Proceedings of the 21st Plastic Pipes Conference, PPXXI
September 25-27, 2023, Lake Buena Vista, FL, USA

LEAK TIGHTNESS OF PVC FITTINGS WITH HYDROGEN

Roland Valk
Kiwa Technology
Apeldoorn, the Netherlands

René Hermkens
Kiwa Technology
Apeldoorn, the Netherlands

Sjoerd Jansma
Kiwa Technology
Apeldoorn, the Netherlands

SHORT SUMMARY

The PVC gas grid in the Netherlands is presumed to be suitable for the transport of hydrogen. To gather evidence to support this assumption, this study explored two topics: the permeation behavior of PVC and the mechanical performance of PVC joints.

The permeation rates for excavated PVC pipes and joints were determined. These were low and below the limit considered as leakage for natural gas distribution purposes. The mechanical performance of excavated PVC joints was tested by determining the maximum angle of deflection. They were tested either without additional ageing or with ageing for 1000 hours at 60 °C in a hydrogen environment (inside the pipes). Both tests showed that the maximum angle of deflection, even after ageing, fulfils the requirements of the appropriate EN-ISO 13844 and NEN 7231 standards.

KEYWORDS

polyvinyl chloride, PVC, hydrogen, maximum angle of deflection, permeation rate

ABSTRACT

The use of hydrogen gas as an energy carrier is seen as a key component of the energy transition. This creates new challenges, including in relation to the transport and distribution of this gas. The low-pressure (natural) gas distribution grid in the Netherlands currently consists of 64% PVC and is presumed to be suitable for transporting hydrogen in the (near) future [1]. To gather evidence to support this assumption, both the maximum angle of deflection before leakage for PVC joints and the permeability of PVC pipes and PVC joints were determined using hydrogen gas. The loss of hydrogen due to leakage and permeation is important from a safety point of view as well as from an environmental point of view, as hydrogen is an indirect greenhouse gas. It also gives an insight into the economic losses.

In this project, the mechanical behavior of joints made of unplasticized PVC (PVC-U) and impact-modified PVC (PVC-Hi) was tested by determining the maximum angle of deflection before leakage. These tests were carried out on old joints (up to 56 years)

excavated from the natural gas distribution grid. The joints were tested either without or with additional ageing. The ageing consisted of exposing the inside of the pipes to hydrogen for a period of 1000 hours at 60 °C as described in earlier research [2]. Both tests showed that the maximum angle of deflection, even after ageing, fulfils the requirements of the appropriate EN-ISO 13844 [3] and NEN 7231 [4] standards (both cover only PVC-Hi).

The permeation rates for three PVC-U pipes and three PVC-Hi pipes were also determined [5], [6]. The permeation coefficient was calculated after correction for the pipe dimensions and applied hydrogen pressure. The permeation coefficient was used to determine the permeation rate for different scenarios. For example, a PVC-U Dn250, SDR 41 pipe of 12 meters in length subjected to a hydrogen pressure of 100 mbar will result in a hydrogen permeation rate of less than 200 ml/day. The permeation rate of four PVC joints (2x PVC-U and 2x PVC-Hi), including a pipe length of approximately 0.6 m, was determined using hydrogen at 200 mbar. The permeation rate ranged from 6.5 ml/day to 7.5 ml/day.
For reference, natural gas distribution leaks above 5 l/h are not permitted [7]. As the reported permeation rates were far below 5 l/h, no safety problems due to hydrogen permeation are expected.

INTRODUCTION

Impact-modified PVC (PVC-Hi) and unplasticized PVC (PVC-U) are both widely used in the Dutch gas distribution grid. These pipe materials and their associated joints have been used successfully since the 1960s. The total length of the PVC gas grid exceeds 80,000 km (of which 20,000 km is made of PVC-U).
Within the context of the climate targets set in the Paris Agreement, the use of natural gas will be phased out in the future. The use of hydrogen as an energy carrier is currently being investigated. Reusing the existing grid would give large-scale access to hydrogen. An earlier study [1] concluded that PVC is a suitable material for the distribution of hydrogen. This report describes the results of a study that aimed to address some of the questions that remained unanswered after the earlier study.
The excavated pipe sections and their joints used in this study had been in service in the Dutch natural gas distribution grid for many years (from 7 to 56 years). Both impact-resistant and unplasticized PVC joints were used.
This report includes results from:

- Permeation measurements for used, as-received PVC-Hi and PVC-U pipes, with hydrogen at 200 mbar(g).
- Permeation measurements for used, as-received PVC-U and PVC-Hi straight joints tested with hydrogen at 200 mbar(g).
- Measurement of the maximum angular deflection before leakage of used, as-received joints after artificial ageing in a hydrogen environment. The joints were tested with air at 100 mbar(g).

EXPERIMENTAL

Permeation method for the pipes

The permeation rate was measured to determine how much hydrogen escaped through the PVC pipe wall. The setup consisted of a PVC pipe surrounded with a steel jacket pipe, inside which the hydrogen eventually accumulated as shown in figure 1. The concentration of hydrogen in the jacket pipe was measured at specific times using a gas chromatograph.

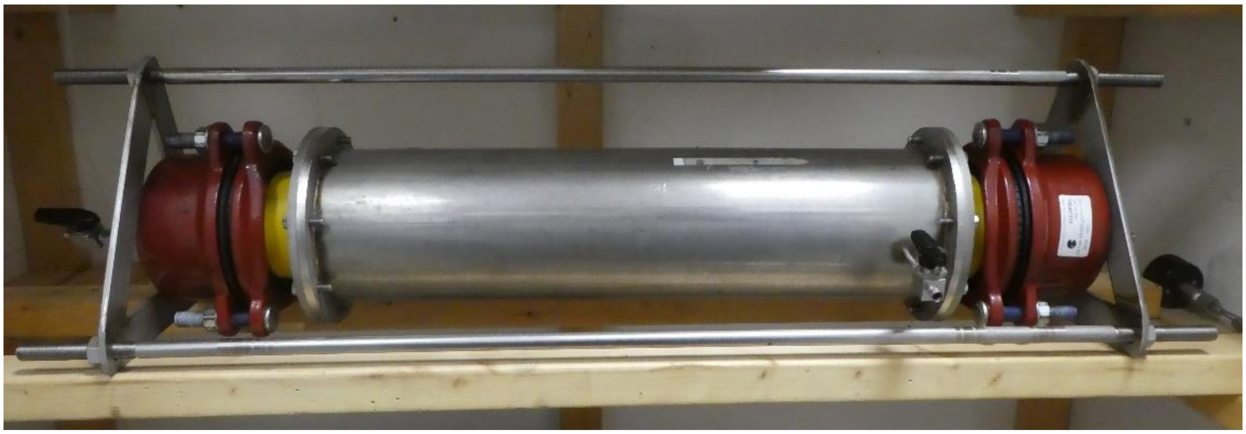

Figure 1. Sealed PVC pipe surrounded with a steel jacket pipe for the permeation measurement.

After an initial phase without any permeation (the breakthrough time or time lag), hydrogen starts to accumulate inside the steel jacket. A stationary permeation phase is later reached. In this phase, the hydrogen accumulation increases linearly with time. The slope of this part of the curve is used to determine the permeation rate. The given volume is applicable at standard temperature and pressure (STP conditions).
The permeation rate is calculated for the pipe segments and corrected for the length of the pipe and the pressure in accordance with Henry's law [8] (in *ml* hydrogen per *day* per *meter* of pipe length at 200 mbar(g) and room temperature).

The permeation coefficient (P_C) for a monolayer pipe can be calculated using the thickness of the pipe (e), the median surface area (A), the partial pressure difference (p) and the flow of the permeant (Q, *in volume over time*), as follows. Please note that a small but negligible error is made in this conversion [5], [9]:

$$P_C = \frac{Q \cdot e}{A \cdot p} \qquad (1)$$

This can be rearranged to give the permeation rate (Q):

$$Q = P_C \cdot \frac{A \cdot p}{e} \qquad (2)$$

Formula (2) can be adapted to use more pipe-related parameters as described in [5], [9]:

$$Q = \frac{P_C \pi \cdot (SDR-1) \cdot L \cdot p}{1000} \qquad (3)$$

where L is the length of the pipe and SDR is the ratio of the pipe diameter to the wall thickness.

The absolute pressure difference (or driving force) between the inner and outer pipe wall will decrease due to the increased concentration of the accumulated gas in the steel jacket pipe. The results were corrected to take account of this decrease in absolute pressure difference. In addition, the maximum concentration of hydrogen in the accumulated gas over all measurements was 5.7%, which is sufficiently low.

The results were used to determine the permeation coefficient for each PVC material. The results are shown in table 1.

Permeation method for the joints
Exactly the same test setup was used for the joints (two pipes with a straight joint in between) as for the pipes alone. All tested joints were DN 110 systems. No leakage was observed for any of the joints. The permeation rate was measured in *ml* hydrogen per *day* at 200 mbar(g) at room temperature. The results are show in table 2.

Maximum angle of deflection method
Four joints, each of which consisted of a socket, rubber ring and two PVC pipes, were artificially aged in a temperature chamber (at a temperature of 60 °C), in which the joints were stored for a period of 1000 hours. The joints were sealed using end caps and flushed and pressurized with air. The pressure was around 30 mbar(g).

An angular deflection was applied based on EN-ISO 13844 after ageing. The leak tightness was measured constantly while increasing the deflection. Instead of limiting the test to a deflection of 2˚, the test was continued until the joints started to leak. The angle of deflection at that moment was determined. The test rig as shown in figure 2 was used.

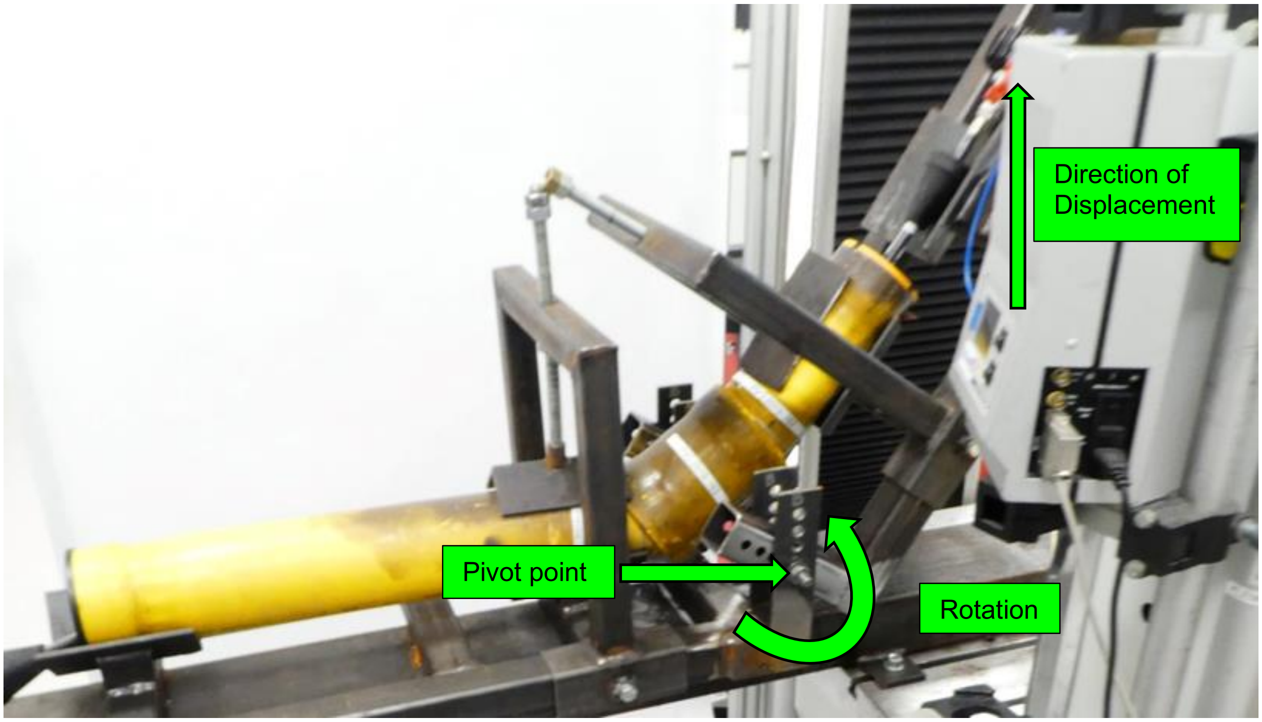

Figure 2 Angular deflection test rig (placed in a tensile test machine)

The test rig consisted of two parts, which were connected with a bolt that acted as the pivot point. The pivot point was located in the middle of the joint to introduce the rotation. The location ensured that the pipes could not be pulled out of the joint, which can happen at greater angles. Depending on the diameter of the pipe and joint, the position of the bolt could be adjusted in such a way that the middle of the joint was centered on the pivot point of the test rig. The pipes (with the joint) were clamped onto the test rig in such a way that the joint could move. In the figure above, the test rig has been placed in the tensile test machine. The tensile test machine was used to apply a constant upward displacement to the movable part of the test rig. A photograph was taken at least every 30 seconds (every 10 seconds during most of the experiments). By measuring the time between the start of the angular deflection and the moment leakage started, the picture corresponding to the moment of leakage could be selected. The measured angle of deflection in that photograph corresponded to the maximum angle of deflection before leakage occurred. As a comparison, another four joints were tested in the same manner without artificially aging before the tests were performed. The results are show in table 2. They show a maximum angle of deflection of approximately 5° for PVC-U joints after ageing with hydrogen.

The angle of deflection of the PVC-Hi joints could not be measured as the test rig reached its maximum capability.

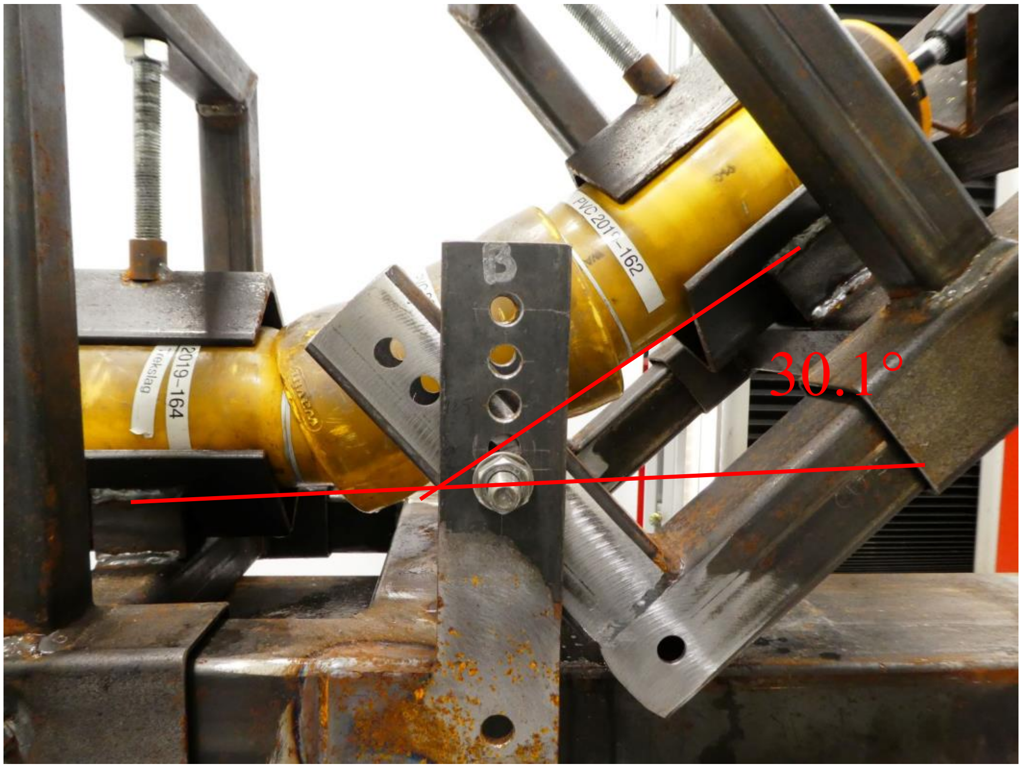

Figure 3 Maximum angle of deflection of the test rig reached. No leakage occurred.

Table 1. The permeation rate and permeation coefficient of the different PVC pipes.

Kiwa reference #	Type of PVC	Diameter [mm]	Wall thickness [mm]	Service life [years]	Permeation rate [ml/(m·day)]	Permeation coefficient [(ml·mm)/(m^2·day·bar)]
PVC 2017-020	PVC-U	111.08	3.02	53	12.1	90.9
PVC 2018-086	PVC-U	110.23	3.44	46	10.2	87.3
PVC 2019-033#06	PVC-U	110.30	2.94	14	11.2	115.3
PVC 2019-003	PVC-Hi	110.43	2.95	27	11.2	117.2
PVC 2016-116	PVC-Hi	110.38	3.08	7	17.0	181.3
PVC 2017-108	PVC-Hi	110.45	2.99	27	10.9	113.3

Table 2. The permeation rate and maximum angle of deflection of the different PVC joints.

Kiwa reference #	Type of PVC	Component	Diameter [mm]	Service life [years]	Permeation rate [ml/day]	Maximum angle of deflection [°]	Aged (60 °C, 1000 hrs, hydrogen)
PVC 2011-088	PVC-U	Injection-molded socket fitting	110	unknown	6.5	5	yes
PVC 2016-064	PVC-U	Thermoformed socket fitting	110	56	7.5	5	yes
PVC 2018-022	PVC-Hi	Thermoformed socket fitting	110	42	7.3	>44*	yes
PVC 2019-163	PVC-Hi	Injection-molded socket fitting	110	31	7.4	>30*	yes
PVC 2018-069	PVC-U	Injection-molded socket fitting	160	53	-	12	no
PVC 2012-064	PVC-U	Injection-molded socket fitting	110	44	-	>29*	no
PVC 2017-045	PVC-U	Injection-molded socket fitting	110	46	-	>9*	no
PVC 2011-067	PVC-Hi	Thermoformed socket fitting	110	unknown	-	>29*	no

*The maximum angle of deflection of PVC-Hi joint could not be determined as the test rig reached its maximum capability. This was partly due to pipe deformation.

DISCUSSION

Determining the permeation rate for hypothetical real-life scenarios

The permeation rate of hydrogen of various designs of the PVC system can be calculated using the values in table 1 and table 2 and formulae (2). The highest value for a certain PVC material, as given in the tables, is used for each calculation.

EXAMPLE 1

One pipe segment of 12 meters of unplasticized PVC DN250, SDR 41 pipe (A = 9.19 m^2, e = 6.10 mm) at a pressure of 100 mbar(g) (1.1 bar absolute pressure p). Over a period of one year, 70 liters of hydrogen will permeate over the full length.

$$115.3 \cdot \frac{9.19 \cdot 1.1}{6.10} \cdot \frac{365}{1000} = 70\ liters/year$$

EXAMPLE 2

One kilometer of impact-modified PVC DN110 SDR 41 pipe (A = 320 m^2, corrected for the pipe ends, which were still present inside the joint during testing, e = 2.68 mm) containing a joint every 12 meters at a pressure of 200 mbar(g) (1.2 bar absolute pressure p). Over a period of one year, 9697 liters of hydrogen will permeate over the full length.

$$\left(181.3 \cdot \frac{320 \cdot 1.2}{2.68} + \frac{1000}{12} \cdot 7.4\right) \cdot \frac{365}{1000} = 9697\ liters/year$$

EXAMPLE 3 - reference

One pipe segment of 12 meters of PE100 RC DN250, SDR 17 pipe (A = 8.87 m^2, e = 14.7 mm) at a pressure of 100 mbar(g) (1.1 bar absolute pressure p). Over a period of one year, 31 liters of hydrogen will permeate over the full length.

$$126.8 \cdot \frac{8.87 \cdot 1.1}{14.7} \cdot \frac{365}{1000} = 31\ liters/year$$

Please note that the SDR class for polyethylene pipe differs from the values used for the PVC-U calculation in Example 1. This class was chosen because the application of PVC pipes differs from the application of PE pipes in the Dutch natural gas distribution grid. We selected a common field of application. The permeation coefficient of 126.8 [(ml·mm)/(m^2·day·bar)] as reported by [10] was used for the calculation.

Permeation compared to leakage

The leak tightness for gas distribution is measured in accordance with EN 12327. The maximum allowable leakage rate for impact-modified PVC pipe systems in the Dutch NEN 7244-5 standard is 5 l/h at maximum operating pressure. To put the measured permeation rate into perspective, the permeated hydrogen in l/h can be compared to the limiting values for a distribution leak (based on methane). The exact allowable leakage rates for hydrogen are still unknown. If the maximum allowable leakage rate is presumed to be in

the same order of magnitude, it is safe to employ a maximum leakage rate of 1 l/h for the time being.
The highest permeated volume observed for the PVC pipes was 17.0 ml/(m·day) at 0.2 bar(g), or 0.71 ml/(m·h), which is over 1400 times lower than 1 l/h for every meter of pipe.
Moreover, the permeated hydrogen is not concentrated at a single location but is distributed over the length of the 1 meter of pipe.

Therefore, the permeation of hydrogen though a PVC pipe is much smaller than the presumed acceptable leakage rate.

Hydrogen permeation will lead to the loss of energy. 0.71 ml/(m.h) will result in an energy loss of approximately 0.0025 Wh (9 Joules) per meter of pipe per hour. The value of an allowable leak in a natural gas distribution grid is approximately 49 Wh (176 kJ) per hour. This means that the energy loss due to hydrogen permeation of a kilometer of PVC pipe is approximately 2.5 Wh (9 kJ), 19 times lower than the energy loss due to leakage from a single permissible leak in a natural gas grid.

Maximum angle of deflection

The minimum angle of deflection for new PVC straight joints/sockets specified in [3] is at least 2°. This means that the angle of deflection as measured in this report for new samples should be at least 4°.
The maximum angle of deflection defined in the Dutch standard [4] is 13° at a distance of 10 times the diameter. In our case, the distance between the applied deformation and the joint was very small. This ensured that the angular deflection in our test was much more extreme than that prescribed in the standard. If we adhere to the value in the standard, an angle of 26° applies to new PVC-Hi joints.
The measured values for PVC-U samples before and after ageing for 1000 hours at 60 °C and an internal pressure of 30 mbar(g) of hydrogen both fulfil the criterion of 4°. As ageing is assumed to equate to at least 50 additional years of distributing low-pressure hydrogen in practice, these results are promising.
As relatively large differences in angles of deflection were measured between PVC-U joints, some additional investigations were carried out. It is known that only O-rings are used in rare cases, although a lip ring is normally used. Due to its shape, the lip ring is expected to have a better resistance to angular deflection. Two PVC-U joints aged with hydrogen were cut in the axial direction to see whether a lip ring was used. The result for PVC 2016-064 is shown in figure 4. The indentation caused by the rubber sealant ring is visible (lower part of the photograph) on the pipe, which was originally inserted into the socket. This clearly shows that the sealant ring is of the lip type, but also that the lip is torn off from the body of the ring. It is unclear whether this was caused by the experiment or whether this was already the case before the test was carried out. The second joint investigated was made of PVC 2011-088. This ring was also of the lip type. The lip ring was fully intact. The measured angle of deflection, which was relatively low, is probably not related to the poor quality of the lip ring from the PVC 2016-064 sample.

Figure 4 Disassembled PVC 2016-064 joint after testing

The exact reason for the differences in the results of the angle of deflection measurements is unclear. The differences may be due to the quality of the original installation of the pipes in the socket, the ageing during use, the excavation and transport, the exposure to hydrogen during ageing or the ageing process itself (1000 hours at 60 °C), or even a combination of these factors.

CONCLUSIONS

The permeation rate of six PVC pipes and four PVC joints (both PVC-U and PVC-Hi) was determined. The permeation coefficient was also determined for the PVC pipe materials. These permeation coefficients can be used to calculate the permeation rate of PVC pipes in other dimensions.

The calculated permeation rate was over 1400 times lower than 1 l/h, which is a worst-case scenario for hydrogen based on the maximum allowable leak rates for natural gas in a gas distribution system. This means that the volume of hydrogen permeating through the pipe walls is rather small and will not lead to safety issues. The measured permeation of the joints is comparable to the permeation of less than 1 meter of pipe.

The maximum angle of deflection of eight PVC joints (both PVC-U and PVC-Hi) was determined. These eight samples were divided into two groups of joints. One group was tested as received and one group was tested after an additional ageing period of 1000 hours at 60 °C with an internal pressure of 30 mbar(g) of hydrogen.

All tests showed that the maximum angle of deflection fulfils the requirements of the appropriate EN-ISO 13844 standard, even after ageing.

The overall conclusion is that both unplasticized PVC and impact-resistant PVC systems used in the Netherlands show good angular deflection behavior and a low level of hydrogen permeation through the pipe wall and rubber sealed socket joints. The good angular deflection behavior, even after additional ageing equivalent to more than 50 years of use, meets the requirements mentioned in the relevant standards for new joints. This shows that the joints can handle slight ground movements, even if used to transport hydrogen in the future.

ACKNOWLEDGMENTS

The authors would like to thank PVC4Pipes, Netbeheer Nederland and all those who cooperated with the research. The pipes and joints were supplied by the Dutch Distribution System Operators, whom we wish to thank for their cooperation. We would also like to thank Jolanda Brugman, Paul Stens, René van Blanken and Matthijs Schrijver for carefully carrying out the many experiments.

REFERENCES

[1] R. Hermkens, *Future proof gas distribution,* 2018.

[2] R. Visser, Residual lifetime assessment of uPVC gas pipes, Enschede, 2009.

[3] *EN-ISO 13844 Plastics piping systems - Elastomeric-sealing-ring-type socket joints for use with plastic pressure pipes - Test method for leak-tightness under negative pressure, angular deflection and deformation,* ISO, 2015.

[4] *NEN 7231:2020 Plastic piping systems for gas supply - Fittings made from modified polyvinyl chloride,* 2020.

[5] F. Scholten and M. Wolters, "Methane Permeation through Advanced High-Pressure Plastics and Composite Pipes", *Plastic Pipes XIV,* 2008.

[6] S. Jansma, "Testing spoolable reinforced flexible pipes and liner material for high-pressure hydrogen transport", in *Plastic Pipes Conference XX*, Amsterdam, 2020.

[7] *NEN 7244-5 Gas supply systems – Pipelines for maximum operating pressure up to and including 16 bar – Part 7: Specific functional requirements for strength testing and tightness testing and for commissioning and decommissioning of gas distribution pipelines,* 2014.

[8] W. Moore, Physical chemistry (fifth edition), Prentice Hall, 1972.

[9] E. van der Stok, F. Scholten and L. Dalmolen, "Cover Blow-Off Resistance of Reinforced Thermoplastic Pipes for Gas Service", *Plastic Pipes XV,* 2010.

[10] R. Hermkens, H. Colmer and H. Ophoff, "Modern PE pipe enables the transport of hydrogen", *Plastic Pipes Conference PPXIX,* 2019.

[11] G. Palermo, "Comparison Between PE 4710 (PE 4710 PLUS) and PE 100 (PE 100+, PE 100 RC)", Plastic Pipes Conference Association papers, 2010.

[12] A. Frank, G. Pinter, M. Kapur and E. Nezbedová, "Comparison of accelerated tests for PE grades lifetime assessment", 2012.

[13] R. De Silvaa, T. Hilditchb and N. Byrne, "Assessing the integrity of in service polyethylene pipes", *Polymer Testing,* vol. 67, pp. 228–233, 2018.

[14] N. Byrne, R. De Silva, K. Lenghaus and T. Hilditch, "Assessing the remaining service lifetime of PE pipes: an Australian case study", in *Proceedings of the 19th Plastic Pipes Conference*, Las Vegas, 2018.

[15] Stefan Schütz; Janko König; Josephine Glandien; Werner Weßing; Stefan Gollanek, "Permeationsuntersuchungen an Kunststoffrohren", *Rorhnetz,* pp. 58-65, 2017.

[16] "NEN 8078, Supply for gas with an operating pressure up to and including 500 mbar – Performance requirements – Existing estate", 2018.