TENSILE IMPACT EXPERIMENTS OF PVC-U AT A WIDE RANGE OF TEMPERATURES

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SUMMARY
More than 20,000 km of rigid PVC (or PVC-U) pipes are currently in use for the distribution of natural gas in the Netherlands. In the next decade the majority of these pipes will reach their initially specified lifespan of 50 years. In the light of a possible replacement surge it is increasingly important to establish the actual material quality of these pipes.

To gain insight into the remaining quality of the PVC-U pipes in the Netherlands, a so-called Exit Assessment programme was started in 2004. In this programme the quality of existing PVC-U material is determined. Field failure studies have shown that the lack of ductile behaviour is the most important reason for incidents involving PVC-U. Therefore the ductility of the excavated pipes is tested using a tensile impact test.

This paper describes a new and improved test method to extract more information from the amount of material available for testing, which is gathered in the Dutch Exit Assessment programme. By adding cooling and heating equipment to the tensile impact test equipment, the PVC-U material can be tested at a temperatures ranging from -27ºC to +50ºC. The tensile impact tester is also equipped with a piezo-electric load cell.

This results in extra information about the fracture behaviour of PVC-U pipes, which can fail with brittle, semi-ductile, or ductile fractures, depending on the temperature. Visual inspections of the test material support these findings. From the 11 PVC-U pipes tested so far using this new method, three pipes could be identified as having poor material properties. Finally a specially developed sawing test was performed to establish a link with practical experience. This shows that the newly developed test method has a good relationship with the practical experience of failure behaviour of PVC-U pipes.

INTRODUCTION
In the Netherlands, the distribution of natural gas takes place through more than 20.000 km of rigid PVC pipes [1]. These pipes are also referred to as unplasticised PVC, or simply PVC-U. Most of these pipes were installed in the 1960s when natural gas field at Slochteren in the north of the Netherlands came into production.

In the next decade from now, the majority of these 20,000 km of PVC-U pipes will reach their initially specified lifespan of 50 years. In the light of a possible replacement surge it is increasingly important to establish the actual PVC-U quality in order to find out what the remaining service life of these PVC-U pipes is. If the quality is deemed to be sufficient, the replacement of the PVC-U material can be postponed without compromising the safety of the gas distribution grid.

To gain insight into the quality of the PVC-U pipes which are still in use a so called Exit Assessment programme was started in 2004 [2]. This programme is supported and sponsored by Netbeheer Nederland and all Dutch Distribution System Operators. In this Exit Assessment, the quality of the existing PVC-U material is determined by taking out samples from all over the Netherlands and subjecting these to various different tests. This paper describes a new and improved test method to extract more information from the amount of material available for testing. Additionally the first results obtained with the test method are given, and a correlation is established with the performance of PVC-U in practical use.

DUCTILITY
When trying to determine the remaining quality of a material, it is important to look at its lifetime-limiting failure mechanism. Field failure studies of fractured PVC-U gas pipes in the Netherlands have shown that a lack of ductile behaviour is the most important reason for incidents involving PVC-U pipes. Spontaneous failure hardly ever occurs in PVC-U pipes and most failures originate from third-party damage (i.e. damage caused by digging) [3]. If a PVC-U pipe fails, it is important that it does so with a ductile fracture, as brittle fractures result in larger gas outflows, and repairing brittle pipes (e.g. when sawing) is more difficult and therefore slower. So brittle PVC-U pipes pose a greater safety risk, making embrittlement a limiting factor in the service life of PVC-U pipes. Therefore the ductility of the excavated pipes in the Exit Assessment programme is tested using a tensile-impact test.

INITIAL RESULTS OF THE EXIT ASSESSMENT PROGRAMME
From the start of the Exit Assessment Programme for PVC-U pipes the ductility was determined by tensile impact testing at one temperature only. The results obtained were interesting. For example, it was found that the quality of the extrusion process of PVC-U (decades ago) still has a major influence on the quality of the pipes excavated today [2]. However, it was also found that the scatter in the results was rather large, probably caused by a lack of homogeneity in the material. Therefore there was a strong need for more information on the impact behaviour of the material.

Basically, there were two options to obtain more information:
1. Perform many more tests on many more PVC-U pipes;
2. Obtain more relevant information from the already available test material.

Option 1 was costly and logistically difficult. More importantly, only a limited number of excavation sites are available every year when the Dutch Distribution System Operators are replacing PVC-U (and these also have to be randomly selected for statistical analysis). So the focus shifted to the second option, increasing the amount of relevant information extracted from the already available PVC-U pipes. These come from approximately 20 excavation sites per year, resulting in 20 unique PVC-U pipes of about 2 meters in length each. The next section discusses the new and improved test method for ductility and the rest of the this article provides a glimpse at the first results.

IMPROVED TEST METHOD
The ductility of a PVC-U pipe is measured using a tensile impact tester in accordance with ISO 13802 [4]. This tester measures the amount of energy needed to fracture the PVC-U material. A series of 18 test bars is prepared from each excavated PVC-U pipe, see figure 1.

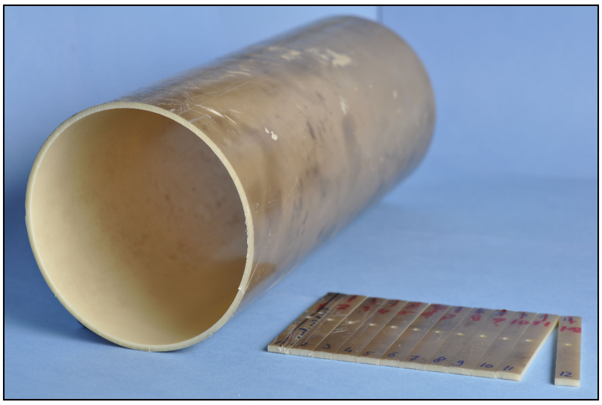


Figure 1: A PVC-U pipe with some test bars.

During the preparation of these test bars, special care is taken to prevent the samples from heating or cracking. The test bars are then hit by a pendulum in the tensile-impact tester to measure the amount of energy needed to fracture each individual specimen, see figure 2.

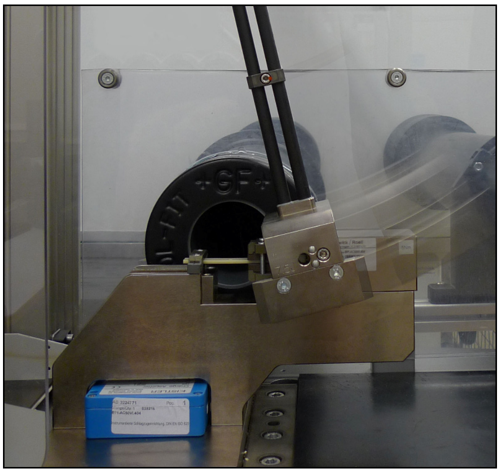


Figure 2: The tensile-impact tester about to hit a test bar.

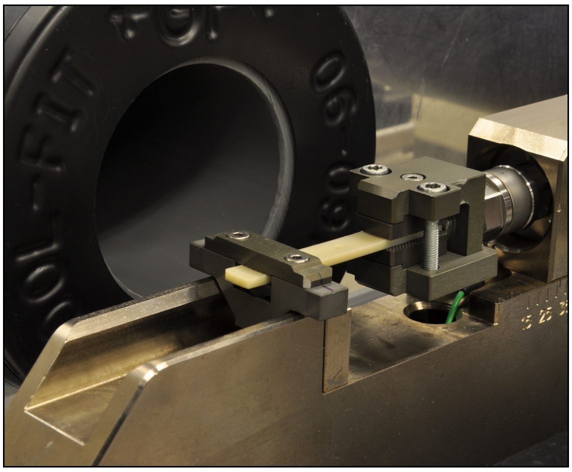


Figure 3: Air from the tube on the left keeps the test bar at the desired temperature.

It is important to realise that this test is intended to measure the material properties as independently of the geometry as possible. Since it is already known that the geometry of a pipe influences its fracture behaviour, the goal in this case is to focus on the changes in the material's resistance to impact loading, as a result of for example aging.

Extra instrumentation

The tensile-impact tester is fitted with a piezo-electric device to measure the load imposed on the test bar during fracture. This makes it possible to review the force-strain curve of the impact blow, providing extra information about the way in which the PVC-U sample breaks.

Extra cooling or heating

A temperature conditioner is added to the test equipment to keep the test bars at the desired temperature during the tensile impact test, see figure 3. This climate control is needed since the small test bars exchange heat (or cold) with their surroundings so fast that for example cooling the samples in a refrigerator at 0ºC and then testing them using a tensile impact tester at room temperature would cause their temperature to rise by 4 to 9ºC within 20 to 25 seconds. 20 to 25 seconds was the average time needed to take a sample from the refrigerator, mount the test bar in the tensile impact tester and then perform the test. At lower temperatures this effect is of course even stronger. Refrigeration prior to the test is therefore not enough when accurate testing at a wide range of temperatures is required. Therefore a system has been developed in which the bar temperature is controlled during the test by means of a large and fast airflow. This cooling system is capable of producing a large volume of dry and cold air of temperatures down to -27ºC. By changing the settings, the machine can also be used to heat the test bars up to +50ºC. An added benefit is that the samples can now be brought up to the right temperature in a matter of minutes whereas up until now it was considered normal to bring test bars at the demanded temperature by keeping them in a climate cabinet for several hours.

Considerations

When setting up the test special care was taken to ensure that the climate control system did not affect the impact tester. Also some important questions had to be answered: What is the actual temperature of the test bars? How and where should this temperature be measured? How accurate are the measurement devices being used?

After some trial and error, these issues were resolved, and eventually the temperature of the test bars is controlled extremely accurate, for example by continuously using multiple temperature sensors to check the test bar temperature.

ACCURACY

Cooling machine: The temperature of the test bars can be controlled within a range of -27ºC to +50ºC with an error margin of ±0.2ºC.
Tensile-impact tester: The error margin introduced by the tensile impact tester and the dimensions of the test bars is ±1.3 kJ/m².

This makes it possible to perform the tests with a very high level of accuracy. The scatter seen in the graphs is mainly by deviations in the material quality itself. This is normal, since PVC-U is known to be an inhomogeneous material. Having a high accuracy makes it possible to completely focus on the material properties itself.

RESULTS SO FAR

In the original tensile impact tests which were performed until 2010, twelve test bars were fractured at a standard temperature of 5ºC ± 3ºC.

By varying the temperature with high accuracy and increasing the number of test bars to 18 in the new setup, extra information about the brittle to ductile transition temperature is generated. By also adding the extra instrumentation on the tensile impact machine itself extra information about the fracture behaviour is provided. As an example two types of pipe behaviour will be discussed next.

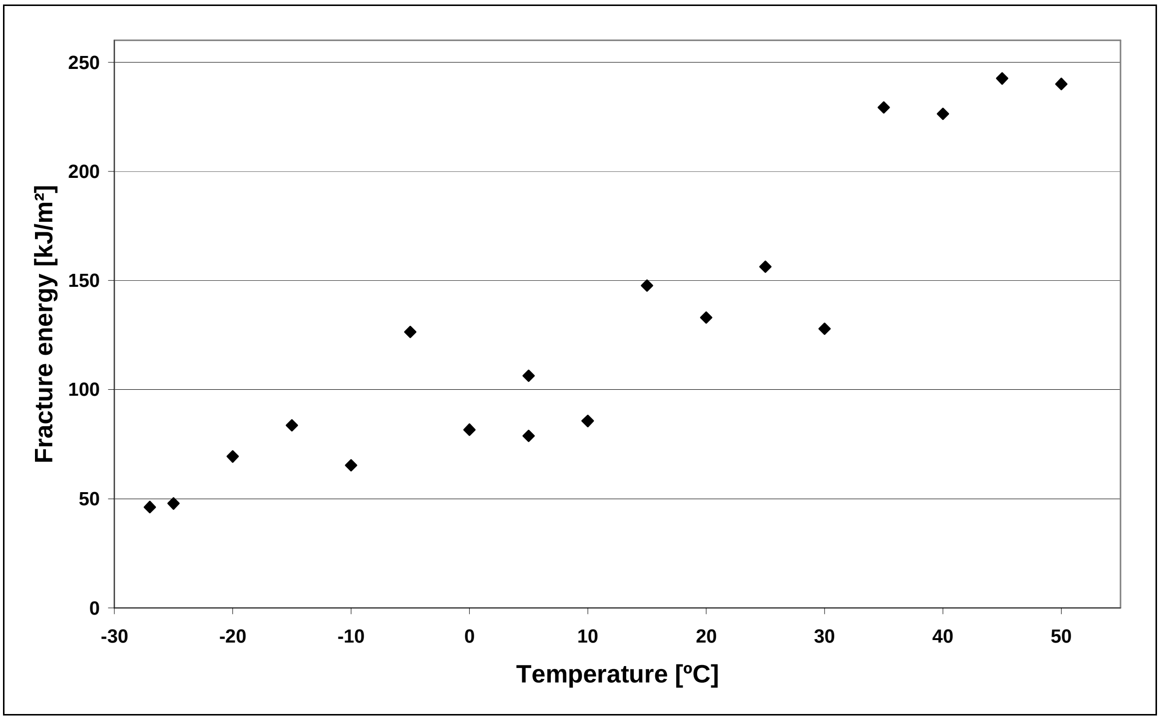


Figure 4: Tensile impact graph of pipe A (PVC-U) at various temperatures.

Figure 4 shows the fracture energy needed to break the 18 test bars of pipe, with each point representing a single measurement. It shows that, as the temperature of the material rises, the amount of energy needed for the fracture also increases. The graph also shows some variance. As already mentioned, this is a material property, since the variation introduced by the measurement and preparation of the test bars is actually smaller than the size of the dots in the graph.

Not only the fracture energy is important, but also the type of fracture (brittle, ductile) is essential to characterise the fracture behaviour of PVC-U pipe samples in impact loading.

The following discusses two methods for determining the type of fracture of each individual test bar. The first method is to analyse the force-extension curves of fracture for each sample, see figure 5.

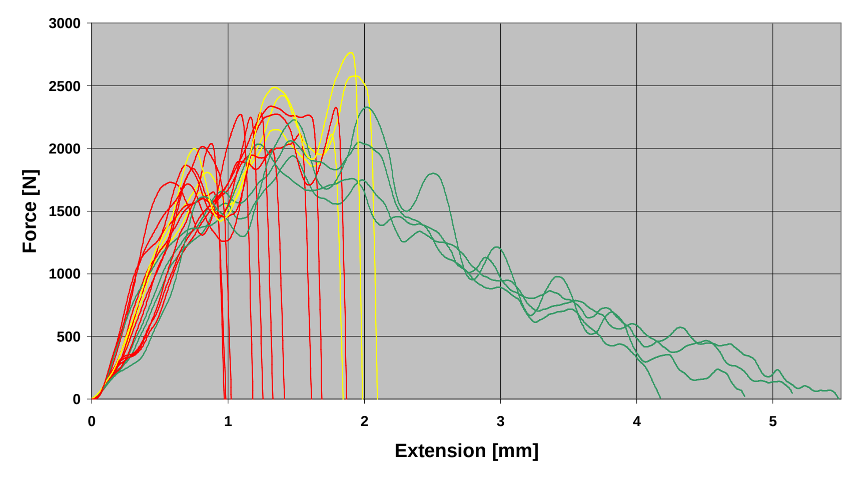


Figure 5: Force-extension curves for the individual test bars of pipe A.

Figure 5 shows that there are actually three different types of failure: brittle, semi-ductile and ductile. The types have been colour-coded. For a better understanding typical plots of the three fracture types are depicted in figure 6.

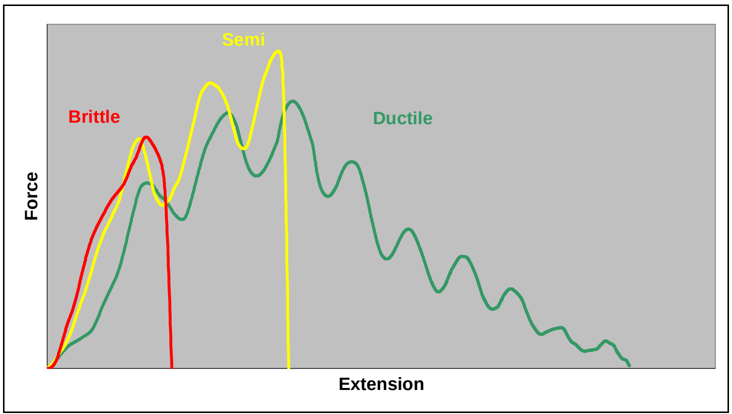


Figure 6: Three types of fracture; brittle, semi-ductile and ductile.

The graphs show that the brittle fractures only have a relatively small extension and the break is characterised by a sharp drop of the curve. The semi-ductile fracture extends a while longer and is usually characterised by two or three peaks after which still a sharp drop occurs. The fully ductile fracture does not have a sharp drop and has a relatively long extension.

This characterisation of the fracture process is supported by the second method to determine the type of fracture, namely the visual inspection of the test bars' fracture surfaces of the broken test bars. The test bars of pipe A are shown in figure 7.

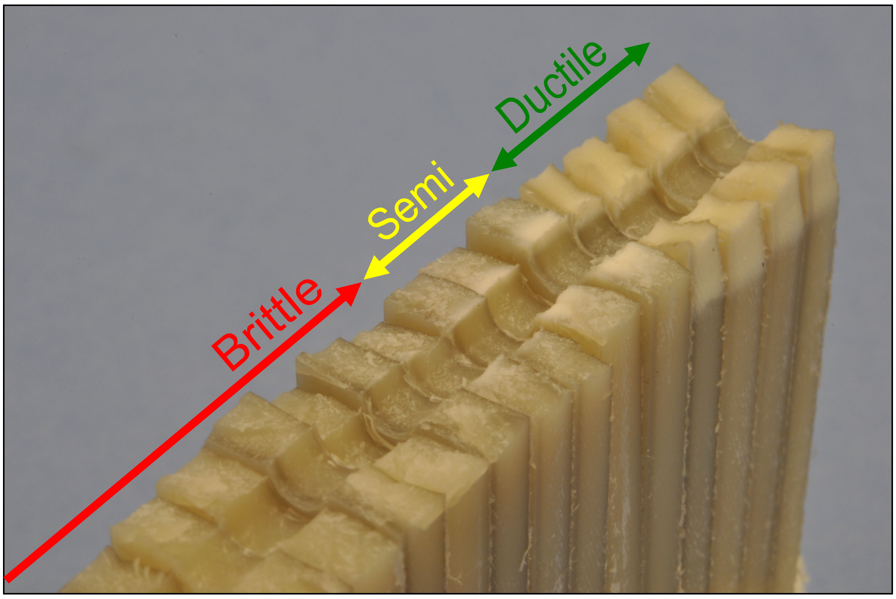


Figure 7: By visual characterization three types of fracture are found.

The visual inspection also reveals three types of fracture. The four rearmost test bars were tested at temperatures ranging from +35ºC to +50ºC. The fractures are completely ductile. The sides have been extended and the fracture has occurred at an angle, indicating the yield and necking typical for a ductile fracture. Moreover, the decolourisation suggests stress whitening over the total bar width. The three middle test bars have been tested from +15ºC to +30ºC. These have not fractured completely ductile, but there is stress whitening in the middle. This indicates that ductile processes started to take place. These are the semi-ductile test bars. The rest of the test bars at the lower left were fractured below 15ºC and show brittle fractures. The correlation between the force-extension curves and the visual inspections is very good, indicating that this is a good way to look at fracture behaviour. Combining the fracture behaviour with the tensile impact curves leads to the graph in figure 8.

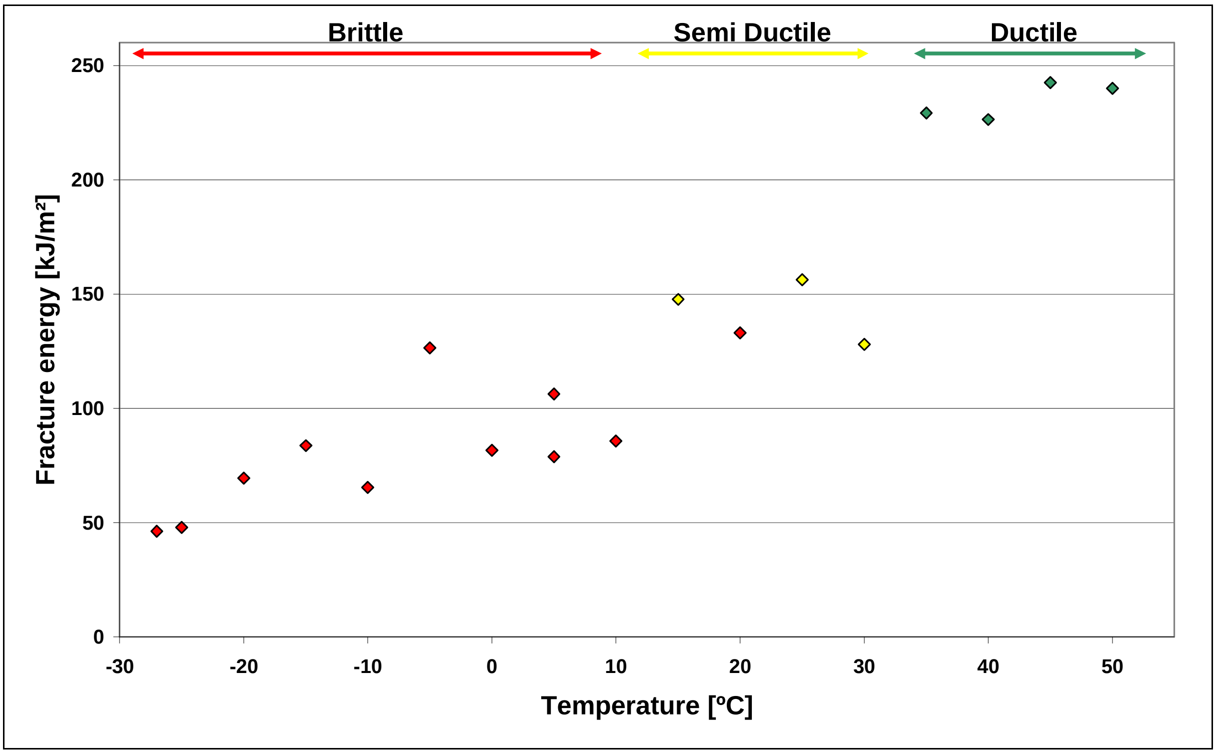


Figure 8: Combination of tensile impact test results and fracture behaviour for pipe A.

As can clearly be seen, a lot of additional relevant information about pipe A is obtained in this way. It shows that around 10ºC the material starts to behave in a ductile fashion, whereas above 35ºC the material acts in a completely ductile fashion. It also can be seen that the energy needed to break the PVC-U material at low temperatures is a lot less than at higher temperatures.

For a better understanding the results of a different PVC-U pipe, pipe B, are shown below. Information on the fracture behaviour can be found in figures 9 and 10, and is combined with the results of the tensile impact tests in figure 11.

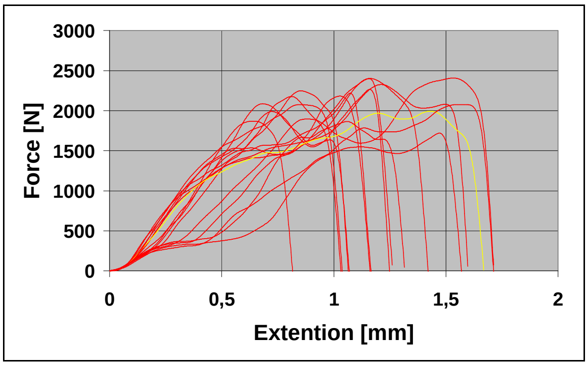


Figure 9: Force-extension curves of pipe B.

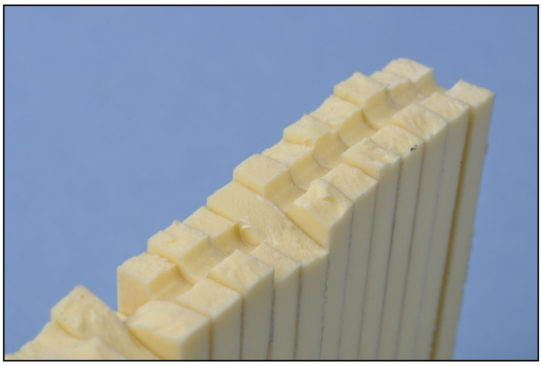


Figure 10: The fractured samples of pipe B.

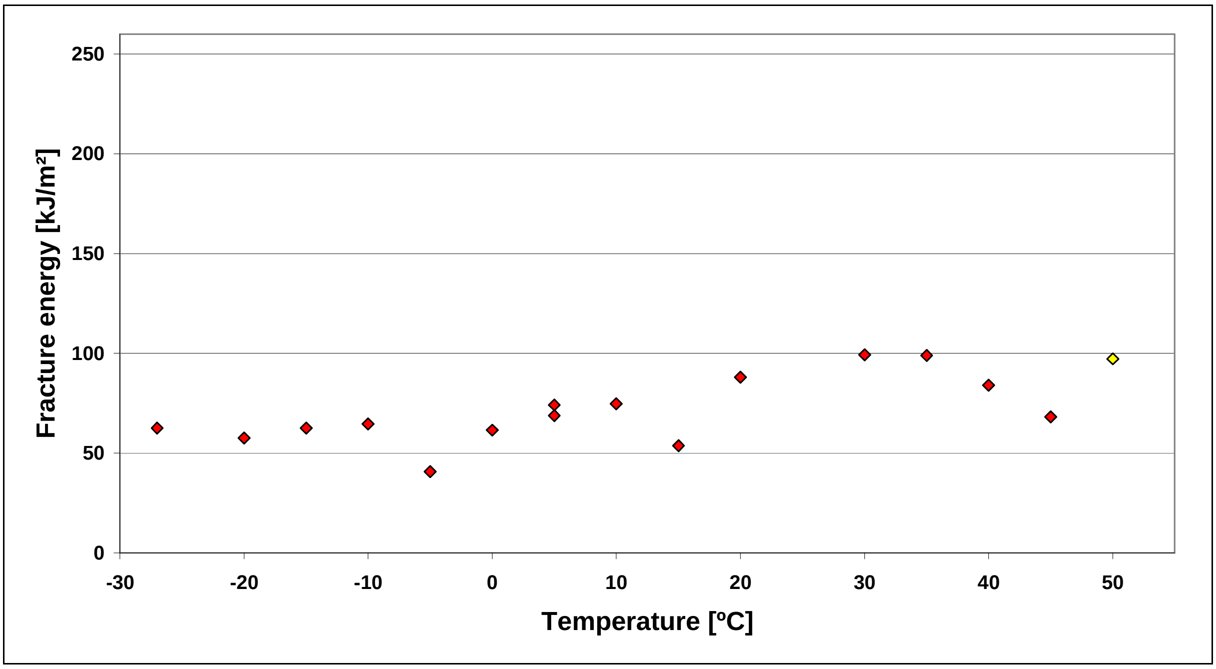


Figure 11: Combination of tensile-impact test results and fracture behaviour for pipe B.

What can be seen from these graphs is remarkable. The failure behaviour of the PVC-U pipe hardly changes with increasing temperatures. It is not until 50ºC that the first test-bar starts to show some semi-ductile behaviour. Figure 11 also shows that the energy needed for fracturing the material hardly increases as the temperature rises. In practice this means that this a PVC-U pipe has very poor material properties.

Combining all the test data accumulated so far using the newly developed test method results in the graph of figure 12.

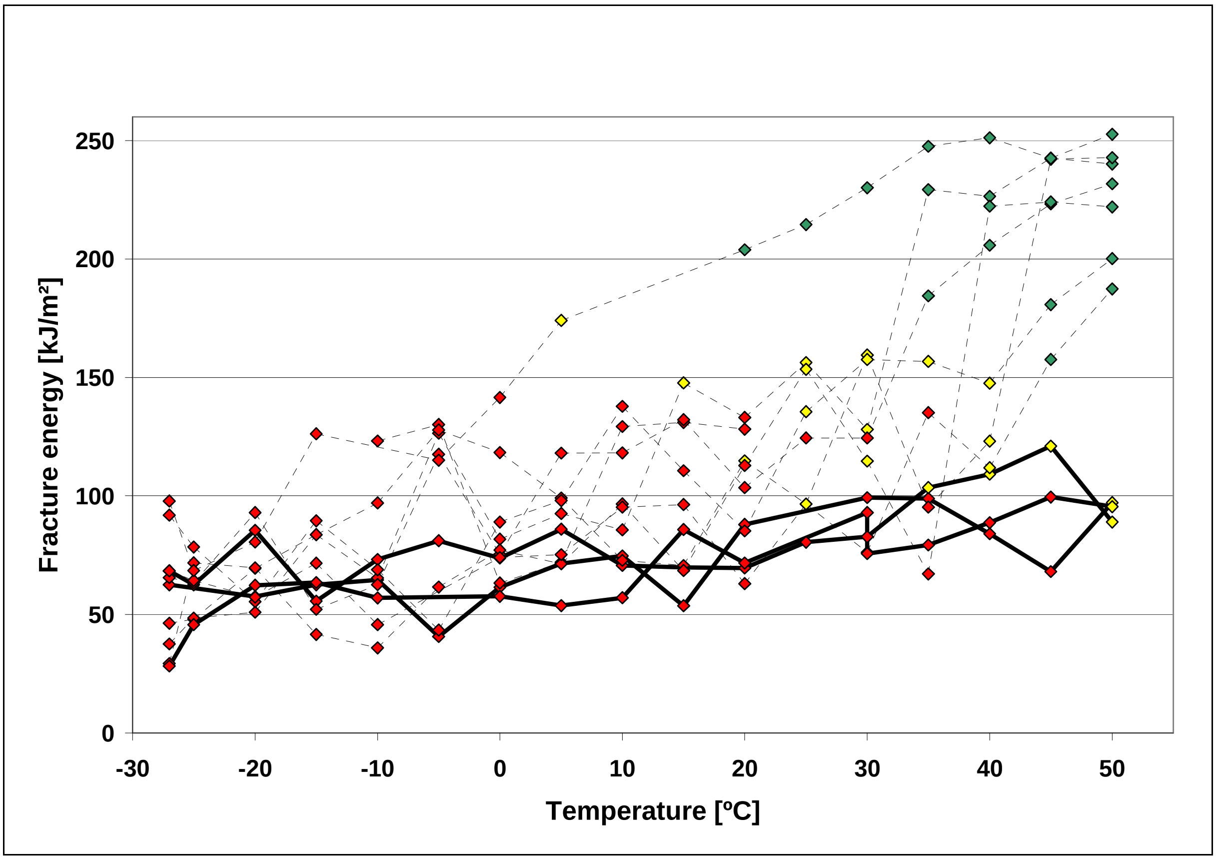


Figure 12: Tensile impact test results of 11 different pipes from at various temperatures

In this graph the results of the tests on each bar of 11 individual pipes have been connected by dotted lines. The thick lines represent the pipes that can be classified as having poor material properties. Future research will focus on parameters that may affect the impact behaviour of PVC-U pipes, such as age and soil conditions.

From figure 12 one might be tempted to conclude that in practice the average PVC-U pipe will only exhibit ductile behaviour above 20ºC. This is incorrect, since the ductile behaviour is also depends on the shape of the test sample and the speed imposed during fracture [5]. For a better understanding of the test results a link with practical use needs to be established.

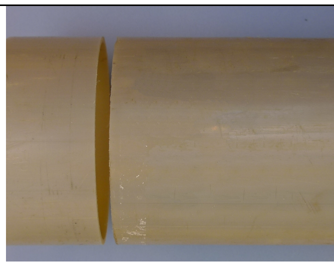
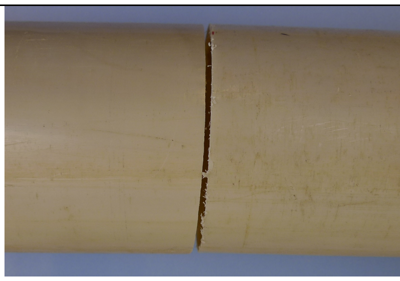
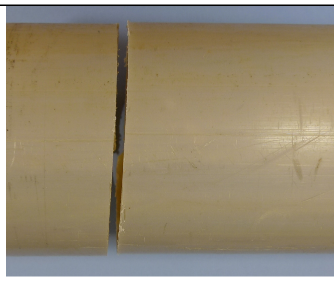
LINK WITH PRACTICAL USE

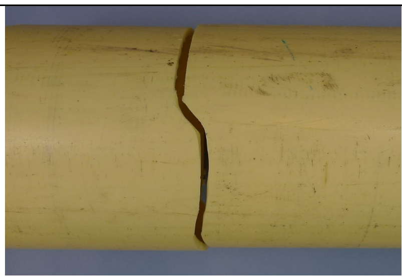
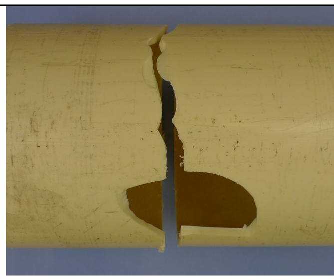
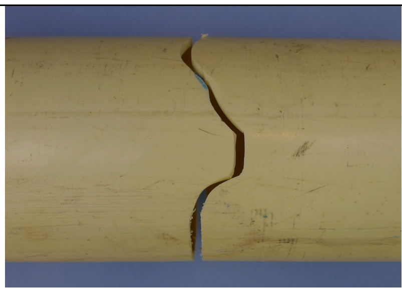
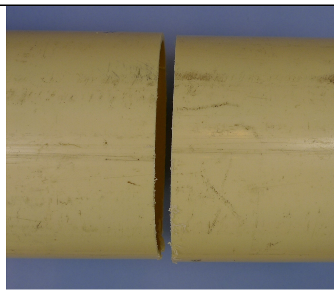
To assess whether this new test method is representative for the behaviour of pipes in practical use a simple test was performed, the so called saw-test, see figure 13.

Figure 13: The saw-test performed on a PVC-U pipe

In this test one end of the PVC pipe is clamped to simulate solid soil. The protruding section is then subjected to a bending moment of 17.6 Nm by suspending a weight from the pipe at a fixed distance. A simple crosscut handsaw is then used to cut the pipe. The experiments are performed at 20ºC (± 2ºC) and in a climate chamber at +5ºC (±0,5ºC). Two sawing speeds are used: slow and rough.

The sawing results for the test pipes A and B (as described before) are shown below:

Test pipe A	5ºC	20ºC
Rough sawing	 Brittle crack	 No crack
Slow sawing	 No crack	 No crack

Test pipe B	5ºC	20ºC
Rough sawing	 Brittle crack	 Brittle crack
Slow sawing	 Brittle crack	 No crack

Pipe B is very brittle and only sawing it slowly at 20ºC prevents it from cracking. This confirms the conclusion which was drawn after reviewing figure 11: this PVC pipe has very poor material properties.

Pipe A shows better material properties and only cracks when, at low temperatures, the sawing is done rather roughly. This also confirms the information found in figure 8. The PVC-U material clearly has ductile behaviour and it also performs a lot better in the saw-test.

CONCLUSIONS

With the newly developed test equipment and method it is possible to extract a lot more information from the amount of annually available test material gathered for the Dutch Exit Assessment programme. For example extra information about the failure process under impact loading is obtained. The typical fracture behaviour of PVC-U pipes (brittle, semi-ductile and ductile) at a wide range of temperatures follows very clearly from the results. Visual inspections of the test material support these findings.

Of the 11 PVC-U pipes tested with this new method so far, three pipes could be identified as having poor material properties.

Finally a so called saw-test was performed to establish a link with practical use. This revealed that the test results from the newly developed test method have a good correlation with the failure behaviour of PVC-U pipes in practical use.

ACKNOWLEDGEMENTS

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DISCLAIMER

The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of Netbeheer Nederland and all cooperating Distribution System Operators in the Netherlands.

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