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PLASTIC SHEET MATERIAL: AN EXCELLENT PROTECTION OF PVC PIPES AGAINST UV-DEGRADATION

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ABSTRACT
More than 75,000 km of PVC pipes are currently in use for the distribution of natural gas in The Netherlands, which make up over 60% of the distribution grid. To gain insight in the factors that influence the quality of those pipes a so called Exit Assessment programme was started in 2004. Part of this programme investigates how the handling of these pipes is influencing their quality. It is shown that PVC pipes wrapped in plastic sheet material are efficiently protected against UV-degradation.

In this research PVC (PVC-U, PVC-A and PVC-CPE) pipes have been exposed to direct sunlight with periods varying from 1 month to a year. Half of these pipes were wrapped in standard packaging sheets. Using a further improved test method [1] the ductility of these pipes was measured. Field failure studies have shown that the lack of ductile behaviour is the most important reason for incidents involving PVC gas pipes. With the further improved test method the ductility of the PVC pipes was determined at temperatures ranging from -25°C to +50°C. With this method it is possible to determine small changes in the ductile-brittle transition temperature of PVC. The influence of direct sunlight was shown by comparing the side of the pipe that was exposed to direct sunlight with the side that had been in the shadow. It also enabled us to measure the influence of using protective plastic sheet material.

Influence of direct sunlight on PVC without sheet material was measurable and visible after 3 months. The plastic sheet material proved to be an excellent protection against UV-degradation and preserved its function during the test period of one year. This also underlines the importance of using the plastic sheet material.

INTRODUCTION
In The Netherlands, the distribution of natural gas takes place through approximately 76,500 km of PVC pipes, which make up over 60% of the Dutch distribution grid. Rigid PVC pipes (or PVC-U) account for 20,800 km, where impact modified PVC pipes (or PVC-HI) account for 55,700 km [2]. Most of the PVC-U pipes were installed in the 1960s when the natural gas field at Slochteren, in the north of The Netherlands came in production. From the 1970s the transition was made to install more PVC-HI. With the withdrawal of the Dutch test specification for PVC-U pipes in gas distribution, the usage of PVC-HI became mandatory in 1974 [3]. PVC-HI is still installed today for the distribution of gas.

To gain insight into the quality of the PVC pipes which are still in use today a so called Exit Assessment programme was started in 2004 [4]. This programme is supported and sponsored by Netbeheer Nederland and all Dutch Distribution System Operators (DSOs). In this Exit Assessment, the quality of the existing Dutch PVC grid is determined by taking out samples from all over The Netherlands and testing those at Kiwa Technology. Part of this programme investigates how the handling of these pipes is influencing their quality, like the exposure to direct sunlight during storage. It is commonly know that direct sunlight can have a negative effect on the ductility of plastics in general and PVC in particular.

This paper describes a research to gain insight in the effect direct sunlight has on the PVC pipes used in the Dutch gas distribution grid. It also investigates the protective value of the protection sheets.

DUCTILITY AND THE BRITTLE TO DUCTILE TRANSITION TEMPERATURE

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 gas pipes in the Netherlands have shown that a lack of ductile behaviour is the most important reason for incidents involving PVC pipes. Spontaneous failure hardly ever occurs in PVC pipes in the Dutch gas grid and most failures originate from third-party damage (i.e. damage caused by digging) [5]. If a PVC 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 pipes pose a greater safety risk, making embrittlement a limiting factor in the service life of PVC pipes. Therefore the ductility of the excavated pipes in the Exit Assessment programme is tested using a tensile-impact test. For this a newly improved test method was developed at Kiwa Technology [1]. From each individual pipe dumbbell-shaped test samples are milled, see figure 1. In turn these dumbbells are broken with high impact velocity at temperatures varying from -25 to +50°C, see figures 2 and 3.

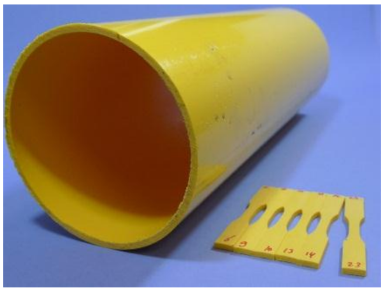


Figure 1: PVC-HI pipe with dumbbell-shaped specimens.

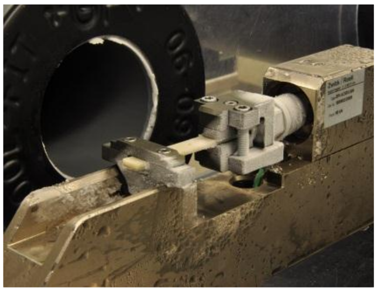


Figure 2: Cooling of a PVC sample.

Figure 3: Impact on a specimen.

When testing the specimens, the difference between brittle and ductile fractures are visually well distinguishable, see figure 4. The specimen that broke ductile shows stress whitening and a distorted fracture area. The specimen that broke brittle does not show any distortion on the macroscopic level. The different behaviour can also be seen from the force-displacement graphs that are measured during testing, see figure 5. It can clearly be seen that ductile fractures consume more energy than brittle ones (surface area under graphs).

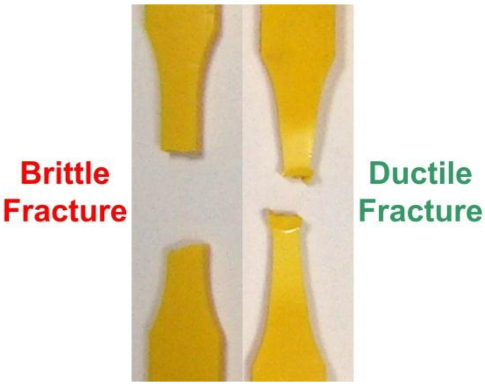


Figure 4: Brittle or ductile fractures can be distinguished visually.

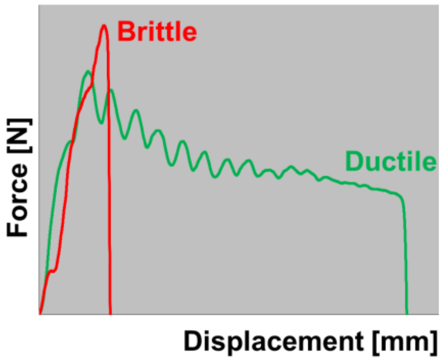
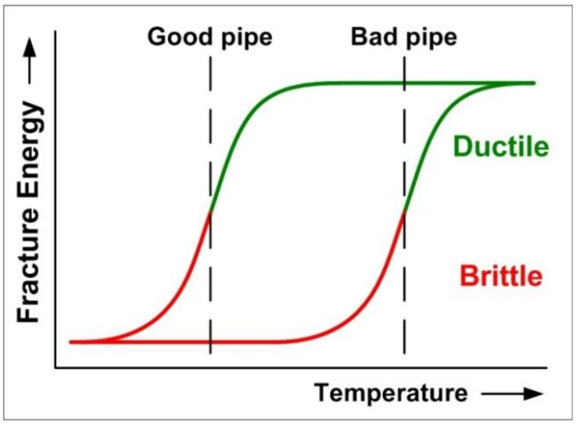


Figure 5: Different force-displacement graphs for brittle or ductile fractures.

The fracture behaviour of PVC does not only depend on the material quality, but is also strongly influenced by its temperature. This is where the brittle-to-ductile-transition-temperature (T_{BD}) plays an important role. This is the temperature where the material behaviour under impact changes from brittle to ductile. A low transition temperature represents a good PVC material and a high one a poor PVC material. The theoretical graph of the transition temperature of a good and a bad PVC pipe is given in figure 6. The experimental graphs look like shown in figure 7. As can be seen the transition temperature is clearly visible, except for some scatter. This is normal and intrinsic to PVC material properties, since PVC is an inhomogeneous material by nature.



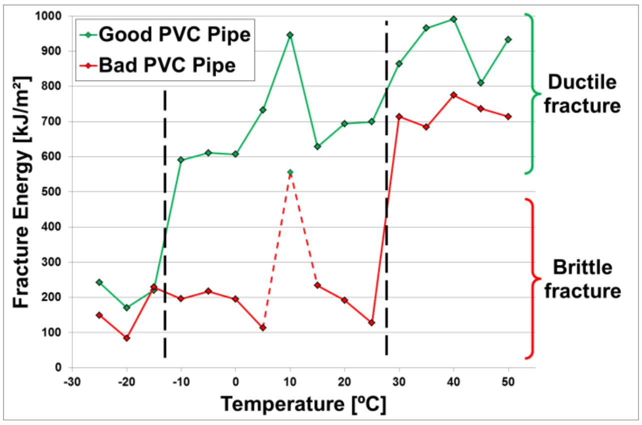


Figure 6: Schematical graph of the brittle-ductile-transition-temperature for a good and a bad PVC pipe.

Figure 7: Graph of the brittle-ductile-transition-temperature for a good and a bad PVC pipe in practise.

According to theory PVC pipes of poorer material quality will have a higher brittle-ductile-transition-temperature and therefore on average a lower fracture resistance then pipes with better material qualities. In practise this means that activities with PVC pipes, like construction or repairs, will preferably be done above this transition temperature.

TEST PROGRAMME PART A – INTRODUCTORY EXPERIMENTS

Most people working in the (Dutch) gas distribution industry have seen sun discoloured PVC pipes, see figure 1. The question arises, does this exposure to direct sunlight influence the quality much?

Figure 8: PVC pipe where the discolouration of the sun side is visible.

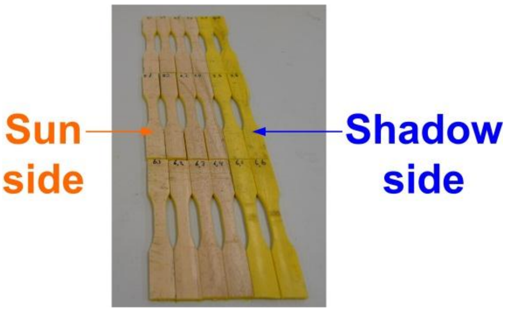


Figure 9: Colour difference between the specimens of the sun and shadow side.

To test whether exposure to direct sunlight has any measurable effect on the impact resistance, 2 pipes were initially tested in Test programme part A:

1. One PVC-HI (CPE) pipe that had been exposed to direct sunlight for a year at Kiwa Technology (exposure from October 2011 to October 2012)
2. One PVC HI (PVC-A) that had been outside for almost 7 years at a DSO, see also figure 8.

Both pipes were divided in a “Sun side” and a “Shadow side”, which in turn have been milled into dumbbell-shaped specimens, see figure 9. These samples have been tested at different temperatures. Looking at these individual specimens, the discolouration by the sun is clearly visible. The results of the pipe that was exposed for 1 year is shown in figure 10.

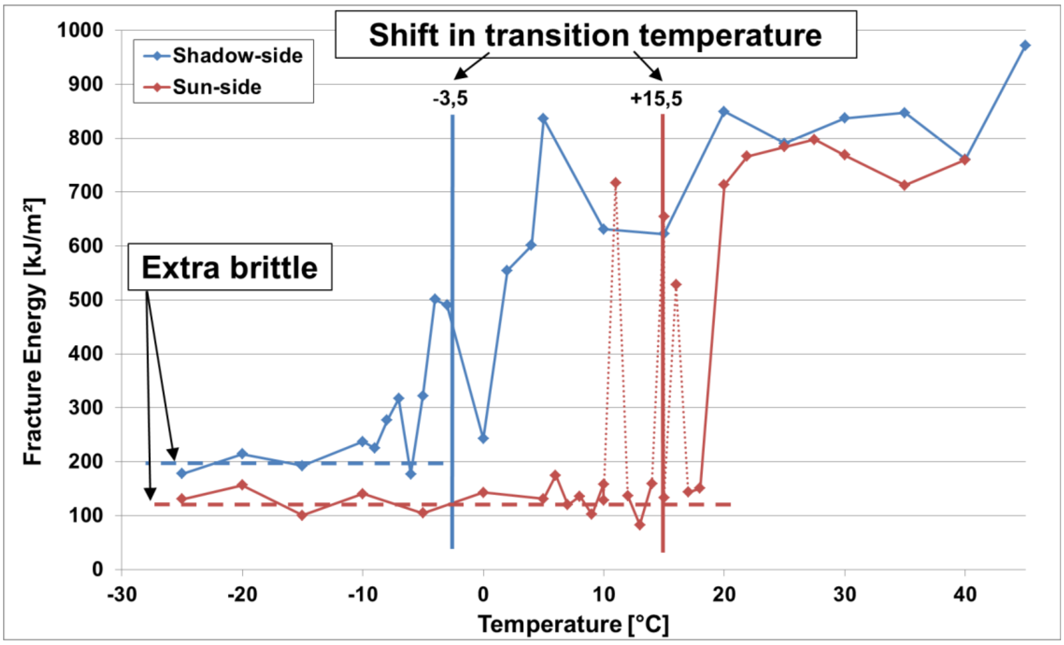


Figure 10: Graph of impact results of specimens from the sun and shadow side of the PVC-HI (CPE) pipe that was exposed to direct sunlight for a year.

The test temperature is on the horizontal axis. The energy needed to break the specimens is on the vertical axis. The blue line represents the shadow side of the pipe and the red line the sun side. It can be seen that the transition temperature of the sun-side material (+15,5°C) is considerably higher than the shadow-side (-3,5°C). This is relevant since the average ground temperature in The Netherlands is 10°C, with variations from about 0ºC to +20°C. So this shift takes place exactly in the temperature range in which the pipes are utilized. Besides the shift in transition temperature the average energy needed to break the brittle specimens is also lower on the sun-side compared with the shadow-side (extra brittle).

Additionally the pipe with seven years of sun exposure was tested, see figure 11 and 12.

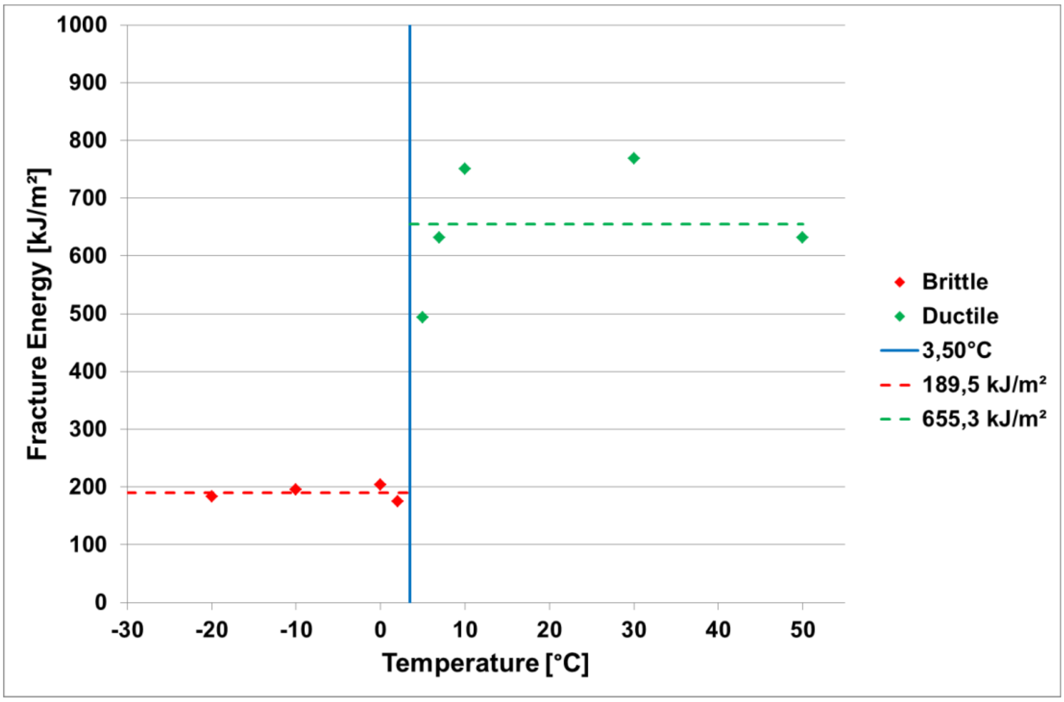


Figure 11: Graph of impact results of specimens from the shadow-side of the PVC-HI (A) pipe that was exposed to direct sunlight for 7 years.

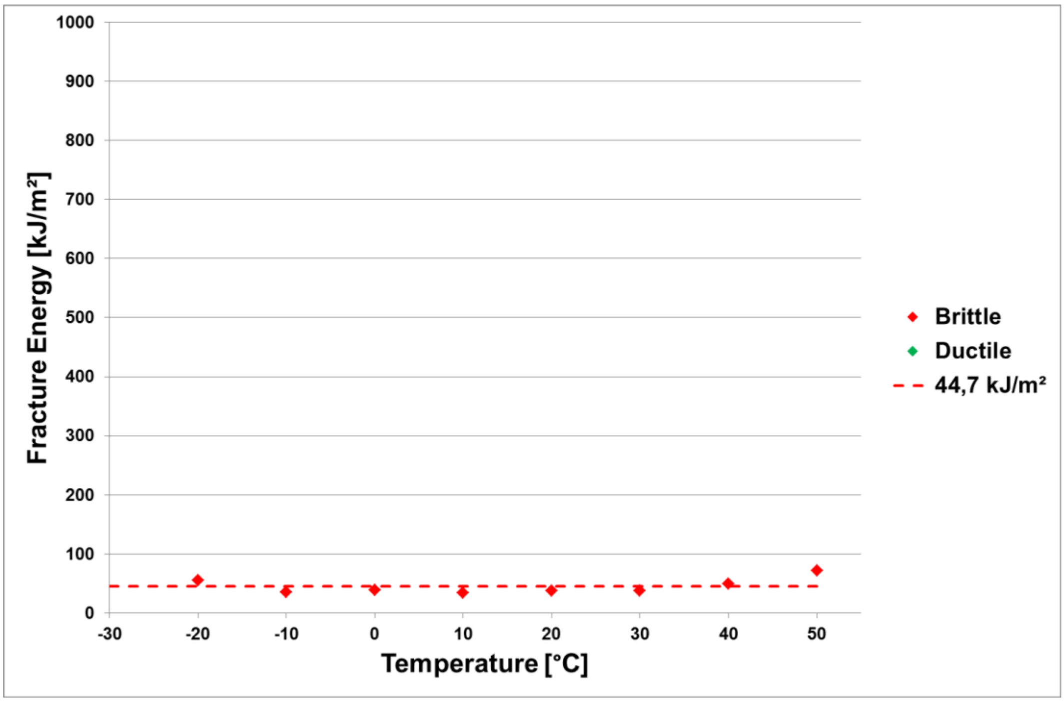


Figure 12: Graph of impact results of specimens from the sun-side of the PVC-HI (A) pipe that was exposed to direct sunlight for 7 years.

It is noted that there is a definitive change in impact behaviour. The sun-side of the pipe does not show any ductile behaviour until +50°C. Also the average impact energy of 44,7kJ/m² is considerably lower than the 189,5kJ/m² of the shadow-side. 7 years of direct sunlight definitely has an effect on the PVC-HI pipes used in the Dutch gas distribution system. A detailed look at the discoloured layer under a microscope shows that the chemically degraded layer is only about 0,05mm thick. This small layer has a profound effect on the mechanical properties of PVC-HI during an impact test however, as is shown above.

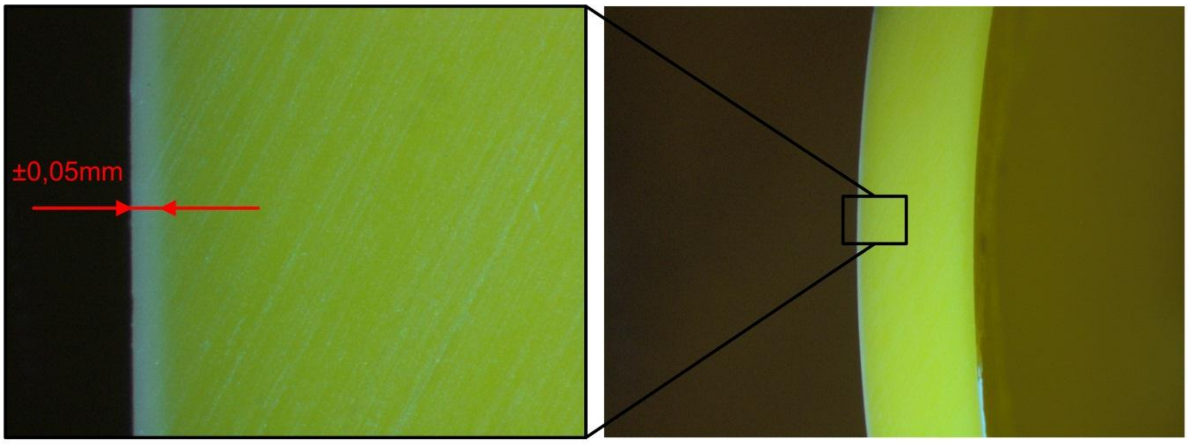


Figure 13: Microscopic view of the discoloured layer of the PVC-HI that was exposed to direct sunlight for 7 years.

TEST PROGRAMME PART B – EFFECT OF EXPOSURE PERIOD AND PROTECTION
Following these results an additional test programme has been performed to determine after which time period the first effects of chemical degradation become mechanically measurable. The following materials were tested:

- PVC-U (type 1), produced in 1973, excavated material from grid, from largest Dutch pipe-producer.
- PVC-U (type 2), produced in 1960, excavated material from grid, from 2nd largest Dutch pipe-producer.
- PVC-HI (CPE), produced in 2012, newly produced material.
- PVC-HI (A), produced in 2012, newly produced material.

These pipes were exposed for 1, 3, 6 and 12 months in The Netherlands, Apeldoorn. The 1, 3 and 6 months exposure time were all divided in an equal period before and after the 21st of June 2013, to ensure worst case scenario exposure. The 12 months exposure was tested from March 2013 to March 2014. Additionally the PVC-HI (CPE) and PVC-HI (A) pipes were exposed, wrapped in standard packaging sheets and exposed for 3 and 11,5 months, to assess the effect of the protective sheet. For an overview, see figure 14.

Figure 14: Overview of the pipes being exposed outside.

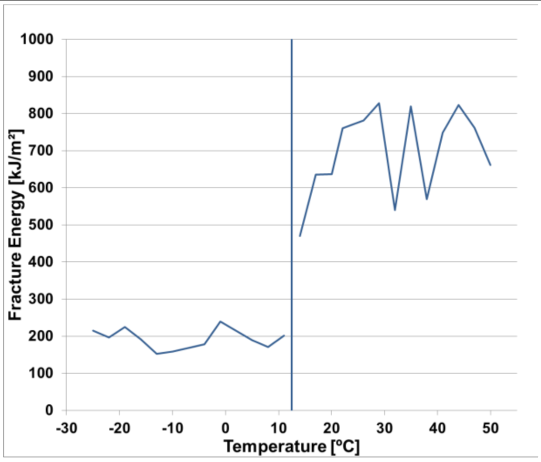


Figure 15: Example of line representation of PVC-U type 1.

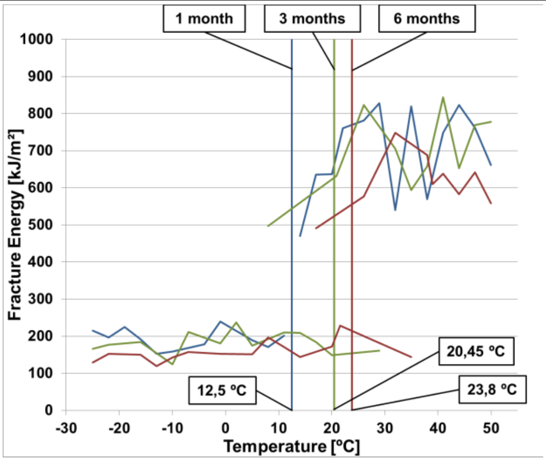


Figure 16: Example of line representations of 3 exposure times of PVC-U type 1.

The graphs like in Figure 11 can also be represented like in figure 15. Combining different exposure times for the PVC-U (type 1) leads to figure 16. It can be seen that with increasing exposure times the transition temperature rises. The transition temperatures (T_{BD}) versus the exposure times are shown in figure 17 for both the shadow- and the sun-sides of the PVC-U type 1 and type 2.

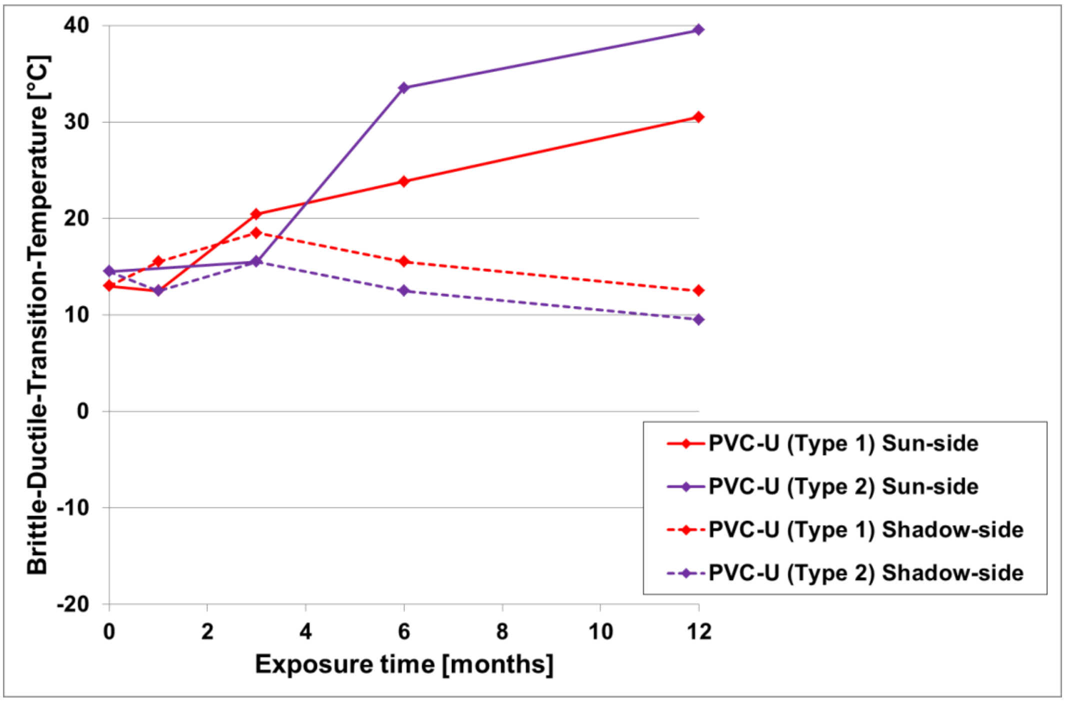


Figure 17: Transition temperatures for PVC-U type 1 and PVC-U type 2 of both the sun and the shadow sides of the pipes versus exposure times.

As expected at the sides exposed to direct sunlight the transition-temperature shifts to higher temperatures (poorer material properties). The pipe sides in the shade seem to show some decrease in material properties, after which they seem to improve a bit.

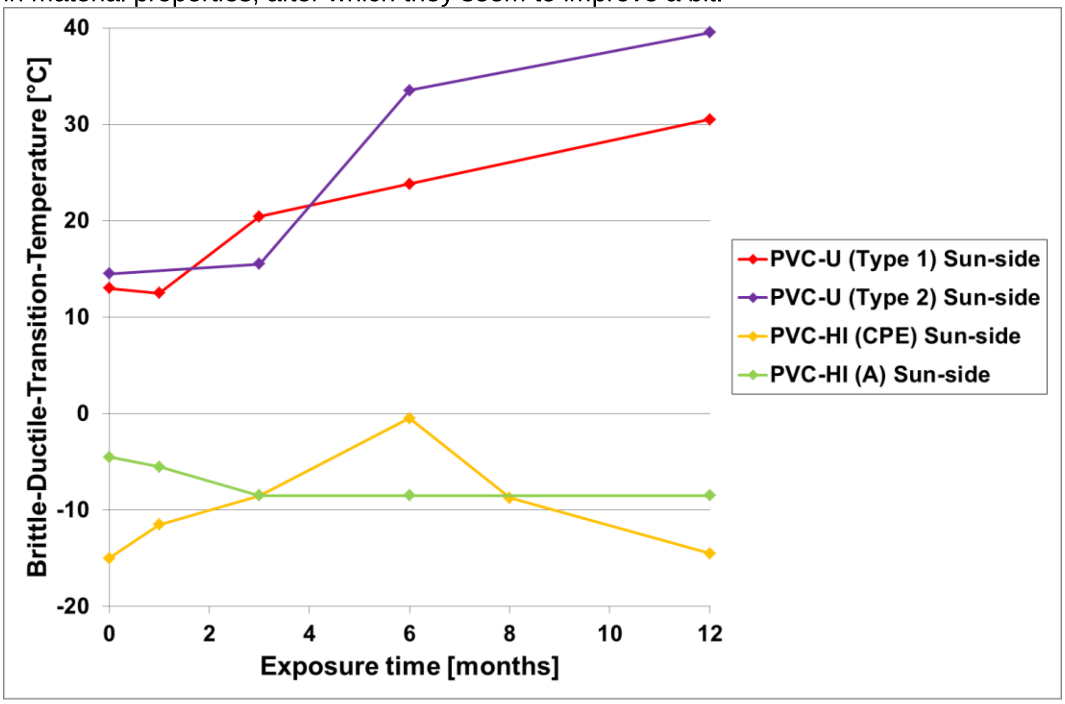


Figure 18: The transition temperatures for PVC-U type 1, PVC-U type 2, PVC-A (HI) and PVC-CPE (HI) of the sides of the pipes after different exposure times (sun-side only).

Adding the PVC-HI measurements makes a different trend visible, see figure 18. The PVC-A (green line) does not seem to be influenced by the exposure to the sun in the first year and the transition temperature stays between -4,5°C and -8,5°C. Visual inspection of the individual specimens after one year exposure shows a discolouration that seems rather limited, see figure 19.

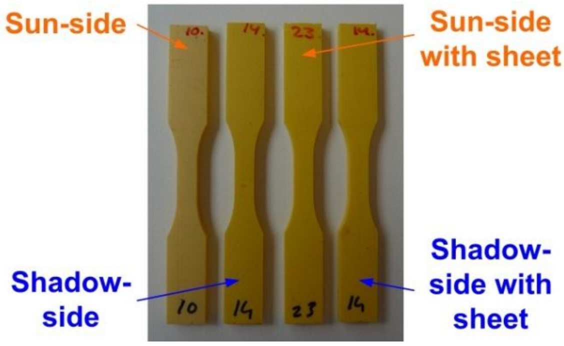


Figure 19: Discolouration of the PVC-A (HI) specimens after 1 year exposure.

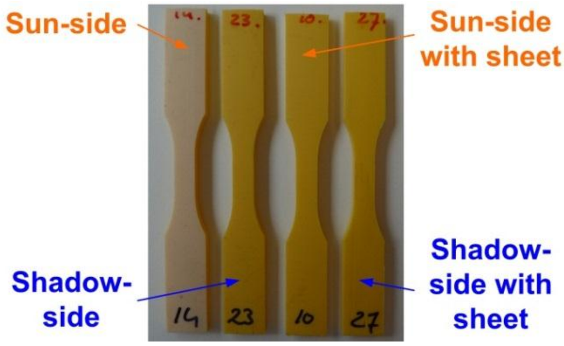


Figure 20: Discolouration of the PVC-CPE (HI) specimens after 1 year exposure.

The PVC-CPE shows more discolouration after 1 year than PVC-A, see figure 20. However it starts with an initially lower transition temperature of -15°C (orange line, figure 18). After 6 months of direct exposure to sunlight the transition-temperature has shifted to 0°C. And then something peculiar happens. The transition-temperature shifts back to -14,5°C. Meaning that the impact properties improve between months 6 and 12.

To investigate the protective property of the protection sheets a comparison between the transition-temperatures of both PVC-HI (A) and PVC-HI (CPE) with and without sheets is given in figure 21.

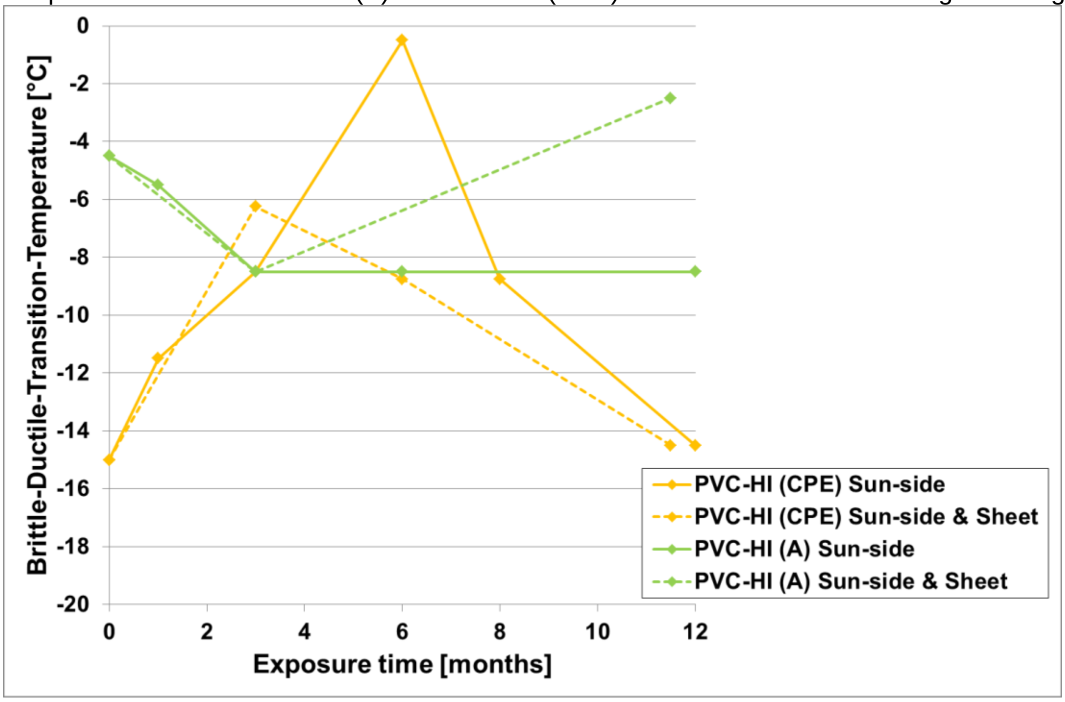


Figure 21: The transition temperatures for PVC-HI (A) and PVC-HI (CPE) with sheet protection and without versus exposure times.

It is noticed that the effect of the direct sunlight on the PVC-HI (CPE) material is suppressed, compared to the PVC-HI (CPE) without the sheet. For the PVC-HI (A) there was no effect by direct sunlight to begin with, and now there even seems to be a slight increase in transition temperature with the protective sheet. Visual inspection of the specimens in figure 19 and 20 shows that after one year no discolouration has taken place on the sun side of the pipes with the protective sheets. This strongly indicates that chemical degradation by direct sunlight has been prevented.

DISCUSSION

The origin of the decrease in transition temperature with increasing exposure time has not been revealed. Here some arguments are presented to explain this phenomenon. First of all, one can state that the improvement of the transition-temperature should merely be regarded as scatter. However the experiments suggest another explanation, since the shadow sides of the PVC-U also show a small but similar improvement effect (see figure 17). Previous studies on PVC window frames showed similar results. The impact energies of PVC window frames initially decreased versus exposure time to direct sunlight followed by a temporarily increase and a final decrease [6].

Besides the chemical degradation other effects might influence the impact properties of the PVC pipes. It is for example known that the degree of physical ageing affect the impact properties [7]. A higher degree of physical ageing results in a higher transition temperature. Heating of PVC followed by a slow cooling step results in a high degree of physical ageing whereas heating followed by a fast cooling (quenching) results in a lower degree of physical ageing , also called rejuvenation [7].

Therefore the October to October and the March to March exposure periods might become relevant. Dutch summer periods are known for long warm evenings and nights, with not too much wind. Thus mainly heating up and cooling down PVC in a gradual way. Dutch winters are known for quickly alternating periods of sun, wind and rain, combined with quicker temperature drops at night-time compared to the summer. It might well be that continuously heating up the PVC material during periods of sunshine in winter and afterward quickly cooling them, actually can improve the material properties to a higher extent than the deterioration from the chemical degradation by the sun. So it is expected to matter for the ductility of PVC-HI if the last period the pipe experiences is a summer or a winter period. This would explain why the March to March pipes are better than the October to October ones. It also explains the improvement of the shadow-side of the PVC-U pipes. Finally it explains the effects seen with the protective sheets.

CONCLUSIONS

After some months the direct exposure to the sun has a negative effect on the brittle-ductile-transition-temperature for both PVC-U, and PVC-HI (CPE). PVC-HI (A) does not seem to be influenced during the first year. The observed degradation effect seems to increase with increasing exposure times. For PVC-U the simple rule applies that longer exposure time leads to more degradation. For PVC-HI (A) and PVC-HI (CPE) this effect is not as clear in the first 12 months. Within 7 years PVC-HI turns very brittle, but in the course of a year, especially in winter there can be a temperature induced rejuvenating effect on PVC-HI which counteracts the chemical degradation effect. This disguises the positive effect of protective sheets somewhat in the first year for PVC-HI (A). However when the discolouration is considered, the sheet material is effectively preventing chemical degradation.

ACKNOWLEDGMENTS

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