

# **PVC PIPES IN GAS DISTRIBUTION: STILL GOING STRONG!**

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## **ABSTRACT**

In the Netherlands (impact-modified) PVC is the preferred material for low-pressure (30 and 100 mbar) gas distribution systems. More than 50% of the total length (about 122,000 km) of this system is rigid PVC or impact-modified PVC. The installation of rigid PVC (uPVC) pipelines started about 50 years ago. Presently, about 22,500 km of rigid PVC is still in operation. In this paper the good experiences with rigid PVC gas distribution systems in the Netherlands will be illustrated by results of regular leak surveys and test results on pipe samples taken from the gas grid. It will be shown that the leakage rate of uPVC pipe systems is very low and about equal to that of PE and steel pipe systems. Impact tests show no significant decrease in ductility with respect to time of use. Furthermore, the ductility of the PVC pipeline materials which have been in use for many years is shown to be mainly dependent on the (initial) quality (degree of gelation). The good performance of PVC gas pipeline systems is also proven by modelling studies. It will be shown that the long-term failure behaviour of uPVC is determined by the ability to yield. Failure will occur if a certain critical value of the plastic strain is surpassed. Using this model the long-term behaviour under internal pressure of rigid PVC pipes can be predicted quantitatively.

## **INTRODUCTION**

Since many years plastics pipes are used in the Dutch gas distribution system. The usage of plastics pipes started in the early sixties. At that time the “Slochteren“-natural gas field in the northern part of The Netherlands came into production. Within a decade almost 90% of all Dutch households were connected to the gas grid. As the number of customers connected to the already existing town gas was rather limited, this was an extreme challenge. To cope with this challenge, the easy-to-handle and easy-to-install rigid PVC (uPVC) pipe system was used. Not only the mains but also the service lines were made of rigid PVC (also referred to as unplasticized or unmodified PVC).

In the seventies the use of rigid PVC for gas distribution was stopped due to the fact that rigid PVC was said to be susceptible for stress cracking and could not withstand any serious mechanical impact. As the impact-modified PVC systems were already available, gas distribution companies in the Netherlands switched to use these systems. At present about 22,500 km of rigid PVC material are still in use as gas mains. 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 company values.

This paper outlines the current status of the efforts being made by the Dutch gas industry to understand the ageing behaviour of rigid PVC.

## 50-YEARS OF EXPERIENCE WITH RIGID PVC

One of the most important indicators available for the gas distribution companies are leak survey data. In the Netherlands rigid PVC is used at a maximum pressure of 100 mbar. According to the Dutch and European legislation mains up to 100 mbar have to be monitored for leakage. In the Netherlands leak survey is based on a 5-year cycle. The annual leakage rate is derived from these leak surveys. In order 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 (1) 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 1 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 1.

*Table 1. 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
Rigid PVC	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

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

## LONG-TERM FAILURE OF PRESSURIZED RIGID PVC PIPES

The long-term failure of pressurized, rigid PVC pipes has been a research topic of many studies in the past (e.g. (2)). In previous work (3) a model was developed to predict this long-term failure time for rigid PVC pipes on which an internal pressure was exerted. The model is based on the hypothesis that an amorphous polymer like PVC will always deform plastically when a stress is applied on it. Furthermore, the polymer fails when a certain amount of plastic deformation is reached (the critical strain). This model is proven to hold for all types of failure which are encountered when conducting pressurized pipe (or burst) tests; brittle fracture, hairline cracking and ductile rupture.

Typical results of burst tests on rigid PVC pipes are shown in figure 1 (data taken from (2)). The predictions of the model are presented with solid and dashed lines. The solid lines represent prediction for the failure time without taking the effect of physical ageing into account. Both the slope and the temperature shift are predicted correctly. The predictions which are presented in dashed lines take physical ageing into account, causing the failure

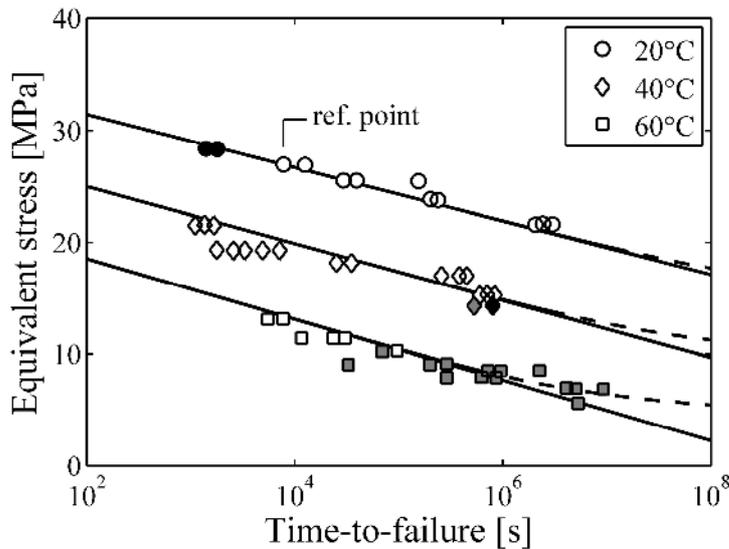


Figure 1. Failure time for uPVC pipes under internal pressure, taken from (2). The model predictions without ageing and with ageing are shown with a solid and dashed lines, respectively.

times to increase at low applied stresses and long failure times. This is a result of an increase in resistance against plastic deformation due to physical ageing. The first extensive study on this relation between physical ageing and deformation behaviour was carried out by Struik (4).

The internal pressure in rigid PVC pipes which are used for the distribution of gas is maximally only 100 mbar. At this pressure, the equivalent stress in a common pipe with a diameter of 110 mm and a wall thickness of 2.7 mm is only about 0.1 MPa. At this stress the model predicts failure after  $5 \cdot 10^{156}$  years (virtually eternity) at 10°C, which is not a big surprise for such a low pressure. It is therefore a safe conclusion to state that failure due to the internal pressure will not be the limiting factor for the lifetime of a rigid PVC gas pipe.

### DUCTILE-TO-BRITTLE TRANSITION TEMPERATURE

Third party damage due to excavation activities is the most important cause of failure for gas distribution pipes. Rigid PVC pipes can either fail in a brittle or a ductile way. Ductile failure is favourable due to three reasons. Firstly, a rigid PVC 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. And in the third place the average amount of gas escaping from a ductile broken pipe is small compared to the amount leaking from a brittle failure. Therefore, brittle behaviour of rigid PVC pipes imposes a high risk for gas distribution companies.

As mentioned previously, physical ageing influences the deformation behaviour of rigid PVC. As a result, the impact behaviour of rigid PVC changes as well as it ages. This change in impact behaviour can have serious consequences for gas distribution companies. Therefore, instrumented falling weight tests have been carried out which simulate impacts encountered during excavations. These tests are used to investigate both the location of the ductile-to-brittle transition temperature of rigid PVC and the shift of this transition due to physical ageing.

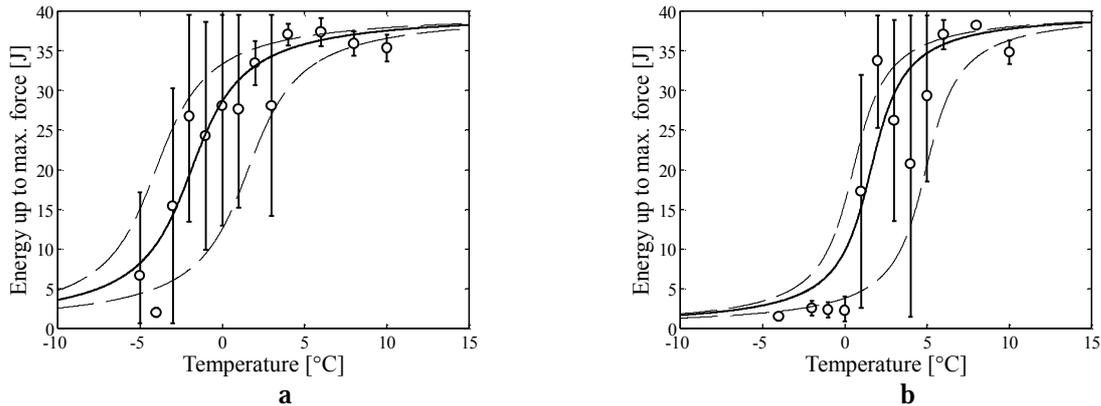


Figure 2. Ductile-to-brittle transition temperature for as received (a) and aged (b) rigid PVC pipe

The energy up to the maximum force is plotted versus the temperature in figure 2. The lines are guides for the eye for the mean energy up to maximum force (solid lines) and the upper and lower limits (dashed lines). The energy up to the maximum is a measure for the amount of impact energy a rigid PVC sample can resist before it fails. This impact resistance versus temperature is plotted for samples that did not receive a heat treatment (subplot 2a) and for aged samples which did receive a heat treatment (34 days at 60°C, subplot 2b). The ductile behaviour can be found at higher temperature in both figures, while the brittle fractures are observed at lower temperatures. As expected, a clear difference between the energy up to the maximum force is observed between the brittle and the ductile failures. The transition from ductile to brittle behaviour is located just below 0°C for the as received specimen, whereas for aged specimen this transition temperature seems to be at a somewhat higher temperature (around 2°C). The existence of this shift cannot be significantly determined with the current measurements. A plausible explanation for the small difference in impact behaviour between the as received and the aged samples is that the as received samples might already had a significant initial age. In that case, the resulting age of the additional heat treatment might just differ one or two orders of magnitude from the initial age. As physical ageing occurs on a logarithmic timescale these differences do not result in a considerable change in impact behaviour. In future work the same tests will be repeated on specimens with a lower initial age to get a clearer image of the influence of physical ageing in the shift of transition temperature.

From the current observations two important conclusions can be drawn:

- Physical ageing, and thus the change in impact behaviour, occurs on a logarithmic timescale. This means that differences are more distinct at a low age.
- The shift of the transition temperature between the as received and the aged samples seems to be a minimal and not of great importance. However, this shift can be of importance due to the location of the transition temperature. Generally, excavations are carried out at temperatures down to 0°C. A transition temperature below 0°C means that in most cases ductile failures will be encountered if a pipe is hit. Transition temperatures above 0°C increase the risk on brittle behaviour.

## EXIT EVALUATION

As mentioned in the introduction knowledge of the remaining quality of rigid PVC pipes systems is of interest to the gas distribution companies. To get insight into the remaining quality of the rigid PVC which is 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” rigid PVC material is assessed.

In cooperation with gas distribution companies about 20 samples have been taken out of the gas grid annually. The choice which sample is taken is based on daily practice within the gas distribution companies. Many pipe segments are taken out of service and replaced by new pipe segments. The reasons for that could vary from e.g. a lack of capacity, a reconstruction of a road to a repair of a leak. The excavated samples are marked and sent to Kiwa Gas Technology for laboratory testing.

To assess the quality, the programme generates two types of information. Firstly the gas distribution companies fill in an inquiry that applies to every sample taken from the grid. This inquiry contains information on the circumstances the pipe segments have been facing 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 from laboratory testing performed by Kiwa Gas Technology are used. To get as much value for money the tests performed on the rigid PVC are limited to two types of experiments to determine both the degree of gelation and the ductility.

The choice for testing these two properties is based on previous work. As design stresses for low pressure gas distribution pipes are relatively low, the theoretical life time based on slow stress cracking is not expected to be dominant. However, the resistance to impact loading (e.g. in third party interference) is important. It is already known that physical ageing can lead to a reduction in ductility of PVC (4, 5).

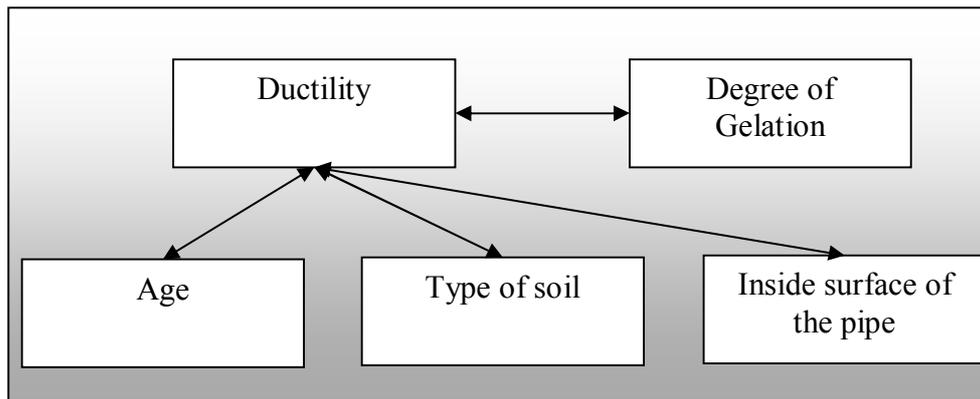
Failure studies of broken rigid PVC gas pipes in the Netherlands show the lack of ductile behaviour as the most important reason for accidents with rigid PVC. The majority of these accidents were caused by third party damage due to excavation.

Experiments on material that has been stored at elevated temperatures (above 30°C) show a decrease of approximately 10% in impact energy (in tensile impact testing) of rigid PVC compared to impact energy before storing. This means that the impact energy will decrease due to physical ageing. Note that the temperature difference between the used storage temperatures and the mean ground temperature of approximately 10° C are relatively large. Up to now it is still unclear, if the conclusion can be drawn that one can expect a reduction of the ductility at ground temperatures. Therefore, the ductility of the excavated samples is tested using a tensile impact test.

It is also well known that the mechanical quality of the pipe shows a correlation with the degree of gelation (5). As the degree of gelation is fixed during the processing and production of the pipe and does not change with time, it is a good indicator of the quality at the beginning of the use of a rigid PVC pipe just after production. As most of the mechanical properties are expected to be dependant on the degree of gelation this is also measured in this programme.

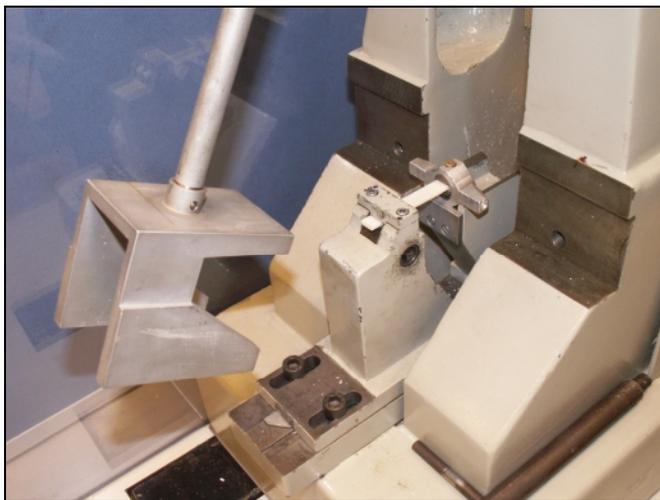
By combining both information sources (inquiry and laboratory tests) possible correlations can be evaluated. The aim is to find easy accessible parameters that are already available within the distribution company and which have a correlation with the relevant mechanical properties of the pipe.

Several analyses have been performed. Ductility 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 most interesting types of analyses are presented in figure 3.



*Figure 3. Analyses performed in this study*

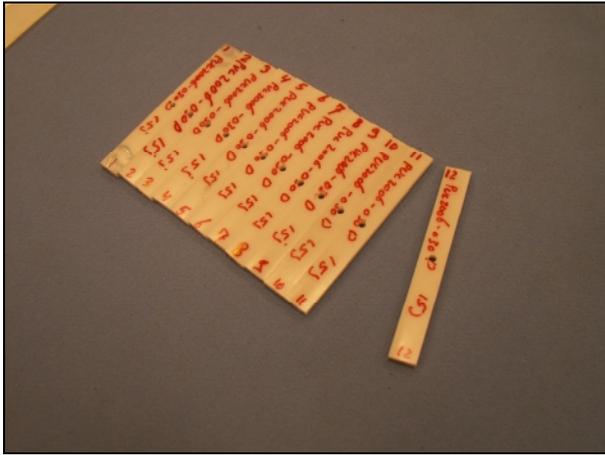
During the past 4 years a total of 86 samples have been excavated and tested. In this study the ductility (or impact resistance) of the rigid PVC pipes was measured using a pendulum tensile impact tester. (see Picture 1). Prior to impact testing the excavated samples have been inspected visually.



*Picture 1 Pendulum tensile impact test machine*

Special care was given to changes in the smoothness of the surface (both in- and outside). To make impact testing possible 12 test bars were processed out of the excavated samples.(picture 2). While processing special care was given to prevent the sample from heating, since this heating could locally induce additional unwanted physical ageing. Of each sample 10 test bars were tested.

As mentioned before, the degree of gelation was also measured. 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 with an “under”, “poor”, “good” or “over” degree of gelation.



Picture 2. Prepared test bars for tensile impact testing.

Since failure in practice is often caused by the lack of ductility, ductility is used as an indicator for mechanical quality. In figure 4 the histogram shows the results of all individual test bars. Statistical analysis of the data, using the software tool SPSS, shows that the results of the tensile impact tests are normally distributed. The mean value of the distribution is  $127.3 \text{ kJ/m}^2$ . The standard deviation is  $23.2 \text{ kJ/m}^2$ .

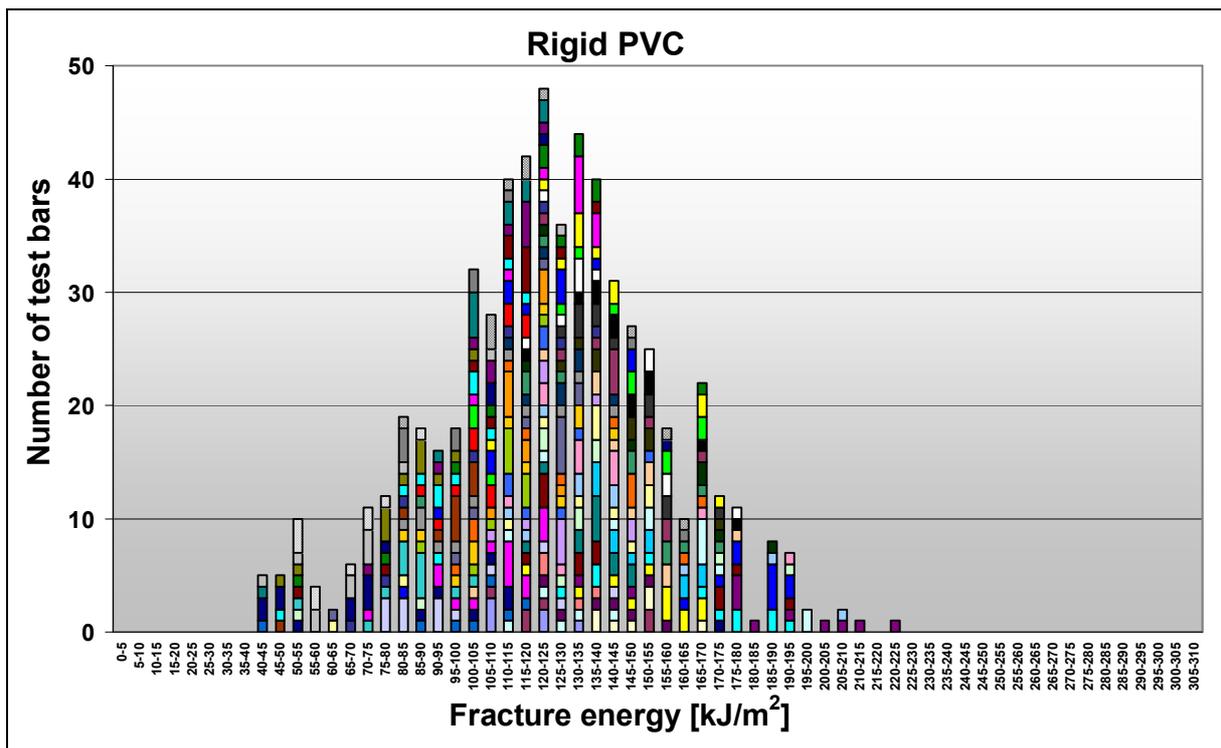
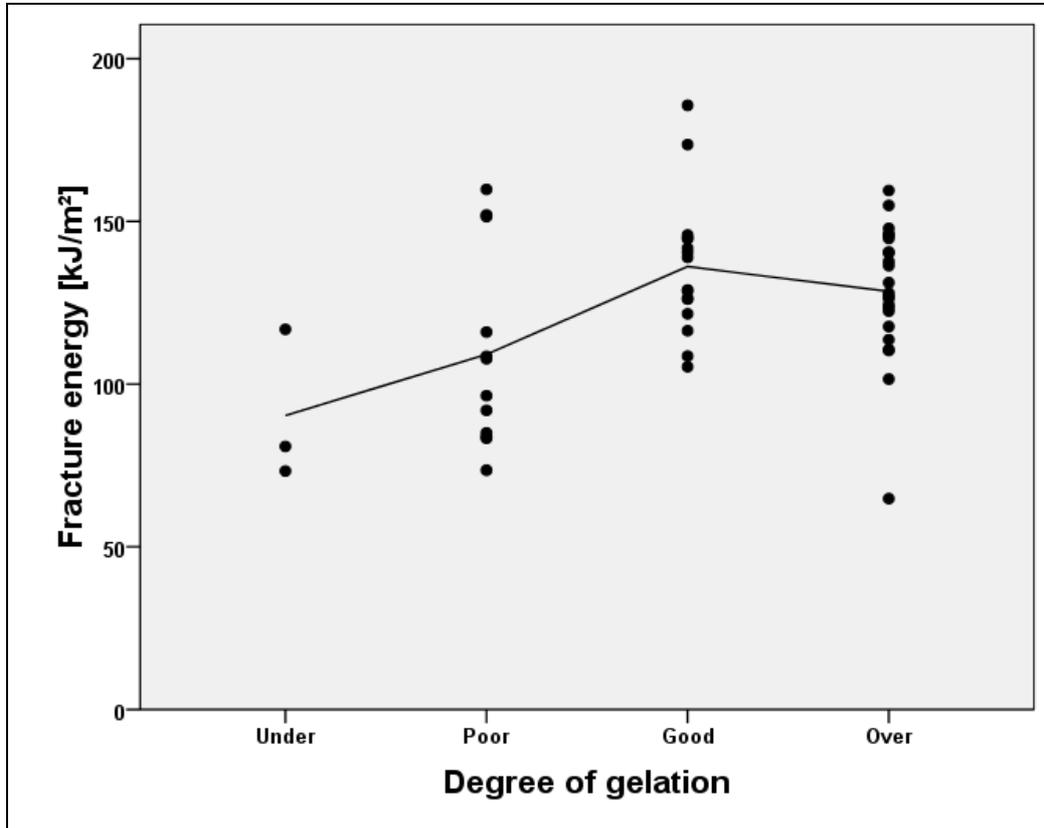


Figure 4. Histogram of tensile impact results

The fact that we are dealing with a normal distribution makes analyses using this data easier. Analyses of possible correlations between the results of the tensile impact tests and all other parameters have been performed using SPSS (version 16) as well. In some cases the numbers of test results were insufficient to carry out a proper analysis.

### *Fracture energy and the degree of gelation*

The results seem to be in agreement with earlier work (5) that shows an optimum of mechanical quality for rigid PVC materials. In spite of the scatter shown in figure 5, statistical analysis shows a significant difference between “good” degree of gelation and “under”, “poor” and “over” degree of gelation. Based on this analysis properly produced rigid PVC pipes having a good degree of gelation show a higher resistance to impact compared to ones that have been produced in a less proper way.



*Figure 5. Quality (ductility) as function of the degree of gelation*

### *Fracture energy and the age of the pipes*

The results of the tensile impact tests as a function of the age of the pipes are shown in figure 6. This figure shows a lot of scatter. In this case age is equal to the time the pipes have been installed under ground. Although it is expected, no indication has been found that could confirm the pipes to show any degradation. The resistance to impact is as we have seen already dependent on the degree of gelation, which is fixed at the time the pipe is produced. While the scatter between the degree of gelation of the complete population is rather high an effect of reduction of the ductility might be present, but cannot be seen at all.

The number of samples however is too limited to analyse the same relation for pipe produced with a “good” degree of gelation.

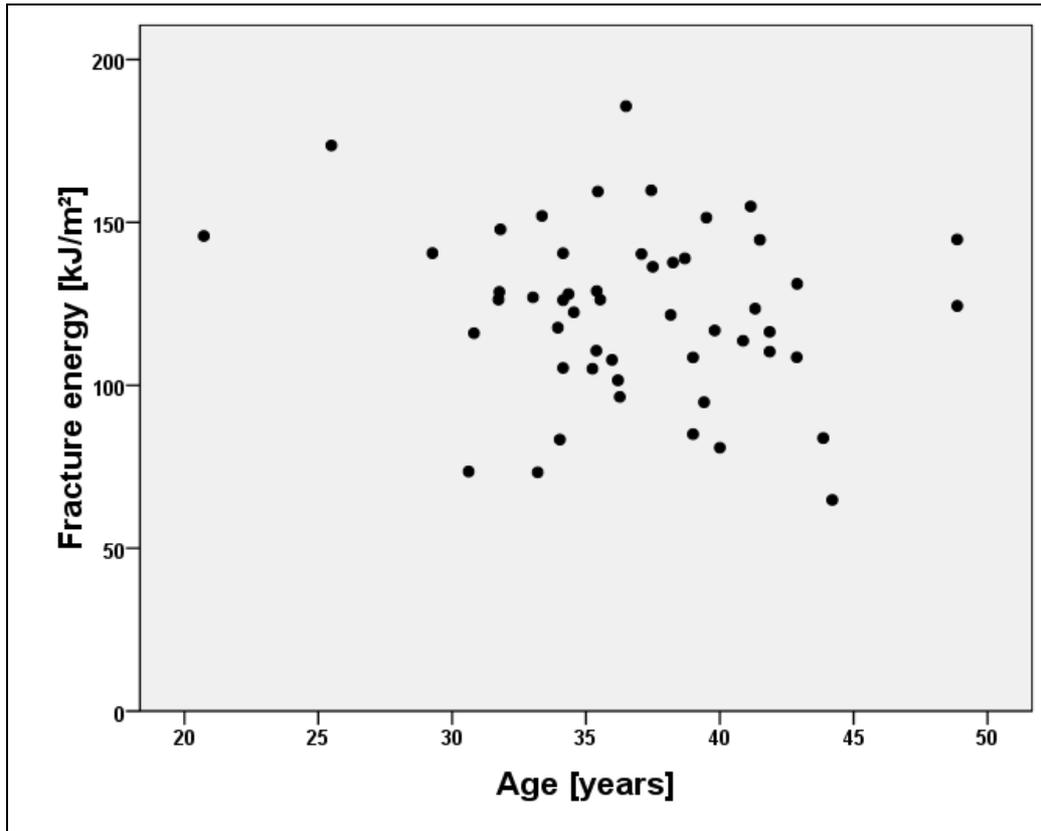


Figure 6. Quality (ductility) as function of the age of the pipes

#### *Fracture energy and the inside surface of the pipe*

All pipes have been inspected visually. The pipes have been ranked dependent on the inside surface. The used gradations are: “smooth”, “spiderlines”, “bumpy”, ”shiny/burned” and “cellulite like”

Statistical analyses show a difference between: “bumpy” and “spiderlines”, ”bumpy”and “shiny/burned”, “smooth” and “shiny/burned”. Although analyses show these differences, they are not yet understood. As the differences are still very small it is possible that we are still short of data and that the results obtained are just a coincidence.

#### *Fracture energy and the type of soil*

In this programme 4 types of soil are taken into account. The types of soil are: sand, clay, loam and sandy backfill. Only the effects of the first two types of soil can be analyzed due to a lack of samples of the later two. Statistical analyses of the data show no effect of the first two types of soil on the ductility of the pipes.

## **DISCUSSION AND CONCLUSIONS**

What we have seen is that the behaviour in practice of rigid PVC after about 50 years of use is equal or even better than other materials in service. Leakage rates after many years of service are extremely low.

The study of long-term failure of pressurized rigid PVC pipes leads to the conclusion that physical ageing, and thus the change in impact behaviour, occurs on a logarithmic timescale. This means that differences are more distinct at a low age.

The study on the brittle-to-ductile transition temperature shows a shift of the transition temperature between the as received and the aged samples to be minimal and not of great importance. However, this shift can be of importance due to the location of the transition temperature. Generally, excavations are carried out at temperatures down to 0°C. A transition temperature below 0°C means that in most cases ductile failures will be encountered if a pipe is hit. Transition temperatures above 0°C increase the risk on brittle behaviour.

In the exit evaluation part several relations have been investigated:

- 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. (5) In this study there was also a maximum mechanical quality found for good produced pipes. This similarity shows that even after 50 years of practice the impact resistance is still dependant on the initial quality fixed during the production of the pipe.
- The relation between impact resistance and the age of the pipes is also investigated. Since the scatter in the test results is high, no relation between impact resistance and age of the pipe can be found. While ageing is known to reduce the impact resistance of rigid PVC pipes, no evidence for reduction of the ductility can be seen for these low pressured buried gas pipes. This is in agreement with the conclusion drawn from the brittle-to-ductile temperature transition study.
- All other analyses performed in this evaluation show only limited changes that cannot be related to ageing. If any physical degradation is present, the effect on ductility is smaller than the scatter as the result of pipe production.

The general conclusion is that physical ageing has influence on the impact resistance of uPVC gas distribution pipes. As the major contribution of the reduction of the impact resistance is expected to occur in the early life of a rigid PVC pipe, the reduction of the ductility after many years of use is limited. In spite of the expectation that the maximum lifetime of rigid PVC is equal to 50 years, uPVC seems, based on the limited number of test results therefore still as good as it was years ago.

## **ACKNOWLEDGEMENT**

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