Measurements of the hydraulic roughness of slimed sewer pipes

J A Perkins and I M Gardiner

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Hydraulics Research Station
Wallingford
Oxon OX10 8BA
Telephone 0491 35381
Telex 848552

Abstract

A series of experiments on the effect of sliming on the hydraulic roughness of foul sewers has been carried out on a specially-constructed rig at a sewage pumping station at Littlemore, Oxford. Three separate runs of 335, 206 and 188 days duration were conducted on a continuous pipeline made up of vertically-cast concrete, uPVC, spun concrete, asbestos-cement and unglazed clay pipes of 225mm diameter. The first two runs were made with the pipes at a gradient of 1 in 250 and a velocity of 0.75m/s: the third run was made at a gradient of 1 in 100 and a velocity of 1.2m/s. In each test the flow was varied continuously on a daily cycle with a peak at 1000 hours, giving approximately half-full depths, and a secondary minor peak at 1900 hours.

At weekly intervals measurements were made of hydraulic roughness and sewage temperature and photographs taken of the slime on the pipe walls. Periodically, sections of pipe were detached and the slime removed and weighed.

The main conclusions from the tests are:-

1. After a rapid, initial build-up of slime, there is a complex balance between growth and loss due to the shearing action of the flow, which shows some seasonal variations but no long-term trend.
2. The pipe material has some influence on the amount of slime present and therefore on the hydraulic roughness.
3. The amount of slime and the hydraulic roughness decrease with an increase in pipe gradient and velocity.
4. The roughness of a free-surface gravity sewer is much larger when running part-full than full.

Values of hydraulic roughness for foul sewers have been recommended for designers, using the Colebrook-White flow equations or the Wallingford Charts and Tables[6,7]. These are consistent with earlier recommended values, based on spot field measurements by Ackers et al[1].

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1 Introduction

There is a limited amount of data on the effect that sliming has on the hydraulic resistance of foul sewers. In the UK the principal sources of data have been the work of Ackers, Crickmore and Holmes[1] and that of Bland, Bayley and Thomas[2].

In 1973, the Department of the Environment Working Party on Sewers and Water Mains recommended[3] that further research be carried out, in order to extend the range of the work previously undertaken. Bland's experiments[2] had been carried out using 100mm diameter pipes, flowing full under pressure with the sewage being re-circulated through the test rig. It was considered that these conditions did not truly represent typical conditions in a normal gravity sewer, in which there is usually an air-water interface and a variation in flow rate throughout the day. The Working Party supported the Hydraulics Research Station's (HRS) proposals to carry out experiments on 225mm diameter pipes of the materials commonly used in the drainage industry, with fresh sewage circulated through the experimental pipe, and with the pipes flowing only part-full, the flow varying with time in a similar fashion to the flow variation in a normal gravity foul sewer.

An experimental rig was constructed by HRS at the Littlemore sewage pumping station of the Thames Water Authority with the co-operation and assistance of TWA staff. At this site there was a sufficient flow of sewage for the requirements of the experiments, thus avoiding the need to re-circulate through the experimental rig. The pumping station is located at the end of one of the main Oxford sewers, and from there, sewage is pumped to the main treatment works at Sandford. The sewage is mainly domestic, but includes a small amount of surface water and some trade and industrial waste amounting to 4 per cent (approximately) of the dry weather flow (DWF).

2 Description of experimental rig

The experimental rig comprised a pipeline 157m long, 225mm in diameter, laid above ground and supported on a series of screw jack props. The site did not permit a continuous length of straight pipe, so that it was necessary to include a 180° bend in the middle of the pipeline.

The general layout of the rig is shown in Fig 1 and Plate 1. Five test sections, from 13 to 20m long, were incorporated in the pipe line: these comprised asbestos-cement (20m length) spun concrete (20m) vertically cast concrete (13m) unglazed clay (20m) and uPVC (18m). Upstream from each of the test lengths, there was a shorter length of pipe of the same material as the test length: this was meant to serve as an entry length and provided a transition between test lengths of pipes of different materials. The test length of vertically cast concrete was incorporated into the rig at a very late stage in design and as a result of space limitations it was shorter than the test lengths of the other materials. Vertically cast pipes were included because a significant quantity of this type of pipe is used, and because of the impression that the surface roughness was different from that of spun concrete pipes.

Ideally the pipes should have been arranged in parallel but the problems involved in providing a control system that would supply identical varying flows to each of the individual pipe lengths and in supplying the large volume of flow needed, ruled this out. It was therefore decided to arrange the pipes in series, particularly as it was thought that this would not have any influence on the slime growth in the various pipes: one of the conclusions from the work of Bland et al[2] was that the order in which the different pipe materials occurred in their pipeline was not a significant factor in their experiments.

Downstream from each test length there were short pipe sections of the same material, specially jointed to allow them to be removed easily from the test rig for the examination and removal of slime growth.

Each test length was fitted with a number of sets of pressure tappings; each set consisted of four brass inserts of 3.18mm ID, set into the pipe. The four tappings were at 0° (soffit of pipe), 60°, 137° and 240°, around the pipe circumference and were inter-connected so that they measured a mean pressure over the cross-section of flow. The various sets of pressure tappings were linked to manometer boards fitted with vernier scales that enabled the pressures to be measured to within ±0.1mm.

In order to prevent the water in the manometer tubes from freezing during the winter,, a 10% solution (by volume) of anti-freeze in water, was used in the tubes. The anti-freeze was a mixture of glycol (2 parts by volume) and methanol (1 part).

The positions of the pressure tapping rings along the test lengths were:

Pipe material	Distance from downstream tapping ring (m)
Vertically cast concrete	0, 2.47, 4.95, 7.35, 9.85
uPVC	0, 5.46, 5.98, 11.44, 11.99, 17.45
Spun concrete	0, 3.67, 7.33, 11.01, 14.67
Asbestos cement	0, 3.99, 7.98, 11.98, 15.97, 19.97
Clay	0, 3.03, 6.06, 9.09, 12.11, 15.14

Special access holes were cut into the soffits of the pipes at the upstream ends of the test lengths in order to allow the insertion of a camera for taking regular photographs of the interior of the pipes.

The whole of the pipeline was insulated with 38mm of expanded polystyrene in order to protect it from extremes of temperature and thus maintain the sewage at the same temperature as the sewage arriving at the pumping station.

The arrangement for supplying flow to the test rig was to pump from the wet well of the pumping station up to a constant head tank 8m above the ground. Here the flow was split, part of it returning to the wet well by means of an overflow in the constant head tank, the remainder passing to the test pipeline via a tilting weir, whose angle (and hence the discharge over it) was controlled in a predetermined pattern by a rotating cam mechanism.

The sewage in the wet well had already received some primary treatment to the extent of having grit and most of the rags removed by grit channels and by coarse screens. The reason for taking the sewage from the wet well rather than from the trunk sewer upstream from the primary treatment, was because the intention was to operate the experiment continuously over a long period of time. If completely untreated sewage had been used, it was certain that there would have been continual problems from rags blocking the pipeline and interfering with the operation of the flow control apparatus in the constant head tank. As it was, problems of this type were still experienced, despite the sewage having received some treatment.

A standard flat-Vee gauging weir was installed at the downstream end of the pipeline for measuring the discharge during the experiments.

An air vent tank was installed at the upstream end of the experimental pipeline in order to allow the escape of any air that had been entrained in the sewage in its passage from the constant head tank to the pipeline, by way of a vertical drop pipe.

In order to be able to determine the roughness of the pipes in the clean condition, before any sliming had taken place, the rig was designed so that clean water could be circulated through the experimental pipeline — a separate fresh water pump was installed and a tank was constructed to serve as a fresh water reservoir.

3 Experimental programme

Three separate, long term runs, were carried out. There were as follows:

Run 1 — Pipeline at a gradient of 1 in 250; hydrograph 1. Run started on 22 January 1976 and concluded on 22 December 1976; total run time 335 days.

Run 2 — Pipeline at a gradient of 1 in 250; hydrograph 2. Run started on 19 April 1977 and concluded on 11 November 1977; total run time 206 days.

Run 3 — Pipeline at a gradient of 1 in 100; hydrograph 3. Run started on 17 April 1980 and finished on 22 October 1980; total run time 188 days.

4 Run hydrographs

Three different 24-hour hydrographs were used in the experiments. The shape of all three was similar; the difference between them lay in the discharges that occured at the peaks and troughs.

The maximum peak discharge occurred at 10.00 hours (approximately) with a secondary peak in the evening at 19.00 hours: the minimum discharge was at 04.00 hours, with a secondary trough at 16.00 hours. The maximum and minimum discharge rates in the hydrographs were based on advice received from a number of drainage engineers.

During any run, the hydrograph was repeated daily, 7 days a week. The characteristics of the different hydrographs are given in the following table and are also shown in Fig 2 (Hydrograph 1), Fig 3 (Hydrograph 2) and Fig 4 (Hydrograph 3).

Hydrograph No.	Peaks						Troughs					
	Maximum			Intermediate			Maximum			Intermediate		
	Discharge m^3/s	Velocity m/s	Prop'l depth *	Discharge m^3/s	Velocity m/s	Prop'l depth *	Discharge m^3/s	Velocity m/s	Prop'l depth *	Discharge m^3/s	Velocity m/s	Prop'l depth *
1	0.02025	0.78	0.6	0.0109	0.67	0.42	0.0047	0.52	0.27	0.0017	0.37	0.16
2	0.015	0.75	0.5	0.010	0.66	0.41	0.0068	0.59	0.33	0.0018	0.40	0.17
3	0.026	1.18	0.54	0.0175	1.07	0.43	0.0115	0.95	0.34	0.003	0.64	0.18

The proportional depths* and the mean velocities are calculated assuming that the pipe surface is slimed, with an equivalent sand roughness of k = 1.5mm.

5 Experimental measurements

All the pipes used in the experiments were taken from the manufacturer's standard stocks and before being installed in the rig, their bores were all measured. A volumetric method was used to determine the mean diameter for the vertically-cast concrete and the clay. The diameters of the other pipes were obtained by means of calipers; two orthogonal diameters were measured at various positions along each pipe. The results are:

Material	Length of individual pipe (m)	Mean diameter (mm)	Standard deviation (mm)
Vertically cast concrete	1.2	225.6	0.80
uPVC	6.0	230.6	0.55
Spun concrete	1.8	222.1	2.36
Asbestos cement	4.0	228.8	0.71
Clay	1.5	227.5	0.38

The general procedure that was followed in each of the three runs was first to determine the hydraulic roughness of the pipes in a clean condition, using clean water; these tests were carried out at Reynolds numbers ranging from 1×10^5 to 3×10^5. Following the clean water tests sewage was passed through the rig, allowing slime to build up; the roughness was determined at regular intervals throughout this sliming phase.

The method for determining the roughness was to stop the discharge hydrograph, supply a known steady discharge to the experimental pipeline (which was made to flow full by throttling a valve at the downstream end) and measure the pressure at each of the tapping positions. A best-fit hydraulic gradient was then calculated for each of the test lengths, from which it was then possible to compute the hydraulic roughness, using the Colebrook-White equation[6,7]:

$$V = -\sqrt{8gDS}\log\left[\frac{k}{3.7D} + \frac{2.51\nu}{D\sqrt{2gDS}}\right]$$

where

V = mean velocity (m/s)

g = gravitational acceleration (m/s^2)

D = pipe diameter (m)

S = hydraulic gradient

k = roughness value (m)

ν = kinematic viscosity of fluid (m^2/s)

In carrying out this calculation it was assumed that the pipe diameter was the original clean diameter; no allowance was made for any effect that the sliming would have on reducing the pipe diameter. This would have been difficult to do because the sliming was not uniformly distributed around the pipe periphery and presented a very uneven surface.

The roughness calculated from the Colebrook-White equation is for a pipe with a perimeter that is partially slimed (up to the maximum depth of flow during the slime-building hydrograph) and partially clean.

On the days when the roughness was being determined, the practice was to carry out three separate tests at Reynolds numbers ranging from 85×10^3 to 150×10^3 for Runs 1 and 2 and from 130×10^3 to 180×10^3 for Run 3. The Reynolds number was restricted to this range in order to ensure that the shear stress during these tests was not greater than the shear stress that was being generated during the slime building process. The maximum shear stress in Runs 1 and 2 during the slime building process was approximately $2.5 N/m^2$, whereas the maximum during the roughness determination tests, was $2.2 N/m^2$.

As well as determining the pipe roughness, a complete photographic record was made of the changing sliming pattern in each of the test lengths. Periodically the removable sections were taken from the pipe, the interiors were photographed and the slime was then scraped off, dried and weighed.

From time to time, dissolved oxygen levels were measured in the sewage in the rig and in the sewage arriving at the pumping station. Occasionally, dissolved oxygen levels were also measured in various of the sewers in Oxford City that contributed flow to the trunk sewer feeding the pumping station.

A continuous record of the temperature of the sewage in the rig was maintained.

Between each of the three main runs, the slime was removed from the pipes by means of the Dyno-Rod pressure-jetting system. This ensured that all the pipes were properly clean before the experimental runs began.

6 Experimental results

Run 1 6.1

Clean water tests

Before any sewage was passed through the rig, clean water was circulated and the 'as-new' roughness of the pipes flowing full, was determined. The values obtained from these tests are overall figures which take into account surface texture as well as joint discontinuities and pipe misalignments; in this case the latter two factors are not considered to have a great influence because of the care that was taken in assembling the pipeline. The results are given in Table 1 and discussed in Section 6.3.

Sewage tests The general experimental procedure has been described in Section 5: details of the flow hydrograph were also given there. Roughness values were determined at weekly intervals. The general pattern of variation of roughness with time is shown in Fig 5A together with the variation in sewage temperature over the period; the plotted roughness is the mean value from the three tests carried out on any one day. In Figs 5 and 6, the origins for the x-axis have been staggered so that the months of the year are aligned in the vertical direction.

It was not possible to start the hydrograph immediately the fresh water tests were completed, because of various teething troubles with the rig. For about a week, the rig was operated intermittently, using sewage, and during this time the roughness increased to the values shown at day zero of the hydrograph.

When the hydrograph began to operate continuously, the roughness increased very rapidly for a period of 30 days, without any clear difference between the roughness of the different materials becoming evident. For the next 120 days the roughness varied in different ways in the five pipes, and there was a marked difference between them. At day 153 a pump breakdown occurred, which put the rig out of commission for two days at a time when the ambient air temperatures were high — Britain was experiencing an unusually hot summer. Although the downstream part of the experimental pipeline was filled with sewage whilst the pump was being repaired, so that the air in the upstream part of the pipeline should have had a high relative humidity, these precautions may not have been sufficient to prevent the slime from drying out. When the experiment was restarted, the roughness did not show any marked drop, but decreased steadily for a further twenty days. This continued the reduction in roughness that was becoming apparent before the pump breakdown had occurred. The interruption to the experiment may have caused the slime to die and subsequently to slough off, but it does not explain why the slime was slow to build up again, once the experiment had been re-started; the pump breakdown may merely have accelerated a process that was already in train.

In order to determine the effect that the high summer temperatures were having on the sewage, measurements of dissolved oxygen concentrations were made at various points in the Oxford sewerage system on 7 July 1976 (day 167) using an EIL portable dissolved oxygen meter (model 1520). Further sets of measurements were made on 20 December (day 333) and on 10 August 1977 (day 112 of Run 2). The results from these measurements are given in Table 2 and are discussed in Section 6.4.

The sharp decline in roughness came to an end by about day 170: for the following 50 days the roughness of all the pipes fluctuated around a low steady mean value. For the remaining period of the run, the roughness started to increase for the two types of concrete pipe and for the asbestos-cement pipe, whereas for uPVC and clay the increase was not nearly so marked. The decision to end the first run was taken when a further pump failure occurred and it was apparent that the rig was going to be out of commission for some considerable time.

More detailed comments on the results are as follows:

Period from day 0 to day 170 In the first 20 days, when the slime was establishing itself, there was no significant difference between the different pipe materials. After this, differences did begin to emerge.

The variation of roughness of the spun concrete and of the vertically cast concrete, although not identical followed a very similar pattern; after peaking at day 28, the roughness fell over a short period of time, but thereafter rose steadily, reaching maximum values of 4.7 and 5.4mm respectively around day 120. There then followed a period of 50 days during which the roughness steadily decreased to values of 0.3 and 0.8mm. The close similarity of the response of the two types of concrete pipe is encouraging in view of the different behaviour of the other three types of pipe that were exposed to the same experimental conditions.

The roughness of the clay pipe peaked at day 20, and then fell. From day 35 to 70 the roughness remained fairly steady, fluctuating between 0.6 and 1.5mm, but it then increased over a period of roughly 20 days, reaching a value of approximately 2.5mm, where it remained for some 30 days. Following this, the roughness steadily reduced, but at a much slower rate than for the two types of concrete pipe.

The roughness of the asbestos-cement pipe varied in a similar manner to that of the clay; it peaked at day 35, fell sharply and then increased equally sharply, rising to a value of 3.0mm at day 49 and remaining reasonably constant around this value until day 146. The roughness then rapidly decreased to a value of 0.5mm at day 167.

The uPVC displayed somewhat different characteristics. The roughness peaked at day 28, but then fell steadily to day 63: it then rose again over the following 35 days to reach a peak value slightly higher than the initial peak value (1.6mm compared with 1.3mmm). Immediately after this the roughness steadily decreased.

The main differences between the behaviour of the different pipes during the first 120 days of Run 1 can be summarised as follows:

The spun and vertically cast concrete pipes were the roughest and were the only ones that showed a fairly continuous increase in roughness with time.

The next roughest pipe was asbestos-cement: this reached its stable value at about day 44 and maintained this value for about 100 days (approximately).

Although the peak roughness of the clay pipe was slightly lower than that for asbestos-cement, the pattern of variation was different. The clay pipe reached its maximum value very much more slowly than the asbestos-cement: there was an initial period (up to day 70) during which the roughness of the clay was steady at around 1 to 1.5mm, but this was followed by a period in which the roughness further increased before reaching its final stable value.

The uPVC pipe was different from all the others: the roughness variation showed two quite distinct peaks, at days 38 and 98. However day 98 appears as a minor peak on all the other pipes. If this measurement is ignored it is evident that uPVC reaches its peak value at about day 28 and remains close to this value for a further 80 days.

Another interesting feature of this part of the run, is the difference in the times at which the decline in roughness became evident. In the two concrete pipes, the roughness decreased after days 125 and 132; asbestos-cement after day 125; clay after day 111 and uPVC after day 98, or day 111 if the day 98 figure is ignored. There is a general pattern to the extent that the pipes with the lowest roughness were the soone. to show a decline. In all cases the decline began when the sewage temperature was between 15°C and 17°C and was well advanced before the pump failure occurred on day 153.

Period from day 170 to day 230

Prior to this period the roughness in all the pipes had very greatly decreased and for a significant part of this period it was less than 1mm. There were no marked trends evident; the roughness stayed fairly constant, spun and vertically case concrete pipes being slightly rougher than the group comprising clay, asbestos cement and uPVC. Throughout this period, covering most of July and August, the sewage temperature exceeded 20°C.

Period from day 230 to day 335

In this period, during which sewage temperatures declined from 20°C to below 15°C, marked differences in pipe characteristics were evident again, although these were not identical with those displayed during the first period of this run.

Again, although the two types of concrete pipe did not show a complete identity in the manner in which the roughness varied, nevertheless they were very similar. The roughness of both started to increase at day 230; vertically cast reached its peak value (3.3mm) on day 266, spun on day 272 (2.3mm). Following the peaks, the vertically cast roughness decreased and then remained fairly constant at around 2 to 2.4mm until day 297, when it again showed a further decrease in roughness. The roughness of the spun concrete varied in a slightly different fashion: after the peak, it then fell to a minimum of 1mm at day 287, before rising again to 2.9mm at day 304. It then decreased, similarly to the vertically cast. During this period of the run the maximum roughness of the two concrete pipes was significantly lower than it had been in the early part of the run (2.9 and 3.3mm compared with 5.3 and 4.7mm previously).

The roughness of the asbestos-cement pipe during this period varied in a manner similar to that of the concrete pipes in the early period of this run: from day 210 to day 303 it showed a steady increase, rising to a maximum value of 3.8mm. Several features are worthy of note. The peak roughness value was greater than it had been for the same pipe in the earlier part of the run; it was also rougher than the concrete pipes, reversing the situation that obtained in the earlier period, when the concrete pipes had been appreciably rougher than the asbestos-cement.

The clay and uPVC both showed a similar pattern, although the absolute values of roughness were not the same. Both showed a peak early on (day 244 for clay, day 258 for uPVC) followed by a trough, with the roughness of both pipes rising to a secondary peak at around day 300. All pipes reduced in roughness over the period from day 304 to day 335, but this may be a misleading conclusion because no measurements were made between these days. However the low values on day 335 may be related to the water temperature of 11.3°C, the lowest reached during any of the 3 runs.

Summary

The most noteworthy features of this run are:

i) The variation of the roughness in the two types of concrete pipe was similar even though they were not laid in sequence in the experimental pipeline.

ii) In the period up to day 125 the concrete pipes continued to increase in roughness throughout; the asbestos-cement and uPVC pipe reached a stable value fairly quickly, whereas although clay soon reached a stable value it then showed a sudden increase of roughness late in this period. Asbestos-cement was rougher than clay, and its roughness increased rapidly in the early days of the experiment.

iii) All the pipes became considerably smoother mid-way through the run; however the time at which the roughness first started to decrease, varied for the different pipes; in all cases the significant rate of decrease began between day 100 and day 130; ie close to the time when the temperature rose rapidly from 15½°C to 17°C.

iv) The roughness for all the pipes was low for a period of roughly 60 days from mid July to early September, the time when the sewage temperatures were at their highest.

v) As the sewage temperatures fell, late in the experiment, the pipes became rougher, but they presented a different picture from that in the early part of the run, viz asbestos-cement was now rougher than concrete pipes and rougher than in the early part of the run, concrete and clay were smoother than they were in the early part of the run; uPVC was much as it was in the early period.

Run 2 6.2

Clean water tests

Following the completion of Run 1, the pipeline was cleaned by pressure jetting. Apart from a black discolouration of the lower part of the concrete and asbestos-cement pipes — possibly the result of sulphide attack — no visible traces of slime remained in the accessible parts of the pipeline.

Clean water was then circulated through the rig once more, and the roughness of the clean pipe determined, see Table 1 and Section 6.3 for discussion.

Sewage tests

The procedure adopted during the run was the same as for the previous one: the variation with time of roughness and of temperature, are shown in Fig 5B. The hydrograph characteristics for this run, were very similar to those for the previous one, as can be seen from the data given in Section 4.

The build-up of roughness in the first ten days was rapid, but thereafter the rate of increase reduced. During this initial period a thin (2mm) continuous film of slime was observed to have developed over the lower parts of the pipes.

In the period from day 15 to day 100 (approximately), there was little systematic change in the roughness of all the pipes: any variation was in the form of variations about a steady mean value. During this period, lumps of slime, 5 to 10mm high started to appear in the region of the mean water line.

On 10 August 1977 (day 112), temperature and dissolved oxygen levels were measured in the Oxford sewers, see Table 2.

More detailed comments about the experimental results are as follows.

Period from day 15 to day 100

Following the initial rapid increase in roughness in the first fifteen days, both types of concrete pipes showed further small increases, with maxima about 1mm greater, although the roughness of both was fluctuating quite rapidly throughout this period. The pattern of roughness variation was similar in both pipes and they both achieved a similar maximum roughness — 2mm for spun and 2.3mm for vertically cast, although the maxima did not occur simultaneously in the two pipes.

The roughness of the asbestos-cement pipe increased to 1mm at day 20, suffered a sharp fall immediately after, and then slowly increased to day 50, when it then settled down to a value of 0.8mm (approximately), maintaining this value until day 83. At this point there was a sharp increase in roughness.

Once the clay pipe had undergone its initial slime building period, the roughness did not undergo any sensible change until day 51, when it rose from a steady value of around 1mm to 1.4mm. This increase was only short-lived, however, the roughness falling to 0.5mm at day 78 and not changing significantly thereafter.

The roughness of the uPVC pipe increased until day 29, suffered a short-lived decrease, followed by a further increase to a value of 1.5mm. The roughness then decreased until day 55, thereafter remaining fairly steady, fluctuating between 0.5 and 0.9mm.

Considering this part of Run 2 in isolation, there is little of major interest to comment on. The roughness of all the pipes remained reasonably constant despite some occasional rather large fluctuations; most of the time the range for all pipes was from 0.5 to 2.0mm. The sewage temperature over the period was between 14°C and 19°C, and had exceeded 10°C by day 20.

Period of day 100 to day 206

During this period some of the pipes showed a marked change in the way that the roughness varied with time. Both the concrete pipes started to increase in roughness, and this trend continued until the end of the run, apart from a short period around day 150 to day 170, when the roughness suffered a decrease. Again, the two concrete pipes behaved in a very similar fashion to one another. Both pipes reached their maximum roughness at the end of the run (4.2mm for vertically cast and 4.5mm for spun), and were appreciably rougher than they had been in the earlier period.

Asbestos-cement behaved in a similar fashion to the concrete pipes. Initially the roughness increased only slowly, but from day 166 the increase in roughness was very rapid, reaching a value of 4.9mm at the end of the run, again appreciably greater than it was during the earlier part of the run.

The roughness of clay and uPVC pipes was very similar to that occurring in the early part of the run. From day 100 to day 140 the roughness of the clay pipe fluctuated between 0.5 and 0.8mm; but from day 140 to the end, the range of the fluctuations was greater, viz from 0.6 to 1.4mm, and the mean roughness was slightly greater. The maximum roughness during this period is the same as the maximum value that occurred between day 0 to day 100.

The roughness of the uPVC pipe during this period did not change to any great extent. From day 100 to day 114 it was constant at 0.3mm, but although it increased slightly thereafter, it still fluctuated between 0.3 and 0.8mm, apart from a single value of 1.1mm that occurred at the end of the run. There was a strong similarity between the variation of the roughness during this period and the variation that occurred in the first 100 days of the run.

Summary

There are several features of the results from this run that are worthy of comment. The concrete and asbestos-cement pipes showed a different characteristic from the other two pipe materials, in that towards the end of the run when the sewage temperature began to fall, the roughness increased very markedly, whereas the roughness of the clay and uPVC was very similar throughout the duration of the run. The results from the asbestos-cement pipe are particularly interesting. During the early part of the run the roughness stayed virtually constant for 80 days and was of a similar order of magnitude to the uPVC pipe. But after this time there was a pronounced difference between them, the asbestos-cement pipe becoming slightly rougher whilst the roughness of the uPVC pipe remained practically unchanged. Also the asbestos-cement pipe was significantly smoother than the concrete pipes during the first 80 days, but ended by being slightly rougher than them, once the sharp increase in roughness had taken place. The pattern of variation of roughness in the two concrete pipes was similar, as it was in Run 1.

Run 3 6.3

Clean water tests

The procedure following the completion of Run 2 was similar to that at the end of Run 1: the pipes were cleaned by high pressure water jets and the roughness of the clean pipes then determined, having first relaid the pipeline to a gradient of 1 in 100. The results are given in Table 1.

There are no consistent trends evident from the measurements on the clean pipe. The roughness of the spun concrete and the clay pipes after this second cleaning is similar to the roughness after the first cleaning. For the vertically cast concrete, uPVC and asbestos-cement pipes, the roughness is of a similar order to the roughness in the 'as-new' condition, ie smoother than they were after the first cleaning. Clearly the data are insufficient to enable any general conclusions to be drawn about the effect of sliming on the roughness of the material forming the original pipe surface. The differences in roughness between this run and the previous one could be due in part to the pipeline having been relaid to a steeper gradient: this had involved re-assembling the pipeline from the individual pipe lengths so that the alignment of all the joints would be changed. Another reason could be that there was a variability in the quality of the cleaning between the runs. When the rig was broken down between Runs 2 and 3 there was evidence of slime still being attached to the pipes; although it was possible to carry out some additional cleaning between Runs 2 and 3 it had not been possible to do this between Runs 1 and 2, which could explain the higher clean pipe roughnesses at the beginning of Run 2. Although the range of roughness is quite large, the corresponding range of capacities is not nearly so great. For instance in a 225mm diameter pipe at a gradient of 1 in 250, an increase in roughness from 0.09 to 0.25mm (as in the vertically cast concrete) represents a reduction in capacity from $0.042m^3/s$ to $0.037m^3/s$, ie a three-fold change in roughness produces a reduction of approximately 12 per cent in the capacity.

Sewage tests

The procedure during this run was the same as that followed in Runs 1 and 2: the variation of roughness with time and with temperature is shown in Fig 6. Although the depth of flow of the peak sliming discharge was similar to that in the previous two runs, the mean velocities in this run were approximately 50 per cent greater.

For the first 100 days of this run, the roughness did not vary to any significant degree once the initial sliming had taken place in the first twenty days. During this time the roughness fell between limits of 0.1 and 0.6mm, apart from a short period of time around day 70 when the roughness of all the pipes showed a sudden, albeit temporary, increase in roughness, corresponding with a dip in the temperature curve. At day 120, differences started to appear, with the concrete pipes showing a large and sudden increase, the asbestos-cement showing a more gentle increase, and the clay and uPVC remaining much as they had been previously. More detailed comments about the different pipe materials are as follows.

Period from day 0 to day 120

The pattern of variation of roughness in the concrete pipes was similar. They both reached an initial peak value after 20 days (0.4mm for the spun and 0.3mm for the vertically cast); the roughness then stayed constant for a further 30 days, when it decreased temporarily before rising to a peak value (1mm at day 61 for the vertically cast, 0.8mm at day 60 for the spun). Following this peak, the roughness fell just as sharply as it had risen, to reach a roughness similar to that which had occurred before the peak.

The roughness of the asbestos-cement pipe was low for the first 60 days (0.2mm or less) and although it increased to 0.6mm at day 69, it rapidly decreased again to its former low value.

The roughness of the clay pipe varied in a very similar fashion to that of the concrete pipes, and the magnitude of the roughness was also very similar. During most of the period the roughness ranged between 0.2 and 0.4mm; for a brief period around day 69, the roughness increased sharply but this was only an isolated instance.

The roughness of the uPVC pipe was very similar to that of the asbestos-cement pipe and the pattern of the variation was also very similar.

Period from day 120 to day 188

From day 120 onwards, the concrete pipes were much rougher. Over a period of 11 days, the roughness of both pipes increased sharply, the spun rising to 1.2mm at day 126 and the vertically cast to 1.7mm at day 131. From this point until the end of the run, the spun pipe roughness fluctuated in the range 0.6 to 1.3mm, the vertically case in the range 1.2 to 1.7mm. There was no systematic increase in the roughness during this period, but the pattern of the variation was similar in both pipes ie, they both showed a sudden increase in roughness, followed by a period of relative stability.

The roughness of the asbestos-cement pipe showed a slow but steady increase during this period, being roughest at the end of the run, having reached a value of 0.9mm, considerably greater than it had been for the whole of the rest of the run (apart from the local peak at day 69).

The roughness of the clay pipe was not significantly different in this period from what it had been in the previous period. For the whole of the period the roughness fluctuated between 0.2 and 0.5mm, with no long-term trend in evidence.

The uPVC pipe was like the clay pipe, in that the roughness did not change significantly over this period, ranging from 0.1 to 0.3mm, with no long-term trend in evidence.

Summary

The main features of interest in this run were that:-

i) The concrete pipes had very similar roughness characteristics and were rougher than the other pipe materials.

ii) uPVC and clay were the smoothest and their roughness did not change to any marked degree throughout the test.

iii) Asbestos-cement had a very similar roughness to uPVC for the first 100 days but thereafter the characteristics of the two pipes diverged, the asbestos-cement pipe displaying a slow increase of roughness with time and ending up only slightly smoother than the concrete pipes.

iv) As in Runs 1 and 2 the increase in roughness of the concrete pipes and the asbestos-cement pipe occurred towards the end of August when sewage temperatures were beginning to fall.

v) The peak roughness values for all pipes were less than one third of the peak values in Runs 1 and 2.

General discussion of results from Runs 1, 2 and 3 6.4

Introduction 6.4.1

The hydrographs for Runs 1 and 2, although not identical, were sufficiently similar for it to be reasonable to compare the results from the two runs. The velocities in Run 3 were higher so that it is not possible to compare the results directly with those from the two previous runs, but it is still possible to compare the trends in all three runs with each other.

The purpose of making such a comparison is to discover if there is a common pattern in the way that the different pipe materials behaved during the experiments. If, during some period of one of the runs, a pattern of behaviour can be identified (even though all the pipes might be behaving differently from one another), which is repeated at other times in the various runs, then it would be reasonable to expect that there was some deterministic mechanism governing the slime growth in the pipes, bearing in mind that all the pipes are being exposed to the same sewage. On the other hand, if there was no repeating pattern of behaviour the assumption must be that there is some random process having a significant effect on the slime in the pipes.

In looking for an explanation of the observed behaviour it is necessary to consider the micro-biology of the slime itself, and this is complex. Slime is formed by bacteria, protozoa and fungi in the sewage: the populations of these various organisms are influenced by the sewage — its temperature, the food that it contains, the amount of dissolved oxygen, and its chemical composition. The sewage slime will be influenced by the fungi present, eg during winter, the fungi tend to be dominant and they produce a slime with a tough skin, whereas in summer the fungi have less influence and the slime is affected by the other organisms in the sewage.

Slime has a life cycle of its own: experiments by Heukelekian and Crosby[4] showed that when sewage slime was cultivated under static conditions, the amount of slime varied in a non-systematic way throughout the course of the experiments. Thus in addition to all the other external factors that come into play, there is the growth and decay cycle of the slime itself to be taken into account.

In the early stages of planning the experiments, discussions were held with staff from Stevenage Laboratory of the Water Research Centre in order to obtain some background information on slime and thus avoid any major shortcomings in the experimental arrangements. The influence of dissolved oxygen was of particular interest. Normal domestic sewage contains dissolved oxygen at 30 per cent saturation level (roughly equivalent to a concentration of 3mg/l, the precise figure depending on temperature and barometric pressure). Sewage bacteria will grow at dissolved oxygen levels down to 10 per cent (roughly 1mg/l), maybe even down to a concentration of 0.5mg/l. The experimental arrangement would inevitably lead to the addition of further dissolved oxygen as the sewage passed around the rig, but WRC were confident that the addition of oxygen to raise the level above 30 per cent, would not lead to an artificially high rate of bacterial activity: the oxygen would simply pass through the rig.

When the experiments were in progress, measurements of dissolved oxygen levels were made at various times and at various points on the site and in the experimental rig; the results are as follows:

Location of measurement	**Dissolved oxygen concentrations (mg/l)** 3.3.76 (Day 41) Run 1	12.4.76 (Day 82) Run 1	8.7.76 (Day 168) Run 1	1.5.80 (Day 14) Run 3
Trunk sewer	0.6	0.6	<0.1	0.2
Downstream from primary sedimentation channels	1.7	1.7	0.7	0.3
Pumping station wet-well	5.6	4.5	1.5	4.2
Constant head tank	5.6	4.7	2.9	4.6

The reasons for extracting the sewage from the pumping station wet-well have been discussed in Section 2 of this report. The measurements of dissolved oxygen show that although the sewage arriving at Littlemore was aneorobic (or nearly so) on 8.7.76 and 1.5.80, it was no longer so by the time it reached the wet-well. Even if it had been possible to avoid adding oxygen to the sewage in the experimental rig, sewage taken from the wet-well would still have been considerably more aerated than the sewage in the trunk sewer. The explanation for the high oxygen levels in the wet-well is that the flow first passes through a critical depth flume, and the action of the hydraulic jump is sufficient to add a significant amount of oxygen to the sewage.

The conclusion from these measurements is that the sewage circulated around the test rig was considerably more aerated than the sewage arriving at the site in the trunk sewer, but that when this incoming sewage contained a dissolved oxygen concentration of more than 1mg/l (or even 0.5mg/l), the addition of further oxygen would not increase the organic life or the slime growth rate in the experimental pipeline.

The position is less clear when the sewage in the trunk sewer has a very low dissolved oxygen concentration. Heukelekian and Crosby carried out a microscopic analysis of aerobic and anaerobic sewage[4] and found that the same microfauna were present in each, but that the predominant types were dependent on the type of sewage. Thus it is possible that the aeration of anaerobic sewage in the trunk sewer would change the characteristics of the microfauna population. However there must be a time element involved in this process; the microfauna are not likely to respond instantaneously to a change in their environment. Although death can be virtually instantaneous, an increase in the population (which is what the addition of oxygen to an anaerobic sewage will produce) must take time. Bacteria multiply by cell division and the time taken for this to occur is measured in periods of from minutes to days, depending on the bacterial type. The maximum time taken for sewage to pass through the test rig was approximately 13 mins, so that as far as the sewage in circulation is concerned, the microfauna population is unlikely to have had sufficient time to respond to any significant degree to a change in its environment. An additional factor to be taken into account in this argument is that as long as there is slime in the experimental pipeline, the bacteria population appropriate to the aerobic conditions will also be present: the addition of oxygen to anaerobic sewage arriving at the site means that the bacteria in the experimental pipeline will continue to have an oxygen supply adequate for them to continue to thrive. In other words, as far as the bacteria in the pipeline are concerned, they are not affected by the oxygen content of the sewage arriving at the site. However it is possible that the aneorobic sewage has other characteristics that are unchanged by the addition of oxygen and that are inimical to the survival of bacteria.

Measurements made at various points in Oxford sewerage system showed that when the sewage in the trunk sewer at Littlemore was anaerobic, elsewhere the sewage was aerobic. The dissolved oxygen concentrations given in Table 2 have been plotted against temperature for sites 1 to 6 and 8 (Fig 7). Although the mean concentrations for the three sets of measurements fall on a straight line, there is a considerable scatter in the results, suggesting that the relationship between temperature and dissolved oxygen concentration varies from place to place over the network. Fig 7 also shows the oxygen concentrations for the 30 per cent and 10 per cent saturation levels, from which it is clear that considerable stretches of the Oxford sewerage system were carrying aerobic sewage even though the sewage temperature was high. The same sewage had become aneorobic by the time it had arrived at the pumping station.

The only measurement of sewage condition that was taken consistently in the experimental rig throughout all three runs was the temperature. Table 2 shows that this was close to the temperature in the trunk sewer. The conclusion from Fig 7 is therefore that this sewage temperature is a measure of the dissolved oxygen in the sewage within the sewer network. It does not however give any information about the composition of the sewage.

Temperature by itself is a significant parameter: according to information supplied by WRC, bacterial growth rate is a direct function of temperature and doubles when the temperature is increased from 10°C to 20°C. Thus if the temperature of the sewage were to be increased without changing any of its other characteristics, it would be reasonable to expect that the slime growth would also increase.

The Thames Water Authority do not make regular analyses of the sewage arriving at the Littlemore pumping station, so no data is available. Regular analyses are carried out at the No. 1 sewage works, where the sewage comprises the discharge from Littlemore plus sewage from other pumping stations and some industrial effluent.

The following table summarises the data that have been provided by the TWA for sewage arriving at the No. 1 works.

		pH	Suspended solids mg/l	BOD mg/l	Ammoniacal nitrogen mg/l	Chloride mg/l
1975	2nd quarter	7.5	320	227	21.8	77
	3rd quarter	7.5	290	221	28.2	83
	4th quarter	7.5	363	255	33.6	96
1976	1st quarter	7.5	379	312	31.3	111
	2nd quarter	7.5	388	285	38.3	112
	3rd quarter	7.4	367	326	41.5	132
	4th quarter	7.5	333	272	32.6	100
1977	1st quarter	7.7	333	265	25.0	94

The opinion of the Group Chemist at the sewage works was that the sewage was significantly stronger than normal from December 1975 to November 1976, with the maximum values occurring around August 1976. In a typical summer the average suspended solids would be about 350mg/l, BOD would be about 250mg/l, ammoniacal nitrogen about 30mg/l.

The sewage works records do not indicate that any industrial toxic discharge in the middle of 1976, but the possibility of an undetected discharge cannot be ruled out because dilution and dispersion before reaching the works might have made it impossible to detect.

Discussion of results 6.4.2

The hydraulic conditions in Runs 1 and 2 were sufficiently similar (maximum proportional depths during sliming hydrograph of 0.6 and 0.5 respectively) for a quantitative comparison of the two runs to be a reasonable approach. The results from Run 3 can only be compared with those from the previous runs on a qualitative basis, because the hydraulic conditions are significantly different. In order to compare the pattern of variation of roughness in a particular pipe material during the three different runs, the roughness data have been plotted separately for each material (Fig 8); the data used are the same as were used to plot Figs 5 and 6.

Comparisons of Runs 1 and 2

The interpretation of the results from these runs would have been more straightforward if the pattern of variation in the two runs had been the same. It is clear from Figs 5, 6 and 8 that this was not the case and that, although the hydraulic conditions for the two runs were virtually the same, other experimental conditions were different. Run 1 was carried out in 1976, a year when summer temperatures were abnormally high and there was a drought. Run 2 was carried out in 1977, when conditions were similar to those of a normal British summer. Furthermore Run 2 was started 3 months later in the year than Run 1 and finished approximately 1 month earlier. Neither of the runs was carried out for a full year.

During the early part of Run 1 the roughness of most of the pipes continued to increase for the first 100 to 120 days: at their peaks, the roughnesses ranged from 1.0 to 5.5mm. In contrast, the roughness during the first 100 days of Run 2 increased very much more slowly than in Run 1 and only ranged from 0.5 to 2.0mm.

In the middle of Run 1, the roughness of all pipes decreased. In Run 2, this occurred only in the case of the clay and uPVC pipes. Both runs showed low roughness values in July and August but Run 1 (with higher temperatures) generally gave lower values in this period.

There was a similarity between the two runs in their later stages, with all of the pipe materials showing a steady increase in roughness from July-August onwards.

After the initial rapid growth period of about 20 days the following general conclusions can be drawn:

(a) In the Spring (March to June) roughness increases at a steady rate until the water temperature reaches a limiting value when the roughness stops increasing. For concrete pipes, based on Run 1, this temperature seems to be about 16°C. The threshold temperatures are lower for the other materials: probably about 15°C for clay, 14°C for asbestos-cement and 13°C for uPVC.

(b) In the Summer (July and August) roughnesses are low relative to other times of the year. The exact mechanism which triggers off the reductions in the Spring roughness is not clear.

(c) In the Autumn (September to November) the roughness increases.

(d) In the Winter (December to February), when water temperatures are lower the roughness falls to a low value, though probably not as low as in mid-Summer. However because none of the runs operated throughout a winter there is only a little evidence to support this deduction.

No precise explanation of these findings can be given but it is possible to go someway to relating these findings to the characteristics of the slime growth described in Section 6.4. It must be borne in mind that the slime thickness, and roughness, arises from a balance between the rate of growth, the rate of sloughing due to the shearing action of the flow and to the natural life-death cycle of the slime itself (see Section 6.4.1). Thus if the rate of growth is reduced the slime thickness and hence the roughness will reduce. It is suggested that the low roughnesses occurring in Summer are due to growth being inhibited by the factors related to the incoming sewage. In Winter growth is inhibited by the low temperatures. Between these two conditions there is a range of temperatures where growth is more rapid and roughness increases.

Various hypotheses were examined in an attempt to explain the relationship between roughness and sewage temperature for each pipe material. Some limited success was achieved but no hypothesis was able to explain satisfactorily, all the observed results.

Comparison of Runs 2 and 3

The hydraulic conditions for these two runs were different, so that quantitative comparisons are not possible: however both runs were started at approximately the same time of year and extended for similar lengths of time, so that a qualitative comparison is reasonable.

After the initial rapid increase in roughness at the start of the runs, there was a long period in both runs, extending to August, during which the roughness of all the pipes remained fairly steady. Around August, the roughness of the concrete and asbestos-cement pipes started to increase slowly, this continuing until the end of the run, whereas the roughness of the clay and uPVC did not change to any marked degree.

In general high and low roughness values were about one third of the corresponding values in Run 2.

7 Roughness of pipes when running part-full

During Runs 1 and 2 a few tests were carried out under part-full conditions in order to get some indication of the variation of roughness with depth of flow.

The procedure during these tests was to set a steady discharge, using the valve at the downstream end of the pipeline to establish uniform flow conditions. In practice this was difficult to achieve, partly because the valve did not allow fine adjustments to be made and partly because the water surface was very undulatory, making it well-nigh impossible to determine when the flow was uniform. The water depths in the pipe were measured by means of the pressure tappings, having first determined the pipe invert levels at each of the tapping points.

The procedure for calculating the roughness of the part-full pipes was first to estimate the mean water surface profile by fitting a straight line, by eye, through the water surface measurements for a particular test length. The depth of flow at each end of the test section was then determined from the mean water surface profile; this enabled the mean velocity and kinetic energy at each end to be calculated and hence the energy gradient. The mean geometric parameters over the reach were also computed, which then allowed the roughness to be calculated from the Colebrook-White equation, assuming that the flow was in the rough-turbulent region. This method of calculation is only an approximation but it was considered to be sufficiently accurate for the main purpose of the tests, which was to examine, in a qualitative way, how the roughness varied with depth of flow. As a check on the method, an alternative method of calculation was used; in this, the measured depths at either end of the test section were used to determine the mean velocity and the total energy at either end of the reach. The mean of the measured depths of flow was used to calculate the mean geometric parameters for the reach. The results from this method was very little different from the more approximate method that was used for the bulk of the calculations.

The part-full tests were carried out in October 1976, towards the end of Run 1 and in November 1977, towards the end of Run 2. The results from these tests are shown in Figs 9-12.

The data show quite a large amount of scatter; there appear to be significant changes in roughness for only small changes in proportional depth. Smooth lines have been drawn through the data points because it is possible that there is a considerable band of error on the data points, eg in Run 1 two tests were carried out under virtually identical conditions and they gave rise to part-full roughnesses of 2.0 and 3.4mm for uPVC pipe, with no apparent reason to explain the discrepancy. Despite such inconsistencies, the general conclusion is that there is a marked increase in roughness when the sewer is flowing only part-full.

The following table summarises the principal results from these tests.

	Run 1			Run 2		
Material	**Maximum part-full roughness k (mm)**	**Pipe-full roughness k (mm)**	**Prop'l depth for maximum roughness**	**Maximum part-full roughness k (mm)**	**Pipe-full roughness k (mm)**	**Prop'l depth for maximum roughness**
uPVC	3.0	0.5	0.7	3.0	1.0	0.5
Spun-concrete	5.5	1.9	0.8	9.0	4.5	0.6
Asbestos-cement	5.0	2.5	0.7	10.0	4.5	0.4
Clay	7.0	0.6	0.4	5.0	1.5	0.5

In general, it appears that the maximum roughness occurs when the depth of flow corresponds to that of the maximum depth of sewage, and that the part-full roughness is significantly greater than the pipe-full roughness.

The variation of roughness with depth of flow will produce a stage-discharge characteristic different from that of a pipe with uniform roughness around the periphery. Instead of the maximum capacity occurring at a proportional depth of 0.95, a slimed sewer with non-uniform roughness will have its maximum capacity when it is flowing full.

The discharge will increase continuously with depth and there will be only one depth corresponding to a particular discharge, unlike the pipe with uniform roughness, which has two values corresponding to a particular discharge when the proportional depth is greater than 0.8.

8 Measurements of slime weight

Weight of accumulated slime 8.1

In addition to the weekly measurements of head-loss in the test lengths of pipe, separate short sections of each type of pipe, except the vertically-cast concrete section, were periodically removed from the rig in order to examine the pattern of slime growth and weigh the accumulated slime. Four 1m lengths of butt-jointed pipe had been added to the rig at the downstream end of each test section and these could be removed and replaced without disturbing the test lengths.

The purpose in making the measurements was to determine whether there was any appreciable difference in the amount of slime accumulated by different pipe materials and whether any significant correlation existed between the amount of slime and the hydraulic roughness of the pipe.

Prior to testing it was felt that the amount of slime would increase slowly with time and the plan was to remove the first three short lengths of pipe in sequence at monthly intervals. Depending on the length of the experiment, this sequence would be repeated and a note made of the time elapsed, since each pipe was last removed and scraped. The fourth, and final, pipe in each series was to be left undisturbed until the end of the run.

In the event, it became clear that the initial growth period of the slime was very short (3-4 weeks) and that, after that time, the quantity of slime present on the walls appeared to depend on other factors, which were not necessarily a function of period in use. Pipes removed late in the sequence appeared on inspection to have the same pattern and degree of sliming as adjacent pipes scraped only one month earlier.

The proposed sequence and interval of pipe removal was, therefore, not strictly adhered to. The following table summarises, for each of the three runs, the number of days from the start of the run at which each pipe was removed and examined.

	Days from start of run			
	Pipe 1	**Pipe 2**	**Pipe 3**	**Pipe 4**
1976 (Run 1)	35	63	98	
	154		210	
	262			304
1977 (Run 2)	28	57	86	156
1980 (Run 3)	28	57	—	191

Each time a pipe was removed from the rig it was photographed. The height of the slime layer above the invert was recorded and the material scraped off for analysis.

Analysis

The following table summarises for all pipe materials the main physical characteristics of the slime removed from the pipe walls.

		Invert	Water-line	Mixture of invert and water-line
No. of samples		**12**	**12**	**56**
Density of wet slime (g/cm^3)	mean	1.064	1.011	1.046
	s	0.018	0.008	0.026
Dry weight as per cent of wet weight	mean	15.74	11.52	14.08
	s	4.01	3.78	3.92
Organics as per cent of wet weight	mean	7.34	8.55	7.26
	s	2.44	3.30	2.20
Sand (>0.06mm) as per cent of wet weight	mean	1.45	0.48	1.40
	s	0.92	0.36	1.29

s = standard deviation in the population sample

There was little apparent difference in the physical characteristics of the slime that grew on different pipe materials and in different runs, but samples taken from the pipe inverts showed significantly higher bulk density and contained more sand than samples taken from the water-line. There was also a difference in appearance. In the early stages of each run the bottom of the pipes was covered with a thin (1-2mm) uniform layer of grey slime, while at the water-line white, gelatinous lumps up to 10mm high were present. This may reflect a difference either in the physical conditions for growth or in the organisms present.

Results

The dry weight of slime per unit area of *slimed* surface (g/m^2) has been used as a measure of the quantity of slime present on the pipe walls. This was determined for each sample from the measurements of wet weight, percentage of dry solids and the proportion of the pipe perimeter that had slime attached.

Values of dry weight for Runs 1, 2 and 3 have been plotted in Figs 13 and 14 for each pipe material represented (except vertically-cast concrete).

The graphs show the following interesting features:

1. The increase in slime weight with time shows a similar pattern to the increase in hydraulic roughness. In particular, the drop in hydraulic roughness which was in evidence before the pump failure on day 156 of Run 1 is also reflected in a drop in slime weight (Fig 13) on day 154. This seems to confirm that some factor other than the pump failure was responsible for loss of slime. In both Run 1 and Run 2 the increase in roughness at the end of the test is reflected in an increase in the amount of slime present.
2. After the initial period of growth on clean pipes, the spun concrete surface showed consistently more slime than clay or uPVC. Although clean asbestos-cement pipe has a very low roughness factor (k = 0.02mm), towards the end of each run both the roughness and the amount of slime present were higher than in either the uPVC or clay pipes.
3. In Run 3 (Fig 14) the higher velocity resulted in much less slime growth in all pipe materials,, although the general pattern of a uniform, smooth layer on the invert with larger slime lumps at

the water-line was still in evidence. The difference between the pipe materials was also much less marked, although spun concrete and asbestos-cement surfaces had slightly more slime than uPVC or clay.

Correlation between slime weight and hydraulic roughness 8.2

As both the slime weight and hydraulic roughness showed broadly similar trends in the course of all these runs, there exists the possibility of a correlation between k values and slime weight. If the correlation coefficient is large, it might then be possible for a drainage engineer to obtain an approximate estimate of k value in a mature foul sewer by removing and weighing the slime from a given area of pipe surface.

All k values described so far in the report are the composite values for both slimed and clean portions of the perimeter when the pipe is running full. Before trying to correlate the data from the test rig, it was necessary to compute k values for the *slimed* portions of the perimeter, so that the influence of the relatively clean pipe crowns (which would have very much lower k values) could be eliminated.

k values for the slimed portion of the perimeter were calculated by the method of proportional friction factors:-

$$\lambda_c = \lambda_s p_s + \lambda_n p_n$$

where

λ = friction factor

p = proportion of total perimeter occupied by a surface roughness

Subscripts:-

c = composite surface

s = slimed surface

n = new (or clean) surface

The procedure is recommended in the HRS Tables and Charts[6,7] for surfaces where:-

$$20 < \frac{k_s}{k_n} < 100$$

The crown of each pipe was assumed to be completely unaffected by slime and to have clean pipe roughness values ie:-

	k_n (mm)
spun concrete	0.09
clay	0.07
uPVC	0.04
asbestos-cement	0.02

Values of k_c for each type of pipe were obtained from measurements of pipefull head-loss immediately before or after the time of slime removal.

Fig 15 shows the calculated values of k_s plotted against the dry weight of slime per unit area of pipe wall. Data from all pipe materials (except vertically-cast concrete) and from all three runs is included.

Although hydraulic roughness tends to increase with the amount of slime present, the correlation is not good enough for a reliable prediction of k_s from slime weight. The textural "roughness" of slime lumps at the water-line, in part-full sewers clearly has a much greater influence on hydraulic roughness than the total volume of slime present.

Correlation between slime weight and velocity 8.3

When a new sewer pipe comes into use, there is usually a fairly rapid increase in slime, which levels out when growth is balanced by sloughing due to the shearing action of the flow. Subsequently the amount of slime present stays roughly constant in the short term but, in the long term, the point of balance may be altered by physical, chemical or biological changes in the slime or sewage and the amount of slime present may increase or decrease before a new balance point is reached.

The point of initial balance is difficult to establish from infrequent spot measurements of slime weight but an examination of data from Yang and Reid(5) and Bland et al(2) as well as the present HRS data indicates that the higher the velocity in the pipe the quicker equilibrium is established.

In Fig 16 the dry weight of slime has been plotted against number of days in contact with sewage. All the data is from part-full pipes and covers a range of velocities from 0.23 to 2.40m/s over a period of 100 days from new.

Before plotting the Yang and Reid data, factors were applied to the reported slime weights to allow for a smaller sample area. Neither the actual pipe diameter nor the area from which each sample was scraped are stated in the report but have been calculated from estimates of pipe diameter and depth of flow. Bland et al analysed slime from above and below the water-line separately. In their tests significant amounts of slime were attached to the crowns of the pipes because of foaming associated with entry conditions to the test lengths; this is not normally a feature of long sewers so only the data from the basal part of the pipe has been plotted in Fig 16.

The times taken to establish an initial equilibrium between slime growth and sloughing, as estimated by the authors concerned or from an examination of their data are as follows:-

Mean velocity (m/s)	Days from new	Source
0.23	70	Yang and Reid(5)
0.36	70	Yang and Reid
0.55	7	Bland et al(2)
0.76	35	HRS, Littlemore experiments
1.18	28	HRS, Littlemore experiments
2.40	7	Bland et al(2)

The table shows that (with the exception of Bland's data at 0.55m/s), the lower the velocity the longer the period of growth before initial equilibrium is established.

The average dry weight of samples taken from all types of pipe within the period of equilibrium for each test have been plotted against mean velocity in Fig 17. In the case of the Yang and Reid and the Bland tests, the equilibrium period is assumed to occur between the times given in the above table and the end of each test. However, the HRS tests continued for much longer periods, during which time, changes in the biological and chemical conditions in the sewage and the slime are thought to have occurred. Slime weights in the HRS tests after 1ι days are, therefore, not included in the plot.

The best fit line to all the data points for all pipe materials has the equation:-

$W = 48.92\ V^{-2.10}$ with a correlation coefficient $r^2 = 0.91$. (W = dry weight of slime per unit area of slimed surface in g/m^2: V = mean velocity in m/s). The exponent suggests that, when there is a state of balance between growth and sloughing, the amount of slime present is inversely proportional to the square of the velocity and hence to the shear stress exerted by the flow.

Appearance of slime in the test pipes 8.4

Fig 15 shows that slime weight is a poor predictor of hydraulic roughness; a better estimate of k value in an existing foul sewer may be possible by comparing the slime deposits with photographs taken in the test rig at a time when the composite pipe-full roughness (k_c) was measured. The selection of photographs in Plates 2 to 7 are all of the same length of 225mm diameter asbestos-cement pipe, which includes a sleeved butt-joint with slight displacement. Similar deposits in other pipe materials and pipe sizes would give roughness values of the same order. In the pipes the pattern of sliming is the result of running a hydrograph giving a maximum flow depth of ½ pipe diameter and a maximum velocity of 0.76m/s. Values of k_c for each photograph were obtained directly by measuring the head-loss with pipe-full flow. Values of k_s have been calculated from k_c and k_n, using the method described in Section 8.2.

9 Comparison of present research with previous work

The main UK sources of data on slimed sewers are Ackers et al[1] and Bland et al[2]. In the USA some work has been done by Yang and Reid[5]; in addition Ackers et al analysed some early American data on sewer roughnesses.

Ackers, Crickmore and Holmes 9.1

This research comprised field measurements in twenty sewers at five sites in England. The sewers ranged in size from 15in to 66in, in age from 2 to 100 years, and at gradients from 1 in 22 to 1 in 2318. The sewers were mainly concrete (12 in all); of the remainder, 4 were brick, 2 were salt-glazed clay, 1 was bitumen-lined steel and 1 was steel-lined brick.

The roughnesses of all the sewers were determined under the part-full conditions that happened to obtain at the time that the measurements were being made and they relate to the condition of the sewer as it was at that particular time; continuous measurements over a long period of time were not made.

The sewer roughnesses determined by Ackers et al have been plotted in Fig 18 as a function of the velocity that was measured during the experiments. Those sewers (which included all the brick sewers) in which sediment deposits were found on the invert have been omitted, in order to make it easier for a comparison with the Littlemore data. The range of roughness measured in the three Littlemore runs have also been shown on the same diagram.

The trend in the Ackers data is for the roughness to decrease as the velocity increases. However there is a considerable scatter in the roughness with an order of magnitude in range for any particular velocity. The Littlemore data from Runs 1 and 2 overlap the Ackers data to a considerable extent whereas the data from Run 3 tend to be below the Ackers data. On the whole, though, there is a satisfactory agreement between the two sets of data.

When making the comparisons a number of factors should be borne in mind. The ranges of Littlemore values are obtained from repeated measurements throughout a number of long-duration experiments on a few pipes, during which the roughness varied appreciably. The Ackers data were obtained from measurements made over a very short period — a few days — on a number of different sites throughout England. Each of Ackers' data points is the equivalent of taking a spot measurement during one of the Littlemore runs, and so is unlikely to be representative of the long-term variation of sewer roughness.

A further difference between the two sets of experiments is that the values obtained by Ackers are for the part-full condition (the proportional depths ranged from 0.07 to 0.72, with the bulk of the sewers flowing at proportional depths less than 0.4). If plotted in Fig 18 on the pipe-full basis the data would be lower by a factor of up to 2.

The results from the experiments at Littlemore have been criticised because they were only carried out over a limited period of time, which was relatively short in relation to the life expectancy of a normal sewer. The critics felt that roughness would go on increasing with time so that eventually it would be found that there was no difference between the roughnesses of the various pipe materials. The continuous measurements that were made at Littlemore did not show any steady continuous increase of roughness with time, nor does other experimental work (see Section 9.2). On the contrary, they suggest that once the initial rapid sliming has taken place, the roughness then fluctuates quite significantly. This is considered to be the result of a continual process in which slime is building up and being sheared from the pipe surface. At any one time, slime will be building up in some places peeling off at others. The photographs of the interior of the experimental pipeline show that the roughness is very uneven in size and non-uniformly distributed.

In order to examine the effect of age on sewer roughness, the Littlemore results have been compared with those in Ackers' paper. The data given is for sewers ranging from 2 to 33 years old; those relating to the 19 concrete sewers have been plotted in Fig 19 together with some data from American concrete sewers, also given in the same paper. One sewer with sediment on the invert has been eliminated. Only four of these sewers had roughnesses greater than 6mm; three of 6.1mm and one of 9.1mm. The average roughness of sewers less than 10 years old was 2.2mm. The average roughness of sewers between 20 and 35 years old was 2.7mm. It is not considered that there is any significant difference between these two mean values, bearing in mind the wide variations in conditions that the various sewers will represent. It is significant that the roughnesses measured in the Littlemore experiments are very much in line with the values plotted in Fig 18, adding support to the view that the age of the sewer is not a significant factor as far as the effect of sliming on the roughness is concerned. It must be acknowledged however that in older sewers, factors other than sliming can have a significant influence on the roughness eg structural condition of sewer, condition of the joints.

The general conclusion from the comparison of the Littlemore data with that given by Ackers et al, is that there is very good agreement between them.

Bland, Bayley and Thomas 9.2

The experiments of Bland et al were carried out on a specially constructed rig at the Water Pollution Research Laboratory (WPRL) at Stevenage (now part of the Water Research Centre). Sewage was passed through a test rig consisting of lengths of unglazed clay and uPVC pipe, 100mm in diameter. Because there was insufficient flow at the site to provide a continuous supply of fresh sewage, it was necessary to re-circulate most of the sewage, with approximately 5 per cent of fresh sewage added to it. In order to simplify the experimental arrangement, the pipes flowed full at all times, and during any particular test the discharge remained constant. The duration of each test was from 50 to 100 days and the velocities during the tests ranged from 0.76 to 2.1m/s.

The WPRL test at 0.76m/s can be compared with Runs 1 and 2 of the Littlemore experiments and there are some similarities in the results. The roughness in the WPRL experiments fluctuated in much the same way as in the Littlemore experiments; the initial slime build up was rapid, in 12 days reaching a peak roughness of 15.7 and 14.5mm for the clay and the uPVC respectively. The mean values over the period of the test were 3.52mm for clay and 3.97mm for uPVC. These are rougher than the mean values of the combined HRS Runs 1 and 2 (taking all values into account), viz 1.2mm for clay and 0.7mm for uPVC. The extent of sliming in the Littlemore experiments was less than in the WPRL experiments because of the different flow conditions under which the slime was formed, but even when this factor is taken into account by calculating the roughness of the slimed portion of the pipes in the Littlemore experiment, the values come out at 2.1mm for clay and 1.6mm for uPVC, still appreciably lower than the WPRL experimental values. Four separate tests were carried out by Bland et al at a velocity of 1.1m/s and despite the difference in velocities, the variation in roughness both during a test, and from test to test, was similar to that which was apparent in Runs 1 and 2 of the Littlemore experiments. Thus in the test of 15 days duration, the peak roughness was 2.7mm for clay and 1.6mm for uPVC. In the 45 day test the peak roughness was 1.7mm for clay and 2.1mm for uPVC: however these peak values were only achieved towards the end of the test and for approximately 40 days the roughness fluctuated between 0.5 and 1.0mm.

In the 90 day test, the peak values were 0.8mm for clay and 1.5mm for uPVC, but these were reached on only one occasion; for most of the test (both before and after the peak value was reached) the roughness ranged between 0.2 and 0.5mm for clay and 0.5 and 1.0mm for uPVC.

The test, lasting 68 days, gave results in sharp contrast to those from the other tests. The roughness gradually increased for the first 35 days and then it remained fairly steady for the rest of the test, fluctuating between 2.9 and 5.0mm for the clay and between 5.0 and 6.3mm for the uPVC. These values are much higher than either the peak or the mean values that were reached in any of the other tests at this velocity. A similar pattern was noticed in the Littlemore experiments, where the roughnesses in the first half of Run 1 were significantly higher than the roughnesses either in the second part of that run or in Run 2.

The test that was carried out at 1.5m/s showed an order of magnitude variation in the roughness — roughly between 0.05 and 0.5mm — but the values were of a similar magnitude to Run 3 of Littlemore experiment, in which the maximum mean velocity during the slime build up was 1.15m/s.

It is clear from the comparison between the WPRL and Littlemore experiments that even after making allowances for the greater surface area of slimed pipe in the WPRL experiments, their values are higher than those that were obtained during the Littlemore experiments. One reason for the difference could be that the amount of slime growth depends on the characteristics of the sewage: recirculated sewage was used in the WPRL experiments, fresh sewage at Littlemore. The absence of an air-water interface in the WPRL experiments could also have affected the slime growth. Unfortunately, there is not sufficient information to be able to throw any light on the most likely explanation for the differences.

Yang and Reid 9.3 Yang and Reid[5] carried out a series of experiments with the aim of determining the relationship between the thickness of a slime layer, the production of odour and the reduction of the carrying capacity of pipes. This work followed some earlier experiments of Reid and Keeley on the relation between slime growth and roughness. The Reid and Keeley experiments were only of short duration — 27 days — and little quantitative data were obtained. Their main conclusions were that:

a) the amount of slime growth reduced as the flow velocity increased,

b) concrete, asbestos-cement and unglazed clay pipes sustained a heavier slime growth than a glazed clay pipe.

The subsequent experiments of Yang and Reid produced conclusions that were similar to those of Reid and Keeley. Although some measurements were taken during the experiments, there is no reference to roughness in the Yang and Reid paper.

Their conclusions were that:-

a) Slime growth decreases with velocity.

b) Rough pipes maintain more slime growth than smooth ones, eg slime weight on asbestos-cement was twice than on glazed pipe.

10 Recommendations for design and analysis

The main purpose of carrying out the research was to provide data for the drainage engineer in design or analysis of sewerage systems. During the experimental runs, see Figs 5, 6 and 8, the roughness varied over a considerable range and it is difficult to choose just one value that reflects this wide range. The discussion in Section 6.4.2 went some way towards explaining the variation in roughness with time during the experiments but not far enough to enable a prediction for any sewer to be made. Therefore, to arrive at recommendations it is necessary to consider Runs 1 and 2 simply as typical of sewers flowing at about 0.76m/s. It is clear that there will be long periods, when relatively high roughness occurs continuously. The designer of a new sewer may therefore need to use such values since it is inevitable that high roughness will coincide with high values of flow at some periods during the year. On the other hand if an analysis is being made of a sewer during a particular event, in the absence of site information on the roughness, a best estimate of the roughness would be the median value obtained during the two runs. In drawing up the following table the high value is taken as the value which the measured roughness exceeded for one month in 1976 (Run 1, which started very early in the year). In most cases this value was also exceeded for a short period towards the end of Run 2. The low values are those which exceeded the measured values for one month in 1977 (Run 2 when the summer temperature was typical of most years). The median values refer to all the data in both runs and are seen to lie roughly mid-way between the high and low values.

Material	High k (mm)	Low k (mm)	Median k (mm)
Vertically cast concrete	3.8	1.3	1.8
Spun concrete	4.2	1.8	2.3
Asbestos-cement	2.8	1.2	1.8
Clay	2.3	0.6	1.1
uPVC	1.1	0.6	0.6

The above values are for pipe-full flow and apply to pipes with velocities of about 0.75m/s, carrying only sewage and slimed to approximately half-depth. For steeper pipes with velocities around 1.2m/s, corresponding to Run 3, high, low and median values are roughly one third of those given in the table.

It is recommended that, wherever possible, the designer should use the above values directly in the Colebrook-White flow equations, using his own discretion to select a value within the appropriate range. His choice will depend on specific site conditions and an assessment of the benefits and risks involved.

For designers using the Wallingford Charts and Tables[6,7] the median and high roughness values have been rounded to the nearest "standard" k values as follows:-

Velocities about 0.75m/s

Material	Values of roughness, k (mm)	
	Mid	High
Concrete, spun and vertically cast	1.5	3
Asbestos-cement	1.5	3
Clay	1.5	3
uPVC	0.6	1.5

Velocities about 1.2m/s

Material	Values of roughness, k (mm)	
	Mid	High
Concrete, spun and vertically cast	0.6	1.5
Asbestos-cement	0.3	0.6
Clay	0.3	0.6
uPVC	0.15	0.3

Interpolation should be used for velocities between 0.75 and 1.2m/s.

11 Summary and conclusions

A series of experiments on the effect of sliming on the roughness of foul sewers has been carried out on a specially constructed rig at the sewage pumping station at Littlemore, Oxford, belonging to the Thames Water Authority.

The purpose of the study was to extend the scope of work carried out by other investigators on how the roughness varies with time, with velocity and with pipe material.

Three separate, long period runs were carried out using a constantly varying sewage flow to form the slime. In the first two runs, the maximum mean velocity produced by the slime forming flow, was approximately 0.75m/s, and the runs lasted for 335 and 206 days, respectively. In the third run, the maximum mean velocity produced by the slime building flow was approximately 1.2m/s and the run lasted for 188 days.

Measurements were made at weekly intervals throughout all three runs, from which the roughness of the sewers was calculated.

The principal conclusions from the experiments were as follows:-

a) Slime builds up on the sewer very quickly: once this initial sliming has taken place, there is no evidence of a subsequent continuous increase; the roughness varies, suggesting that there is a continuous process of slime building and slime removal taking place.

b) Although it was possible to identify similar trends in the three runs, there were also instances when some of the pipes displayed inconsistencies in their behaviour, suggesting that deterministic and random factors both have a significant influence on the amount of sliming.

c) The pipe material does have an effect on its roughness; the results from all three runs pointed to the same conclusion.

d) The runs from the Littlemore experiments are in general agreement with those obtained from the field experiments of Ackers et al. There is not such good agreement with the results from the experiments carried out by Bland et al at WPRL.

e) Some limited experiments were carried out to determine the roughness of sewers flowing part-full. These showed that under these conditions the roughness was much greater than when the sewer is flowing full.

On the basis of the Littlemore experiments roughness values for slimed foul sewers have been recommended for use in design.

12 Acknowledgements

The research work described in this report formed part of the research programme of the Hydraulics Research Station and is published with the permission of the Managing Director. The work was carried out in Mr J A Perkins' section in the Rivers and Drainage Division headed by Mr A J M Harrison. Mr I M Gardiner was in control of the site measurements. These were undertaken under what were, at times, very trying conditions and recognition must be made of the significant part played by Mr D Lord, Mr M Evers, Mr G Wooldridge, and Mr I Fish in bringing the work to a satisfactory conclusion.

The Hydraulics Research Station is grateful for the contribution of £5000 from the Clay Pipe Development Association to the cost of the research: this money was used in analysing the results from the experiments.

Finally grateful thanks are due to the staff of the Thames Water Authority for the tolerance they showed throughout our long presence at the pumping station and for the valuable assistance that they provided whilst the experimental rig was being constructed and whilst the experiments were in progress.

13 References

1. ACKERS P, CRICKMORE M J and HOLMES D W. Effects of use on the hydraulic resistance of drainage conduits. Proc. Instn. Civil Engineers, Vol 28, pp 339-360, July 1964.

2. BLAND C E G, BAYLEY R W and THOMAS E V. Some observations on the accumulation of slime in drainage pipes and the effect of these accumulations on the resistance to flow. The Public Health Engineer, January 1975.

3. DEPARTMENT OF THE ENVIRONMENT. Working Party on Sewers and Water Mains. First report. HMSO, London, 1975.

4. HEUKELEKIAN H and CROSBY E S. Slime formation in polluted waters. Sewage and Industrial Wastes. Vol 27, No. 12, December 1955, Vol 28, No. 1, January 1956, Vol 28, No. 2, February 1956.

5. YANG T S and REID G W. Sewer odours and pipe materials. Paper delivered at Texas Annual Water and Sewage Short School. Bureau of Water Resources Research, University of Oklahoma, March 1959.

6. HYDRAULICS RESEARCH STATION. Charts for the hydraulic design of channels and pipes. Fourth edition (metric), HMSO, London 1978.

7. HYDRAULICS RESEARCH STATION. Tables for the hydraulic design of pipes. Metric edition, HMSO, London 1977.

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Tables

Table 1 **Roughness of clean pipes**

Material	Roughness, k (mm) Before Run 1	Before Run 2	Before Run 3
Vertically cast concrete	0.09	0.25	0.09
uPVC	0.04	0.10	0.06
Spun concrete	0.09	0.18	0.16
Asbestos-cement	0.02	0.07	0.04
Clay	0.07	0.18	0.13

Table 2 **Dissolved oxygen measurements**

Site No.	Location	7 July 1976 Temperature °C	Dissolved oxygen mg/l	20 December 1976 Temperature °C	Dissolved oxygen mg/l	10 August 1977 Temperature °C	Dissolved oxygen mg/l
1	Five mile Drive/ Rothafield Road	22.1	3.8	9.8	6.6	17.9	5.2
2	Hamilton Road/ Kings Cross	20.7	1.5	10.8	5.84	18.3	2.43
3	Bradmore Road/ Norham Gardens	23.0	3.3	14.1	5.15	20.5	4.25
4	Maltfield Road/ Stockleys Road	19.1	1.7	10.9	5.3	16.7	1.03
5	Gypsy Lane	23.1	2.2	11.7	7.0	16.4	7.1
6	Bottom of Edgeway Road	19.3	<0.1	10.6	4.9	17.1	0.3
7	Holywell Street/ Mansfield Road	24.1	2.05	15.5	4.9	20.4	4.02
8	Radcliffe Road/ Iffley Road	20.8	0.7	11.8	6.68	18.1	2.78
9	Mill Lane	22.6	<0.1	10.3	3.61	19.2	<0.1
10	Littlemore trunk sewer	22.6	<0.1	12.0	3.98	19.3	0.2
	Experimental rig	21.5	—	11.8	—	19.1	—
	Mean of sites 1 to 6 & 8	21.2	1.9	11.4	5.9	17.9	3.3

Figures

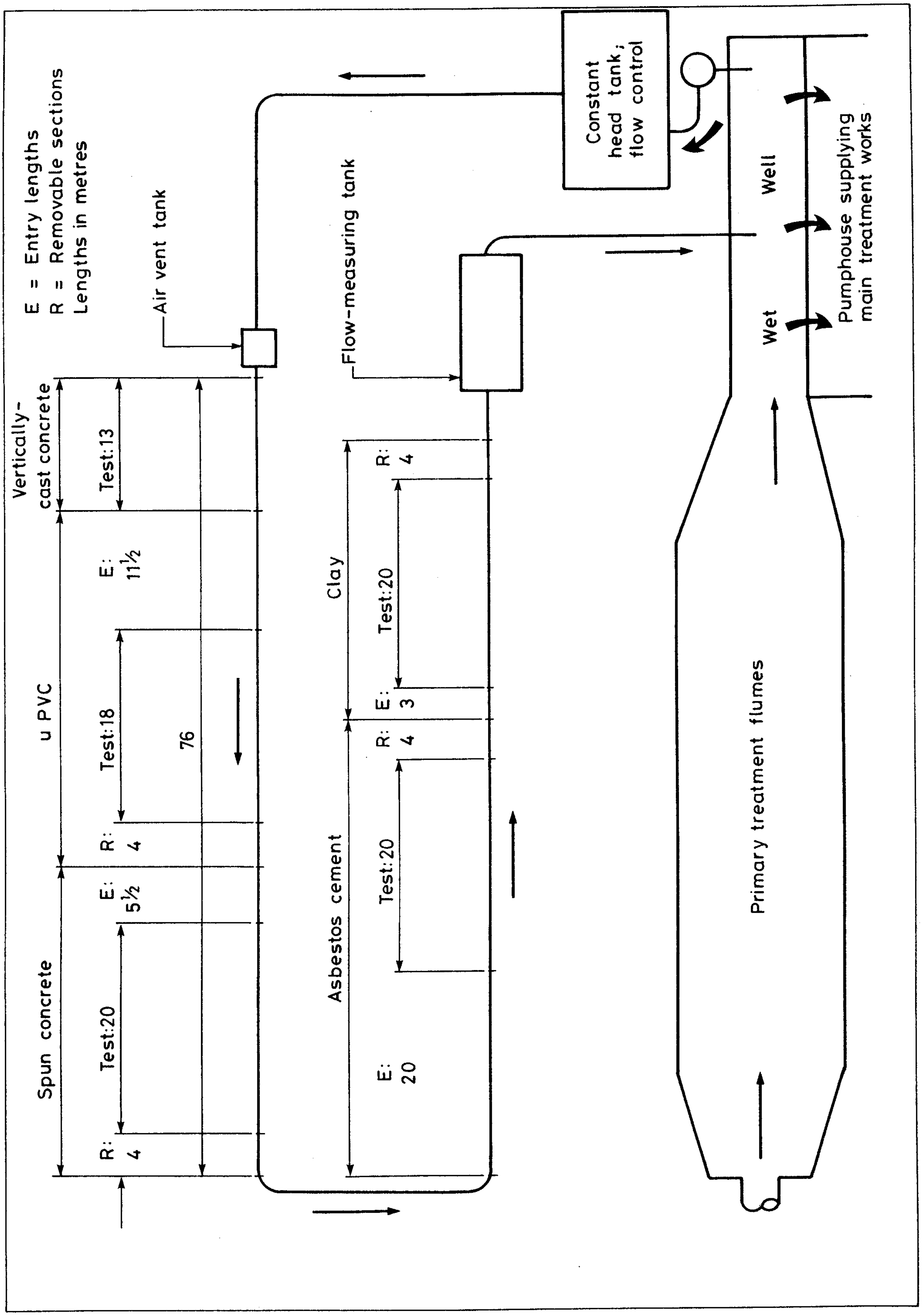


Fig 1 Layout of rig

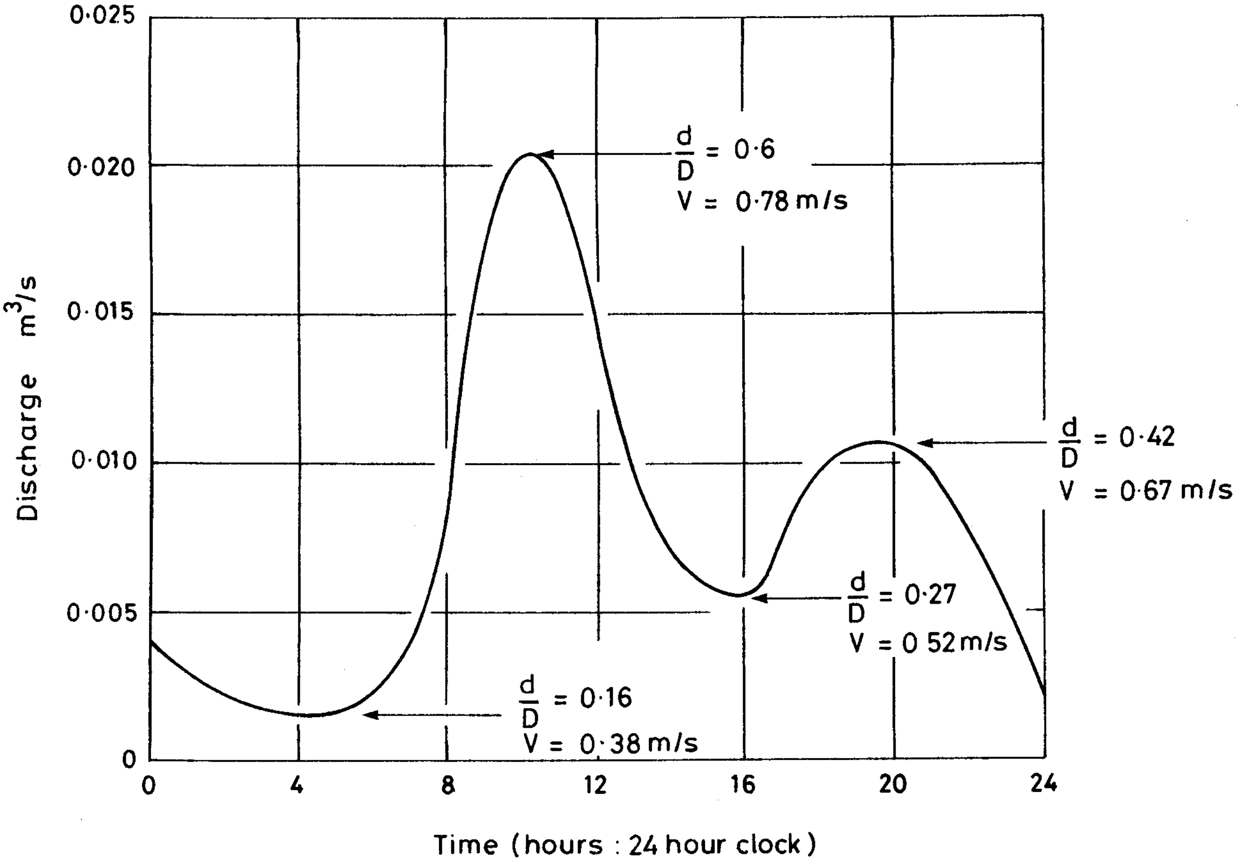
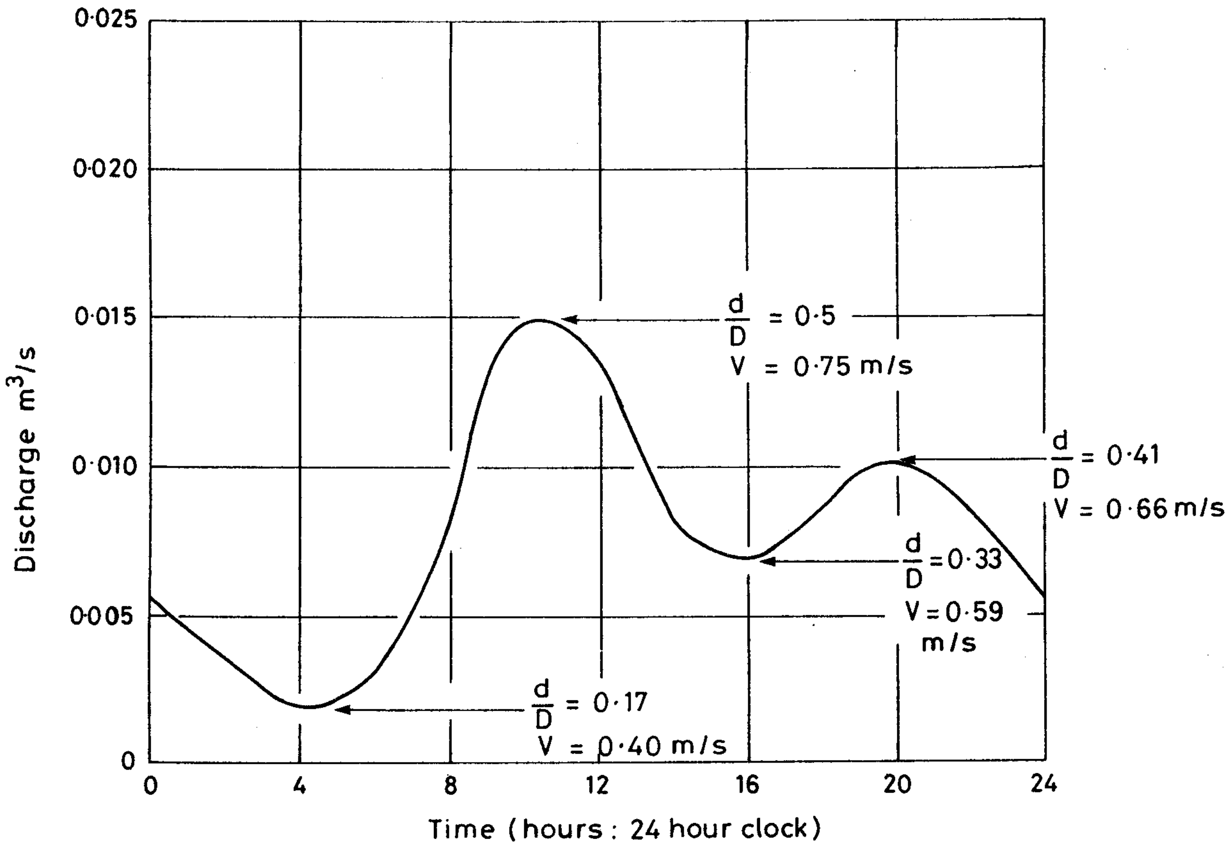


Fig 2 Hydrograph : Run 1 (1976)



Hydrograph : Run 2 (1977)

Fig 3 Daily hydrographs

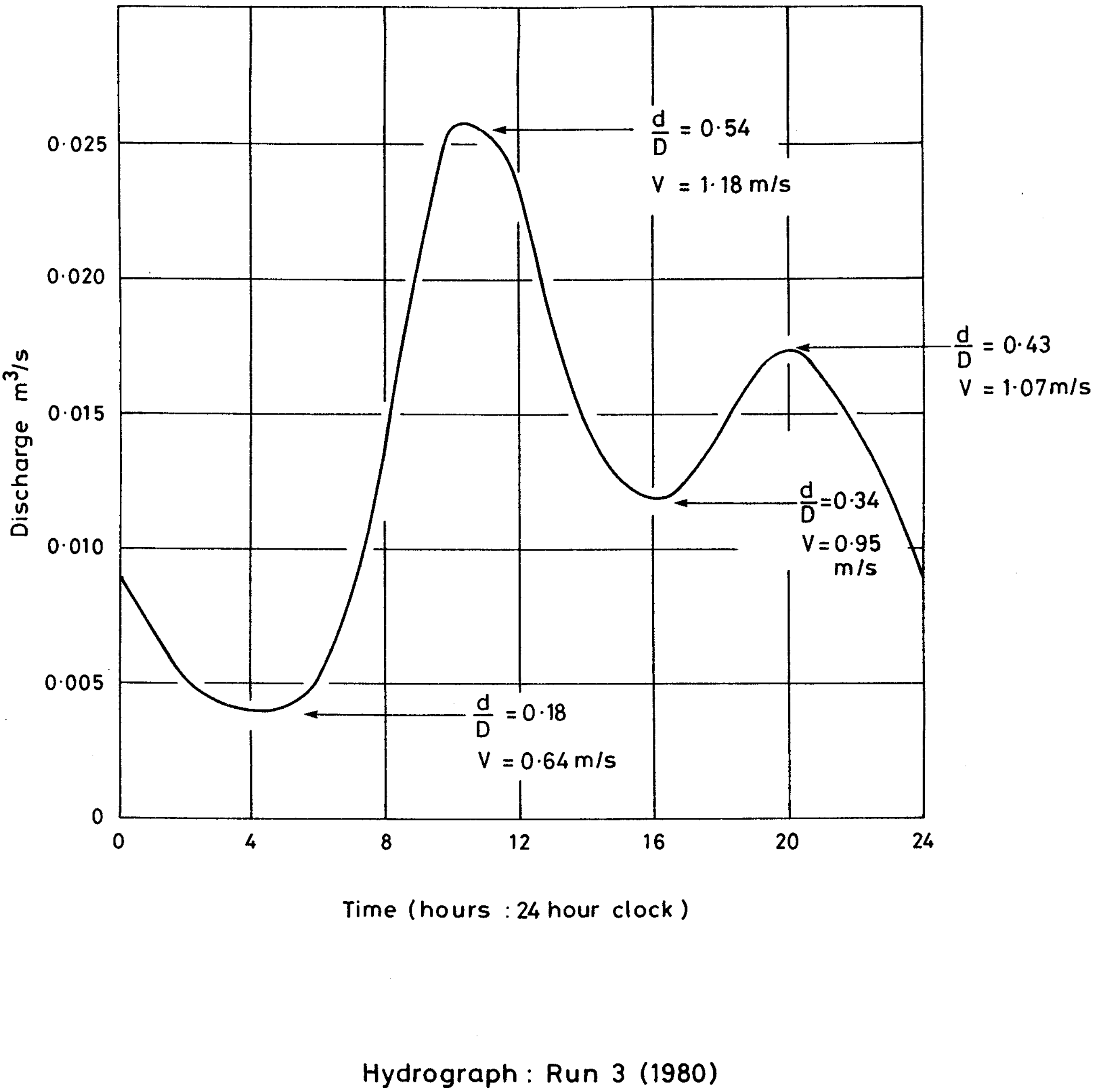


Fig 4 Daily hydrograph

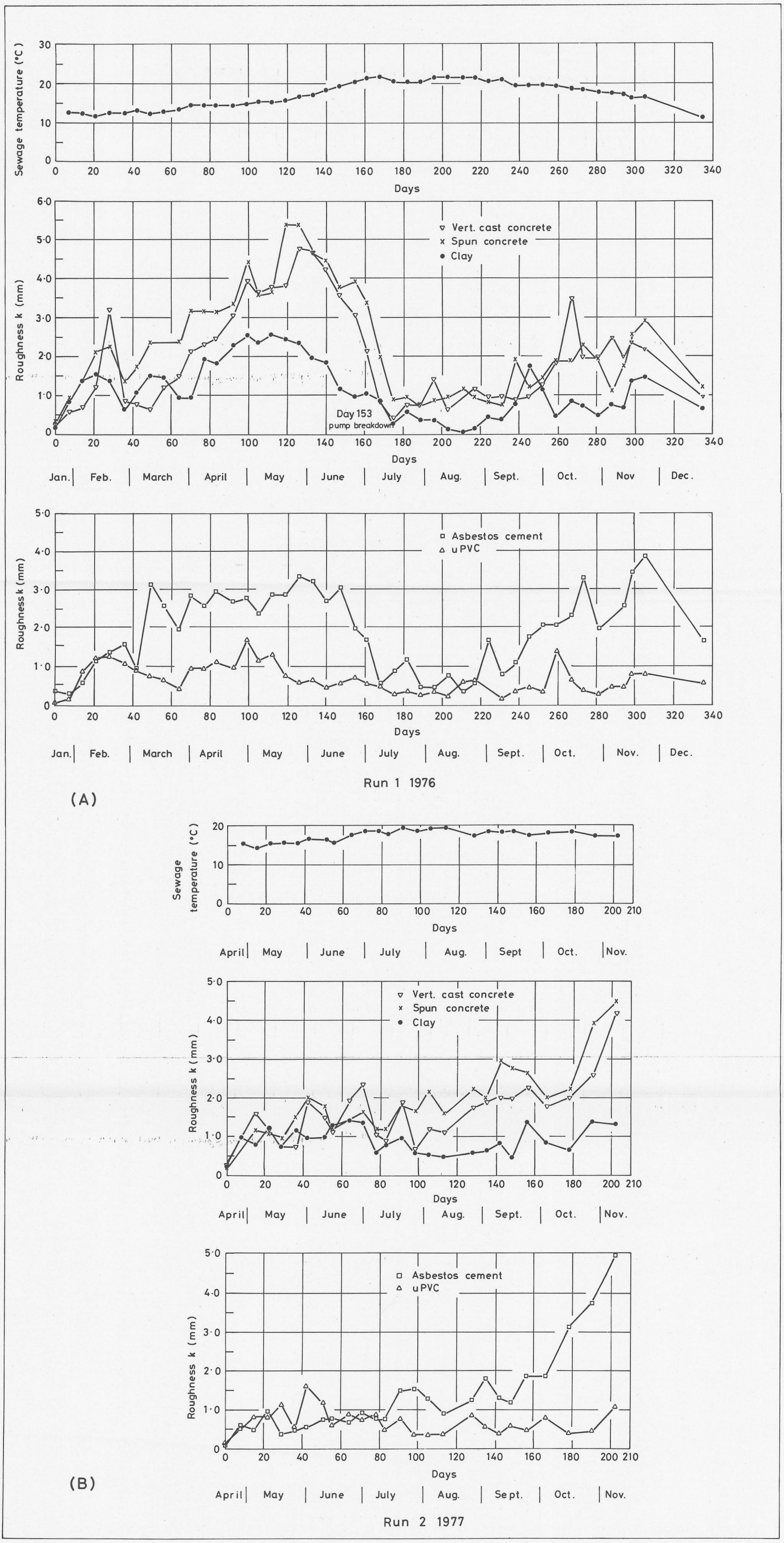


Fig 5

Variation of roughness with time – Runs 1 and 2

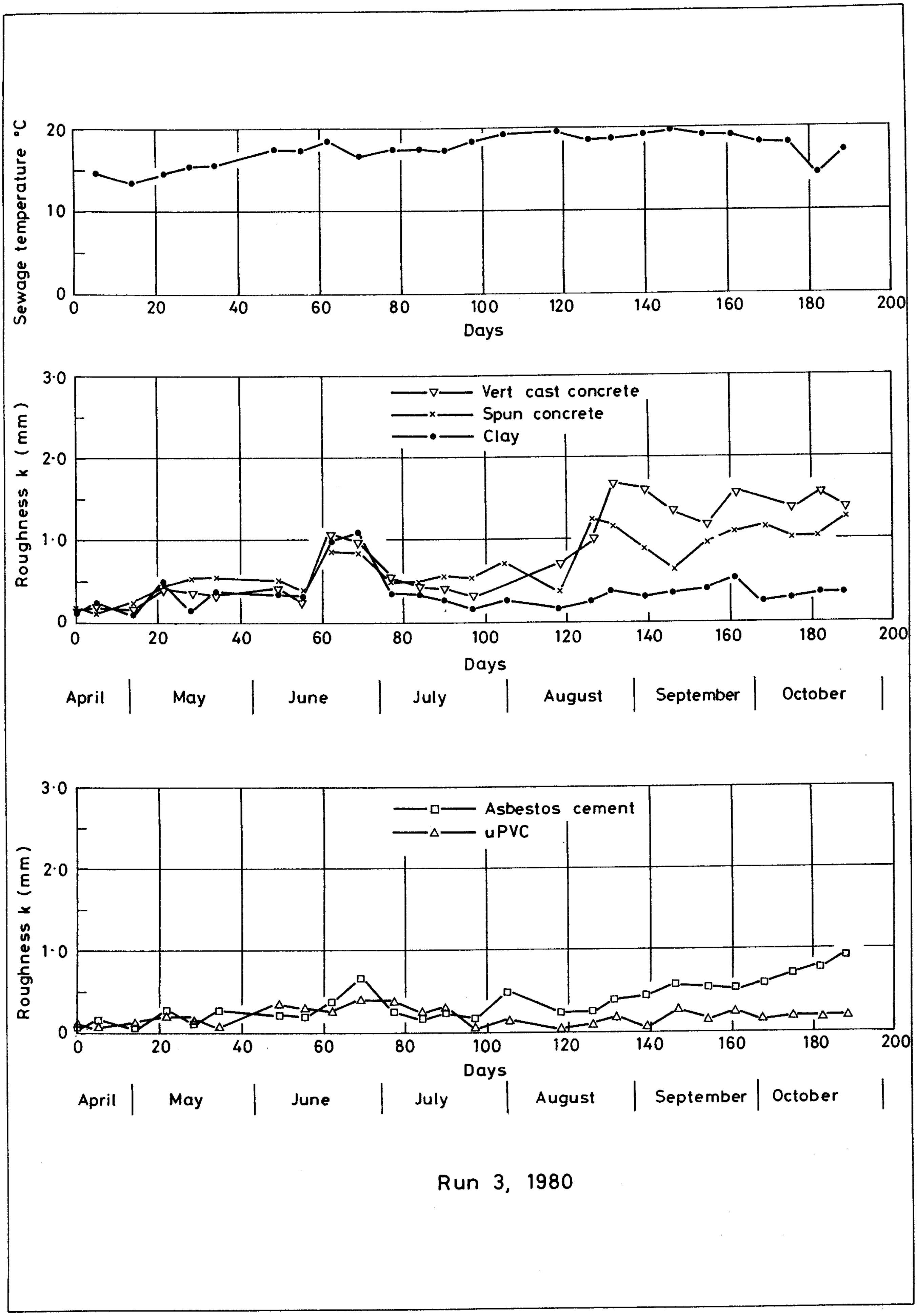


Fig 6 Variation of roughness with time – Run 3

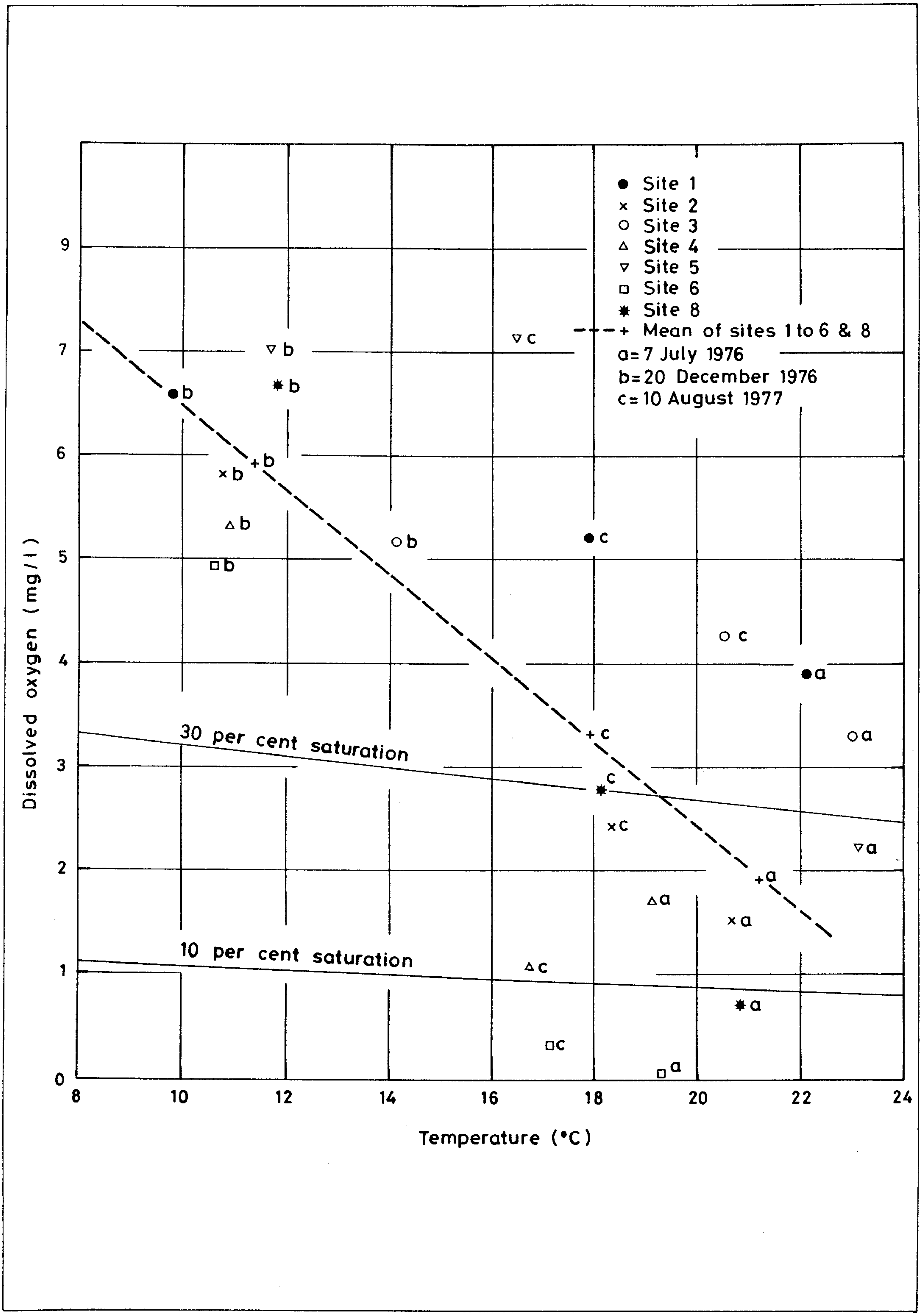


Fig 7 Dissolved oxygen levels in Oxford sewers

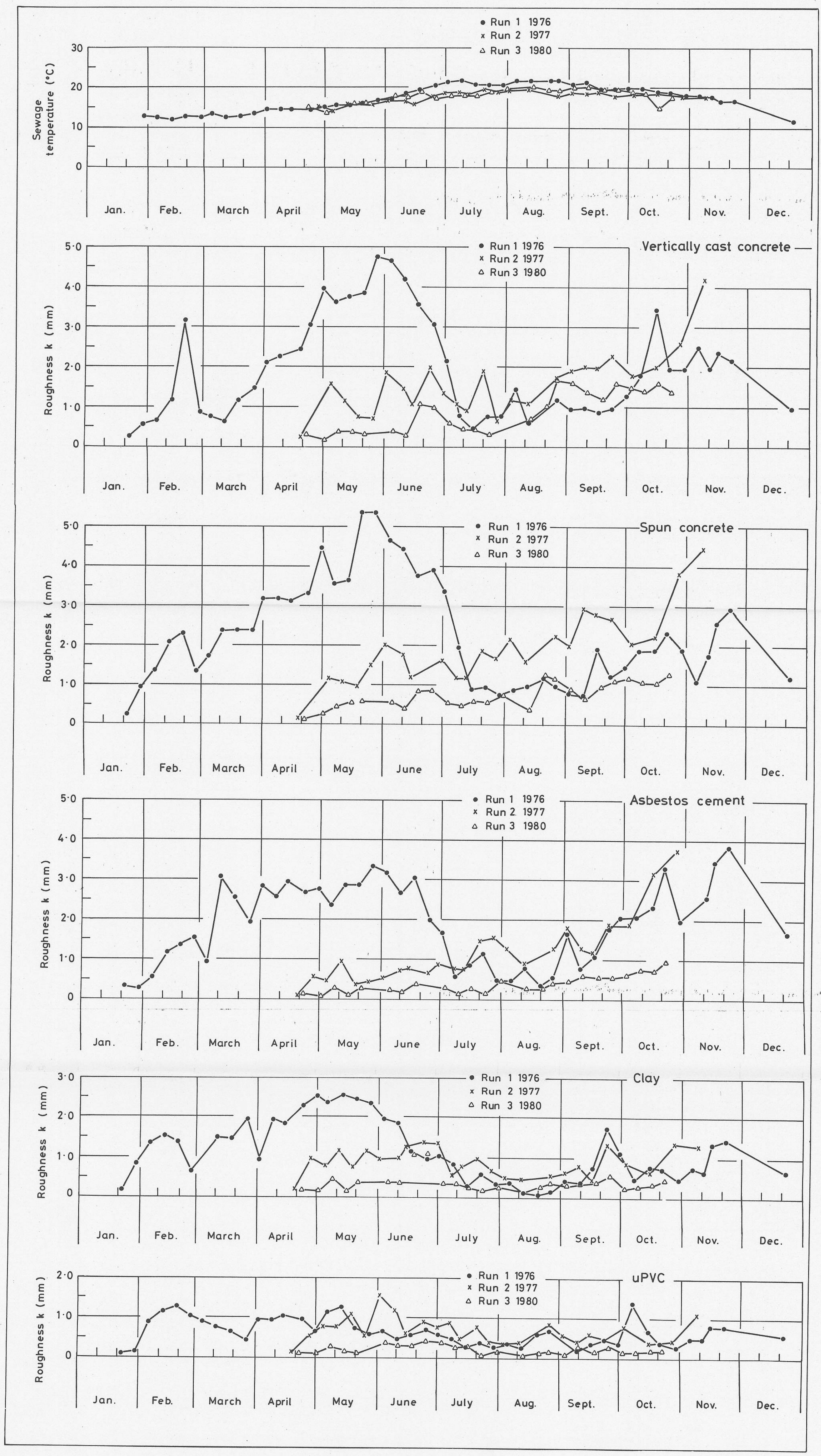


Fig 8

Variation of roughness in test pipes

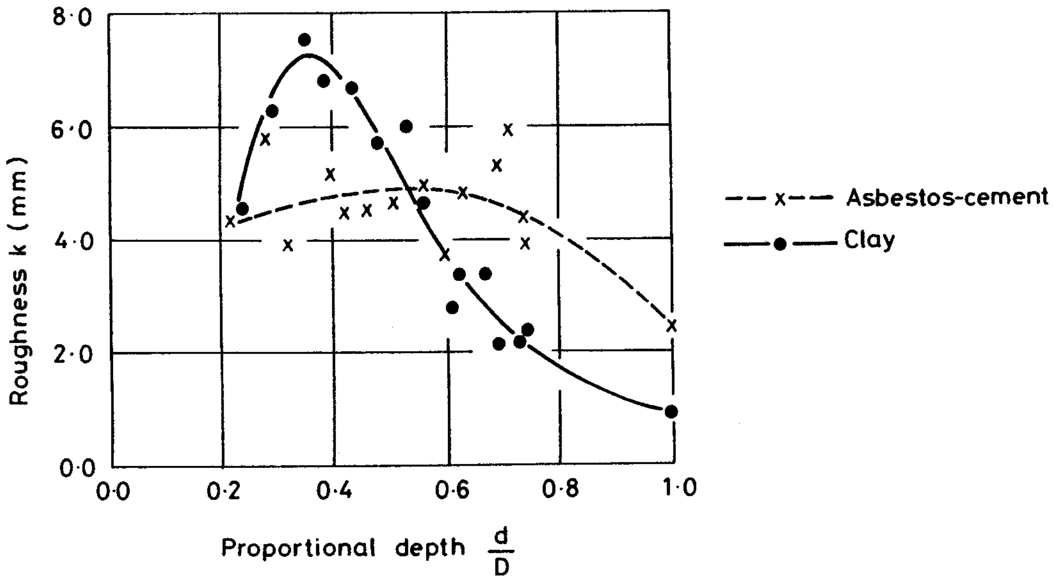


Fig 9

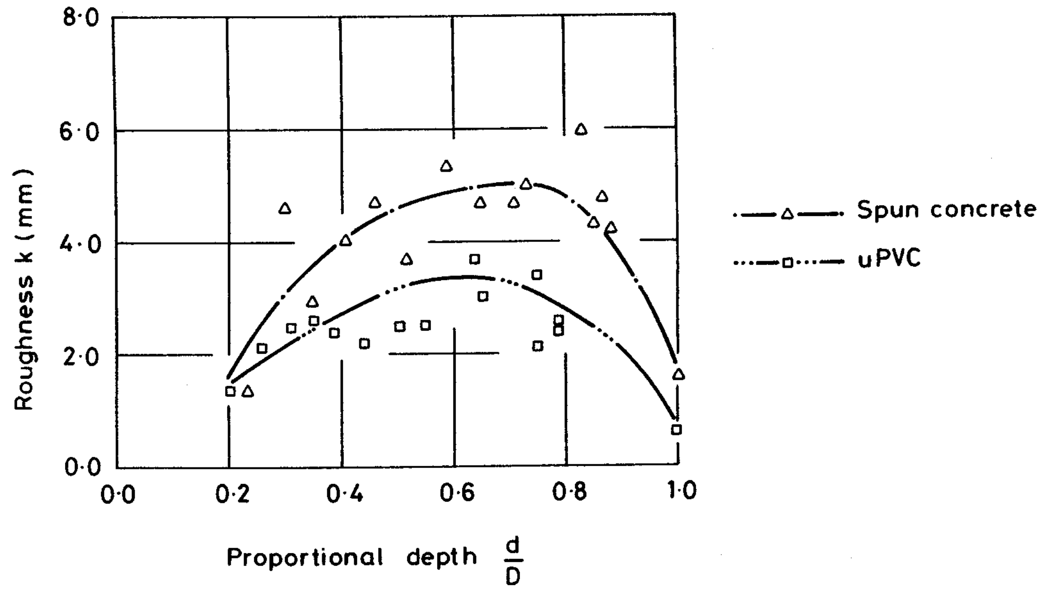


Fig 10 Variation of roughness with depth of flow – Run 1

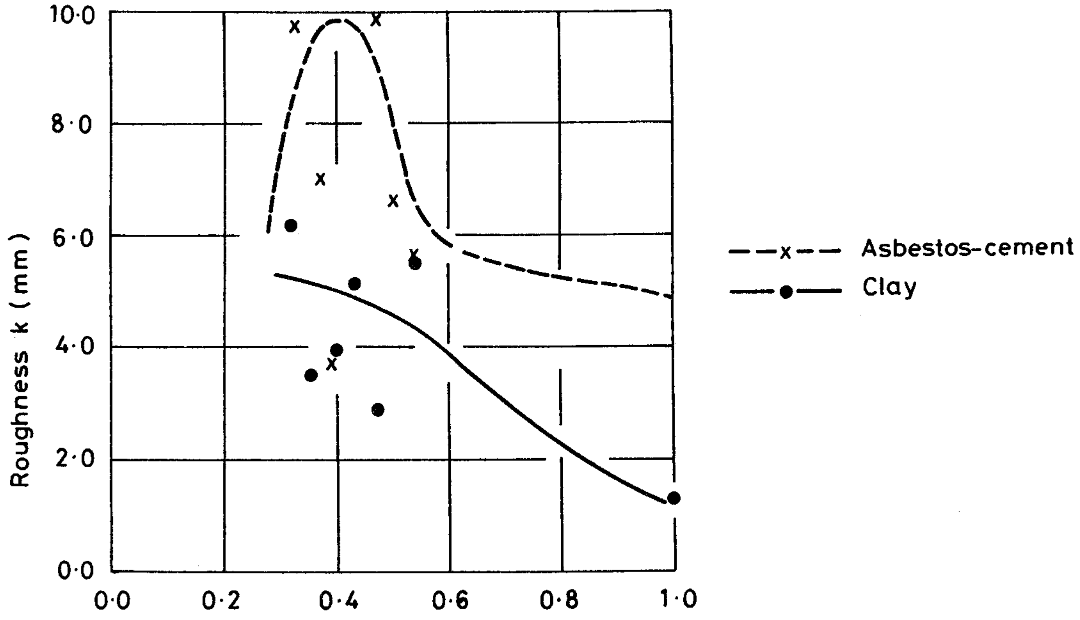


Fig 11

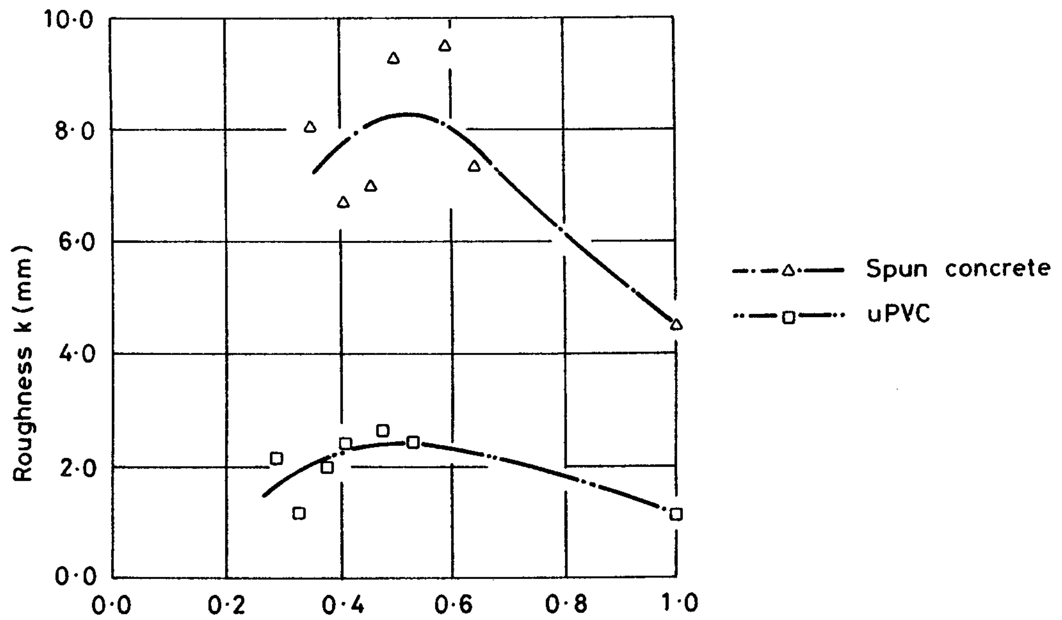


Fig 12 Variation of roughness with depth of flow - Run 2

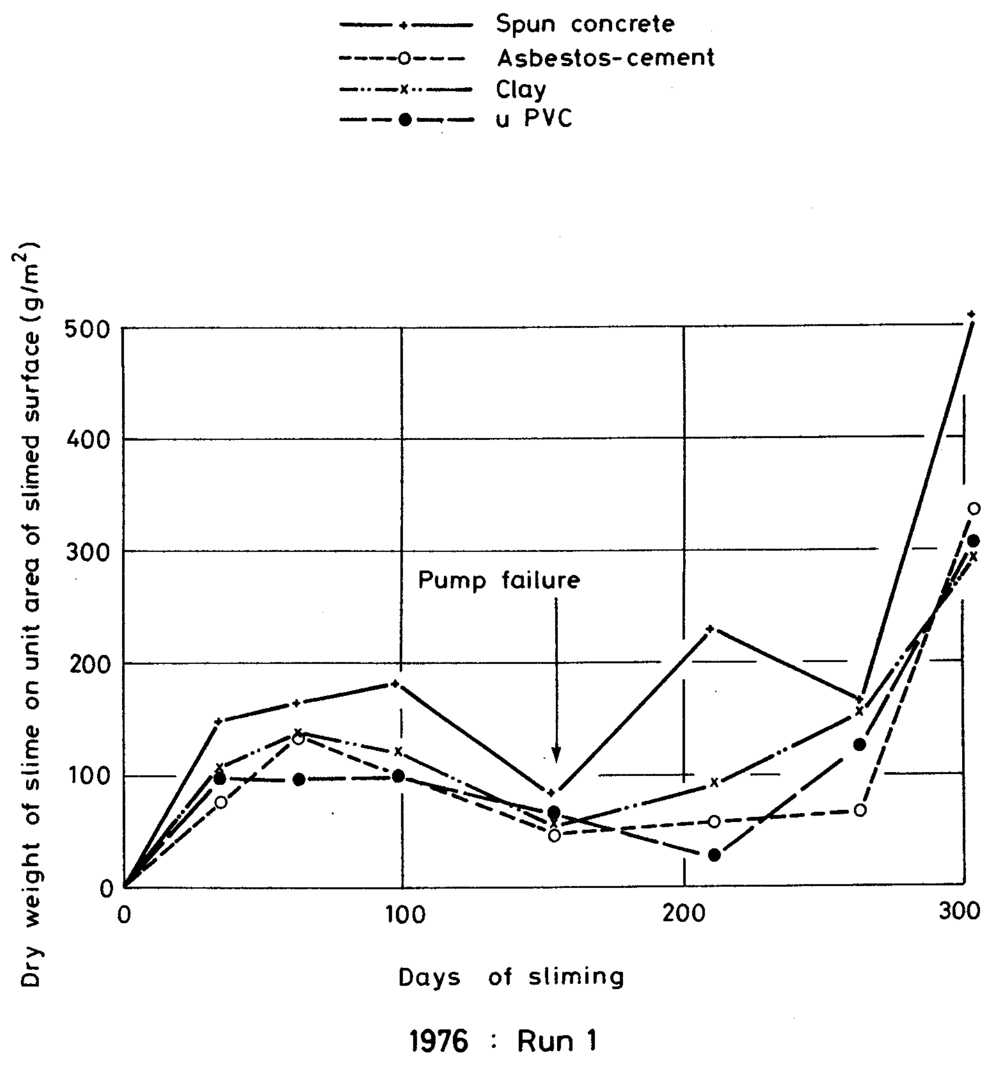


Fig 13 Weight of slime scraped from pipe walls - Run 1

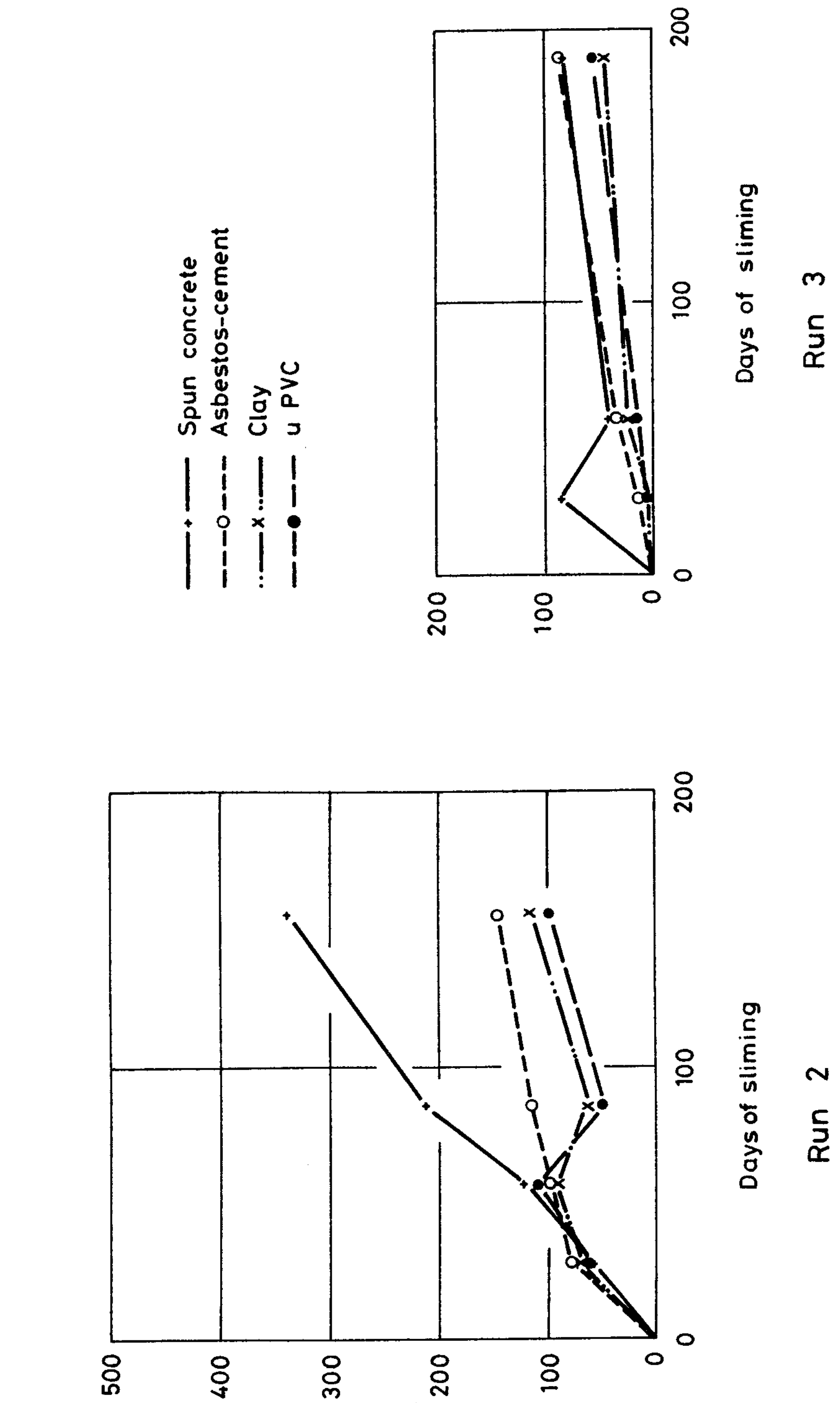
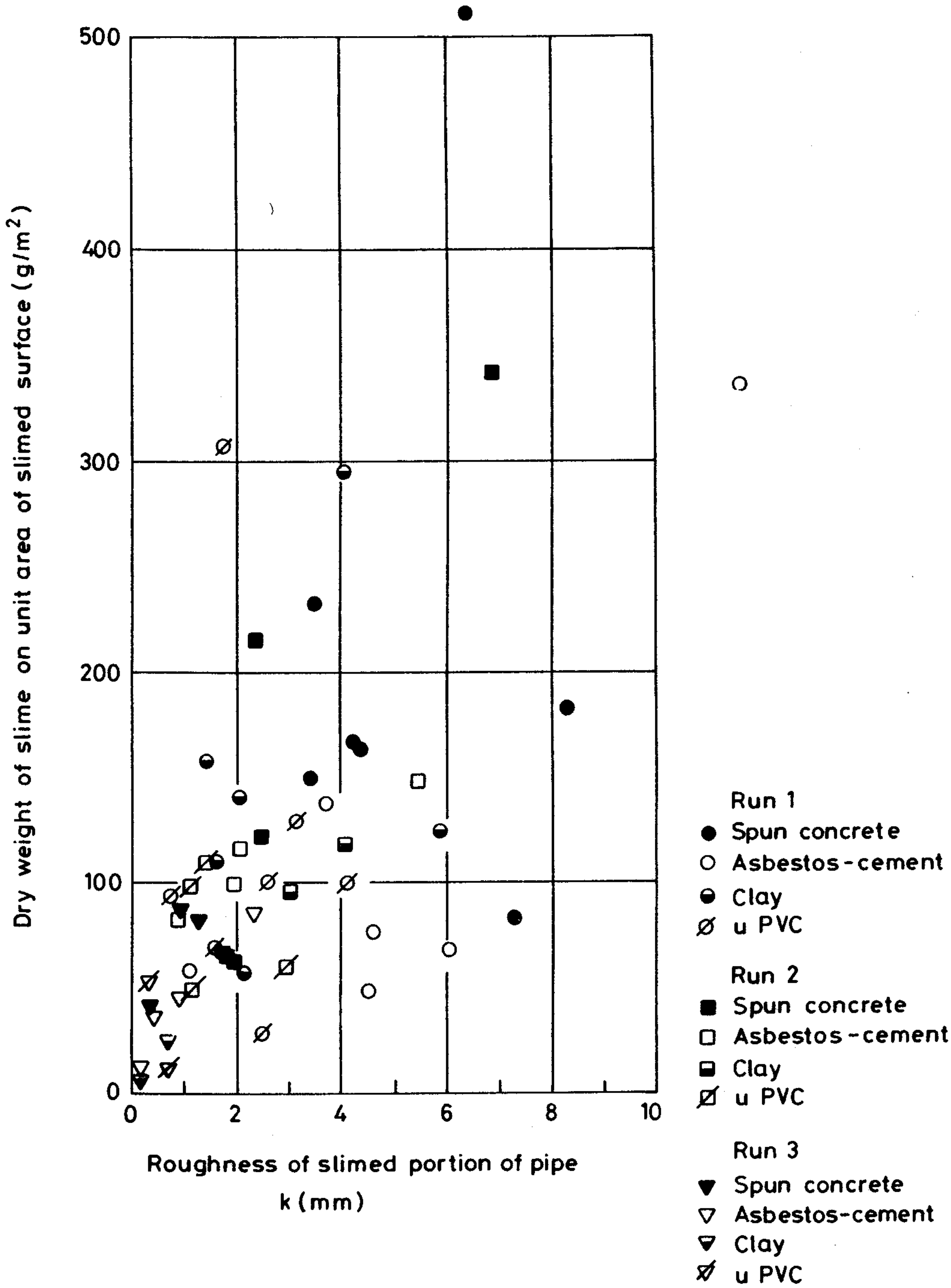


Fig 14 Weight of slime scraped from pipe walls - Runs 2 and 3



15 Relation between slime weight and pipe roughness

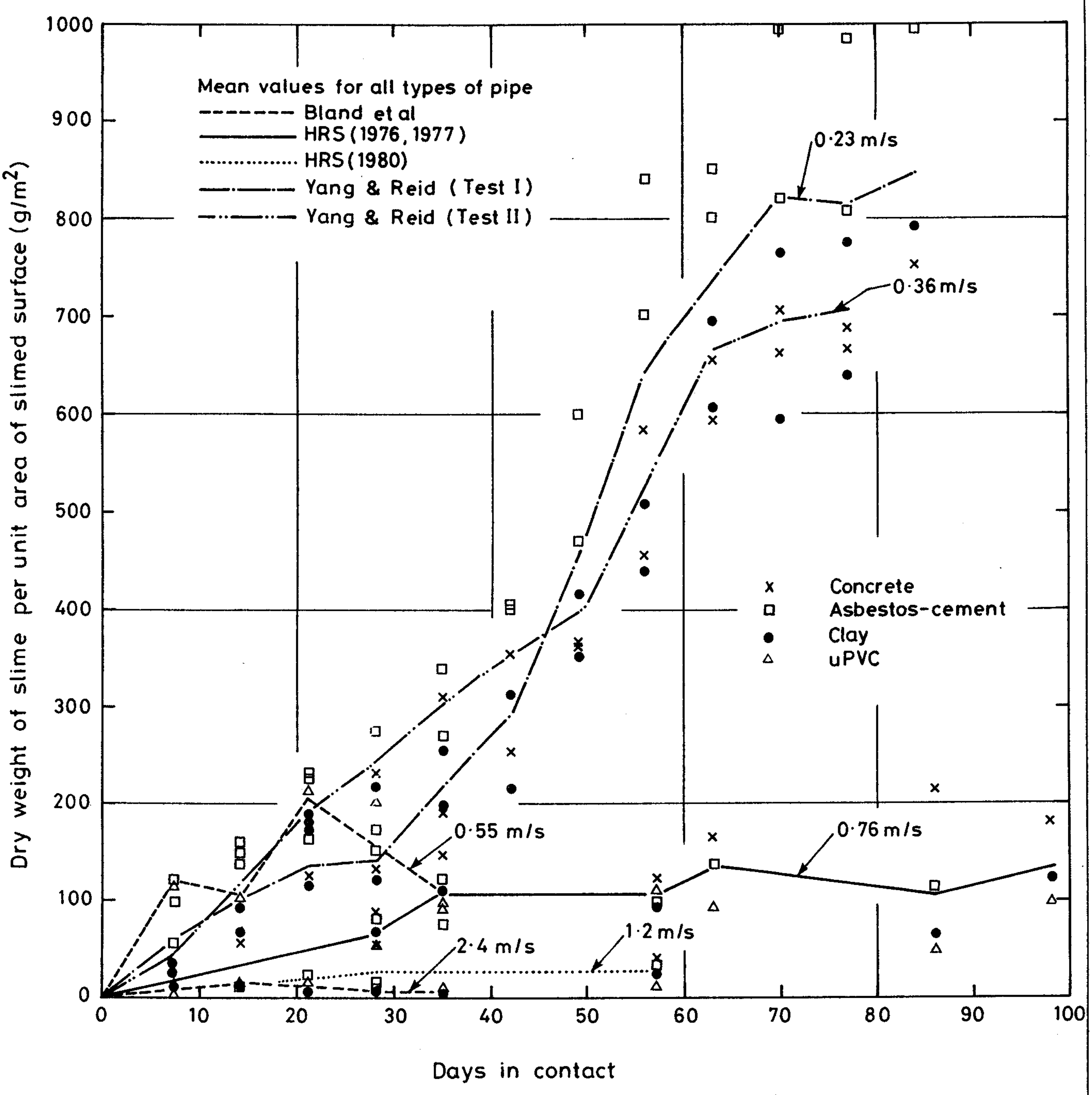


Fig 16 Variation of slime weight with time

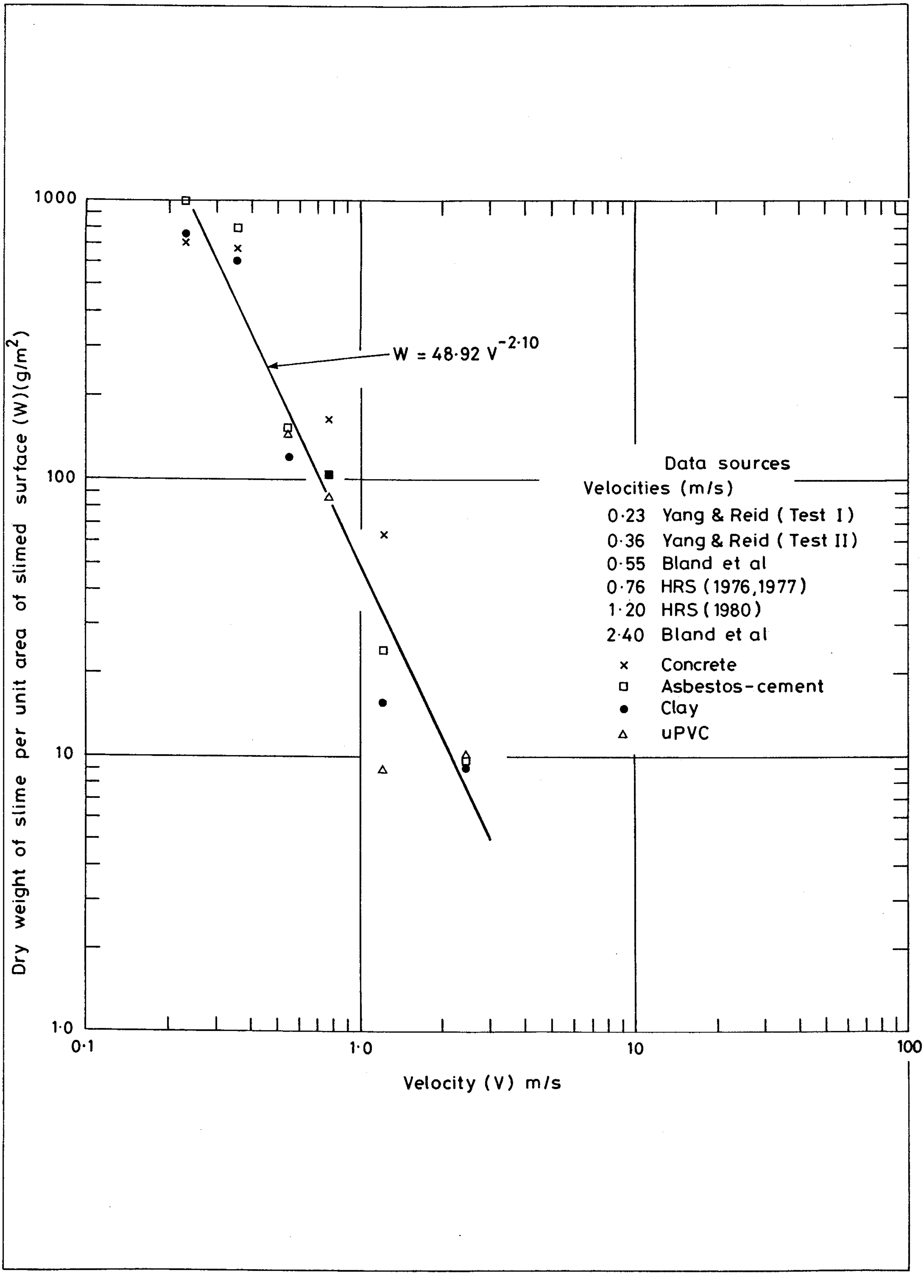


Fig 17 Equilibrium slime weight as a function of velocity

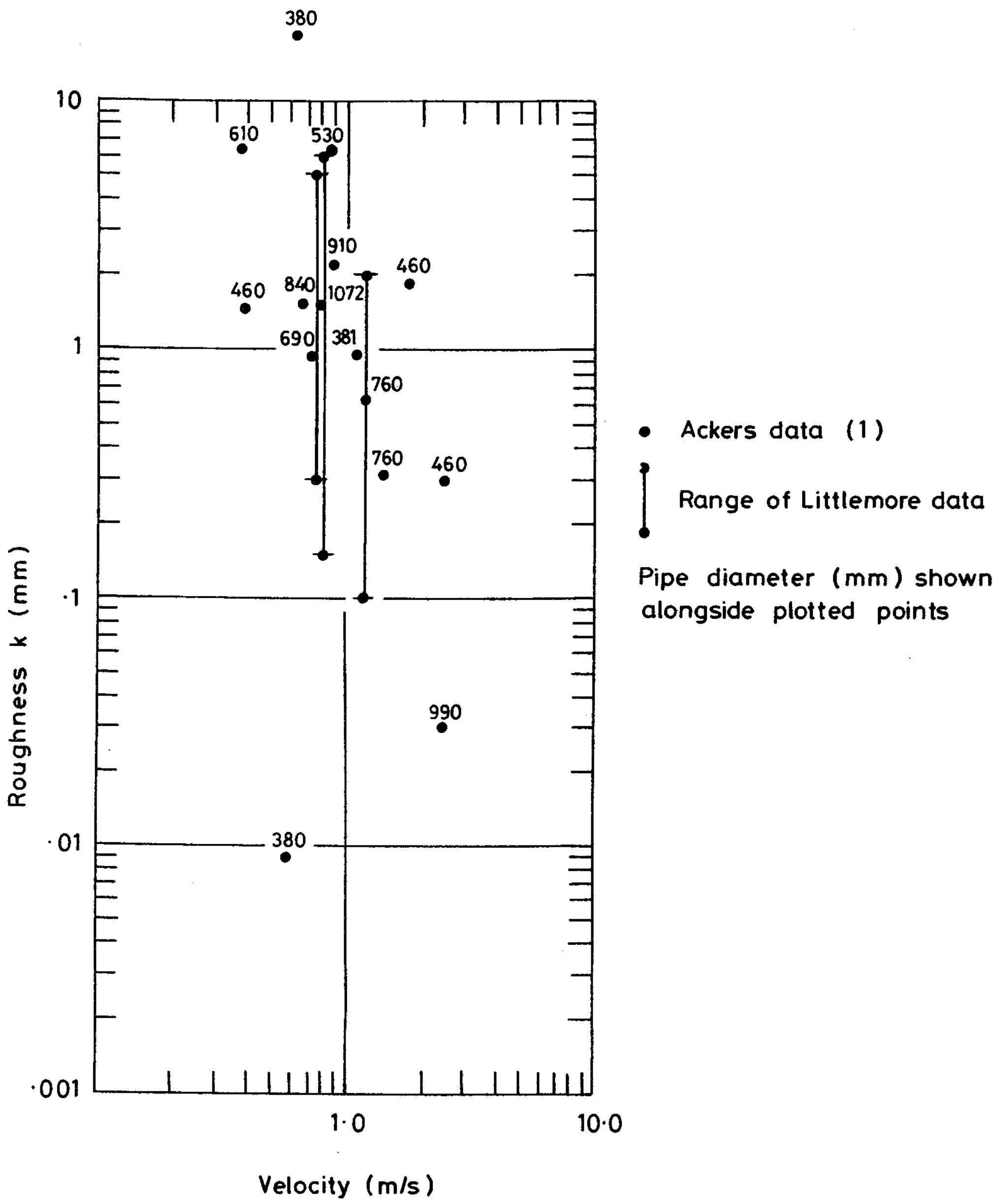


Fig 18 Variation of roughness with velocity : Ackers and Littlemore data

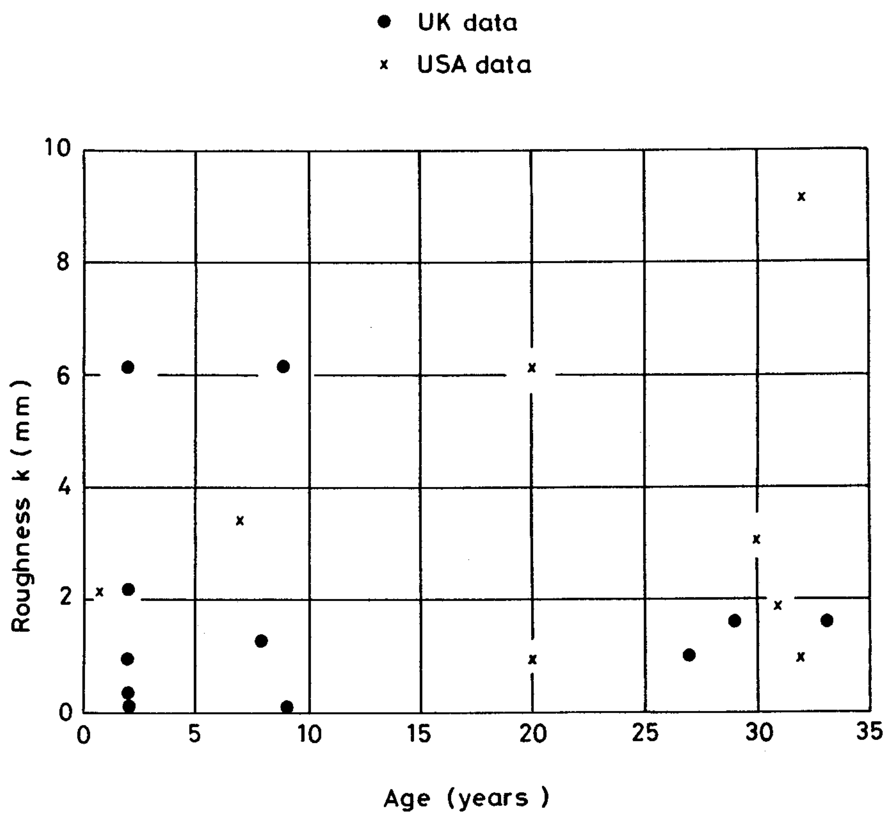


Fig 19 Roughness as a function of age in concrete sewers

Plates

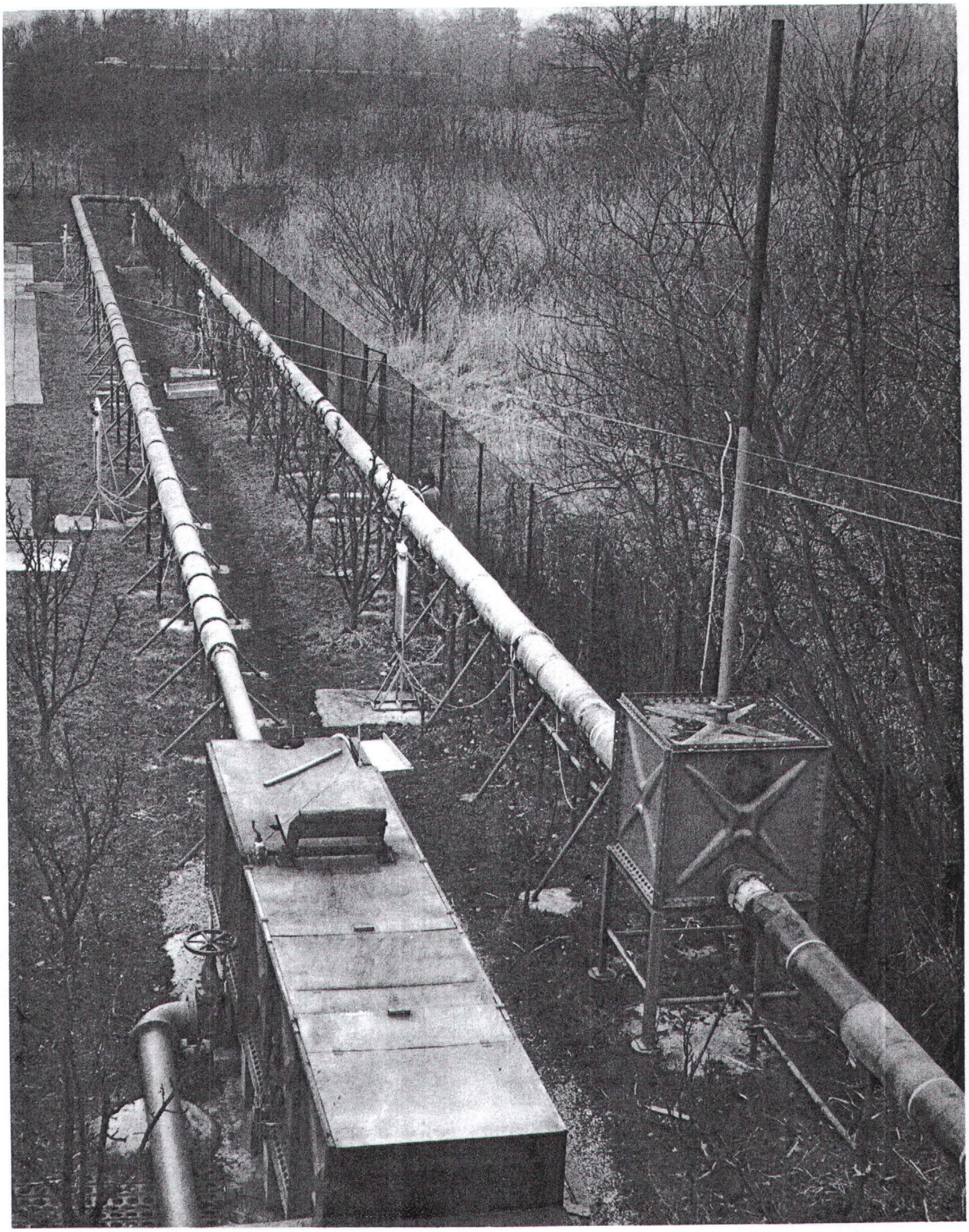


Plate 1 Test rig

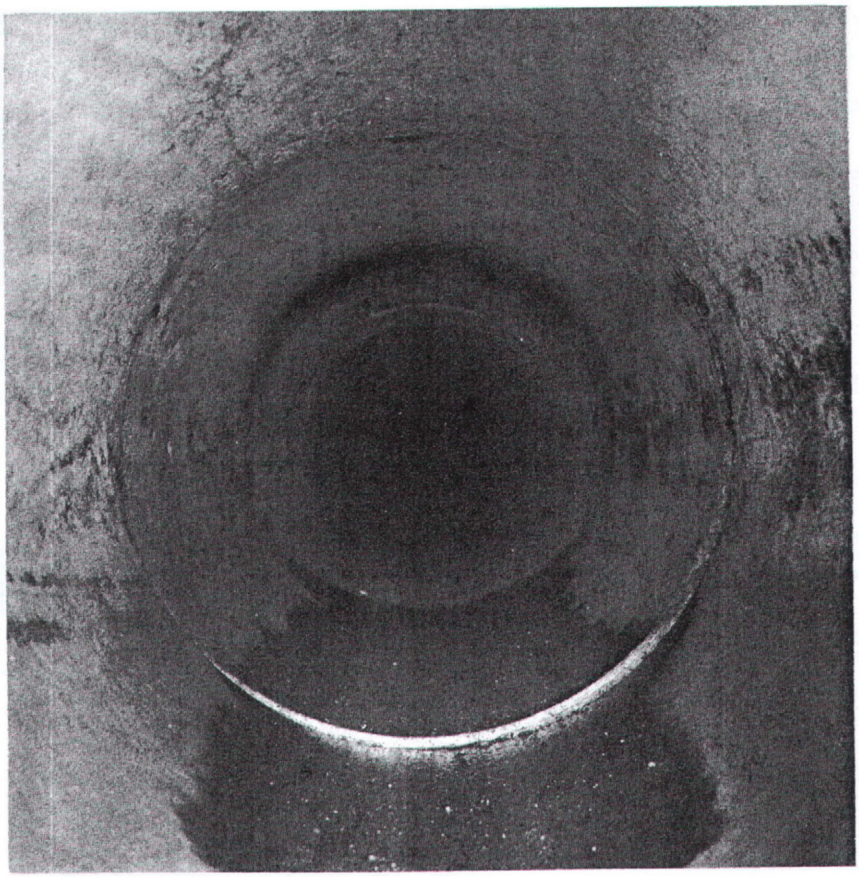


Plate 2 Clean. Roughness k = 0.02mm

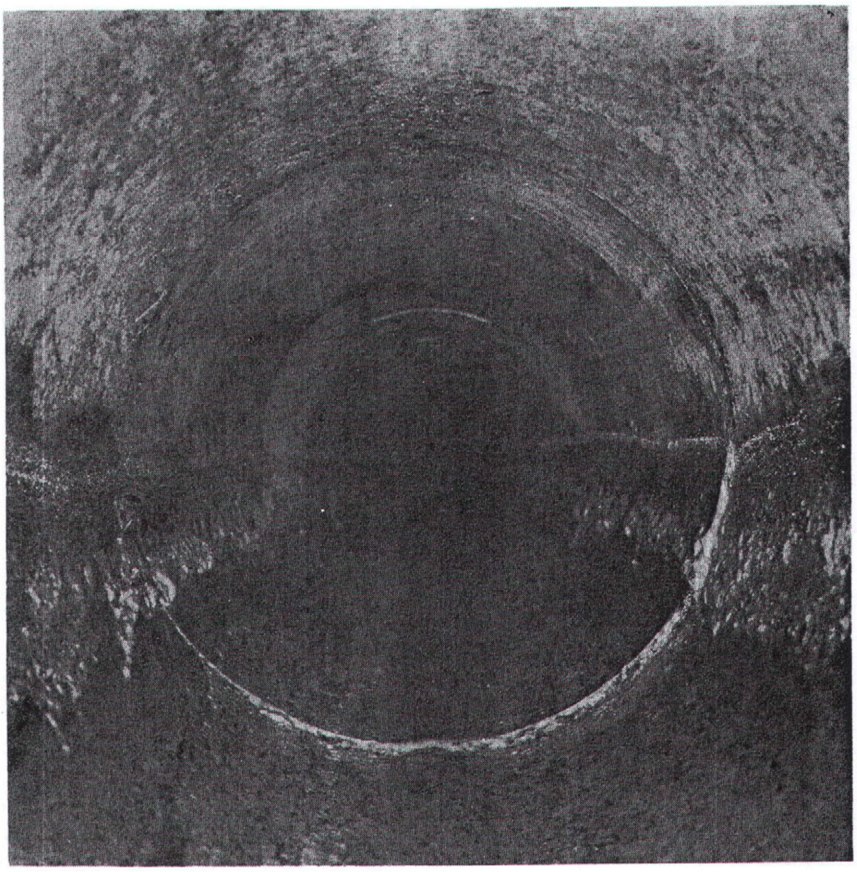


Plate 3 Roughness of composite surface (pipe-full) k_c = 0.4mm

Roughness of slimed surface (half-full) k_s = 1.1mm

Slime in asbestos-cement test pipes

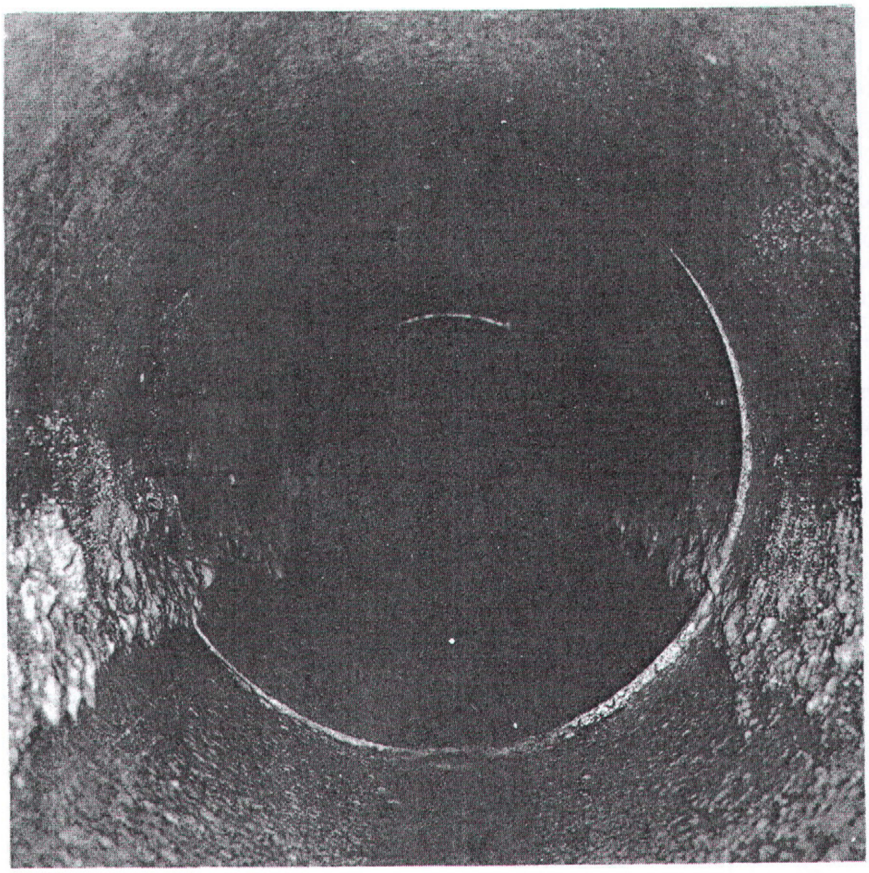


Plate 4 Roughness of composite surface (pipe-full) $k_c = 0.8mm$

Roughnessd of slimed surface (half-full) $k_s = 2.4mm$

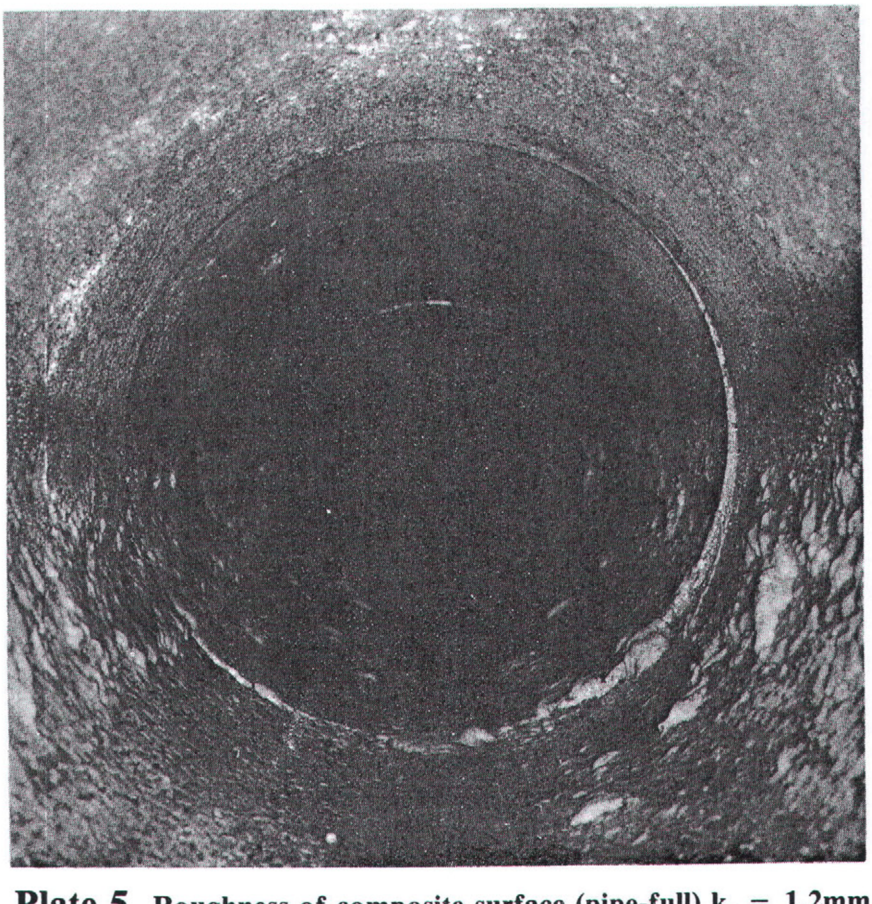


Plate 5 Roughness of composite surface (pipe-full) $k_c = 1.2mm$

Roughness of slimed surface (half-full) $k_s = 3.7mm$

Slime in asbestos-cement test pipes

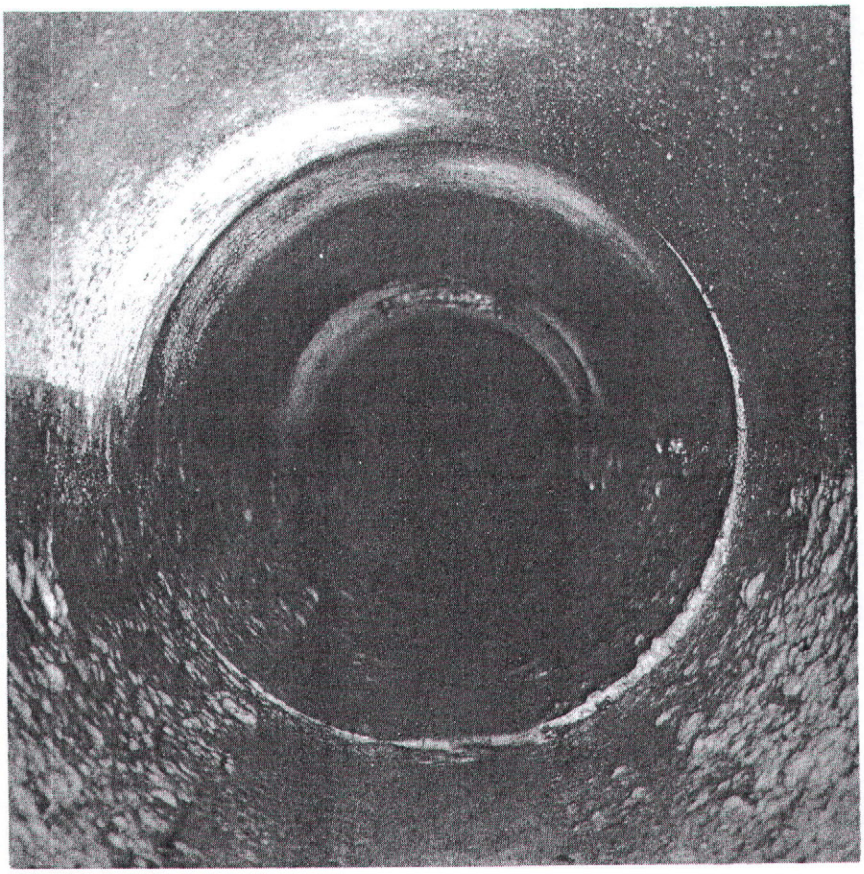


Plate 6 Roughness of composite surface (pipe-full) k_c = 1.8mm

Roughness of slimed surface (half-full) k_s = 5.7mm

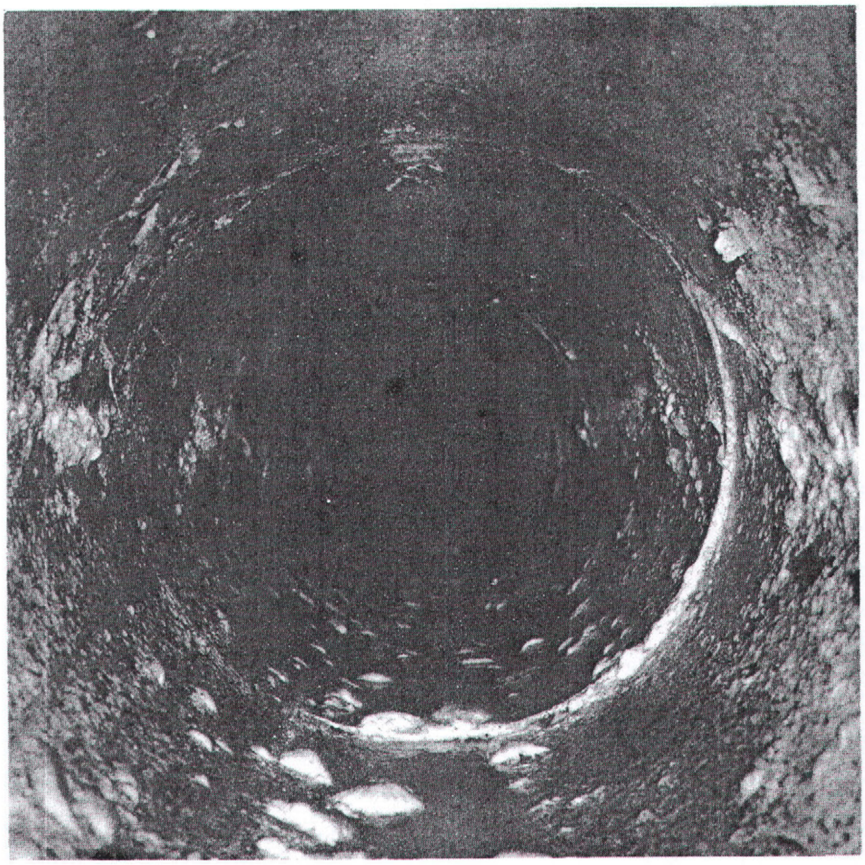


Plate 7 Roughness of composite surface (pipe-full) k_c = 3.2mm

Roughness of slimed surface (half-full) k_s = 10.3mm

Slime in asbestos-cement test pipes