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CT-Scans: Game-Changer in the Maintenance of PVC Drinking-Water Mains †

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Abstract: CT-scans were successfully used to—for the first time—detect inclusions of foreign material in the pipe walls of PVC pipes. This is of interest because these formerly undetectable inclusions dominate the main failure mechanism of PVC: crack growth. The technique unlocks a step forward in the condition assessment of PVC pipes in several ways: it provides researchers with a new way to investigate crack growth in PVC pipes; it provides drinking-water utilities with a method for destructive condition assessment; and CT provides the industry with the reference knowledge needed to develop relevant in-line inspection techniques for PVC mains.

Keywords: PVC; condition assessment; asset management; inspection techniques; crack growth

1. Introduction

PVC (polyvinyl chloride) is a common pipe material for drinking-water mains worldwide and is the dominant pipe material in the Dutch drinking-water distribution network. The main failure mechanism of PVC—crack growth—is well understood, but rather difficult to predict [1,2]. One of the key reasons for this is that the occurrence and speed of crack-growth mechanisms are dominated by inclusions of foreign material in the PVC (e.g., sand, badly processed PVC, or iron particles). These inclusions are small (millimeter scale) and rare, making them impossible to find. Up until the moment of writing, the water utilities have had no way of anticipating or measuring the presence of these inclusions in specific pipes. This makes it impossible to intercept failure of PVC pipes with proactive maintenance.

X-ray Computed Tomography (CT-scan) is a technique that is especially well suited to map differences in material throughout the bulk of an object. CT was previously used to successfully assess the degradation of asbestos cement mains [3]. In the presented work, it was investigated whether CT can be used to detect material aspects of PVC mains relevant for condition assessment as well.

2. Materials and Methods

2.1. Collection and Preparation of Field Samples

Three different water utilities brought together twenty pieces of PVC pipe in total. The field samples were collecting during regular digging activities which were conducted for various causes: planned pipe placement, repair of a failed pipe and removal of a pipe from polluted soil. The collection also included several pristine pipes, taken from the warehouse directly. The collected pipes had outer diameters ranging from 110 mm to 500 mm, and years of production ranging from 1967 to 2022. Sample 04, a 400 mm pipe from 1973 that was replaced to repair a small leak due to a short crack, is shown in Figure 1a, with the inset showing the location of the leak.

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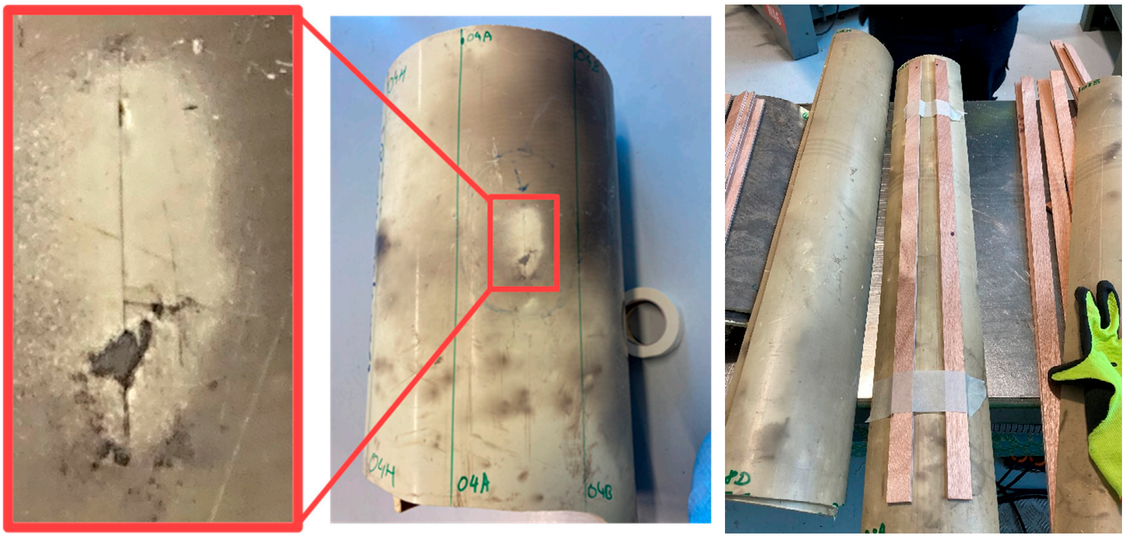


(**a**) (**b**)

Figure 1. Example of one of the field samples: (**a**) Sample 04, a 400 mm pipe from 1973, as it was collected by the utility. The inset shows the leak that was the reason for the replacement of this piece; (**b**) Sample 04 was cut into ribbons 1 m long and 0.15 m wide to fit into the CT-scanner.

Samples were sawed off to be 1 m long. Moreover, samples with a diameter larger than 150 mm were sawed into ribbons more than 150 mm wide and stacked with wooden spacers in between so that they would fit the field of view of the CT-scanner. The preprocessing of Sample 04 is shown in Figure 1b.

2.2. CT-Scans and Analysis

Every sample was scanned with a medical CT-scanner (Siemens, Somatom Definition, Erlangen, Germany) with a field of view of 150 mm $\times$ 150 mm, an imaging resolution of 512 $\times$ 512 pixels and a slice distance of 1.5 mm. The collected slices of every pipe were inspected visually with the ImageJ software package (Fiji distribution, version 1.53c) to identify peculiarities within the PVC. Subsequently, ten peculiarities of special interest were removed from the samples by with a 25 mm diameter hollow drill bit. The peculiarities in these new samples were then scanned with a micro-CT-scanner (TESCAN, CoreTOM, Brno, Czech Republic) for further inspection with ImageJ.

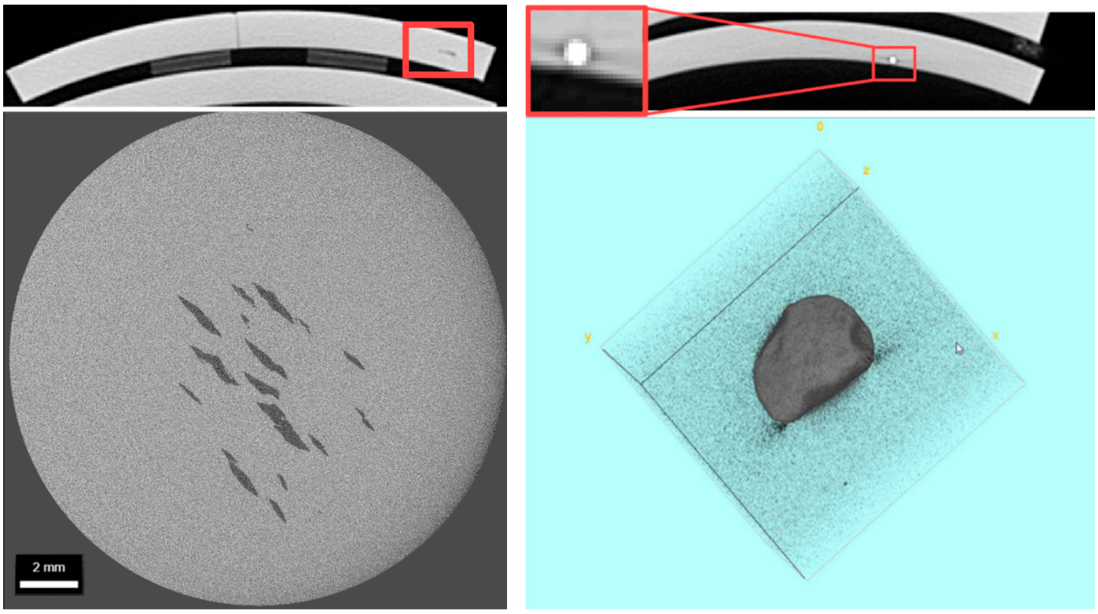
3. Results

In Sample 04, three peculiarities were encountered in the scans with the medical CT. Figure 2a shows a dark spot in the low-resolution medical CT (top, marked with the red square). A dark spot presumably indicates a void or an inclusion of very low density. Note that, similarly, the crack in the pipe is also visible as a dark vertical line through the center of the sample. The micro-CT was used to zoom in on the presumed void (bottom), showing that the peculiarity rather is a cluster of smaller voids that seem to be aimed along the same direction. The nature of these voids is unclear.

Figure 2b shows a high-intensity (high-density) inclusion encountered in Sample 04 (top, marked with the inset). The inclusion has a diameter of about six pixels, which corresponds to approximately 2 mm. A scan with the micro-CT (bottom) provides a clearer view on the inclusion and shows that, in fact, the inclusion has a length scale of around 1 mm, indicating that the image of the medical scanner is distorted (presumably due to a combination of the high density of the inclusion and its length scale compared to the resolution of the scanner).

A third peculiarity encountered in Sample 04 is shown in Figure 3. A high-density inclusion is visible in the crack, close to the inner pipe wall, in the center of the crack along its length (a). The cross-sections made with the micro-CT (b, c) and the 3D reconstruction

(d) show a spherical particle, broken in two, with some of its material spread out along the crack. In all likelihood, this is the inclusion that originally served as the initiation point of the crack. In the micro-CT images, the inclusions shown in Figures 2 and 3 have gray values of around 50,000 and 20,000, respectively, indicating that they consist of different materials.



(**a**) (**b**)

Figure 2. Peculiarities encountered in the pipe wall of Sample 04: (**a**) a low-density void is visible in the medical CT (top, red square) and in the micro-CT (bottom); (**b**) a high-density inclusion is visible in the medical CT (top, red square and inset) and in the micro-CT (bottom).

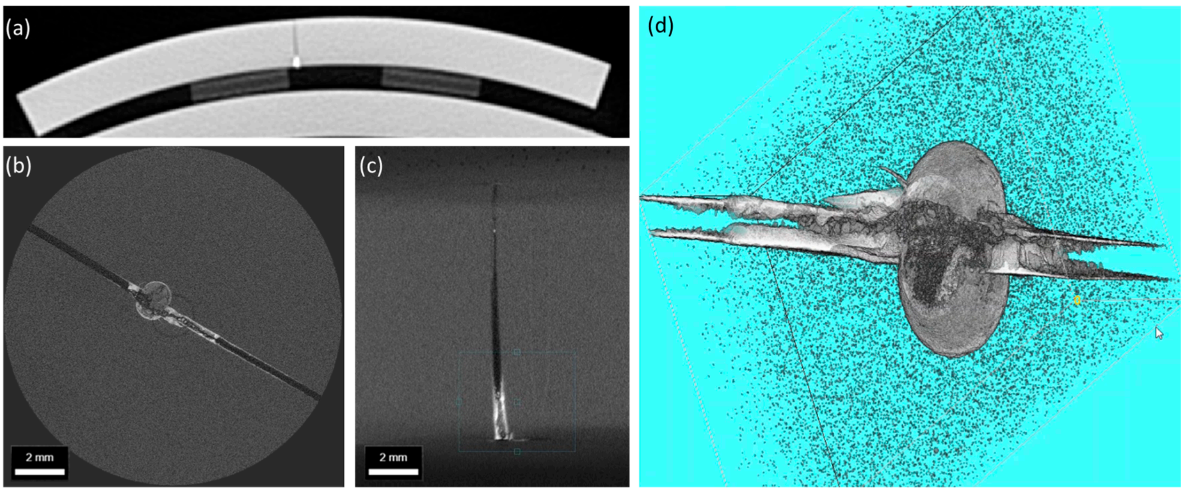


Figure 3. Peculiarity encountered in the pipe wall of Sample 04: (**a**) a high-density particle is visible in a crack in the inner pipe wall, imaged with the medical CT; (**b**) and (**c**): Micro-CT cross-sections of the same particle; (**d**) volume reconstruction of the particle based on all micro-CT cross-sections.

Based on visual inspection, a rough count was made of the number of inclusions encountered in each sample. It should be noted that not all samples contained exactly the same amount of bulk PVC material, and the normalization of these counts according to a detailed volume estimation could shift the relative results by 25% easily. Noteworthy was the relation between the number of inclusions and the year of production of a pipe:

- 40+ inclusions were encountered in samples from 1965, 1967, 1970, 1973 and 1975;
- 5 to 20 inclusions were encountered in samples from 1966, 1972, 1973 and 1975;
- 3 or fewer inclusions were found in samples from 1971, 1975, 2000, 2016 and 2022.

4. Discussion and Conclusions

The above numbers show that a high amount of inclusions may occur in pipes produced in 1975 or before. It is also shown, however, that pipes from that time may also have a low number of inclusions. This matches with the sector knowledge that a high variability in material quality is to be expected from PVC stemming from that time (due to the experimental developments that the pipe-production processes underwent in that period). As the presence of inclusions does not necessarily lead to pipe failure, however, counting inclusions is not sufficient for condition assessment. More research is needed in order to learn how problematic inclusions can be distinguished from benign ones.

Inclusions are known to be a dominant factor in PVC pipe failure and crack growth. The direct measurement of inclusions in PVC water mains has not been achieved previously, other than through visual inspection of the crack surface of a failed pipe. These reported measurements reveal a novel approach to inspections and condition assessments aimed at anticipating failure. The process of digging up, processing and scanning pipes is far from a non-destructive technique that can be applied in-line. It is already suitable, however, for exit assessments and targeted investigations preliminary to large-scale construction work. Moreover, the ability to finally measure inclusions in real pipes will allow developers to procure reference samples, which will increase the viability of developing and validating in-line techniques that are easier to apply in the field.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Burn, S.; Davis, P.; Tiganis, B.; Tjandraatmadja, G.; Cardy, M.; Gould, S.; Sadler, P.; Whittle, A.J. *Long-Term Performance Prediction for PVC Pipes*; Awwa Research Foundation: Denver, CO, USA, 2005; pp. xxiii–xxxi.
2. Breen, J. *Expected Lifetime of Existing PVC Water Distribution Systems*; TNO Science and Industry: Eindhoven, The Netherlands, 2006; pp. 1–16.
3. Van Laarhoven, K.; van Steen, J.; van der Hulst, F.; Hernandez Delgadillo, H. CT scans of asbestos cement pipes as a reference for condition assessment of water mains. *Water* **2021**, *13*, 2391. [CrossRef]