-1	+1	-1	-c
-1	-1	+1	-1	-1	+1	+1
-1	-1	+1	-1	-1	+1	-c
-1	-1	+1	-1	-1	-1	+c
-1	-1	+1	-1	-1	-1	-1

(112)

-1	-1	-1	+1	+1	+1	+c
-1	-1	-1	+1	+1	+1	-1
-1	-1	-1	+1	+1	-1	+1
-1	-1	-1	+1	+1	-1	-c
-1	-1	-1	+1	-1	+1	+1
-1	-1	-1	+1	-1	+1	-c
-1	-1	-1	+1	-1	-1	+c
-1	-1	-1	+1	-1	-1	-1
-1	-1	-1	-1	+1	+1	+1
-1	-1	-1	-1	+1	+1	-c
-1	-1	-1	-1	+1	-1	+c
-1	-1	-1	-1	+1	-1	-1
-1	-1	-1	-1	-1	+1	+c

-1	-1	-1	-1	-1	+1	-1
-1	-1	-1	-1	-1	-1	+1
-1	-1	-1	-1	-1	-1	-c

(128)

<u>Star Points</u> (Limit in each dimension)

A	B	C	D	E	F	G
+a	0	0	0	0	0	0
-a	0	0	0	0	0	0
0	+a	0	0	0	0	0
0	-a	0	0	0	0	0
0	0	+a	0	0	0	0
0	0	-a	0	0	0	0
0	0	0	+a	0	0	0
0	0	0	-a	0	0	0
0	0	0	0	+a	0	0
0	0	0	0	-a	0	0
0	0	0	0	0	+a	0
0	0	0	0	0	-a	0
0	0	0	0	0	0	+a
0	0	0	0	0	0	-a

(142)

<u>Centre Points</u>

A	B	C	D	E	F	G
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

(154)

APPENDIX 4 - BS486 TRANSVERSE CRUSH

TRANSVERSE CRUSHING TEST

The test was carried out on a piece of pipe of a length cut to

200mm for pipes of nominal diameters from 50 to 300.

after immersion for 48 h.

The load was applied through press-blocks as shown in Figure A4, at a constant rate regulated so that the rupture occured after at least 15 s and not more than 30 s, according to the diameter.

The lower press-block consisted of a V-shaped support having an included angle of 150°, made of metal; the flat upper press-block made of the same material, had a width b which varied with the nominal diameter of the pipe. The values of b are given in Table A4.

The load was applied vertically.

Strips of rubber of suitable width and length were interposed between the press-blocks and the test piece. The rubber strips were 15mm thick and of a hardness of 60 ± 5 Shore A-degrees.

Table A4 - Width of upper press block

NOMINAL DIAMETER	WIDTH b
	mm
50 to 250	25
300 to 350	35
375 to 450	50
500 to 600	60
675 to 825	85
900 to 1050	105
1100 to 1200	130
1300 to 1400	150
1500 to 1600	175
1700 to 1800	195
1900 to 2000	220
2100 to 2200	240
2300 to 2400	265
2500	290

The unit transverse crushing strength R_{e} expressed in newtons per square millimetre, is given by the formula:

$$R_{e} = \frac{K M_{e}}{W_{e}}$$

where

$$K = \frac{3d + 5e}{3d + 3e}$$ is a factor resulting from the curvature of the pipe.

d being the actual internal diameter of the test piece, in millimetres, taken as the average of two perpendicular measurements; e being the actual thickness of the wall of the test piece in the broken section, in millimetres, taken as the average of three measurements made along the line of fracture at the top of the ring;

$M_e = nP_e \frac{(d + e)}{2}$ is the maximum ring bending moment.

n being equal to 0.26 for diameters up to 100mm and equal to 0.30 for diameters exceeding 100mm.

P_e being the breaking load, in newtons;

$W_e = \frac{1}{6} le^2$ is the modulus of resistance of the wall of the pipe.

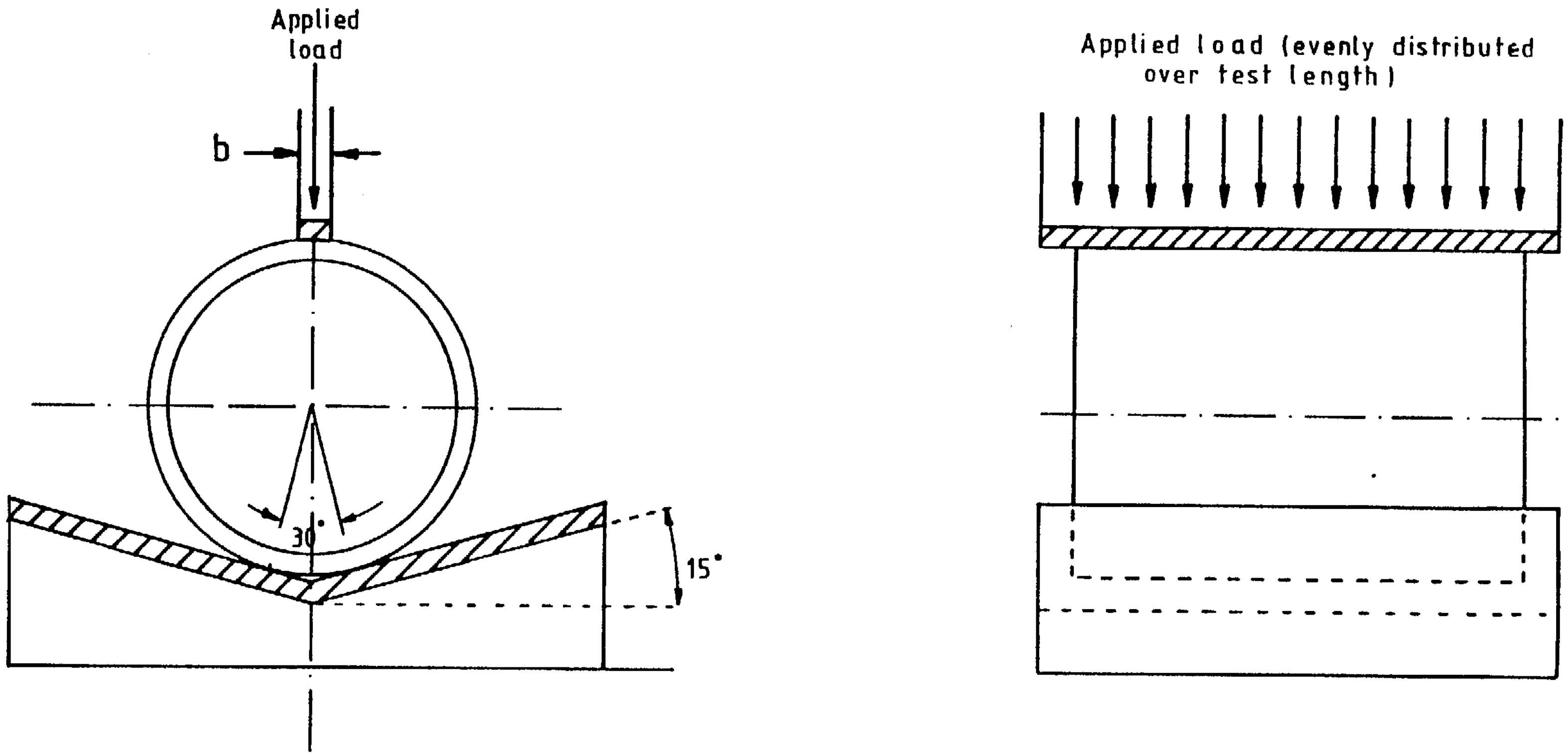
l being the actual length of the test piece, in millimetres.

NOTE: The value of R_e may be derived directly from the formula

$$R_e = n \frac{P_e}{l} \frac{(3d + 5e)}{e^2}$$

the terms being expressed in the same units as above.

FIGURE A.4 BS 486 LOADING FOR TRANSVERSE CRUSHING TEST



APPENDIX 5

Elemental analysis through the pipe sections were performed at the Harwell Research Laboratory.

The analyses was performed on a Cameca Camebax microprobe analyser using energy dispersive spectroscopy.

Operating voltage	15 keV
Operating filament current	45 mA
Area scanned per step	50µm x 50µm
Step size	50µm

TRACOR EDS system	
Take off angle	40°
Detector	Standard with 7.5µm Beryllium window

APPENDIX 6

ASBESTOS CEMENT PIPE DEGRADATION : RESULTS

THE DATA

IPS1 and IPS2 are two measures of pipe degradation. The five predictor determinands are diameter, age, pH, alkalinity and hardness. Alkalinity, pH and hardness were combined into one variable, the aggressive index, by the formula:

$$AGG = pH + LOG_{10} \text{ (alkalinity * hardness).}$$

CORRELATIONS AMONG THE VARIABLES

Examination of the correlation matrix revealed that all the predictor variables were poorly correlated with the two dependent variables. The greatest correlation (in absolute terms) was between pH and IPS1, but the correlation coefficient was only 0.147. This was not statistically significant at the 5% level. It followed that none of the other correlations between the dependant and the predictor variables was significant either.

Among the predictor determinands, with one exception, there were no strong correlations. This lack of correlation among the predictors is highly desirable for statistical analysis, otherwise the coefficients estimated by regression techniques will be unreliable, and the apparent relationship between degradation and the predictor variables may be spurious. The avoidance of these problems justifies the care taken in designing the experiment on the basis of sound statistical principles.

The single exception was between alkalinity and hardness, where there was a large correlation coefficient with a value of 0.914. In view of this high correlation, and the confounding of the effects of the two determinands, it is sensible to consider discarding one of them. The second highest correlation was between pH and hardness, with a value of only 0.168, which is not significant at the 5% level.

The derived variable, AGG, was quite closely correlated with pH, alkalinity and hardness as might have been expected.

REGRESSION ANALYSIS

Several different combinations of predictor variables were used to fit multiple regressions to both IPS1 and IPS2. The best fit, in terms of minimising the residual variance, included age, pH, hardness and alkalinity, but excluded diameter which has no effect in the presence of the other variables. Hardness was also be dropped from the model, since its effect is not significant in the presence of alkalinity with which it is highly correlated. The regression coefficients and the associated analyses of variance are given on the attached sheets.

Although the model:

IPS = a.AGE + b.PH + c.ALK + k

is statistically significant at the 5% level, it does not explain a great deal of the variation in degradation. For both IPS1 and IPS2, less than 6% of the variance, equivalent to under 3% of the standard deviation, is accounted for. The remainder may be due to other variables, as yet unexplored, or to the inherent variability of the measure of degradation.

The alternative model obtained by replacing the pH, hardness and alkalinity terms by the aggressiveness index did not improve the fit, and in fact was not significant for IPS2.

(i) The best linear fit for the simple water quality parameters is

IPS1 = 0.019 age - 0.365 pH - 0.003 alkalinity + 3.26

which is significant at 5% but not at the 1% level. The percentage variance accounted for was 5.9.

(ii) Considering the aggressiveness index the best linear fit is:

$$IPS1 = + 0.019\ \text{age} - 0.188\ AI + 2.32$$

which is significant at the 5% but not the 1% level. The percentage variance account for was 3.4.

APPENDIX 7

ASBESTOS CEMENT PIPE DEGRADATION

SPLITTING THE DATA

Following the poor fit found when trying to fit a linear relation to the full set of data, modifications were made to the model:

1. quadratic terms were introduced;

2. the data was split into two subsets at pH = 7.5.

Stepwise regression techniques were used to find the group of explanatory variables that minimised the residual mean square error in each subset.

CORRELATIONS AMONG THE VARIABLES

Examination of the correlation matrix revealed that for pH under 7.5, there were improved correlations between some of the predictor variables and the two dependent variables. The greatest correlation (in absolute terms) was between alkalinity-squared (alk2) and IPS1 where the correlation coefficient was -0.321. This is statistically significant at the 5% level. Other significant predictors for IPS1 were pH, pH-squared (ph2) and alkalinity (alk).

For pH over 7.5, there were no significant correlations between IPS1 and any of the predictors.

REGRESSION ANALYSIS

To obtain the best combination of predictor variables to be used to fit multiple regressions to IPS1, stepwise regression in both the forward and backward direction was employed. Variables were added or eliminated from the model one by one, choosing the move that minimised the residual mean square error until no further improvement was possible. Because it is possible to get stuck at a local minimum, several different starting points were chosen, including the full set of predictors and the empty set. The best model found for the set with pH under 7.5 is:

$$IPS1 = -28.72 - 1.436.pH + 7.66\ agg - 0.3618\ agg2$$

This is statistically significant at the 0.1% level, and it explains 28% of the variance, equivalent to 15% of the original standard deviation.

For pH over 7.5, the best model found was not statistically significant.

FURTHER WORK

Significant regressions were also found when the data was split in other ways, but again for only one of the two subsets in each case. These were for alkalinity under 75, and aggressive index under 10.5.

(i) For pH <7.5 and considering water quality parameters only

$$IPS1 = -56.3 + 17.8pH - 1.37pH^2 - 0.012alk + 0.014\ hardness$$

which is significant at the 1% level. The percentage variance account for = 17.0.

(ii) For alkalnity <75 and considering uncombined water quality parameters

$$IPS1 = 2.93 + 0.0003age^2 - 0.307pH + 0.00002\ hardness^2$$

which is significant at 2.5% but not 1% level. The percentage variance accounted for = 9.5.

(iii)For Aggressiveness index <10.5 and considering uncombined water quality parameters

$$IPS1 = -0.254 - 0.038 \text{ alkalinity} + 0.088 \text{ hardness} - 0.0002 \text{ hardness}^2$$

which is significant at the 1% level. The percentage variance accounted for 32.7.

In each of the cases pH>7.5, alkalinity >75 and Aggressiveness Index >10.5 no significant correlations were found.

APPENDIX 8

PART 1 - PRODUCTION OF STANDARD DEGRADED ASBESTOS CEMENT PIPE

1.1 INTRODUCTION

The aim was to produce artificial degradation in an asbestos cement pipe resembling as closely as possible that found in naturally degraded pipe. The process had to achieve a sufficient depth of degradation (approximately 2mm) within a suitable time period (2 days).

1.2 METHOD

The basic process involved in the degradation of asbestos cement is the removal of calcium compounds from the cementitious matrix. Therefore various acids were tried to study their effect on asbestos cement. 10% solutions of the following acids in water were used initially:

(1) Hydrochloric acid (HCl);
(2) Nitric acid (HNO_3);
(3) Sodium hydrogen sulphate ($NaHSO_4$);
(4) Sulphuric acid (H_2SO_4);
(5) HCl + HNO_3;
(6) HCl + HNO_3 + $HNaSO_4$.

Small pieces of pipe were placed in the acids and left for 2 hours. These samples were then examined for depth of degradation. Acid (3) was found to produce very little degradation and acids (4), (5) and (6) produced deposits on the samples which rendered them unsuitable for this project.

In the case of acids (4) and (6) the deposit probably ettringite formed by sulphate attack of the cement.

Both HCl and HNO_3 produced similar results and further tests were carried out to determine the optimum times and concentrations. Sections of pipe 30 x 30mm were placed into 20% solutions of these acids for varying lengths of time and the depths of attack measured.

More concentrated 20% solution of the acids were used to increase the rate of attack. HNO_3 was seen to have a higher rate of attack than HCl (Figure A8). No differences between the visual appearance of the areas degraded by HCl and HNO_3 were observed. Therefore it was decided to use a solution of 20% nitric acid in water for the production of a standard degraded pipe.

A further series of tests was carried out with 20% HNO_3 at a temperature of 60°C in an attempt and further increase the rate of reaction. Some increase in the rate of attack was measured, however, the problems and hazards resulting from using hot acids made any benefits unworthwhile and it was decided to use a 20% solution of HNO_3 at ambient temperatures.

Stirring was also tried to simulate the movement of water through a pipe. It was anticipated that this may produce a less dense structure in the degraded area as seen in naturally degraded pipe. This however did not occur to any visible extent.

For use in the lining experiments 1m lengths of artificially degraded asbestos cement pipe were produced. This involved first removing the bitumen lining from the pipe bore using xylene as a solvent.

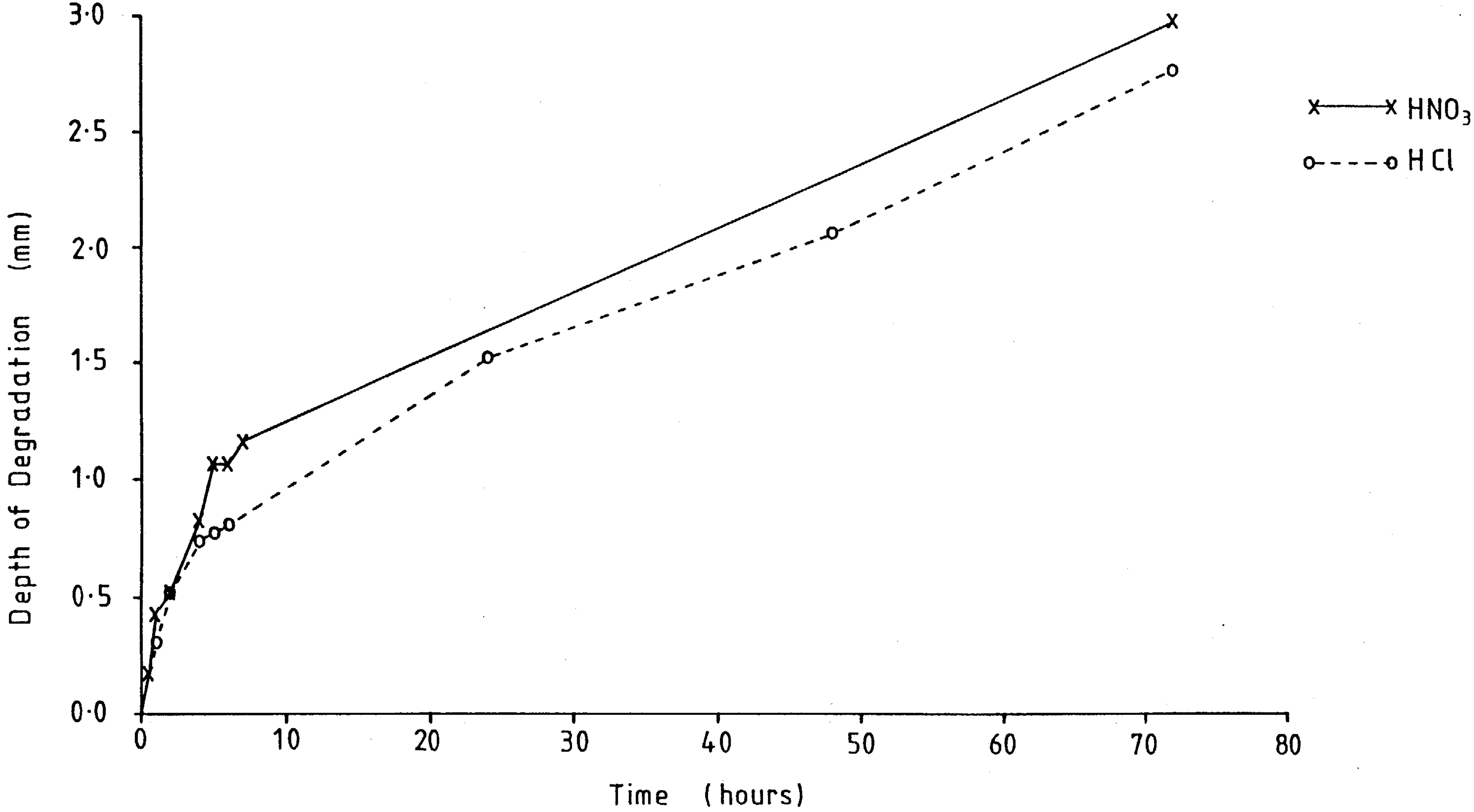
The pipe ends were then sealed with PVC plates and silicone rubber, two holes in the top plate allowed the ingress of acid and egress of gases.

The pipe was filled with a solution of 20% HNO_3 in water and left to stand for 48 hours. After 48 hours the acid was removed by unsealing the bottom plate. The pipe was thoroughly washed out to remove any remaining acid.

1.3 DISCUSSION

A standard artificially degraded pipe was produced. The degraded material however appeared more dense than that occurring in naturally degraded pipe. The probable reason for this is time. In service conditions the flow of water would remove any degradation products produced. However the artificial degradation may not have allowed sufficient time for complete removal of the reaction products.

Figure A8 Degradation Depth against Time



APPENDIX 9 - DETAILS OF ACCELERATED CORROSION EXPERIMENTS

The experiments were designed to model the conditions prevailing in a distribution system conveying very aggressive water. Two experiments were devised to determine their suitability for assessing the performance and durability of coatings on various substrates as compared to uncoated control specimens.

For each experiment, the aggressive solution was deionised water saturated with carbon dioxide. This results in a low pH water, high in aggressive free carbon dioxide with a very low buffering capacity. These conditions are more extreme than those occurring in distribution systems and should therefore accelerate the rate of degradation.

i) PIPE TESTS

The experiment was designed to use lengths of coated pipe, thereby avoiding damage to the samples by machining.

300mm lengths of 75mm nominal diameter pipe were cut from each of the coating/substrate combinations. Glass plates were sealed to one end of the pipe using silicone rubber. A specially machined perspex plate was sealed to the other end to allow the connection of pipes for the inflow and egress of the test water. The inlet pipe which was fed to the bottom of the sample, and the overflow pipe (see Figure A9.1) were made of 4mm bore glass tubing. The pipe samples were mounted on immersible magnetic stirrers which were used to prevent the formation of concentration gradients in the solution. The apparatus was placed in a temperature controlled water bath maintained at 10°C to prevent any variations of dissolution mechanism due to different solubilities of various components when compared to the field operational conditions.

The aggressive water was supplied from a reverse osmosis unit with an ion exchange system, and continuous saturation with carbon dioxide. This was fed to the pipe samples via needle valve flow meters. The flow was maintained at a rate to give a 3 hour contact time in the test vessel.

The pH of the effluent water from the overflow was periodically monitored.

ii) **TUBE TESTS**

These tests were devised to determine whether a more simple evaluation technique than that provided by the pot tests could be used.

Small samples 30mm x 30mm were cut from the coated asbestos cement pipes. The cut faces and the external pipe wall were masked with epoxy resin to prevent attack. These samples were suspended in a clear perspex tube to allow visual examination of samples during the exposure period (Figure 3.4). A controlled flow of the test water was allowed to pass continuously over the samples. At periodic intervals a sample of each coating was removed for examination and measurement of any degradation which may have occurred.

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DoE 0001-SW/1

DETERIORATION OF ASBESTOS CEMENT WATER MAINS
(MSP 9731 SLD)

Final report to the Department of the Environment