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Durability of Reinforced Concrete Sewer Pipeline over 23 Years

Authors: G E Blight[1] and M G Alexander[2]

[1]Department of Civil Engineering, University of the Witwatersrand, Johannesburg
[2]Department of Civil Engineering, University of Cape Town

ABSTRACT: A reinforced concrete sewer pipeline in Johannesburg, South Africa, is exposed to the weather where it crosses three dry valleys over a series of pipe bridges. In 1975, a year after commissioning the sewer, it was discovered that the pipes were cracking, that the cracking was spreading on each affected pipe, and that more and more pipes were being affected.

A programme of field measurements soon established that the cracking resulted from restrained thermal bending. Pipes were insulated experimentally, and it was shown that the thermal bending could be very much reduced by this means. It was therefore, decided to permanently insulate the pipes on all three pipe bridges. Twenty-three years later in 1998, poor people living in shack settlements near the pipe bridges, began to steal the aluminium sheeting protecting the insulation and also removed the insulation, thus exposing the pipes to the elements once more.

This provided an opportunity to inspect the condition of the pipes and to assess the long-term efficacy of the insulation. It was found that the pipes had been almost perfectly protected by the insulation and it was decided to reinsulate them immediately, using an equivalent insulation system that it is hoped will not be so susceptible to theft.

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Journal Contact Details:
PO Box 75364
Lynnwood Ridge
Pretoria, 0040
South Africa
+27 12 348 5305

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Durability of reinforced concrete sewer pipeline over 23 years

G. E. Blight* and M. G. Alexander†

University of Witwatersrand; University of Cape Town

A reinforced concrete sewer pipeline in Johannesburg, South Africa, is exposed to the weather where it crosses three dry valleys over a series of pipe bridges. In 1975, a year after commissioning the sewer in May 1974, it was discovered that the pipes were cracking, that the cracking was spreading on each affected pipe, and that more and more pipes were being affected. A programme of field measurements soon established that the cracking resulted from restrained thermal bending. Pipes were insulated experimentally and it was shown that the thermal bending could be very much reduced by this means. It was therefore decided to permanently insulate the pipes on all three pipe bridges. Twenty-tree years later in 1998, poor people living in shack settlements near the pipe bridges began to steal the aluminium sheeting protecting the insulation and also removed the insulation, thus exposing the pipes to the elements once more. This provided an opportunity to inspect the condition of the pipes and to assess the long-term efficacy of the insulation. It was found that the pipes had been almost perfectly protected by the insulation and it was decided to reinsulate them immediately, using an equivalent insulation system that it is hoped will not be so susceptible to theft.

Introduction – history of the pipeline

The Diepsloot outfall sewer from Johannesburg crosses the valley of the Jukskei River and two other valleys by means of a series of pipe bridges. Where it crosses a valley, the sewer consists of a line of reinforced concrete pipe 3.350 m o.d., with a 230 mm thick wall. The pipes were spun and made of concrete with dolomite aggregate. Unfortunately, details of the concrete mix and properties of the reinforcing have not survived. Each pipe segment is approximately 3m long, with spigot-and-socket joints sealed with rubber O-rings and an external polysulphide rubber filler. Each length of pipe rests on two pedestals which support the pipe at its ends. The pipelines were completed between October 1973 and May 1974, and the sewer was commissioned shortly thereafter. Fig. 1 (taken in 1998) shows part of one of the three pipe bridges. The aluminium cladding and insulation have been removed over 36 pipe lengths, as seen in the photograph. Fig. 2 shows a close-up of a pedestal and the joint between the two pipes it supports (also taken in 1998). After a year of service (winter of 1975) it was noticed that cracks were appearing in the pipes, that cracking in affected pipes was spreading and that more and more pipes were becoming affected. The first author was commissioned to investigate the causes of the cracking and to recommend remedial measures. This he did with the assistance of the second author.

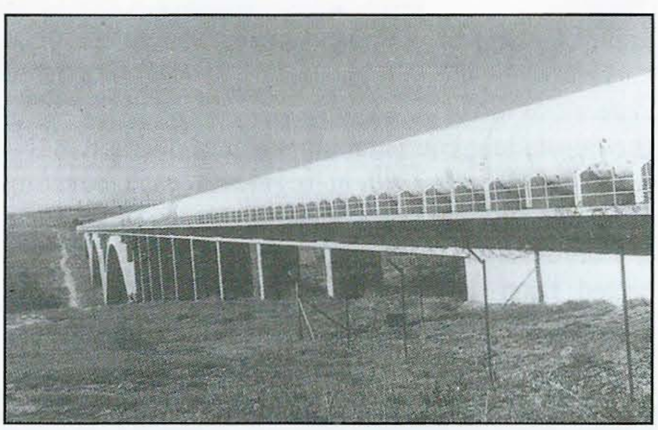

Fig. 1. Part of one of the three pipe bridges carrying the sewer pipeline. (Insulation has been removed from 36 pipe lengths from right to left)

* Department of Civil Engineering, University of Witwatersrand, Johannesburg, Private Bag 3, WITS 2050, South Africa.
† Department of Civil Engineering, University of Cape Town, South Africa.

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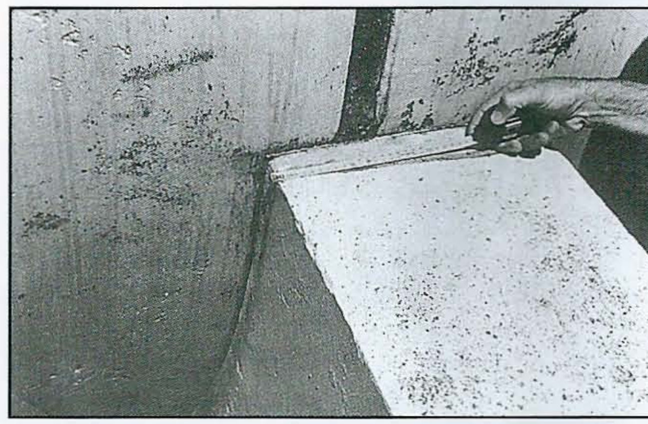

Fig. 2. Joint between two pipes, and supporting pedestal. Insulation has been removed from pipes and excellent condition of concrete is evident

A programme of strain measurements, started in August 1975, soon established that the cracking was caused by restrained thermal bending within the pipe wall. There were also indications that the pipes were moving relative to their pedestals and there was a fear that this differential movement, accumulating over the years, could lead to the unseating of certain pipes, resulting in failure of the sewer. It was recommended that the exposed pipes be insulated to reduce the thermal bending, although the 'pipe train movement' effects might thereby be exacerbated.

Strain measurements, on individual pipe lengths insulated experimentally, confirmed that the thermal bending could be much reduced by insulating the pipes. Because cracking of the pipes appeared to be the most serious effect of the thermal strains, it was decided to insulate all of the exposed pipes.

The insulation consisted of saddles of rigid polyurethane foam preformed in segments, each covering 120° of the pipe circumference and strapped in place with fibre-reinforced plastic strapping. The foam was protected from the weather by means of aluminium sheet, grade 3SH8, thickness 0·9mm, spring-tensioned around the foam saddles. The total length of pipeline insulated was 2770m, having a surface area of 28 750m^2.

Recently, large areas of the aluminium sheeting have been removed and stolen from the pipeline, presumably for sale as scrap, or for building shacks in a nearby shanty town or informal settlement. The insulating slabs do not appear to be considered worth stealing, and most of the foam, after cutting the retaining straps, has either been discarded, or burned. The first author was commissioned to investigate and report on the

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present condition of the pipeline, and recommend a suitable system for protecting the pipe from continued deterioration as a result of thermal movements.

This paper will describe the original investigation and its results and show how the performance of the insulating system was evaluated. It will also describe the condition of the pipes 23 years later, and the replacement insulation system.

The 1975 field investigation and measurements

The measurements described in this section were never published in full. A brief summary of the work and findings was, however, published in Australia[1] in 1981.

Progression of cracking

Figure 3 shows the results of crack surveys to establish the extent and progression of the cracking.

A sequence of cracking was evident in the pipes on all three bridges. Typically a pipe would develop a circumferential crack at mid-length on top. The crack would then grow down the sides of the pipe, usually advancing quicker down the east side where higher temperatures were experienced than the west side. This primary crack from the top would frequently coalesce with a secondary crack that had initiated on the bottom of the pipe and grown upwards, thus encircling the pipe completely. The next phase of cracking was when longitudinal branch cracks at regular spacing grew outwards from the main circumferential crack. The branching cracks were followed by a new circumferential crack initiating on the top of the pipe about 300 or 600 mm away from the initial circumferential crack. This new crack would follow the same sequence of cracking, growing down the sides of the pipe, intersecting the longitudinal branches, and itself producing longitudinal cracks. The whole sequence of cracking as outlined took between six months and a year to occur.

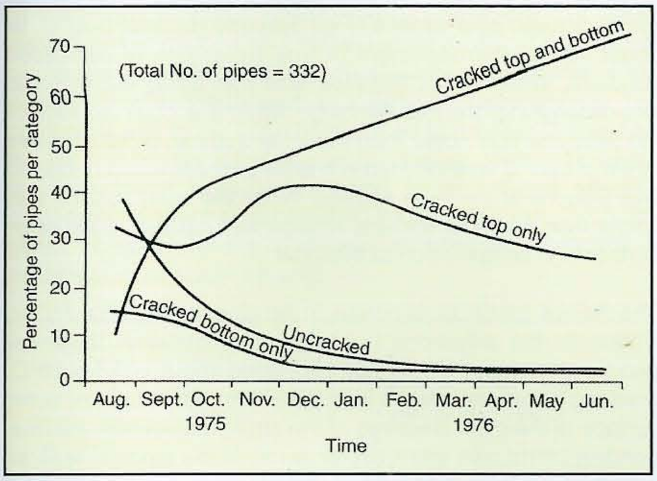

Fig. 3. Progression of cracking with time

Thus the pattern of cracking in advanced stages represented a series of rectangles, with sides of approximately 300 or 600 mm. All the pipes were expected eventually to exhibit this cracking pattern, with serious long-term consequences.

Initially, the cracks were of hairline width and difficult to detect through the heat-reflective paint layer on the pipes. With time, individual crack widths increased, as each crack grew through the pipe wall and became mechanically 'blocked' by dust and small concrete particles. At no time did crack widths exceed 0·1 mm. The cracks advanced or grew at an average rate of 11 mm per day, but with wide variations on either side of this mean.

Thermal strains in pipes

It was suspected that the cracking resulted from restrained thermal movements, and a series of temperature and strain measurements was started. Strains were measured by means of a demountable 'Demec' gauge of 200 mm gauge length, while temperatures of the outer surfaces of the pipes were measured by means of thermocouple junctions embedded 5-10 mm into the concrete and secured in place by means of epoxy putty.

Figure 4 shows typical diurnal ambient temperature variations and variations of the temperature of the concrete surface at the top of a pipe. The temperature of the concrete in early

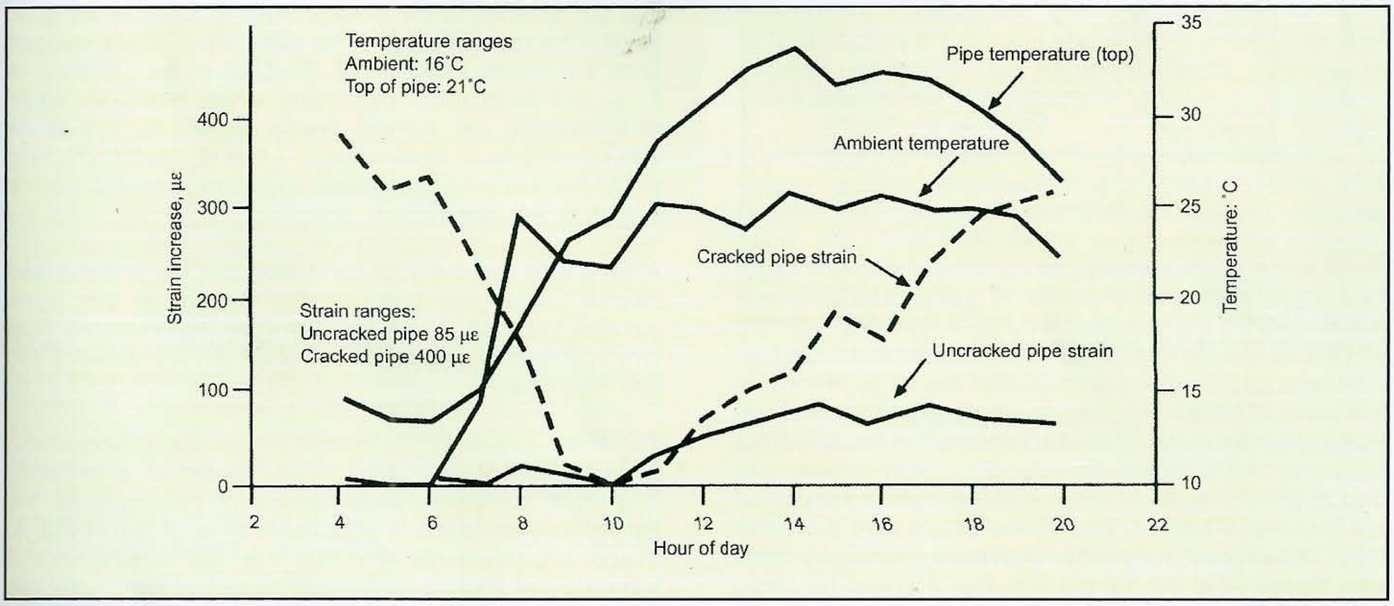

Fig. 4. Comparison of thermal strains measured on cracked and uncracked pipes

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afternoon was 7-8°C above ambient temperature, and 5°C warmer than ambient in the early morning. The surface of an uncracked pipe expanded longitudinally as the temperature rose and contracted as it fell. In contrast, longitudinal movements measured across a crack showed a decrease at first as the uncracked concrete on either side of the crack expanded towards the crack, followed by an increase once the crack had closed and the whole top of the pipe expanded. Movements measured across a crack were much higher than those measured on an uncracked surface, as shown by Fig. 4, but this obviously depended on the distance between cracks.

Figures 5(a) – (c) summarize measurements of temperature strain on the surface of a typical pipe.

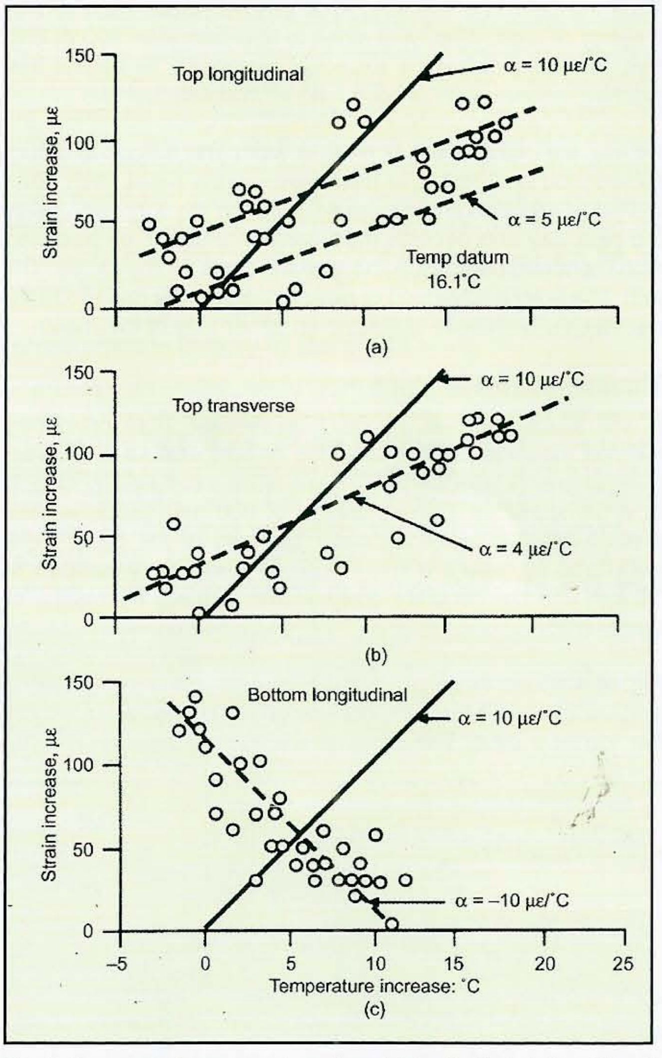

Fig. 5. Thermal strains measured on pipes: (a) longitudinal strains at top of pipe; (b) transverse strains at top of pipe; and (c) longitudinal movement (expressed as strain) across a transverse crack

At the time of measuring, this pipe was largely uncracked, but a circumferential crack did exist at mid-length of the pipe at the lower end of the vertical diameter. The strain targets were fixed at the mid-length of the pipe at the ends of the vertical and horizontal diameters. Longitudinal strains were measured at top, bottom, east and west positions and transverse strains were measured at the top position. Figs 5(a) and (b) show, respectively, longitudinal and transverse thermal strains measured on the top of the pipe on three days (16 and 18 September and 16 October 1975). The measurements are somewhat scattered but nevertheless show a clear trend.

The effective coefficient of expansion/contraction of the pipe surface both longitudinally and transversely was found to be 4 to 5με/°C(1με = 1×10^{-6}) compared with an assumed coefficient of 10με/°C. The coefficient of free expansion/contraction of the material of the pipe wall was not measured at that time. In preparing this paper, the coefficient was measured on a piece of concrete cut from a similar pipe and found to be between 9 and 11με/°C with the concrete conditioned to a 70% relative humidity (RH) atmosphere. The value assumed in the original investigation therefore appears to have been realistic. The 70% RH was chosen on the basis that the inside of the pipe must have been (and still is) at an RH of 100%, as it was carrying sewage. The outside RH was much lower, but previous measurements on other structures in the same climatic zone[2] suggested that an RH of 70% was a reasonable assumption for the near-surface pores of the concrete. Strains measured on the west and east sides of the pipe were very similar to those measured on the top of the pipe.

The fact that the effective coefficient of thermal expansion of the uncracked pipe surface (Figs 5(a) and (b)) was 5με/°C, or about half of the coefficient of free expansion of reinforced concrete, showed that the pipe wall was being subjected to two-dimensional thermal bending. When the outer surface of the pipe wall was hotter than the inner surface, a compressive strain of 5με/°C was induced in it while a tensile strain of 5με/°C was induced at the inner surface. When the outer surface was colder than the inner surface, tension was caused at the outer surface and compression at the inner.

The failure strain of concrete in tension being 100–150με, whenever the difference in temperature between the inner and outer surfaces of the pipe exceeded about 100/5 = 20°C, cracking would have been initiated either at the inner or outer surface of the pipe. Because of the strain distribution, thermal bending on its own was unlikely to cause the pipes to leak as any crack passing right through the pipe wall would always be closed either at the inside or the outside. However, if sand and grit particles in the sewage were to lodge in an open crack in the invert of the pipe, the crack would remain wedged open and a leak could ensue. Because of the presence of hoop and longitudinal reinforcing which acted as strain concentrators, the thermal cracks tended to run either circumferentially or longitudinally — that is, thermal cracking would eventually have produced a uniform rectangular crack pattern on the pipe surface.

A convincing argument for concluding that the cracking had thermal origins was given by the observation that pipes completely buried in soil and therefore well-insulated from temperature changes, remained completely uncracked. (Also see Fig 9, later.)

The strain targets at the bottom of the pipe straddled the circumferential crack and the 'strains' measured at this point (Fig. 5(c)) represent mainly closure of the crack as the temperature increased in the same way as shown in Fig. 4. These measurements are thus not real strains, but a summation of thermal movements in cracked and uncracked concrete accumulated over the distance between the pair of

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targets, expressed in strain units. The negative slope of the trend line in Fig. 5(c) shows that crack closure as the temperature increased was the predominant component of the movement.

Differential moisture expansion of the interior of the pipes relative to the exterior was also considered as a possible cause of the observed cracking. To investigate this possibility, strain measurements were made on the inside and outside surfaces of a section of pipe set on end and filled with water. Both longitudinal and circumferential strains measured on the inside and outside surfaces fluctuated with temperature but no significant differential swelling was observed over a period of 30 days.

Thermal movement of pipes relative to bridge decks

Thermal strains were measured on the surface of the deck of one of the pipe bridges in a direction parallel to the bridge centreline. The strain targets were fixed to the top of the main longitudinal support beams. A set of these measurements is shown in Fig. 6. Details of the concrete mix used for the bridge have been lost. However a 30 MPa concrete was specified and the aggregate used was a local Witwatersrand quartzite. In preparing this paper, the coefficient of free expansion/contraction was measured on a core of 30-year-old nominally 30 MPa concrete made with a similar quartzite aggregate and conditioned in a 70% RH atmosphere. The coefficient was found to be between 10 and 13με/°C. Because the support beams are massive, it was expected that recorded thermal strains would correspond to a reduced effective coefficient of thermal expansion, as was the case with the pipes. However, as Fig. 6 shows, the effective coefficient of expansion was about 12με/°C.

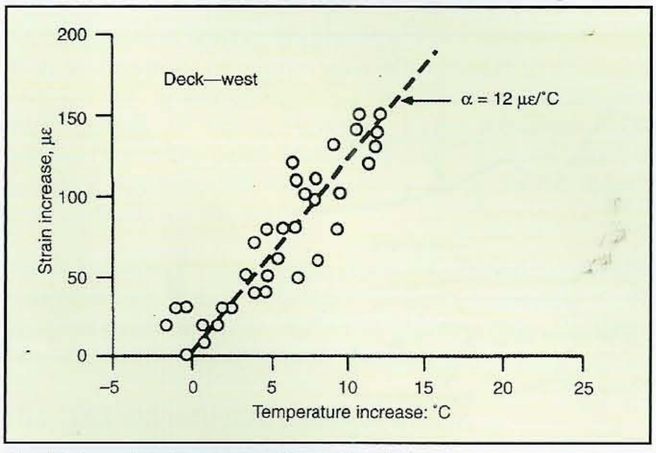

Fig. 6. Thermal strains measured on bridge deck

As the pipe pedestals are attached to the deck, they would have been expected to move with the deck — that is, their movement should have corresponded to a coefficient of 12με/°C over the distance between their transverse centrelines. If each pipe were to move independently of its fellows, its movement relative to the pedestals would thus correspond to a coefficient of thermal expansion of about (12 – 5) = 7με/°C (see Figs 5(a) and (b)).

Figure 7(a) shows the movement of the two ends of pipe Z46 relative to its pedestals, expressed as a strain over the full length of the pipe. It can be seen from the figure that the performance of this pipe was close to expectation. Fig. 7(b) shows the corresponding relationship between the thermal expansion of pipe Z46 (top longitudinal gauge) and temperature. Adding the two effective coefficients of expansion gives a coefficient of expansion for the bridge deck between pedestals of 14·5με/°C which corresponds reasonably well with the data shown in Fig. 6.

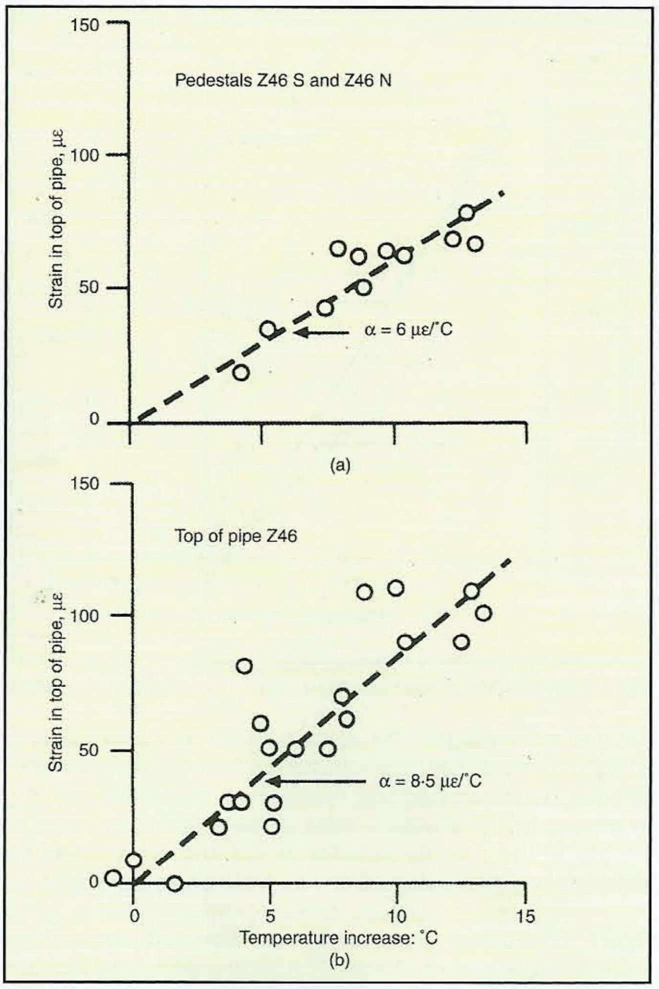

Fig. 7. Strain of pipe between supporting pedestals (a) compared with strain of top of pipe (b)

Other sets of measurements, however, were not so reassuring. The movements of another pipe relative to its pedestal are shown in Fig. 8. Movement was only measured at one end of the pipe, but the magnitude of the movement appears to indicate that some pipes were moving relative to the pedestals in 'trains' made up of several pipes. In this case the train appeared possibly to consist of 32/6 ≈ 5 pipes. It was estimated that the pipe joints could only tolerate an opening movement of 15 mm before starting to leak. This amount of movement could occur at a single joint if a train of ten pipes moving as a unit were to be subjected to a temperature change of 40°C. This was very unlikely to happen, but was by no means impossible.

Effect of insulating pipes against temperature change

After initial experiments with fibreglass insulation, it was

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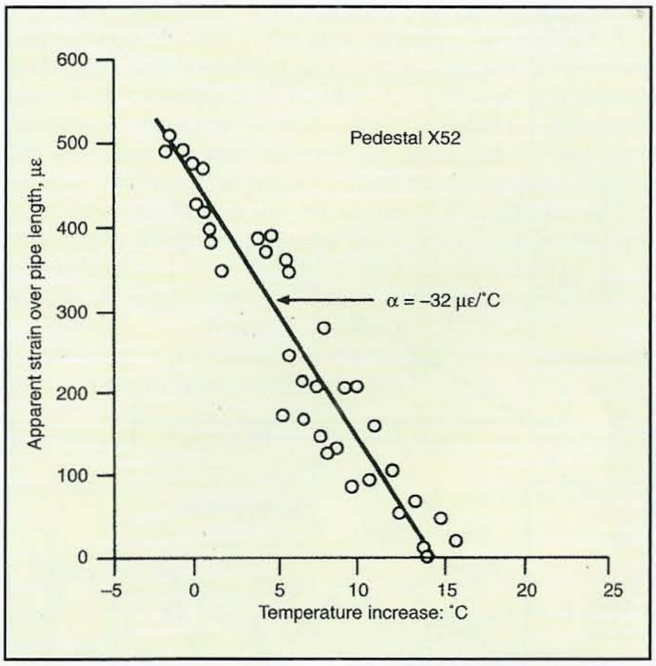

Fig. 8. Apparent strain of pipe relative to pedestal illustrating 'pipe train' effect

decided to investigate the efficacy of 50 mm thick sheet of 30 kg/m^3 polyurethane foam, protected from the weather by an external aluminium cladding. Preliminary measurements (Fig. 9) showed that this system reduced the temperature range on the top of the pipe by a factor of 4·5 and approached the temperature protection provided by a generous soil cover.

Figure 10 shows a direct comparison between temperatures and thermal strains on the surface of an unprotected pipe and that of two insulated pipes. Fig. 10(a) shows that the maximum temperature range at the surface of an insulated pipe is only 0·26 of that at the surface of an unprotected pipe while Fig. 8(b) shows that thermal strains are similarly reduced by a factor of 0·26. This means that a maximum likely ambient temperature fluctuation of 40°C would produce a variation at the surface of an insulated pipe of only 10°C which, in turn, would induce tensile strains at the pipe surface of about 50–60με. Strain of this magnitude would be insufficient to initiate thermal cracks in intact concrete, but would still be sufficient to extend existing cracks. This conclusion is supported by the observation that before insulating the pipes, the average rate of crack extension (over a 75-day period) appeared to be 11 mm / day. After insulating the pipes, the rate of crack extension fell to 3 mm / day but crack extension did not stop.

Possible movement of insulated pipes relative to bridge decks
The thermal movement between each pair of pipe pedestals on any one of the bridges will be $3000\bar{\alpha}$ mm /°C where $\bar{\alpha}$, the effective coefficient of thermal expansion of the bridge deck, appears to be about 12με/°C (Fig. 6) and the spacing of the pedestals is 3000 mm. If each pipe were free of its neighbours and fully insulated so that its temperature did not change, the movement of each end of the pipe relative to its supporting pedestal would be $1500\bar{\alpha}$ mm/°C.

However, if the pipes behave as if they are linked in 'trains', the movement relative to the pipe pedestals could be much larger than this. But, as the following calculation will show, actual unseating of pipes by differential movement was not considered likely.

The width of the pipe seatings is 180 mm.
If $\bar{\alpha} = 12{\cdot}10^{-6}$/°C and the change of temperature
$\Delta\theta = 40$°C, then the maximum numbers of pipes in a train that can accommodate the movement relative to the pedestals is

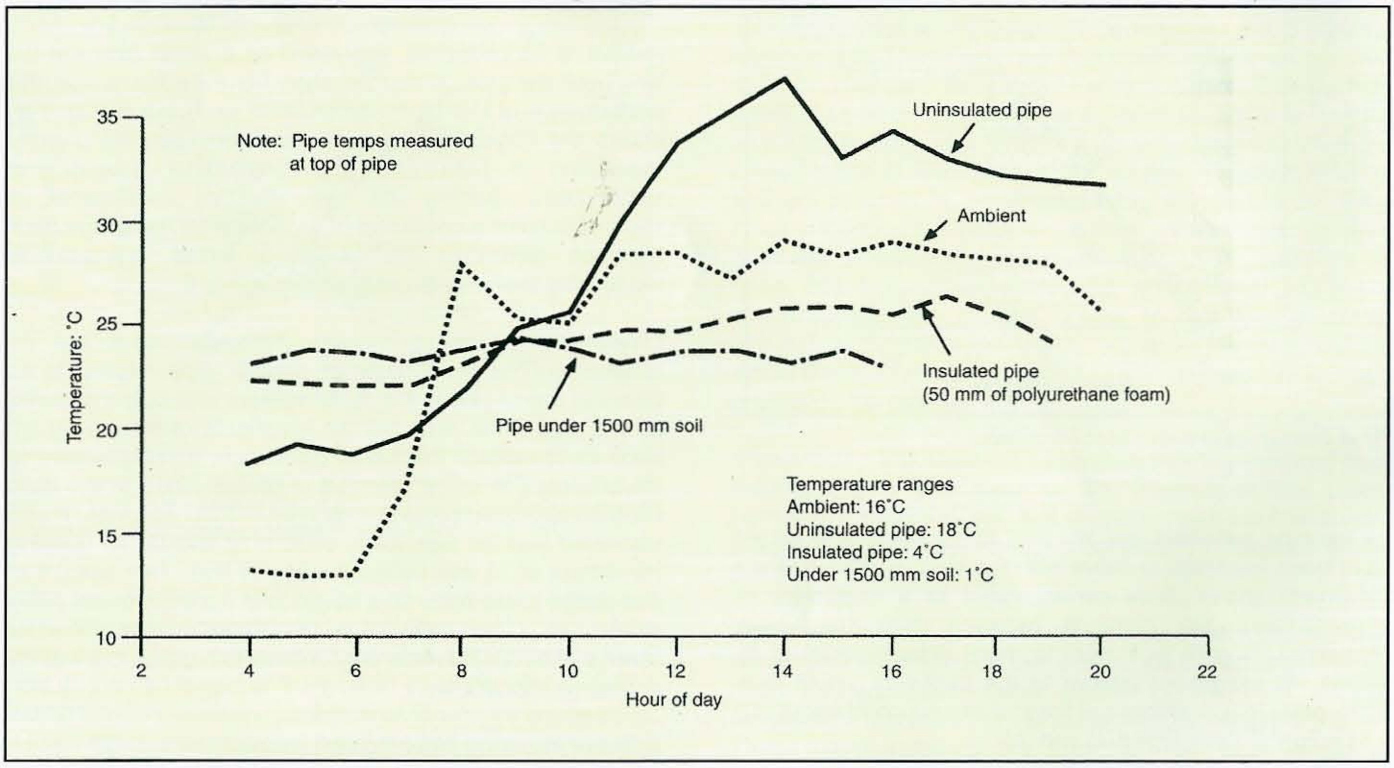

Fig.9. Effect of insulating pipe on thermal strains

Durability of reinforced concrete sewer pipeline over 23 years (cont.)

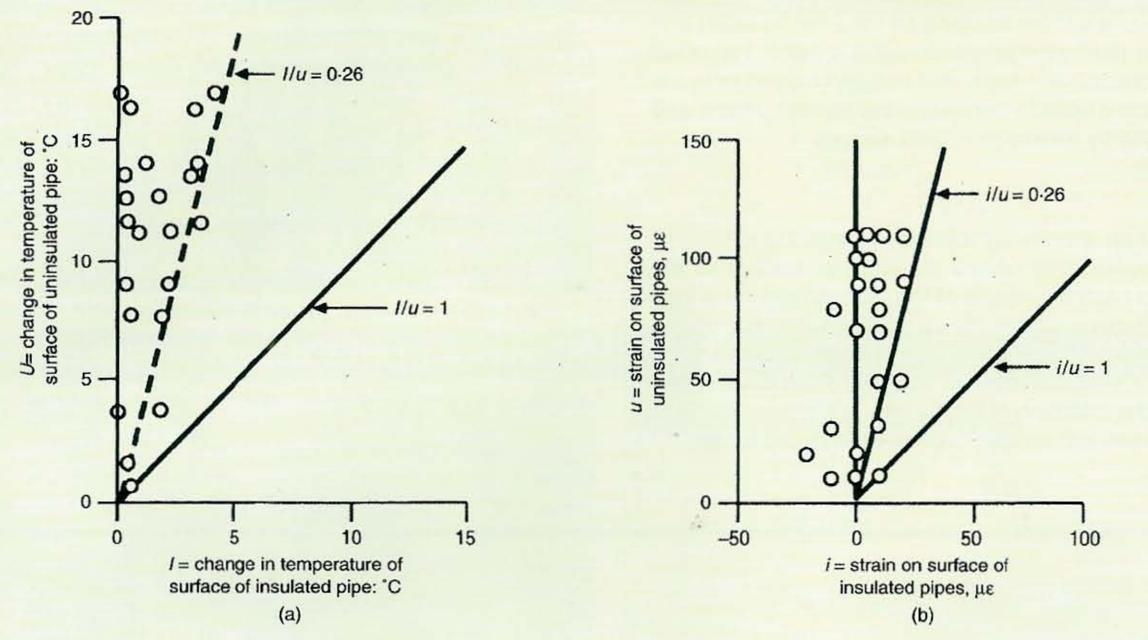

Fig. 10. Effect of insulation on reducing: (a) pipe temperatures; and (b) thermal strains

$$P = \frac{180}{3000 \times 12 \times 10^{-6} \times 40} = 125$$

As the maximum number of pipes in any one section of the line (from an abutment to an expansion joint or between expansion joints) is 87, unseating by this mechanism was considered most unlikely to occur. However, if the expansion gaps between individual pipes were all to close up, there might be sufficient play available, if not to unseat a pipe, then at least to cause a badly leaking joint.

As the benefits of insulating the pipes outweighed the possible disadvantages, it was decided to proceed to insulate all the exposed pipes using 50 mm of polyurethane foam, protected from the weather by aluminium sheeting.

The 1998 inspection

The pipes that had been stripped of their insulation by thieves were carefully examined in November 1998, just less than 23 years after the insulation had been applied. In the course of the 1975 investigation, the progression of the cracks had been marked with a marker pen. These markings were as clear as the day they had been applied, and it was thus a simple matter to assess the change in the condition of the pipes over the intervening 23 years. All cracks were found to have extended, but most had terminated a metre or so beyond the last marking. All cracks were very fine–too narrow to insert a 0·1 mm feeler gauge. There were signs of very slight leakage below the inverts of some of the pipes, but these leaks appeared to have stopped, possibly by autogenous healing. There were absolutely no stains or cracking that could have indicated corrosion of the pipe reinforcement. Figs 1 and 2 are typical of the generally excellent condition of the pipes.

The pedestals were inspected for cumulative thermal movement. All those inspected showed signs of slight, repeated, but reversible movement. No signs of cumulative and progressive movement in one direction only were found.

It was concluded that the insulation had functioned very well and that the pipes had deteriorated very little while protected.

Remedial measures

It was clearly essential that the pipes be reinsulated over those sections where the insulation had been removed. Obviously, the system to be used to replace the original insulation and its aluminium protection should have no attraction for thieves.

The insulation itself appeared to have no theft value and this would continue unless it were realized that the sheet of foam could be used to insulate the walls of shacks. Hence it would be preferable to choose a system in which the insulation is bonded or glued to the concrete pipe surface and could not be detached, except in small useless fragments.

If a closed cell foam were used, it would not absorb water, but the outer surface would have to be protected against deterioration caused by ultraviolet light. This could be done by means of a paint system, or a membrane and paint system. Such a system would not have the durability of aluminium sheeting but should give a life of at least five years before repainting would be necessary.

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Two such systems were identified. One consists of a closed-cell premoulded polyurethane foam that can be glued to the concrete pipe surface (after stripping off the existing paint) and protected with a paint or a membrane and a paint. The other consists of a polyurethane foam that can be sprayed onto the pipe wall *in situ*, will bond to the cleaned concrete surface, and then be protected by means of a paint system.

Conclusions

It is seldom that an opportunity arises to assess the efficacy of a repair intervention that covers the original surface of the concrete. In this case the results of the assessment were very reassuring. They showed that the conclusions drawn from the original investigation were correct and the expenditure on the original insulation was fully justified. Sections of the pipeline that have escaped the attention of the thieves are still in first-class condition and could last another quarter-century and longer.

Blight and Alexander

Acknowledgement

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References

1. ALEXANDER M. G. Thermal cracking of exposed concrete pipelines. *Proceedings of the 2nd Australian Conference on Engineering Materials, Sydney*, 1981, 210–212.
2. BLIGHT G. E. The moisture condition in an exposed structure damaged by alkali – silica reaction. *Magazine of Concrete Research*, 1991, **43**, No. 157, 249–255.