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Excellent impact performance of PVC pipeline materials in gas distribution networks after many years of service

Main author
H.A. Visser
University of Twente
the Netherlands
h.a.visser@ctw.utwente.nl

Co-authors
R.J.M. Hermkens
M. Wolters
J. Weller
Kiwa Gas Technology
the Netherlands
and
L.L. Warnet
University of Twente
the Netherlands

1. ABSTRACT

It has been about fifty years ago since the first unplasticized poly(vinyl chloride) (uPVC) pipes were installed for use in gas distribution purposes. Currently, about 22,500 km of uPVC is still in use in the Dutch gas distribution network. The pipes were originally designed for a lifetime of 50 years, but due to positive experiences the question arises if (and how long) the lifetime can be extended without any concessions to safety. This is supported by the data of leak surveys presented in this paper. The amount of leaks per installed km of uPVC is even slightly lower than that of polyethylene or steel pipes. Only impact modified PVC has a better performance. The impact behaviour is presumed to be the limiting factor for the lifetime of uPVC. Therefore, the impact behaviour was studied as a function of the age. Two types of research have been carried out: instrumented falling weight tests were carried out on recently produced uPVC pipes (some of which were aged artificially) and tensile impact tests were carried out on excavated uPVC pipes which had been in service for 20 to 50 years. The overall conclusion that can be drawn from these experiments is that the most significant change in impact behaviour is likely to occur in the early stages, just after the production of the uPVC pipe. Physical ageing occurs on a logarithmic timescale, thus the changes occurring between the 20th and the 50th year of service are relatively small compared to the changes that occur in the first 20 years. This leads to the conclusion that uPVC pipes that currently show good impact behaviour, are expected to have good impact properties for many years to come.

CONTENTS

2. INTRODUCTION

About 50 years ago the first plastic pipe material for gas distribution systems was introduced in the Netherlands. At first unplasticized poly(vinyl chloride) (uPVC) was used. At that time the Dutch gas grid was extended largely, caused by the discovery of the large Groningen gas field in the North of the Netherlands. More than 25,000 km of uPVC pipelines were installed for low-pressure (<100 mbar) gas distribution systems. Presently still about 22,500 km of uPVC is in use.

Like many (plastic) pipe systems, the PVC gas distribution network was originally designed for a period of 50 years. This means that the oldest PVC pipeline systems in use now approach this design lifetime. Therefore, research into the -present and future- condition of these old PVC pipeline materials has been started up at the University of Twente and at Kiwa Gas Technology. The main question is: Is replacement of uPVC gas pipes after 50 years of service necessary or can the lifetime of the gas pipes be extended, without any concession to safety? One of the most common causes of pipe failure in the gas distribution network is a result of third party damage due to excavation activities. In case of pipes used for gas distribution brittle fracture can lead to dangerous situations. Therefore, it is of great importance that the pipes have a good impact performance. In this respect the main focus in this paper will be on the evolution in time of the resistance to impact loading and disregard effects related to the mechanical loading of the uPVC pipes by the relatively low internal pressure.

The research consists of two parts. In the first part the present status of a more fundamental study into the effects of physical ageing on the impact performance of uPVC pipe material will be presented. The goal of this study is to get an idea of the kinetics of the ductile-to-brittle transition temperature as a function of physical ageing. Therefore, the ductile-to-brittle transition temperature was measured for uPVC pipe samples which received different ageing treatments, using an instrumented falling weight test. The results and some preliminary analyses will be presented in this part of the paper.

In the second part of the research uPVC pipeline materials in use are studied. Generally it can be stated that the performance of these uPVC pipelines is satisfactory. This will be illustrated by data of observed incidents and leak survey data. However, this gives only information when the pipeline has already failed. We are more interested in the present condition of the pipeline materials and the residual lifetime of these materials. To obtain information on the present condition of the PVC pipeline materials in use, many samples were taken from practice. These samples were used for a number of tests, like determination of the degree of gelation (a measure for the initial quality) and tensile impact testing. Results of these tests will be presented and possible relations with various parameters (e.g. age, soil type, etc.) will be discussed.

3. PART 1: DUCTILE-TO-BRITTLE TRANSITION TEMPERATURE

3.1. Background

Pipes made of uPVC can either fail in a brittle or a ductile way. Ductile failure is most favourable for two reasons. Firstly, a uPVC pipe that fails in a ductile way can resist significantly more impact energy compared to a pipe that fails in a brittle way. Secondly, it is easier to stop the gas flowing from a pipe that failed in a ductile way, as the crack growth is more stable. Therefore, brittle behaviour of uPVC pipes imposes a higher risk for gas distribution companies.

It is widely acknowledged that the initial impact performance of a uPVC pipe is influenced by its processing conditions. In the past, this has led to research into the relation between impact performance and several process related material properties, like the molecular mass ([1]), the molecular orientation ([2]) and the level of gelation (e.g. [2-5]). However, the long service lifetime of uPVC requires a good impact performance over several decades and not just during installation. Therefore, the influence of physical ageing, which occurs during the total lifetime of a glassy polymer, on the impact behaviour of uPVC is reported in this paper.

Since the extensive study of Struik [6] it is known that physical ageing can have a significant influence on the mechanical behaviour of glassy polymers like uPVC. The polymer chains in glassy polymers still have some mobility below the glass transition temperature, i.e. around 80°C for uPVC. During physical ageing the polymer chains try to settle into their thermodynamically favoured positions. As a result the polymer chain network becomes denser, resulting in an increase in secondary bond strengths. This decreases the molecular mobility, making physical ageing a self retarding process, and increases the resistance against deformation. The increase in resistance is proven by a significant increase in the yield stress of uPVC during physical ageing [7,8].

Kramer [9] showed that plastic deformation precedes failure, irrespective of the failure mode. This seems obvious for the case of ductile fracture, but it also holds in the case of brittle fracture. Brittle fracture is preceded by the formation of crazes which are formed by strong *local* plastic deformation. This means that failure at impact tests initiates with plastic deformation and therefore will be influenced by physical ageing. Physical ageing not only increases the resistance against plastic deformation, but also causes the deformation to occur on a more local scale (resulting e.g. in a decrease in elongation at break [8,10]). This localized behaviour can eventually lead to a transition from ductile towards brittle behaviour. This statement is in agreement with the results of studies on the effect of ageing on the Izod [8,11,12] and Charpy [2] impact performance of uPVC. It is expected that the decrease in impact performance leads to a shift of the ductile-to-brittle transition temperature towards higher temperatures. Legrand [13] already showed this behaviour for the ductile-to-brittle transition of the glassy polymer polycarbonate.

In this study the ductile-to-brittle transition temperature of uPVC is studied using instrumented falling weight test equipped with an impactor with an hemispherical tip. This method was described by Meijering [14] and simulates third party damage. The goal is to reveal the kinetics of the shift as a function of physical ageing, possibly leading to a criterion for the “critical age”. At this stage of the research only experimental results and a preliminary analysis are presented.

3.2. Experimental

3.2.1. Sample preparation

All samples were taken out of a uPVC pipe with a diameter of 110 mm and wall thickness of 2.7 mm as produced by Wavin for use in water distribution systems. Cylinders with a length of 55 mm were cut off from pipe sections with a lathe. These cylinders were cut in half (in the axial direction) to obtain two identical semi-cylindrical specimens. Each sample consists of at least 180 specimens. To obtain samples with a different age, each sample was given a different heat treatment, a summary of the 5 samples are given in table 1. Ageing is accelerated at elevated temperatures. The equivalent ageing time of the heat treatment at a temperature of 10°C (average ground temperature) is given in the last column, enabling direct comparison of the age of the samples.

Table 1: Heat treatments of the different samples

Sample #	Ageing temperature	Ageing time	Age time at 10°C
1	60°C	$3 \cdot 10^6$ s	120 year
2	60°C	$1 \cdot 10^6$ s	40 year
3	60°C	$1 \cdot 10^5$ s	4 year
4	45°C	$2 \cdot 10^6$ s	10 year
5	As received	-	-

3.2.2. *Experimental setup*

All impact tests were conducted on an instrumented falling weight impact machine (Dynatup 8250). The specimens were placed on a temperature controlled anvil and impacted with a spherical tup with a diameter of 15 mm. The tup is installed on steel plates with a weight of 23 kg on a height of 460 mm above the specimens. Theoretically, the velocity at impact is around 3 $m \cdot s^{-1}$, resulting in an initial kinetic energy of around 100 J. The force during impact is measured with a 15 kN Kistler force cell (9011A) and recorded with a Yokogawa DL 1540 digital oscilloscope. The displacement of the weight was measured using a Meter Drive ZAM 301 AAS linear encoder with a resolution of 0.1 mm.

The impact tests were carried out at various temperatures. The temperature of the specimens was controlled in a Sanyo MIR 583 Incubator. The temperature of the anvil was controlled by a Haake F3 thermal bath filled with ethylene glycol. A thin layer of vaseline was applied on the anvil to prevent ice forming on the surface. In most cases 30 specimens were tested per temperature. A schematic representation of how the specimens are mounted on the anvil is shown in figure 1.

3.3. *Results*

3.3.1. *Types of failure*

As an excess of kinetic energy is exerted on the specimens, they all fail during the impact test. The behaviour of the specimens during impact can roughly be divided in three categories: ductile, semi-ductile and brittle behaviour. A force-displacement diagram of each of these three types of failure is shown in figure 2, 3, and 4, respectively. The times corresponding to the high speed camera images are indicated in the curves.

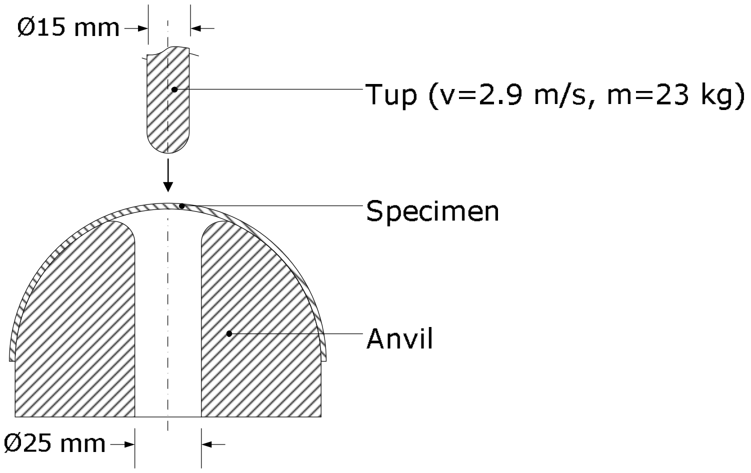
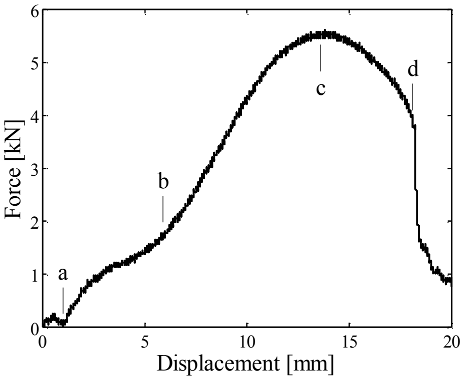
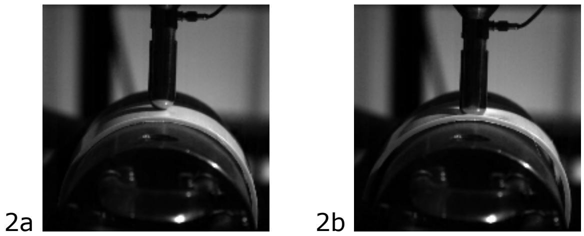


Figure 1: Schematic representation of the constraints of the specimen during impact





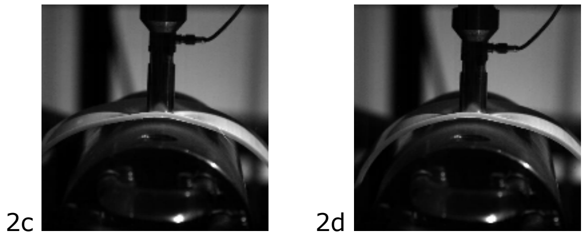
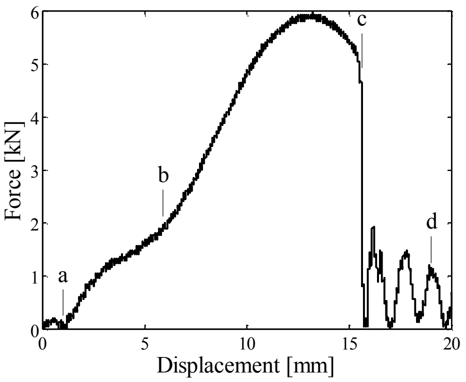


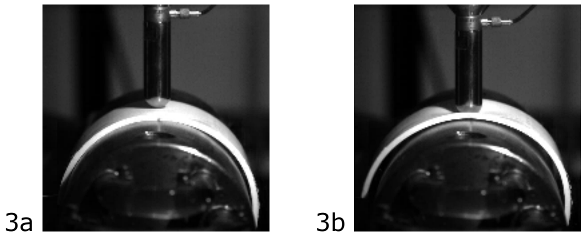
Figure 2: Typical force-displacement curve for a ductile fracture, with high speed camera stills on the right.

For ductile specimens a "shoulder" can be distinguished during the start of deformation, between *a* and *b*. Presumably, this shoulder can be allocated to mainly elastic deformation, whereas the deformation after the shoulder is mainly plastic (see section 3.3.2). When the maximum force is reached (at *c*) the sides of the specimen have deflected upwards and loose contact with the anvil. Furthermore, microcracks start to form in the specimen, underneath the tup. As these microcracks grow and coalesce, a crack forms that is large enough for the tup to penetrate the sample. The material folds around the tup, between the tup and the hole in the anvil. After this puncture of the tup the force does not decrease to zero directly due to frictional forces between the tup and the specimen.

The semi-ductile specimens follow the same path as the ductile specimen up to the maximum force is reached. When point *c* is reached the tup punches out a piece of material which is roughly the size of the hole of the anvil. This part of the fracture is ductile, but the remaining part of the specimen fractures in a brittle way. Due to the build up of elastic energy, the fractured pieces scatter around at high velocity.

Brittle failure occurs somewhere on the curve of the ductile specimens, far before the maximum force is reached. Most of the brittle fractures fail before the earlier mentioned shoulder can be distinguished, thus before a significant amount of plastic deformation is build up. After fracture, dynamic effects cause waves to occur in the force signal although no forces are exerted on the specimen anymore.





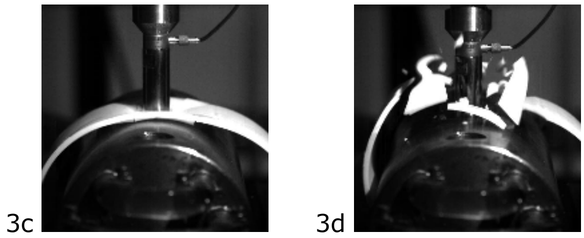


Figure 3: Typical force-displacement curve for a semi-ductile fracture, with high speed camera stills on the right.

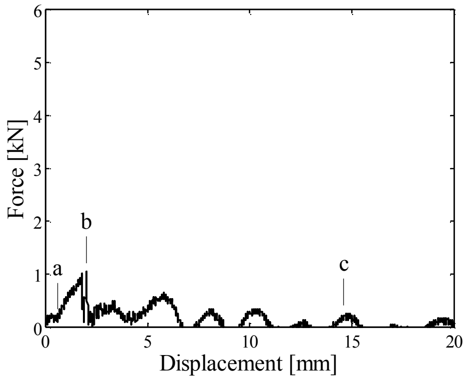
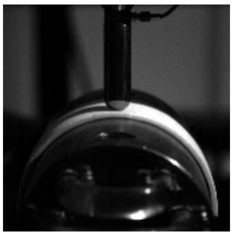
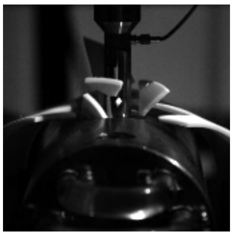


Figure 4: Typical force-displacement curve for a brittle fracture, with high speed camera stills on the right.

4a



4b



4c

3.3.2. *Elastic and plastic deformation*

To investigate which part of the deformation during impact is elastic and which part is plastic, tests where different amounts of energy are exerted on the specimens were carried out. By changing the weight of the impactor and the impact verlocity a variation in impact energy was realized. Theoretically, the change in impact speed leads to different mechanical behaviour of materials with viscoelastic properties such as uPVC. In this case the initial speed ranged from 0.77 m·s^{-1} up to 3 m·s^{-1}, a difference of two thirds of a decade. The yield stress is linearly dependent on the logarithm of the deformation speed, therefore only minor differences are expected. Nonetheless, the results as shown in figure 5 should be used for qualitative analysis only.

The force-displacement plots in figure 5 give a clear indication in the distribution of elastic and plastic deformation during the impact test. Up to the shoulder, the deformation seems mostly elastic as the deformation almost returns to zero after impact. After the shoulder, the part of the curve after the maximum forces seems to shift parallel indicating an increase of plastic deformation.

3.3.3. *Impact energy analysis*

During impact testing the kinetic energy of the impactor is partly transformed into deformation energy of the specimen. The amount of energy absorbed by the specimen is a measure of how ductile the specimen behaves upon impact. In this report the absorbed energy up to the maximum force is used as a measure for the ductility. This criterion is chosen from a practical point of view. Cracks begin to appear after the maximum force is reached, when ductile and

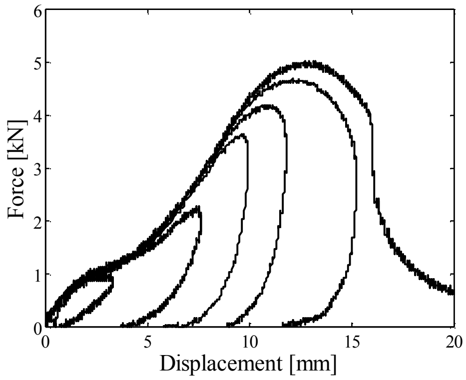


Figure 5: The force versus displacement curve for different amounts of applied impact energy

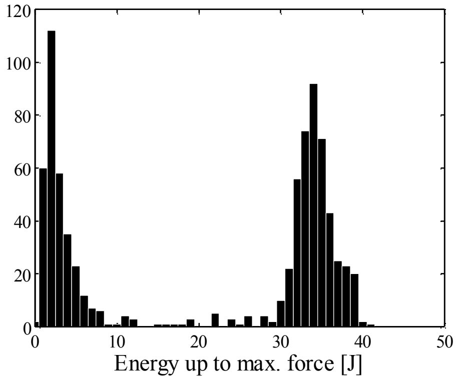


Figure 6: Histogram of the absorbed energy up to the maximum load of all samples

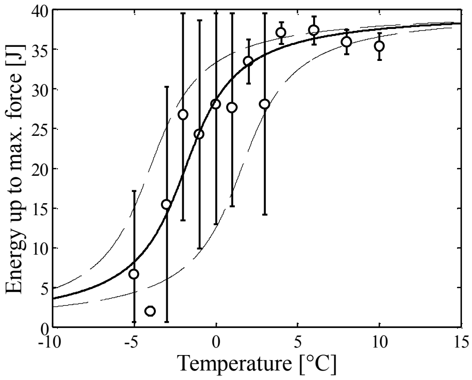


Figure 7: Mean value of energy up to max. force per temperature for as received sample (set 5)

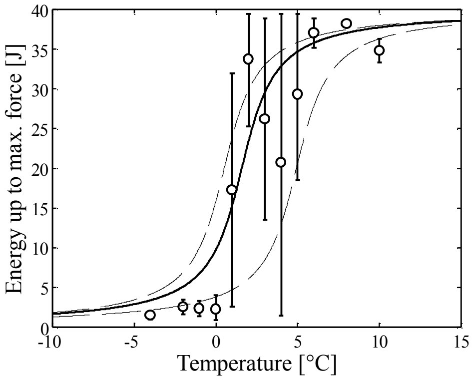


Figure 8: Mean value of energy up to max. force per temperature for the aged sample (set 1)

semi-ductile failures occur. Therefore, in practice the pipe would start to leak after this amount of deformation. Obviously, the same holds for brittle fracture.

The energy up to the maximum force can be calculated with:

$$E_{F_{\max}} = \int_{t=0}^{t_{\max}} F \cdot \mathrm{d}s \,, \tag{1}$$

Where F is the force, s is the displacement and t_{max} is the time when the maximum in force is reached. The energy up to the maximum force is calculated for all experiments carried out during this study and is presented in an histogram in figure 6. This figure clearly shows the existence of two distinct populations. The distribution of these populations can both be best described with a lognormal distribution. The brittle fractures have a mean energy up to the maximum force of 3.03 J. As the semi-ductile behaviour is equal to ductile behaviour until the maximum force is reached, these populations coincide and are brought together under the ductile population. The mean energy up to the maximum force of these failures is 34.1 J.

The energy up to the maximum force was determined for a range of temperatures for each sample. The mean values are plotted versus the temperature in figure 7 and 8 for the as received sample and the sample that received an ageing treatment of $3 \cdot 10^6$ seconds at 60°C, respectively. The errorbars are equal to the standard deviation (with an upper limit equal to the maximum energy and a lower limit of 0 J). The lines are used to determine the transition temperature region, which will be explained later this subparagraph. The results clearly show that the mean initiation energy is nearly constant for higher temperatures, when only ductile failures occur. Furthermore, figure 8 shows that at low temperatures the deviation is small as well, when only brittle failures occur.

As already stated, the difference between ductile and brittle failure is very distinct. Nevertheless, the transition from ductile towards brittle behaviour is not very distinct. In the transition range both brittle and ductile failures occur, causing large standard deviations for measurements in this transition region (even at a large amount of tests at one temperature).

The mean value of the energy up to the maximum force at temperatures in the transition region has little physical significance, as in reality very little fractures will occur with an absorbed energy equal to this mean value. Nonetheless, the mean value is used to determine a brittle-to-ductile transition temperature from the experimental data. The mean value is expected to follow a step function, from the mean brittle energy at low temperature to the mean ductile energy at higher temperatures. For this preliminary analysis the inverse tangent function is used to describe the experimental data.

$$E_{impact} = A + B \cdot \arctan(C \cdot T + D) \tag{2}$$

In this equation T is the temperature. A and B are constants related to the average impact energies for both brittle and ductile failure and C and D (related to transition temperature) are fit factors. Equation (2) is fitted on the mean impact energy at each temperature for all five samples. Furthermore, D is fitted on the mean value plus and minus the standard deviation to get an idea of the lower and upper confidence limits. The resulting curves are given in figure 7 and 8. The solid lines are the best fit for the mean energy up to maximum force and the broken lines represent the shifts corresponding to the lower and upper values for the energy up to the maximum force.

The transition temperature range for the different samples is given in figure 9 as a function of the ageing time at 10°C, to relate the experimental data with situation in service for gas distribution pipes. As the abscissa has a logarithmic scale, the as received sample (set 5) cannot be plotted correctly. Therefore, its data point is added using a different marker near the ordinate. Although an increase in transition temperature can be observed as the ageing time increases, no significant difference is observed. A plausible explanation for the small differences between the aged samples and the as received sample is that the initial age of the samples is in the same order of magnitude as the additional ageing treatment when translated towards ageing at 10°C. Using the ageing theory as described in [7], storing uPVC pipe for a year at 23°C is equal to ageing the pipe for about 8 years at 10°C. Thus, when assuming an initial age of around 10 years, no differences in impact behaviour are expected to be found between set 3, 4 and 5. The line that is shown in figure 9 to indicate the trend is based only on the transition temperature of set 1, 2 and 3. To find a greater difference in transition temperature the specimen should either be aged more, or be rejuvenated (=cancelling the physical ageing effects by "resetting" the initial age). One can conclude that the transition temperature will change mostly during the first year of storage or service, as can be expected for a process that occurs on a logarithmic time scale.

Although the shift is small in magnitude, it is of importance due to the location of the shift. The transition temperature shifts from below 0°C for the as received samples towards above zero degrees for the aged sample. This can mean a difference between ductile or brittle failure during third party damage, as in most countries groundwork is carried out at temperatures down to 0°C.

So far the analysis of the experimental results are still labelled *preliminary* as the data still has to be analysed in several other ways, to bring forward the transition region clearer way. One idea comes from a paper of Jones and coworkers [1], who use the coefficient of variation (ratio between the mean and standard deviation) in their analysis of instrumented falling weight test data. In this case the standard deviation gives a clearer picture as the mean energy value is quite small for brittle fracture (resulting in a high coefficient of variation despite the low

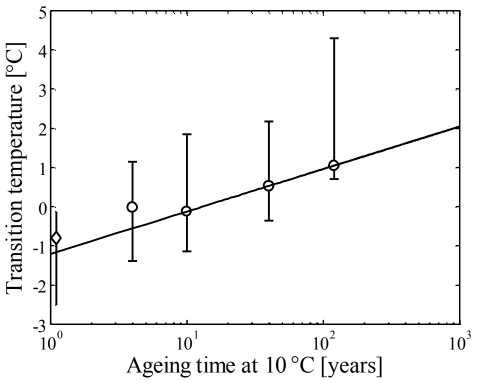


Figure 9: Ductile-to-brittle transition temperature for samples which received different ageing treatments. The solid line is drawn to guide the eye.

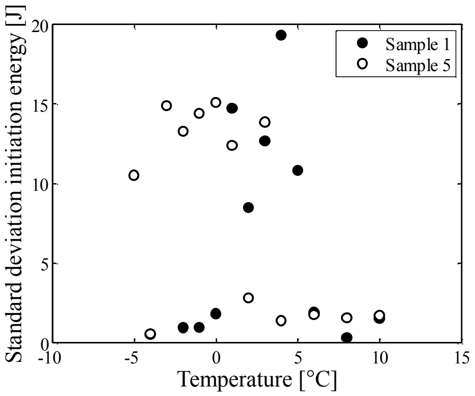


Figure 10: Standard deviation of the initiation energy versus the temperature for sample 1 and 5.

standard deviation). The standard deviation of the energy up to maximum force is shown as a function of temperature for sample 1 (longest ageing treatment) and 5 (as received) in figure 10. For both samples a clear transition region can be observed, where the standard deviation suddenly increases. Rijpkema and coworkers [15] use another way to analyse their instrumented falling weight test data. They look at the percentage of ductile fracture per temperature. This analysis gives results similar to the analysis already presented here and will not be presented.

3.4. Conclusions

- Three different types of failure were observed during the instrumented falling weight tests: ductile, semi-ductile and brittle failure. The temperature at which the impact test is carried out has the most influence on which type of failure occurs.
- In the analysis of the energy up to maximum force during impact, two different populations can be distinguished: ductile and brittle behaviour (the ductile and semi-ductile failure are identical in energy up to maximum force). The mean value of the energy up to the maximum force for these two populations differ one order of magnitude.
- Outside of the transition temperature region, the deviation of the energy up to maximum force is low for both ductile and brittle behaviour.
- Five samples have been tested which were given different heat treatments. For each of these samples a transition region is observed, which are roughly located between -5°C and 5°C.
- For aged samples the transition temperature seems higher than for the as received samples. The difference in transition temperature is estimated to be close to 2°C, but could not be measured significantly. A plausible explanation for this small difference is that the as received sample was stored at room temperature for at least one year, corresponding to about eight years of ageing at 10°C. The additional heat treatment that was given to sample 1 resulted in an age of about 120 years at 10°C. This difference of about one order of magnitude does not bring about large differences as physical ageing occurs on a logarithmic time scale.
- Despite the small difference in transition temperature between the aged and the as received samples, it is a relevant difference in practice. As the transition temperature shifts from below 0°C towards a temperature above 0°C, it can lead to a difference between ductile or brittle fracture as a result of third party damage.

3.5. Future work

- As already stated, the yielding behaviour is related to the impact behaviour of uPVC. In previous work the change in plastic deformation kinetics during physical ageing was modelled. This model will be used to predict the shift in transition temperature, which will be compared to the experimental results.
- Obtain more information of the kinetics on the transition temperature by rejuvenating samples prior to the ageing step. Starting of with "younger" samples will make it possible to study the shift of transition temperature for samples over a wider range of ageing times.

4. PART 2: EVALUATION AFTER 50 YEARS OF USE

4.1. Background

As mentioned in the introduction the total length of uPVC gas pipelines in the Netherlands is large. As they all tend to reach their theoretical lifetime of 50 years, knowledge of the remaining quality of these pipe systems is of major interest to the gas distribution companies since safety is one of the most important corporate values.

This part of the paper outlines the current status of the efforts being made by the Dutch gas industry to clarify the present quality of uPVC. In this regard the influence of physical ageing on the impact behaviour of uPVC is measured and related to other material properties and pipe properties like the degree of gelation and the age of the pipe.

4.2. Leak survey

One of the most important indicators available for the gas distribution companies are leak survey data. In the Netherlands leak survey is based on a 5-year cycle. The annual leakage rate is derived from these leak surveys. To compare the quality of different materials, the numbers of leakages formed during one year have to be used. Also the system pressure is registered. This leads to an extensive database with reliable data. In 2006 Wikkerink [16] presented the results of this database during the World Gas Conference in Amsterdam. His data were based on measurements in 2004. The results for the most interesting materials like PE and steel as well as the data obtained for both rigid PVC and impact-modified PVC derived from the 2004 data are listed in table 2 below. In 2005, 2006 and 2007 additional data has been gathered. The mean values of the numbers of leakages formed in this period (including 2004) are also shown in table 2.

Comparison shows that the annual leakages per km length of uPVC are comparable to those of polyethylene and impact-modified PVC and that they are even lower than those of steel.

4.3. Exit evaluation

To get some insight into the remaining quality of the uPVC still in use, an “exit evaluation” programme was started in 2004. Since 2005 this programme was merged in the “Kenniscentrum Gasnetbeheer” programme, supported and sponsored by “Netbeheer Nederland” and all Dutch energy distribution companies. In this “exit evaluation” the quality of the “in service” uPVC material is assessed.

Table 2: Annual number of leakages of different materials used in gas distribution in the Netherlands

Material	Pressure range [bar]	Annual number of leakages per length of mains * [#/(km·year)]	Mean annual number of leakages per length of mains** [#/(km·year)]
Polyethylene	0.03 – 0.1	0.06	0.04
uPVC	0.03 – 0.1	0.04	0.03
Impact-modified PVC	0.03 – 0.1	0.02	0.02
Steel	0.03 – 0.1	0.13	0.16

* 2004 data only

** data over the period 2004-2007

4.3.1. Programme

In cooperation with gas distribution companies about 20 samples have been taken out of the gas grid annually. The excavated samples are marked and sent to Kiwa Gas Technology for laboratory testing. Information concerning the quality of these pipes is gathered in two ways. Firstly, the gas distribution companies fill in an inquiry that goes with every sample taken from the grid. This inquiry contains information on the circumstances the pipe segments faced during their service time. Examples of the information gathered are: age of the pipe, manufacturer, depth of cover, ground water level, presence of chemicals, presence of mechanical stresses, et cetera. Secondly, the results originating from laboratory testing performed by Kiwa Gas Technology are used. The tests performed on the uPVC are limited to measurements to determine the degree of gelation and the ductility (impact resistance).

Since third party interference is one of the main reasons for failure, impact resistance is an important property for uPVC. After almost 50 years of service, the impact resistance of uPVC might be reduced due to physical ageing [6,17]. Therefore, the tensile impact test is one of the tests used to measure the present mechanical quality in this programme. The second test in this programme is the measurement of the degree of gelation. This property is known to be fixed right at the time of production [17]. It is also known that the degree of gelation does not change with time and therefore it is a good indicator for the initial quality of a uPVC pipe.

By combining both information sources (inquiry and laboratory tests) several possible correlations can be evaluated. The aim is to find easy accessible parameters that are already available within the distribution companies and which have a correlation with the relevant mechanical properties of the pipe.

Several statistical analyses (with the software SPSS 16) have been performed. Ductility (as determined with the tensile impact tester) is presumed to be the main parameter in the determination of the pipe quality for the use of gas pipes in low pressure systems. The two most interesting types of analyses will be discussed further on in this paper. This will be the correlation of the ductility with the degree of gelation and the correlation of the ductility with the age of the pipes.

4.3.2. Experimental

During the past 4 years 86 samples have been excavated and tested. In this study the ductility of the uPVC pipes was measured using a pendulum tensile impact tester. To make impact testing possible, 12 test bars were processed from each excavated sample. During the processing special care was given to protect the sample from heating, as this heating could locally induce additional unwanted physical ageing. Of each sample 10 test bars were tested.

The test method for determination of the degree of gelation used is EN 580 "Test method for the resistance to dichloromethane at a specified temperature (DMCT)". Based on the combination of the amount of attack and the test temperature the tested pipes are classified as "under", "poor", "good" or "over" gelation.

4.3.2.1. Fracture energy and degree of gelation

The fracture energy is plotted versus the degree of gelation in figure 11. The results seem to be in agreement with earlier work [17] that shows an optimum of the mechanical quality for uPVC with an increasing level of gelation. In spite of the scatter shown in figure 11, statistical analysis shows a significant difference between "good" degree of gelation and "under", "poor" and "over" degree of gelation.

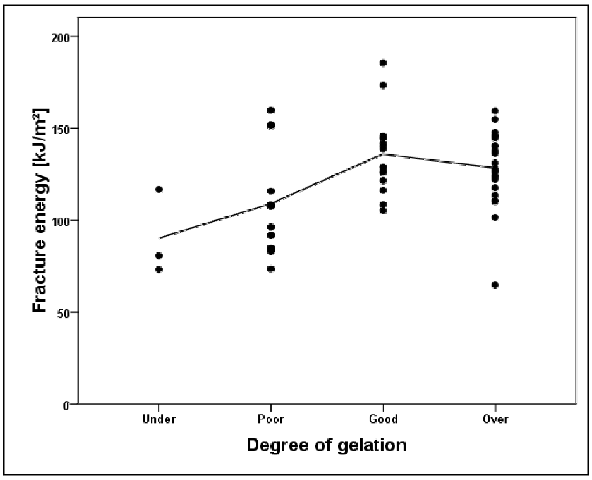


Figure 11: Fracture energy as function of the degree of gelation

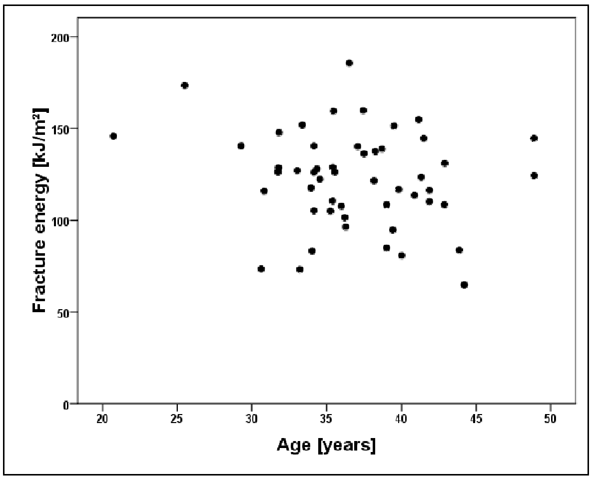


Figure 12: Fracture energy as function of the age of the pipes

4.3.2.2. Fracture energy and the age of the pipe

The results of the tensile impact tests as a function of the age of the pipes are shown in figure 12. This figure shows a lot of scatter. In this case age is equal to the time the pipe has been installed. Although physical ageing is expected to influence the mechanical quality, no indication has been found which could confirm that the pipes show any degradation, within the range of ageing times.

4.4. Discussion and conclusion

As presented in section 4.2, the leakage rates in practice of uPVC is after about 50 years of use equal or even better than other materials in service. Leakage rates after many years of service are still extremely low.

In the exit evaluation part, two relations have been investigated in this paper. The relation between the mechanical quality (impact resistance) and the degree of gelation shows an optimum quality in terms of impact resistance for the pipes where the degree of gelation can be classified with "good". This relation is in agreement with comparable tests results obtained in the early seventies [17]; a maximum in the measured fracture energy is found for pipes with "good" degree of gelation. This similarity shows that even after 50 years of practice the impact resistance is still dependant on the initial quality, determined by the processing parameters during extrusion of the pipe.

The relation between impact resistance and age of the pipes is also investigated. As the scatter in the test results are high, no relation between impact resistance and age of the pipe can be found. While ageing is known to reduce the impact resistance of uPVC pipes, no evidence for reduction of the ductility can be seen for these low pressured buried gas pipes.

The general conclusion therefore is that although reduction of the resistance to impact due to ageing is known for uPVC pipes, the absolute reduction of the resistance to impact did not show a noticeable change for the ageing period studied here. This is, of course, only valid for buried uPVC pipes used in a low pressure application. The conclusion therefore is that in spite of the expectation that the maximum lifetime of uPVC is equal to 50 years, no further decrease in impact resistance has to be expected. The uPVC pipes are still as good as they were 30 years ago, since no effects can be observed between the samples with ages ranging from 20 to 50 years. Therefore, physical ageing is not expected to induce significant changes in the impact resistance within the upcoming 50 years.

5. CONCLUSIONS

The main conclusion that can be drawn for both parts of the research is that physical ageing seems to influence the impact behaviour of uPVC pipe material. As physical ageing occurs on a logarithmic timescale, most changes occur during the early stages of the life of a uPVC pipe, just after its production. Therefore, the ageing timeframe of the samples used in the first part of the study, is too short to measure a significant, ageing induced change in ductile-to-brittle transition temperature. During the second part of the study, it was not possible to use samples with a low age, as pipe section which have been in service have been investigated and uPVC has not been installed for gas distribution purposes since the mid seventies. The experiments on the used uPVC pipe materials show that the ductility does not change significantly between the 20th and the 50th year of service, as can be expected. Therefore, it is likely that physical ageing will not induce significant changes in the impact behaviour of uPVC pipes currently in service within the upcoming 50 years.

6. ACKNOWLEDGEMENTS

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