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Cavitation damage to potential sewer and drain pipe materials

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ABSTRACT

High-pressure water-jet testing of a range of polymeric and ceramic (clay and concrete) materials was carried out with a view to assessing their performance as potential materials for use in the manufacture of non-pressurised drain and sewer pipes. This work describes test equipment calibration, jetting resistance tests on 20 potential pipe materials, and post-processing of the eroded test samples. The relationships between spatial and temporal fluctuations observed in the water-jet formed the basis for the understanding of the cavitation erosion mechanisms giving rise to the observed damage rates. Mie scattering data provided evidence of droplet and cavity sizes in the cavitating jet upon which initial cavity radii for future Rayleigh–Plesset equation analysis could be based. Those candidate materials with the longest time until the onset of damage (in descending order) for the top five of the materials tested were concrete, clay, 30% (by volume (v/v)) glass-filled nylon, polysulphone, and polyetherimide. The candidate materials capable of resisting the greatest pressure without showing signs of damage for 30 s (in descending order) were polyetheretherketone, clay, polyetherimide, polyphenylene sulphide, and polysulphone.

1. Introduction

A high-pressure water-jet was used to induce cavitation erosion in a range of materials that were tested on the basis that they may have offered the potential to be prototyped as sewer and drain pipe wall construction materials (or as liners to refurbish existing installations). High-pressure water-jet cavitation erosion resistance testing was described as follows: test equipment calibration, jetting resistance tests on candidate pipe materials, and post-processing of the test samples. The relationships between spatial and temporal fluctuations were observed in the jet. Mie scattering data provided evidence of droplet and cavity sizes in the jet upon which initial cavity radii for future use of the Rayleigh–Plesset equation may be based. The aim was to rank the materials tested in terms of their cavitation erosion resistance expressed through the proxies of their ability to resist the onset of damage for a certain time, or sustain the application of a certain pressure for a minimum time.

The research was industrially-driven: The Foundation for Water Research, in 1994 [1], identified some 235,000 km of non-critical sewers in England and Wales within which maintenance was reactive (*e.g.* responsive to public, or Local Authority, call-out in the event of a blockage as often evinced by local flooding or odour): failure rates in these non-critical sewers amounted to approximately 4000 incidents *per annum*. Cant and Trew [2] recognised that much low-level maintenance involved high-pressure water-jetting which used irresponsibly, damages drains and sewers. Their experimental research saw the testing of a range of pipes with a standard nozzle configuration and led to codified limits for jetting resistance (clay and concrete: 34 MPa, and plastics: 18 MPa) which influence the market to this day [3]. This blunt approach, although commendable in its necessary caution, had been augmented by, *inter alia*, Camarinopouls et al. when assessing the reliability of buried utilities [4]: their research uses statistical methods (approximate quadrature and Monte Carlo simulation) to assess the likely residual service life and structural integrity of a buried utility. The perceived lack of value in supposedly non-critical sewers means that such sophisticated methods are unlikely to be used on such utilities, but are more likely to be applied to perceived higher value utilities and energy pipelines; for example the probabilistic modelling of particulate matter-induced erosion proposed by Zhang et al. [5] is both valuable and valid, but unlikely to be applied to sewers and drains, even in the research and development of novel prototype materials for such applications. In their work, Hattori and Itoh [6] highlight the paucity of data on liquid erosion rates in plastics and provide a detailed examination of the effects of the impact of cavitation bubble collapse upon material properties: their key conclusion informing the author's thinking here lies in the fact that the progression of damage to their plastics was fatigue-based and therefore attributable to cyclic effects and not merely a one-off impact event. Hattori et al. [7] also investigated cavitation erosion

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and its effects on steel water pipes: a Gumbel distribution was used to show that the depth of erosion damage was proportional to $t^{0.5}$ which led the author to ponder the equivalent exponent in plastics.

Comparison of the various tests available for cavitation erosion resistance testing: pin-on-disc (where da Silva and Sinatora found that the wear rate was dependent on local heat dissipation [8]), compact disc apparatus (where Bazanini and Bressan [9] found a new test method for evaluating cavitation erosion resistance which found micro-jet impact from bubble collapse to be a dominant cause of damage), water-jet based test methods (where Gant et al. [10] developed new apparatus which yielded a rate of erosion damage that was proportional to t in metals), or micro-scale abrasion tests (where Gee et al. [11] undertook an inter-laboratory repeatability and reproducibility analysis across 14 organisations and found that the procedure was robust) justified the current experimental approach whereby candidate materials for next-generation sewers were subjected to the widely adopted UK standard [3]. Essentially, the complexity of the cavitation erosion under the action of a high-pressure water-jet has been shown to be such that traditional abrasion or erosion tests did not quite match the situation faced by sewers and drains as they underwent routine cleaning.

Previous, material-specific, research yields useful background data, but only in *ad hoc* terms or in such a way as to provide general information about the likely best-performing candidates for the next generation of sewers. That said, the selection of candidate materials in this current work was based on the available literature and the premise, potentially flawed given the aforementioned comment about broad *versus* narrow applicability of test data, that if a material performed well across a few such tests, it was likely to be a candidate for the next generation of sewers. Examples include: plastics in general [12,13], polymethylmethacrylate (PMMA, Perspex®) [14], polyetherimide (PEI) [15], polyamide (PA) [16,17], polyoxymethylene (POM) [18], and clay and concrete [19].

Finally, the financial imperative of the UK's Sewers for Adoption policy [20] drives, and justifies, this quest for high-pressure water-jet resistant materials for sewers and drains: politicians, and gradually, the public, are waking up to the importance of our buried municipal infrastructure.

2. Test procedure and its calibration

2.1. Rig calibration data

This section presents data from: pressure monitoring, run-up and run-down times, pressure fluctuations and stability, nozzle exit dimensions, and flow rate trials. The test set-up shown in Fig. 1 followed protocols [3] for high-pressure water-jetting resistance testing enshrined in Water Industry Standard (WIS) 4-35-01. The pressures quoted were those driving the flow of mains water through the 1.5 mm diameter nozzle to form the jet itself. All tests used a stand-off height h_s of 5 mm and an angle of attack α of 30°.

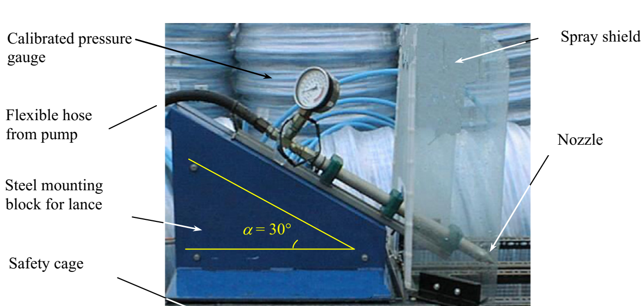

Fig. 1. High-pressure water-jetting rig to WIS 4-35-01 [3].

2.2. Pressure and flow rate monitoring

To ensure that the readings on the Bourdon gauge were an accurate representation of the pressure P in the lance feeding the nozzle, data from a digital pressure gauge were recorded (Fig. 2). Nominal pressures on the Bourdon gauge of 13.8 MPa, 27.6 MPa, 41.4 MPa, 55.2 MPa, and 69.0 MPa were set and the flow valve opened. This replicated the means by which a maintenance contractor would set the pressure on their rig before cleaning a live sewer so establishing the error therein was useful as a field guide. Fig. 2 shows that for the aforementioned nominal pressures, the more accurate, digitally-logged, pressure scans recorded deviations therefrom. Table 1 shows that the deviations lay between 4% and 22% of the nominal values with no particular trend evident with regard to pressure. The 13.8 MPa trace exhibited a larger error because the pressure had to be set by a combination of both the throttle and the pressure valve. Pressures greater than 13.8 MPa were set with the pressure valve fully open and only the throttle adjusted. The 13.8 MPa target pressure could not be achieved with the pressure valve fully open as this dumped a minimum pressure in excess of 13.8 MPa. There were therefore multiple combinations of valve and throttle settings (neither of which exhibited linear characteristics) which could generate 13.8 MPa. Incidentally, although some tests were carried out at pressures as low as 13.8 MPa, none of the candidate materials were in danger of succumbing at this pressure.

The digital data detected pressure fluctuations at the frequencies shown in Table 1. These frequencies may be compared with spatial and temporal fluctuation frequencies derived from high-speed video footage of the jet at the same pressures to confirm that the frequencies normally associated with vortex ring cavitation were being driven by genuine hydrodynamic phenomena and not machine vibrations.

On a practical note, the differences between the nominal (analogue Bourdon gauge) pressure readings and the higher-resolution, higher accuracy digital sensor data were insignificant with regards the municipal engineer and their desire for a clean, undamaged sewer. For instance, such fluctuations as existed were insufficiently large to erode a competent pipe manufacturer's factor of safety on jetting resistance were that fluctuation to be an increase above the nominal. Should the aforementioned fluctuations cause a decrease below the nominal, it is unlikely that such a small decrease would be sufficient to prevent cleansing of the sewer. The higher resolution demands of analysing jet fluctuations at 20 μs intervals required this level of detail in the pressure measurements. Visual inspection in Fig. 2 revealed no drift from the root mean square value over the 60 s test period: notwithstanding the observed local fluctuations, the system could be deemed stable.

The maximum deviations from the root mean square value were taken as absolute error bounds on the test pressure for subsequent pressure–time material characterisation. It should be noted that the pressure traces did not rise instantly to the nominal, or target, pressure. They did not fall instantaneously to zero upon closure of the pressure valve which led to the subsequent examination of the run-up and run-down times.

2.2.1. Run-up and run-down times

Table 2 shows run-up and run-down times for P=13.8 MPa, 27.6 MPa, 41.4 MPa, 55.2 MPa, and 69.0 MPa. These were based on