

Thermally induced strains and stresses in cast iron water distribution pipes: an experimental investigation

D. A. Jesson, B. H. Le Page, M. J. Mulheron, P. A. Smith, A. Wallen, R. Cocks, J. Farrow and J. T. Whiter

ABSTRACT

Full-scale tests have been carried out on lengths of unrestrained and restrained plain and jointed distribution pipe sections ($\sim 4''$ or ~ 100 mm internal diameter) in order to investigate the strains and loads generated in cast iron water distribution mains as a result of temperature fluctuations. Tests on unrestrained sections enabled the coefficient of thermal expansion of the pipe material to be measured. In a fully restrained situation, which can occur in a pipe section in service when the joints are locked, tensile stresses arise from a decrease in temperature (in accordance with the predictions of a simple one-dimensional model) and it is shown that these stresses are sufficiently high to fracture a corroded pipe. In situations where the tensile stress leads to joint slippage, leakage through the joint is observed. Water leakage was also observed through the wall of corroded pipes that retained sufficient structural stability to carry load without failure.

Key words | asset management, cast iron, induced stress, leakage

D. A. Jesson (corresponding author)
B. H. Le Page
M. J. Mulheron
P. A. Smith
 Faculty of Engineering & Physical Sciences,
 University of Surrey,
 Guildford, Surrey GU2 7XH,
 UK
 Tel.: +44 1483 686299
 Fax: +44 1483 686291
 E-mail: d.jesson@surrey.ac.uk

A. Wallen
R. Cocks
J. Farrow
J. T. Whiter
 Thames Water Research and Development,
 Reading STW,
 Island Road,
 Reading, Berks RG2 0RP,
 UK

SYMBOLS

α coefficient of thermal expansion, K^{-1}
 ΔT temperature difference, K
 E Young's modulus, GPa

INTRODUCTION

It is generally accepted in the water industry that the failure rate of small diameter cast iron water distribution pipes increases during periods of low temperature. While there are a number of factors that may contribute to this behaviour, the simplest explanation is that the low temperature generates a tensile stress in the pipe that is of sufficient magnitude to cause failure, particularly when the pipe has experienced graphitisation in service.

A number of studies have contributed in providing evidence to support this hypothesis, in particular work that

has considered the extent to which tensile thermal stresses can be generated in jointed pipe sections and other studies which have investigated the extent to which material and pipe strength can be degraded by corrosion. Work at the University of Southampton (O'Shea 2000) has suggested that, in situations where the lead-run joints between adjacent lengths of pipe become 'locked', a longitudinal tensile stress may be generated in pipes in service as a result of thermal effects, associated with seasonal variations in water temperature. Tests on joints extracted from the ground confirmed that the assumption of locking is reasonable, at least for some pipes. A number of researchers have reported on the degradation of strength of cast iron pipes as a result of graphitic corrosion and its relationship to residual performance (Yamamoto *et al.* 1983; Sheikh *et al.* 1990; Conlin & Baker 1991; Rajani & Makar 2000; Atkinson *et al.* 2002; Seica & Packer 2004). In particular, recent studies (Belmonte *et al.* 2007, 2008) have used Weibull-based methods to investigate the strengths in tension and

doi: 10.2166/aqua.2010.078

flexure of small samples of cast iron extracted from cast iron water distribution pipes. It has been shown that the strength is degraded significantly as a result of graphitic corrosion in service and Weibull-scaling arguments lead to the conclusion that the strength of a corroded pipe could be lowered by as much as an order of magnitude compared with the strength of the pipe in its as-manufactured condition.

Putting these pieces of work together provides support for a working hypothesis of the potential failure process associated with the onset of cold weather. In particular, the thermal strains resulting from changes in temperature can produce stress levels comparable with the (tensile) strength of aged pipe. Depending on the geometry of the pipe system, the support conditions along its length, and the degree of degradation of the individual pipes, this may have the capacity to produce either opening of a joint between adjacent lengths of pipe or individual pipe failure.

The purpose of the present study is to examine further the validity of this model by carrying out full-scale tests on ex-service pipe sections. To this end, a series of tests have been conducted to monitor the behaviour of a number of cast iron water distribution pipes that have been taken from the ground (while still intact) and subjected to controlled temperature changes. These tests were performed on prepared sections of pipe between 1.0 and 2.0 metres in length. Results are presented for both continuous lengths of pipe (referred to here as ‘plain’) and lengths of pipe containing a discontinuity, such as a lead-run joint or repair clamp (referred to here as ‘jointed’).

The structure of the paper is as follows. The next section describes the experimental techniques developed to thermally cycle the pipes under unrestrained and restrained conditions and the measurement of the associated thermal strain (unrestrained pipes) and load (restrained pipes). Subsequent sections present the results from the two types of test. Data from the unrestrained tests enable the coefficient of thermal expansion to be determined, while in the restrained tests the load induced as a result of known temperature variation is determined. The response of the pipe sections examined was also recorded, in terms of pipe behaviour (including failure), any movement of the lead-run joint and water leakage.

EXPERIMENTAL PROCEDURE

Pipe samples

A number of lengths of $\sim 4''$ (~ 100 mm) internal diameter plain and jointed cast iron distribution pipe were sourced from service in the ground at five different locations, A–E, courtesy of Thames Water plc. Table 1 summarises the six pipe samples used for tensile testing in the present study. The samples provided were of length 1.5–2.5 m and had a nominal outer diameter of 125 mm with a wall thickness in the range 10–12 mm. The pipes were typically encrusted in a mixture of soil and corrosion product. It should be noted that in selecting samples for testing it became apparent that some of the pipes supplied were badly affected by graphitic corrosion (Figure 1). Such pipes could not be tested because the gauges employed to measure the thermal strain could not be bonded reliably to such a surface. In addition, it was found that some badly graphitised pipes were prone to through-wall leakage when subject to the 4 bar (~ 400 kPa) of water pressure employed in the tests. This had the potential both to disrupt the strain measurement system and to lead to water ingress into the loading frame used to restrain the pipe samples.

Development of controlled thermal cycling procedure

The thermal cycling facility was designed to subject lengths of pressurised cast iron water distribution pipes to a temperature change of 25°C. In these experiments the temperature of the pipe was controlled by altering the temperature of the water flowing through it. A temperature cycle 30°C \rightarrow 5°C \rightarrow 30°C was employed as this avoided the possibility of water freezing in the cooling system. It is probable that the associated change in temperature is larger

Table 1 | Pipe location and sample reference codes

Location	Pipe code	Joint
A	A1	No
A	A2	Yes
B	B1	No
C	C1	No
D	D1	Yes
E	E1	Yes



Figure 1 | Typical surface condition of supplied cast iron pipe showing extensive graphitic corrosion of pipe wall.

than any seasonal variation experienced by buried pipes in the UK. However, from an experimental perspective it produces changes in thermal strain that are sufficiently large to measure accurately, in a regime over which the response is anticipated to be linear.

The outer surface of the pipe was cleaned of adhering soil and loose corrosion product. The ends of the pipe were then cut perpendicular to the length to permit the fitting of an ‘Ultragrip’ flange adaptor (type 2, manufactured by Viking Johnson) at each end. One end of the pipe was then designated as the ‘bottom’ of the test specimen and the adaptor at that end was fitted with a steel blank plate which served to seal the pipe during testing. The pipe length was then stood upright on the floor, resting on the bottom end-plate, and secured in this position so that it was free to move as a result of thermal expansion (or contraction) effects but could not topple sideways during testing.

The end-plate at the top of the pipe length was then fitted. This had been specially adapted to allow both entry and exit of the pressurised cooling water (Figure 2). The



Figure 2 | Modified top end-plate to allow entry and exit of the cooling water.

inlet point was connected to a special ‘dip tube’ which allowed the pressurised, temperature controlled, water to enter the test pipe near to the bottom endplate. The water then flowed back up the length of the test pipe and exited at the underside of the top end cap. This arrangement helped to ensure complete circulation of the water and uniform cooling (or heating) of the pipe along its length. The system was designed to allow the water to be recirculated through the temperature control system (Figure 3).

Temperature control of the circulated water was accomplished using a heater/chiller chamber. The chamber contained two 30 m lengths of 10 mm diameter copper pipe connected in parallel. The water flowing through this heat exchanger was heated (or cooled) depending on the temperature of the chamber relative to the water. Water flows from the circulating pump, through the heat exchanger, through the pipe and back to the pump (Figure 3). Air was removed from the water by an air separator on the flow side of the pump and bled off from a vertical collection pipe. An automatic bypass was in place around the pump to avoid damaging the pump in the event of the heat exchanger freezing. Tap water was used in all of the experiments reported here. This limited the minimum temperature which could be employed in each thermal cycle to about 2°C in order to avoid problems of freezing within the cooling circuit.

The system was pressurised by a booster pump, running at 5.5 bar, via a pressure regulator set to 4 bar. The booster pump was fitted with an expansion vessel to reduce the number of starts made by the pump. The heating/cooling water circuit also had an expansion vessel to compensate for the change in volume of the water with temperature. The rate of change of temperature is controlled by the thermal mass of the system and the various heat losses (and gains) to the environment. The connecting pipe-work and the cast iron pipe under test were lagged with a combination of glass fibre and foam insulation to reduce uncontrolled heat loss (or gain) from the environment (Figure 4). This also helped to provide a uniform temperature along the length of the specimen. The pipe wall temperature was measured using a thermocouple attached to the outer surface. A second thermocouple was used to measure the air temperature in the laboratory during each experiment.

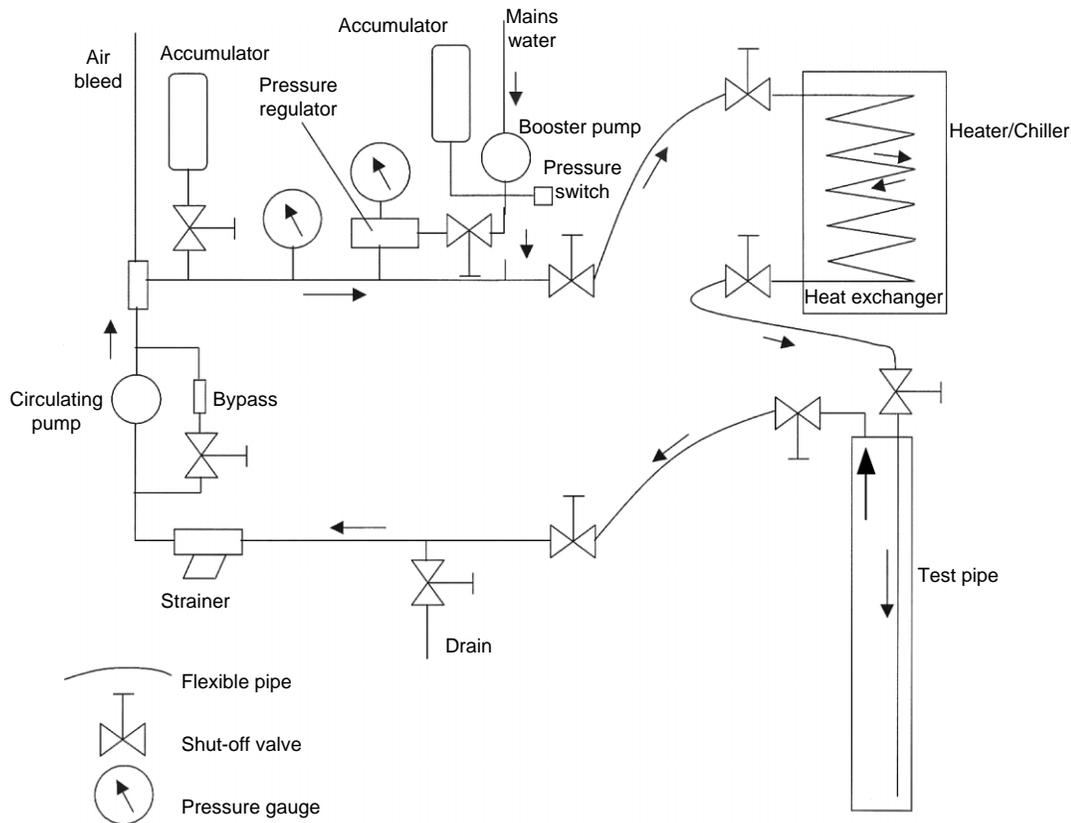


Figure 3 | Details of thermal cycling equipment.

To begin a typical thermal cycle the system was set to heat the circulating water to 45°C and the pipe wall temperature allowed to reach slightly above 35°C. The chiller system was then used to cool the water over a three-hour period until the outer wall of the pipe had reached 5°C. The water was then heated slowly until the pipe had reached a temperature slightly in excess of 30°C at which point the cycle was either stopped or repeated. [Figure 5](#) shows a typical plot of pipe temperature as a function of time for the normal temperature cycle used during the measurement of thermal strains and thermally induced loads.

Measurement of thermal strain (unrestrained pipes)

Strains in the pipe wall were measured using 6 mm long, surface-mounted, electrical resistance, foil strain gauges. These were attached to the carefully cleaned and abraded outer surface of the pipe using a suitable commercial adhesive

and were subsequently covered with a protective layer to improve their longevity. In order to measure the thermal strain using a strain gauge, a reference material of known thermal expansion behaviour is needed. In the present study, a standard bar of Invar metal was used, which has a constant coefficient of thermal expansion of $1.4 \times 10^{-6}/\text{K}$ over the temperature range of these experiments. The measurement gauge and compensation gauge were connected as adjacent arms of a Wheatstone bridge circuit following the procedure detailed in [Vishay Technical Note TH-513-1 \(2007\)](#).

The Invar bar, with its surface mounted strain gauge, was clamped to the wall of the pipe next to the other strain gauge ([Figure 6](#)). A layer of heat-sink compound was used between the Invar bar and the pipe wall in order to minimise the thermal gradient between the two materials. The temperature of the pipe was measured using a thermocouple placed between the pipe wall and the Invar bar. Using the measuring system developed in conjunction with the controlled temperature cycle it was possible to



Figure 4 | General arrangement of unrestrained pipe test showing position of top end-plate and thermal insulation in place.

monitor the induced strain in the unrestrained pipe specimens as a function of the pipe wall temperature over the range $30^{\circ}\text{C} \rightarrow 5^{\circ}\text{C} \rightarrow 30^{\circ}\text{C}$.

Measurement of thermally induced load (restrained pipes)

The aim of this part of the work was to measure the load developed in fully restrained pipe lengths (both plain and jointed) subject to controlled cooling over the range $30^{\circ}\text{C} \rightarrow 5^{\circ}\text{C}$. This approach seeks to mimic those conditions in the ground up to the point where the full thermal strain has been generated and held by the section under test (and the

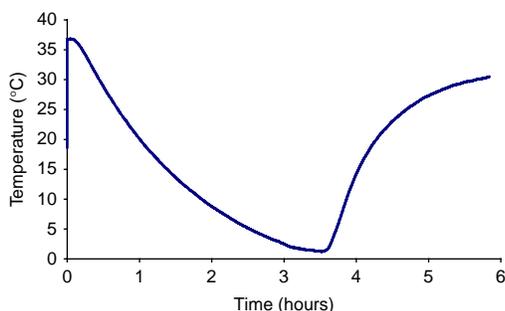


Figure 5 | Variation of pipe temperature with time during a typical thermal cycle.



Figure 6 | Invar bar, with its surface mounted strain gauge, attached to the pipe adjacent to the measurement gauge.

test is finished), or either pipe failure or joint movement occurs. The procedure adopted was to hold the instrumented pipe section in the loading frame of a universal testing machine, an Instron 8805, while subject to controlled cooling. The method employed relied on adjusting the load to maintain zero overall strain in the measurement system.

In carrying out these tests, a special mounting system was developed to ensure automatic alignment of the load chain under uniaxial loading and restraint, but the greatest challenge was to devise a suitable means of gripping the pipe. After various trials, the best arrangement was found to be to bond the flange adaptors (used previously in the unrestrained tests) to the ends of the cast iron pipe using a structural-grade epoxy resin adhesive. This was necessary as testing was carried out above the manufacturer's rated strength for these adaptors. Firstly, the pipe ends were abraded using abrasive cloth tape with 80 grit carborundum abrasive. Secondly, the inside of the adaptors was blasted with glass beads to roughen the protective coating. The surfaces to be bonded were then cleaned with propan2ol. The adhesive was then smeared over the plastic teeth of the adaptor and the area of the pipe where these were to grip. The adaptor was positioned on the pipe and tightened. When the epoxy adhesive had cured it was observed that there was a small annular gap between the body of the adaptor and the pipe. The gap was too small to inject the epoxy adhesive successfully and so an acrylic floor anchor adhesive was injected instead as this was less viscous. Once the adhesives had reached full-strength (after 48 hours) the pipe was ready for testing. Care was taken to minimise the time for which water was held in the pipe, in order to minimise any associated degradation of the adhesive bond.

Using this arrangement it was possible to achieve thermal loads in excess of 100 kN with no slippage of the adaptors.

The general test procedure adopted was as follows. The insulated pipe was mounted into the Instron 8805 and attached to the loading frame at the bottom end. The pipe was then brought to a temperature of 30°C and the top end of the pipe was then connected through the specially modified end-plate to the load-cell. A small pre-load (2–3 kN) was then applied to help align the load chain after which it was reduced to around 1 kN and the strain measuring system balanced. The pipe was then cooled at around 10°C/hour following the normal cooling profile established previously. As the temperature dropped an incremental tensile load was applied manually to the pipe that was just sufficient to keep the strain in the measuring system at 0 ± 2 micro-strain. In this way a number of tests were completed on both plain and jointed pipe specimens under restrained conditions.

RESULTS AND DISCUSSION

Measurement of thermal strain (unrestrained pipes) and CTE values

Figure 7 shows data for the thermal strain measured on the pipe wall (relative to the Invar bar reference sample) as a function of temperature during the first experiment investigating the response of pipe A1 under conditions of cooling and heating. There is a high degree of linearity to the data. The coefficient of thermal expansion (CTE) for the pipe material was determined from the slope of the line, with the addition of the CTE value for the Invar reference. Proceeding in this way, the data for all the samples investigated are summarised in Table 2. There is very good consistency of the data between the heating and cooling regimes, as well as reproducibility and consistency between the different pipes, with the exception of pipe D1. The measured values of CTE are in the range $11\text{--}13 \times 10^{-6}/\text{K}$ and as such are consistent with published values for grey cast irons (White 1990). Pipe D1, which showed a much lower CTE, is believed to be another (iron-based) material rather than a grey cast iron. The physical appearance and wall thickness of pipe D1 were different from the other pipes tested, consistent with the different CTE value.

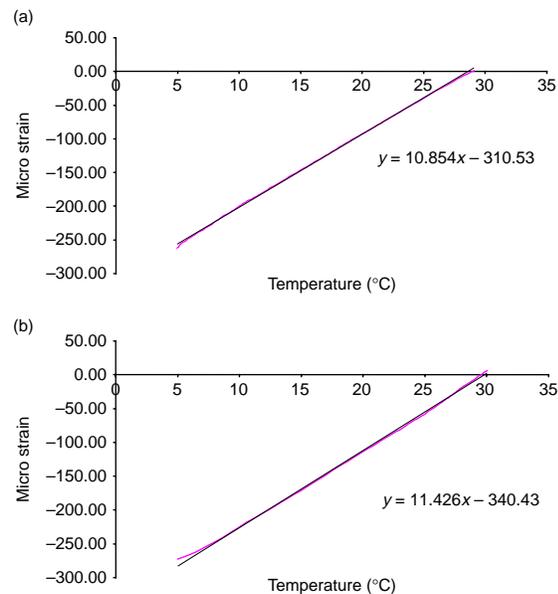


Figure 7 | Pipe surface strain as a function of temperature during the first thermal cycle of sample A1, (a) cooling and (b) heating.

Measurement of thermally induced load (restrained pipes)

Plain pipe

Following optimisation of the gripping arrangements, pipe A1 (no joint) was tested according to the procedure outlined above. Following equilibration at a temperature of 30°C, the temperature was reduced, leading to a build up of tensile load in the pipe; catastrophic tensile fracture of the pipe occurred when the temperature had been lowered by an amount ΔT of 20°C, at which point the load on the pipe (as measured by the Instron load cell) was 95 kN, corresponding to a tensile stress in the pipe wall of approximately 28 MPa.

For this test arrangement, simple theory predicts that the longitudinal stress developed in the pipe is given by the product $E\alpha\Delta T$, where E is the Young's modulus of the cast iron, α is the CTE and ΔT is the temperature difference. Based on the known CTE of the pipe material ($12 \times 10^{-6}/\text{K}$), the ΔT of 20°C that caused failure, then the Young's modulus of the cast iron would have to be 117 GPa, which is reasonable for the type of cast iron employed in such pipes. (A value of 117 GPa is at the upper end of the typical range of 80 to 120 GPa for these materials.) Moreover the measured tensile stress at failure

Table 2 | Coefficient of thermal expansion (CTE) data for all pipe samples tested

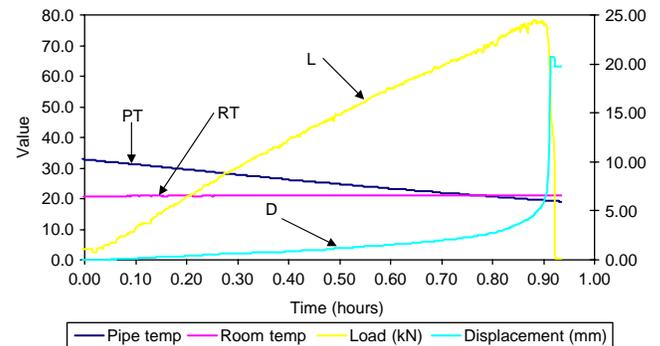
Pipe code	Run	Derived CTE ($\times 10^{-6}/\text{K}$)		Average
		Cool	Heat	
A1	1	12.3	12.8	12.6
A1	2	12.2	12.2	12.2
A1	3	12.2	12.0	12.1
A1	4	12.2	12.1	12.2
A2	1	13.0	12.3	12.7
A2	2	12.9	12.7	12.8
B1	1	11.6	11.7	11.7
B1	2	11.8	11.7	11.8
B1	3	11.7	11.7	11.7
B1	4	11.7	11.7	11.7
C1	1	11.7	11.8	11.8
D1	1	7.7	7.1	7.4
D1	2	7.7	7.4	7.6
E1	1	11.8	12.3	12.1
E1	2	11.4	12.9	12.2

for this pipe is consistent with residual strength measurements and associated Weibull-scaling arguments presented in previous work on degraded pipe samples (Belmonte *et al.* 2007, 2008). Clearly a pipe with a greater degree of degradation will require a smaller temperature difference to trigger fracture.

Jointed pipe

Pipe E1 was used to investigate the thermal cooling of a fully restrained jointed pipe. With the bonded adaptors in place, this pipe was placed into the reaction frame of the Instron 8805 and, once heated to slightly above 35°C, the ends were restrained. The pipe was then cooled at around 10°C/hour following the normal cooling profile. As the pipe was cooled, an increasing load was applied to maintain the required restraint (Figure 8). At a load of around 65 kN it was observed that the joint itself was being pulled apart. As the test continued a limited amount of water leakage occurred at the lead-run joint. When 20 mm of pipe had been pulled out from the joint the test was stopped to prevent complete separation of the joint. The maximum load recorded during the test was 78 kN.

This result for the jointed system, taken in conjunction with the observed failure of the plain pipe, appears to confirm

**Figure 8** | Data from thermal cycle on fully restrained jointed pipe section E1.

the hypothesis that 'locked' joints can result in significant tensile loading being transferred to the pipe system under thermal loading. Thus temperature changes of only a few degrees can lead to loads of the order of tens of kilo-Newtons in the pipe, and generate tensile stresses that are sufficient to either fail a degraded pipe or cause joint opening.

Water leakage issues

During the main experimental programme both plain and jointed pipe sections were subject to testing under the equivalent of a standard mains pressure (4 bar). In a number of cases water leakage was observed and, where possible, an attempt was made both to identify the source of the leakage and to measure rate of water loss. This section summarises those findings.

Plain pipe

As noted previously, a number of the pipe sections provided for testing exhibited significant graphitisation making them unsuitable for instrumentation and, in some cases, prone to through wall-thickness leakage when placed under standard mains pressure (4 bar). Typically, such leakage manifested itself by the appearance of a 'wet patch' on the outer surface of the pipe wall that did not disappear over time, suggesting a process of slow, but ongoing, water loss. This raises the possibility that, in service, some graphitised pipes may leak even though they have sufficient residual mechanical properties to carry both in-service loads and mains pressure without failure being initiated.

As well as large-scale, through wall-thickness graphitisation, a section of plain pipe (taken from location E) was found to have a hairline crack, less than 50 mm in length, present on its surface. When this pipe section was pressurised to 4 bar the leak took the form of a high pressure stream (Figure 9(a)). The resulting leakage rate, measured using a flow meter, was found to vary between 100 and 150 cm³ min⁻¹. Careful observation of the pipe suggested that the ‘wet’ area around the crack seemed larger than could be accounted for simply from associated spray, splash-back, or lower pressure fluid at the edge of the crack. There was also a localised wet patch, away from the main stream (Figure 9(b)).

Taking these results together it is apparent that under normal service pressure a plain pipe can exhibit through-wall leakage (at a measurable rate) without being associated with catastrophic failure. Such leakage may be associated with both cracks and graphitisation. Across a sizeable, ageing

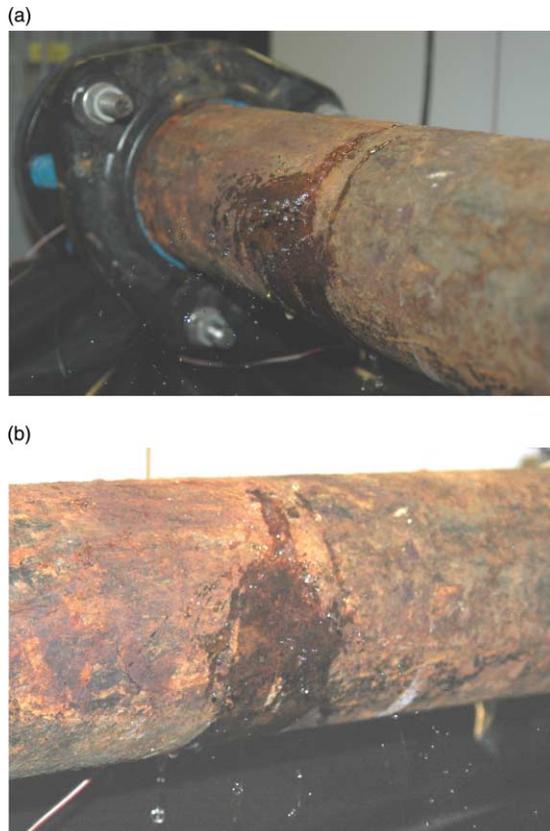


Figure 9 | Leak from a plain section of pipe E.

infrastructure (in which pipes may contain significant areas of through wall-thickness graphitisation and cracking) such leakage could lead to a considerable loss of water.

Jointed pipe

Prior to the thermal testing procedure, it was observed that the jointed specimens (A2, C1, E1) showed some weeping from the joint after initial pressurisation, although this ceased after 6–9 hours. This is consistent with either existing corrosion product or oakum (present in the lead-run joint) becoming hydrated and swelling in order to seal the joint.

At the end of the thermal loading experiment the overall movement at the joint in pipe E1 was approximately 20 mm, with the majority of the displacement occurring around the peak load (Figure 8). After the thermal cycle test had been completed (and the pipe restraint removed) a continual leakage of water was observed at the joint. While below the limit detectable using commercially available flow meters, it was possible to collect the water that leaked from the pipe over time and record its volume. Using this method a stable, and reproducible, leakage rate of 2–3 cm³ per minute was determined (Figure 10).

The jointed pipe (E1) was then subject to a compressive load of the order of 15 kN with the objective of pushing the leaking joint closed. After this, the pipe was again filled with water and pressurised. The leakage rate was then measured at ~15 cm³ min⁻¹, much higher than that seen when the joint was first opened. Over a period of 100 hours, this rate decreased to below 1 cm³ min⁻¹. This demonstrates the capacity of lead-run joints to tolerate opening and closing movements while retaining significant water tightness.

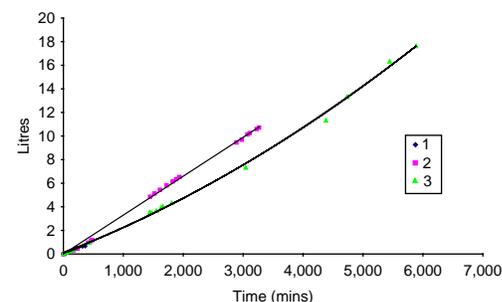


Figure 10 | Total leakage (litres) as a function of time (minutes) for the leaking joint in pipe E1 opened by 20 mm during thermal cycling (1, 2 and 3 represent three independent measurements of leakage).

CONCLUDING REMARKS

A methodology has been developed for the controlled thermal cycling of lengths of aged pipes at pressures of 4 bar over the temperature range 30°C → 5°C → 30°C. From the thermal strain data collected, and the unrestrained nature of the test arrangement, it has been possible to calculate the coefficient of thermal expansion of the various pipe materials. These have been found to be in good agreement with published data for grey cast irons, with one exception thought to be a different material, possibly ductile iron.

A method has been developed to subject fully restrained pipes to the thermal cycle 30°C → 5°C. The results have shown that the thermal cycle used can generate significant tensile loads (up to 100 kN) within the pipe. For the pipe sections investigated such loads correspond to a pipe wall stress of approximately 25 to 30 MPa, which is capable of failing plain pipe that has degraded with time in service. For the plain pipe that failed there was good agreement between the measured stress at failure and that predicted from simple theory.

For the jointed pipe samples examined, thermal loads of the order 35 kN were found to be sufficient to cause 'rotation' of a conventional 'aged' lead-run joint. Such joints have been shown to be 'opened' (leading to water leakage) by loads of the order 65 kN.

Under normal service pressure a plain pipe can exhibit through-wall leakage (at a measurable rate) without being associated with catastrophic failure. Such leakage may be associated with both cracks and graphitisation. Across a sizeable, ageing infrastructure such leakage would lead to a considerable loss of water.

In meeting the objective of this work (which was to understand the behaviour of cast iron water distribution pipes under controlled temperature changes) the results have highlighted the need to understand the role of joints in more detail and the leakage mechanisms and associated rates possible from buried cast iron distribution pipes. Both of these issues have relevance to the management of degraded, small diameter, water distribution systems.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions to prior work of Natalie Ford and Dr Hal Belmonte at the University of Surrey and the continuing technical support provided by Peter Haynes and Nigel Mobbs of the University of Surrey.

The opinions expressed in this paper are those of the authors and not necessarily endorsed by the University of Surrey or Thames Water Plc.

REFERENCES

- Atkinson, K., Whiter, J. T., Smith, P. A. & Mulheron, M. 2002 *Failure of small diameter cast iron pipes*. *Urban Water* **4**(3), 263–271.
- Belmonte, H. M. S., Mulheron, M. J. & Smith, P. A. 2007 *Weibull analysis, extrapolations and implications for condition assessment of cast iron water mains*. *Fatigue Fract. Eng. Mater. Struct.* **30**, 964–990.
- Belmonte, H. M. S., Mulheron, M. J., Smith, P. A., Ham, A., Wescombe, K. & Whiter, J. T. 2008 *Weibull based methodology for condition assessment of cast iron water mains and its application*. *Fatigue Fract. Eng. Mater. Struct.* **31**, 370–385.
- Conlin, R. M. & Baker, T. J. 1991 *Application of Fracture Mechanics to the Failure Behaviour of Buried Cast Iron Mains*, Transport Research Laboratory Contract Report No. 266, Wokingham, UK.
- O'Shea, P. J. 2000 *Failure Mechanisms for Small Diameter Cast Iron Water Pipes*. PhD Thesis, University of Southampton, UK.
- Rajani, B. & Makar, J. 2000 *A methodology to estimate remaining service life of grey cast iron water mains*. *Can. J. Civil Eng.* **27**, 1259–1272.
- Seica, M. V. & Packer, J. A. 2004 *Mechanical properties of aged cast iron water mains*. *J. Mater. Civil Eng.* **16**, 69–77.
- Sheikh, A. K., Boah, J. K. & Hansen, D. A. 1990 *Statistical modelling of pitting corrosion and pipeline reliability*. *Corrosion* **46**(3), 190–197.
- Vishay Micro-Measurements 2007 Tech Note TN-513-1, *Measurement of Thermal Expansion Coefficient Using Strain Gages*, Document Number: 11063, Revision 16-July-07. Available from <http://www.vishay.com/strain-gages/knowledge-base-list/technotes-list/> (accessed 12 August 2009).
- White, C. V. 1990 *Gray iron*. In *ASM handbook*, ASM International, Materials Park, Ohio, pp. 12–32.
- Yamamoto, K., Mizoguti, S., Yoshimitsu, K. & Kawasaki, J. 1983 *Relation between graphitic corrosion and strength of cast iron pipes*. *Corros. Eng.* **32**(3), 157–162.

First received 19 August 2009; accepted in revised form 21 December 2009