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TNO report

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Expected lifetime of existing PVC water distribution systems
Management summary

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Expected lifetime of existing PVC water systems; summary

Issue

PVC water systems of Dyka, Pipelife and Wavin have been applied for several decades for the distribution of tap-water in the Netherlands. A test procedure was developed in the past to guarantee the lifetime of 50 years. Although it is common knowledge that the lifetime of PVC water systems will exceed 50 years under most service conditions, no fundamental evidence is available and procedures to quantify the residual lifetime of existing systems are not available.
The 50 years service period will be reached within some years for the PVC systems installed in the nineteen sixties in the Netherlands. The water companies are thus faced with the dilemma replacement or rehabilitation of PVC water systems in service for more than 50 years.

Description of activities

An investigation was started on the residual lifetime expectance of existing PVC water systems in the Netherlands at TNO Science and Industry in co-operation with the producers of PVC water distribution systems Dyka, Pipelife and Wavin, the PV material manufacturers LVM, Shin-Etsu and Solvin and Kiwa as representative of the water companies.
No procedure was available for the quantification of the residual lifetime of existing PVC water pipes. The existing assessment methods for the 50 years lifetime start with newly produced PVC pipes. On the one hand, initial properties are determined and on the other hand long tem properties. The latter are obtained by performing experiments at elevated temperatures. This procedure is less appropriate for the existing PVC water systems, because exposure to elevated temperatures can counteract degradation processes occurred over the years. Moreover, initial properties, material properties, additives and processing will interfere with the evolution of the degradation processes.
The degradation processes, which influence the lifetime of the existing PVC water systems, have been evaluated and procedures have been developed to accelerated the degradation processes as representative as possible. The relevant degradation processes and the expected degradation after a service period of several decades have been compiled. The critical levels of the functional properties have been defined in combination with the installation, the soil conditions and service conditions. Methods to determine the functional properties have been worked out together with accelerated methods to quantify the evolving degradation processes. A residual lifetime has been determined for the PVC pipes studied from the experimental results obtained and applied extrapolation methods.

Results and conclusions

The lifetime of a plastic product is determined by the intrinsic properties of the polymer applied, the processing of the polymer into a product and the final operation conditions. Although PVC is not very sensitive for chemical degradation, the chemical structure of a PVC polymer can deteriorate. The chemical reactions involved will ultimately result in chain scission and decrease of the functional properties. PVC is most vulnerable for chemical degradation during the processing from powder into a product. Chemical degradation is neutralized by the presence of a stabilization package. The remaining fraction of active stabilizer found the PVC pipes studied was sufficient to protect the corresponding PVC water pipe against chemical degradation for at least 100 years in the given application.
It was well-known that the processing of PVC powder into a PVC product is an essential step to realize optimum properties. However, a reliable method to determine the quality of the processing was developed in the nineteen seventies – nineteen eighties. The knowledge was obtained on the optimum level of gelation for the given application. A gelation level between 60 and 85 % will result in an optimum in properties as fracture toughness, strength, crack resistance and impact strength. Some materials from the nineteen seventies and nineteen eighties studied showed lower levels of gelation and a dramatic decrease in crack resistance after an accelerated physical ageing.
The expected residual lifetime of most of the PVC water pipes studied is at least 100 years, provided that the pipes are properly applied and that damages in the PVC pipe walls are less than 1 mm in depth.
The reliability of the lifetime of PVC water systems is strongly related to the uncertaincy about the future loadings to be experienced by the PVC pipes. External loadings and non-uniform soil settlements can cause enormous local stresses in a PVC pipe and preliminary failure. A lifetime of less than 10 years is possible when a calamity occurs.

Applicability

The results of this investigation are applicable for the long term assessment of the functional properties of PVC water systems, but also for other plastic distribution systems.
The owners and managers of water distribution systems now have methods to determine the crack resistance of parts of the existing PVC water distribution systems.

Contents

1 Introduction

PVC (polyvinyl chloride) tap water pipe systems have been installed since the nineteen fifties in the Netherlands and have shown to be very reliable. The insight in the behaviour of the PVC pipe systems has been increased over the years. The quality checks and procedures from the synthesis until the final installation have been improved and herewith the reliability of PVC pipe systems. However, the long term behaviour and actual operation time of PVC pipes is still not quantified.

An investigation was performed on the residual lifetime of existing PVC pipes within the framework of a co-financed project performed at TNO Industry and Science. The aim of this research was the development of procedures to quantify the current situation and of a model to predict the residual lifetime of existing PVC pipes. The partners in the project were Kiwa, Dyka, Pipelife, Wavin, LVM, Shin-Etsu and Solvin. The investigation consisted of two phases.

A compilation of the external (soil) loads on PVC water pipes was performed in co-operation with TNO Built Environment and Geoscience in the first phase. Moreover the different degradation processes (chemical, physical and mechanical) were evaluated theoretically and experimentally. A procedure was developed for the controlled accelerated ageing of each degradation process and the corresponding lifetime prediction. The first phase resulted in reports on:

1 Degradation mechanisms and other lifetime related factors.
2 Chemical degradation (thermal, HCl splitting, oxidation,..);
3 Physical degradation, especially crack growth;
4 External factors, especially soil loads during installation;
5 Development of methods and experimental results.

Five excavated PVC and two recent produced PVC pipes were studied in detail during the second phase. The diameter of the PVC pipes studied varied from 160 to 400 mm. Physical chemical measurements were performed to quantify the residual effective stabilisor concentration, the distribution of stabilisors, the composition, the molecular weight distribution and the degree of gelation. Furthermore, craze initiation and slow crack growth experiments, fatigue, impact measurements at low temperatures and burst tests were performed on pipe segments as received and aged. Additional validation measurements were performed on excavated PVC pipes, of which only limited lengths were available. The second phase resulted in reports on:

6 Evaluation and recommendation for validation;
7 Modelling of residual lifetime;
8 experimental validation of methods;
9 Expected operation conditions and prediction of residual lifetime.

The different processes considered are explained in the following chapters. The effects of the different phases within the life of a PVC pipe are discussed per process. The applied procedure is explained for one degradation process, namely slow crack growth. Moreover, some recommendations are presented to quantify the expected lifetime of the different batches of PVC pipes in a water distribution system.

2 Chemical degradation


Distribution of additives (white dots) in PVC matrix; surface shown: ca. 0.2x0.2 mm

Chemical degradation in PVC means breakage of covalent bonds caused by temperature, oxygen or other factors. The chemical degradation of a PVC chain is often initiated by dehydrochlorination (HCl splitting). The dehydrochlorination can be followed by oxidation and chain breakage.

A small fraction of irregularities will be built in the PVC chain during polymerisation. These irregularities causes the chain to be more sensible for chemical degradation. The suspension polymerisation results in PVC powder. A range of averaged molecular weight (K value) is prescribed for the material applied in PVC pipes.

Critical parameters for chemical degradation are the high temperatures and high shear forces experienced during extrusion of the PVC powder into a viscous melt, which is transformed into a pipe.
Part of the stabilisers is consumed during this processing. Lead stabilizers can be found in the PVC pipes of existing pipe systems. The lead stabiliser was replaced by one based on calcium zinc in 2006.

After cooling to ambient temperature, the PVC pipe will not show a significant chemical degradation rate provided that the pipe is excluded from solar UV radiation. The rate of chemical degradation is very low in a PVC pipe wall of buried pipes.

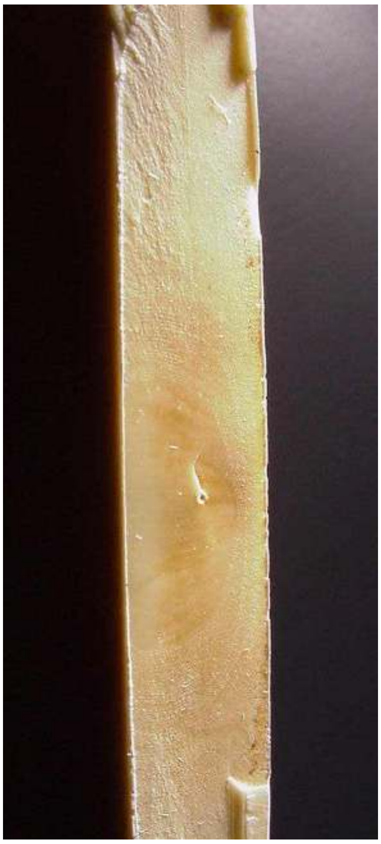
The chemical degradation due to the processing and the operation for many years was quantified for 5 PVC pipe systems produced between 1959 and 1997. The operation period of those tap water pipes ranges from 6 to 42 years. The molecular weight was quantified by the K-value.
Besides the excavated pipes, some recently produced pipes were studied.

The K-values found do not indicate that chain scissions have occurred during the history of these PVC pipes. Moreover the content of chlorine was determined. Excluding one of the excavated pipes examined, it was concluded that no significant HCl splitting had occurred.

The PVC chain scission rate will increase significant when the effective concentration of stabilisers becomes low. Therefore the consumed and remaining stabiliser was quantified in the PVC pipes under study. Moreover, the induction period for the dehydrochlorination process was determined.
The extrapolated induction time was calculated to be thousands of years for the excavated pipes at 15 °C.

In summary, the chemical degradation is not limiting the lifetime of buried PVC pipes for the next 100 years.

3 Physical ageing



Crack growth starting from inhomogeniety in pipe wall

Physical interactions, for example Vanderwaals interactions among PVC chains, determine largely the mechanical properties. The change as a function of the history of the product is called physical ageing. The PVC chains show motions during the processing at high temperatures, which can be compared with spaghetti. Besides PVC chains, additives among which stabilisers are mixed during processing. The high temperature configuration is frozen in when the PVC product is cooled below its glass transition temperature. During the cooling from the glass transition temperature down to the storage and the operation temperature, a slow process occurs, in which the PVC chains reorientate to reach a more dense state with a higher.

The processing of PVC powder changed over the years. PVC granules were first obtained until the beginning of the nineteen seventies. The PVC pipes were then produced from these granules in a second extrusion step. The additional processing, in which granules were produced, was left in the nineteen seventies as a result of improved extruders and knowledge about processing of PVC powder.

The processing is a critical step in obtaining optimal long term mechanical properties. The fusion of the individual PVC chains is a complex process due to the structure of the PVC powder. The level of fusion is characterized by the degree of gelation. When the degree of gelation is low, the PVC powder structure can still be found and the toughness is very low. It is also known that a high degree of gelation results in a reduction of the toughness. The optimum properties for PVC pipes are realised with a degree of gelation in the PVC wall in the range of 60-85 %.

Low degrees of gelation, less than 40 %, were found in some of the excavated PVC pipes produced in the nineteen seventies. Moreover, the degree of gelation was relative low, 50-60 % for some of the excavated PVC pipes produced in the eighties. When a relative low level of gelation is found, it is too premature to draw the conclusion that the residual lifetime of this PVC pipe is low, but some caution is needed and an additional residual lifetime investigation is recommended.

Synthesised PVC powder can obtain a small fraction of particles, which will not fuse well with PVC matrix and cause weak spots in the PVC matrix during extrusion. Furthermore, additives and other particles, which mix with the PVC powder during the transfer into and through the extruder, will often show a lower anchoring in the PVC matrix. An evolving decrease in interaction among additives and the PVC matrix leads in weaker areas and an increased probability for crazing and cracking. (see Mechanical degradation).

The degree of physical ageing depends among others on the rate at which the PVC pipe is cooled directly after production. The physical ageing is a slowly evolving process, which can be accelerated by exposure at elevated temperature. The influence of physical ageing was studied by the quantification of the resistance to craze initiation, slow crack initiation and growth. The PVC pipe systems produced in the nineteen seventies showed the larger decrease in resistance to slow crack growth after the accelerated ageing...

4 Mechanical degradation

Crack initiation and crack growth is representative for mechanical degradation and occurs as a result of mechanical loads.

Fractured surface after impact (4x6 mm)

High shear stresses, which can result in chain scission, occur during the processing of the PVC powder and the melting in the extruder under non-optimum processing. This degradation phenomenon was not found in the PVC pipes studied.
The mechanical loads experienced by the PVC pipe are expected to be low between the production and the installation.
The installation is a critical phase, in which mechanical damages can be initiated in the PVC pipe. A poor compacting of the soil in the pipe trench will result in an oval shaped pipe with large tensile stresses in the inner diameter at the poles. Crazes and cracks will initiate as soon as the critical stress for crazing is exceeded.
A hoop stress will be present in the pipe during operation as a result of the water pressure. The current design prescribes that the hoop stress is not allowed to exceed 12.5 MPa under the applied water pressure. A higher allowable stress level seems possible under strict conditions, namely no fluctuations in the water pressure and exclusion of other internal or external stresses on the PVC pipe.
An internal stress gradient over the PVC pipe wall exists as a result of the cooling from the outer diameter of the PVC pipe after extrusion. The higher tensile stresses act on the inner diameter. Tensile stresses in the range 1.5 and 4.8 MPa were found in the excavated pipes studied. Water pressure variation can not be excluded during the operation of a tap water distribution system.

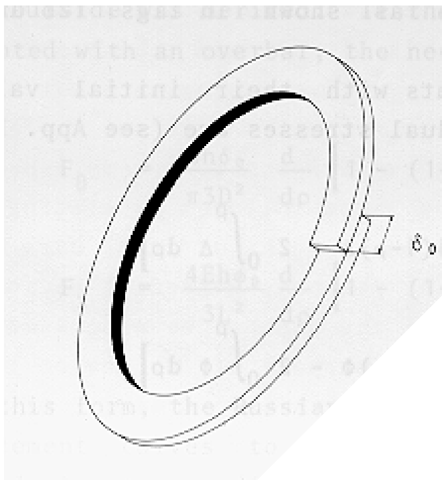


Fig. 4.1 Size of overlap of a cut PVC pipe segment is related to internal stress gradient.

Moreover, unforeseen mechanical stresses in the PVC pipe can occur as a result of non-uniform soil settlement and traffic loads.
Digging activities in the vicinity of the pipe system and the installation of new connections followed by dumping and compacting of soil may lead to additional mechanical loads on the PVC pipe system as well (see TEPPFA research).

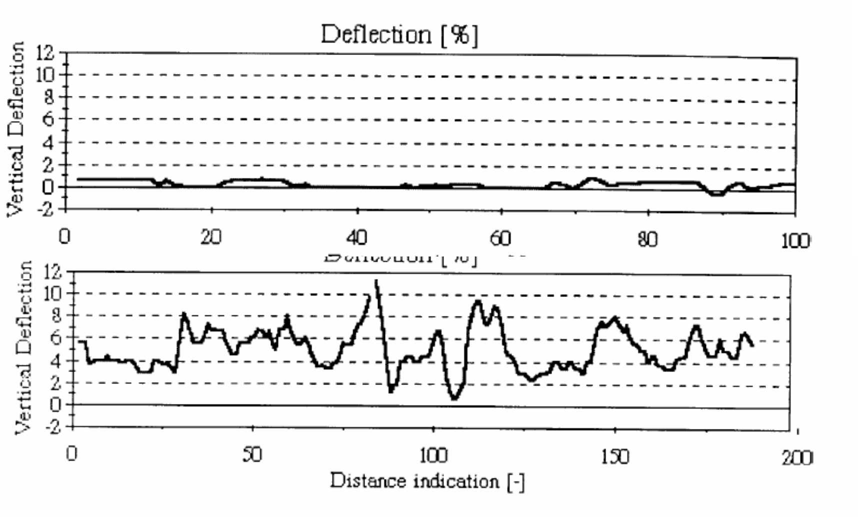


Fig. 4.2 Measured vertical deflections after well (top) and poor (bottom) compaction.

The mechanical degradation was investigated within this project on specimens cut from excavated and recently produced PVC pipes as received and after accelerated ageing by tensile, craze initiation, burst test, slow crack growth, impact test and fatigue measurements. These measurements resulted in critical stress levels for damage initiation and growth. A reliable prediction on the (residual) lifetime is then possible provided that the operation conditions, external loads and internal stresses are estimated correctly and included in the prediction model.
The expected lifetime exceeds 100 years under the conditions that the stress in the PVC pipe wall will never exceed 12.5 MPa and no crack initiation or other mechanical damages have occurred in the PVC pipe yet.
All PVC systems studied will operate for at least 100 years under normal conditions with exception of some of the excavated PVC pipes studied from the nineteen seventies and nineteen eighties. Those exceptions can still have a lifetime of more than 100 years provided that they are operated under mild conditions, i.e. low water pressure, insignificant water pressure fluctuations, no digging activities, no installation of new connections or other stress raising phenomena.

5 Procedure and prediction

The procedure and the long term prediction of the residual lifetime are explained in this chapter using the slow crack growth as dominant degradation process.

Specimens were cut and notched from arches of the PVC pipe under study. Parts of these specimens were subjected to an accelerated ageing at 60 ºC in water for a period of 500 to 2000 hours. The failure curves for slow crack growth were determined using single edge notched specimens under three point bending before and after accelerated ageing at 60 ºC. The results are schematically shown in the figures 5.1 and 5.2. Figure 5.1 represents a poor quality PVC pipe. Such a PVC pipe will show failure under slightly unfavourable external load variations within the forthcoming period of 50 years.

The slow crack growth rate is determined as a function of the applied stress at the notch tip using PVC pipe as received/excavated and after accelerated physical ageing. These accelerated ageing periods are representative for a forthcoming operation period of about 50 to 200 years.
Interpolation and extrapolation resulted in curves which correspond to a constant crack growth rate. The fast crack growth rate is defined here as a growth rate which results in a through the wall crack after about 1 day. For fast growth to occur, a hoop stress is required which exceeds the hoop stress due to the water pressure and the internal stress by almost a factor of two.
The slow crack growth rate is defined as the crack growth rate which results in a through the wall crack after about 50 years.

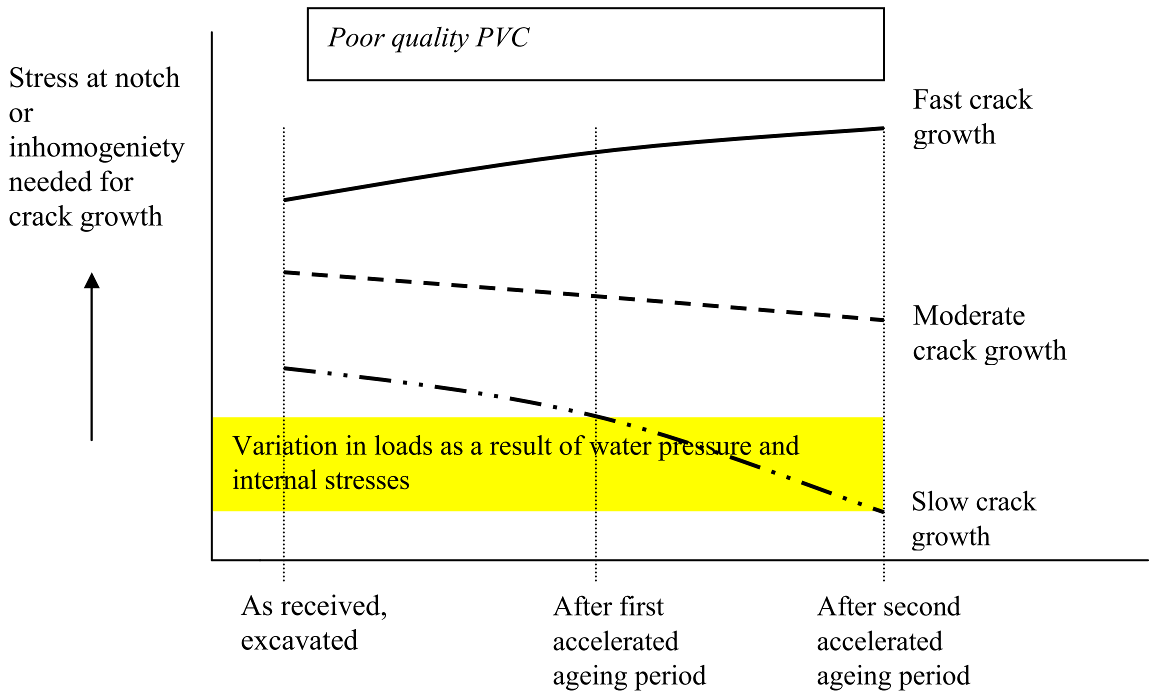


Fig. 5.1 Schematic illustration of results of slow crack growth measurements for poor quality PVC pipes; leakage is expected when the dashed line representing the slow crack growth intersects the coloured zone.

As soon as the calculated curve representing the slow crack growth intersects the range of stresses as a result of operation conditions (e.g. water pressure), leakage of the PVC pipe system is predicted as a result of through the wall crack growth.

Figure 5.1 is representative for some of the PVC water pipes studied from the nineteen seventies and nineteen eighties.

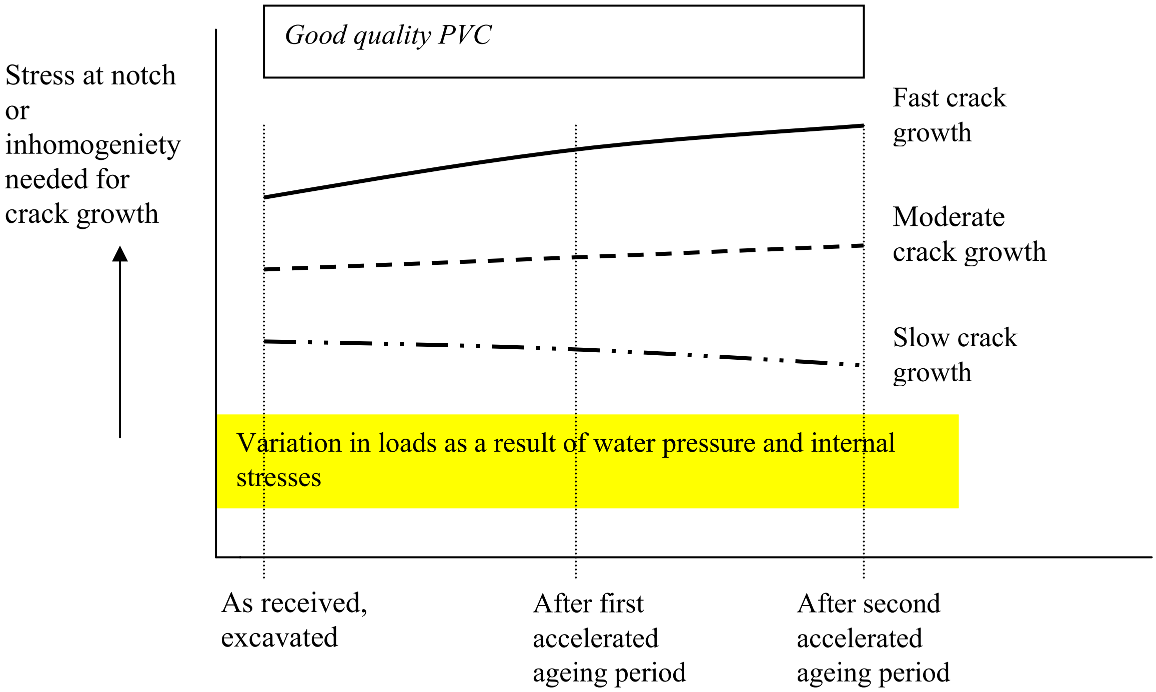


Fig. 5.2 Schematic illustration of results of slow crack growth measurements for good quality PVC pipes.

Figure 5.2 represents a PVC pipe of good quality and is representative for most of the PVC water pipes excavated and studied. Here a certain gap remains between critical stress level for crack initiation and crack growth and the stresses due to external and internal loads. No failure is expected within a forthcoming period of 100 years, provided that calamities can be excluded.

6 Summary and conclusions

The TNO project “Long term performance prediction of existing PVC water distribution systems” was co financed by the partners Kiwa, Dyka, Pipelife, Wavin, LVM, Shin-Etsu and Solvin. Procedures to quantify the current situation and a model to predict the residual lifetime of existing PVC pipes were developed after some fundamental studies.

The ageing processes in the PVC pipe wall are of a chemical or physical nature. Although its nature is physical, the mechanical ageing process is considered independently. The mechanical degradation process is dominated by the initiation and the growth of crazes and cracks.

The chemical degradation rate in buried PVC pipes can be neglected provided that the existing PVC pipe systems all contain a considerable amount of non-consumed stabilizers. Therefore, it is concluded that the residual lifetime of PVC water distribution pipes is not limited by chemical degradation.

The physical ageing rate in the PVC pipe wall is a self retarding process, which will slowly evolved at soil temperatures in the range of 5-15 °C.
The influence of physical ageing is moderate for well-gelled PVC pipes. The resistance for slow crack growth will decrease very slowly in time.
The influence of physical ageing can become significant for poorly-gelled PVC pipes. The resistance to slow crack growth, which is already low for poorly-gelled PVC pipes, was shown to decrease significantly upon physical ageing.

The loading history can have resulted in some micro-cracks in the PVC pipe wall. The presence of micro-cracks in some of the excavated PVC pipes studied resulted in a reduction of the resistance to impact and fatigue loads.

In summary, it is concluded that the existing PVC tap water pipe systems in the Netherlands will operate for at least 100 years provided that the internal and external loads do not result in hoop stresses which will exceed 12.5 MPa and that no micro-cracks and mechanical damages are present in the PVC pipes.
The residual lifetime of existing PVC water pipe systems in particular when the PVC pipe is of marginal quality can be reduced by among others fatigue loads, the presence of micro-cracks and non-uniform ground settlements. Some of the excavated PVC water pipes from the nineteen seventies and nineteen eighties showed some marginal quality.

7 Recommendations

Different aspects need to be considered for a prediction of the residual lifetime of existing PVC water pipe systems.
Methods were developed to quantify the degradation rates for the degradation processes active in the PVC pipe wall within the project “Long term performance prediction of existing PVC water distribution systems”. Moreover, the degrees of ageing of the PVC material were quantified. However, it was concluded that the evolving mechanical degradation as a result of internal and external loads dominate the time to failure. The current state of the PVC material determined by a chemical, physical and mechanical degree of degradation and the evolving physical and chemical ageing processes are less important parameters for well-gelled PVC pipes.
The uncertainty about the internal and external loads and existing mechanical damages complicates a simply approach to predict the residual lifetime of existing PVC water pipe systems. An active approach, in which premature failure is avoided, is recommended. The alternative passive approach will lead to some additional damage and more inconveniences.

Active approach
An active approach means that the whole PVC tap water system is assessed. The state of the PVC pipe systems and the expected residual lifetime under the corresponding conditions, among which the non-uniform soil settlements have to be mapped and quantified per installation period and per PVC pipe delivery. This approach is rather laborious and time consuming. Therefore, it is recommended to start with the part of the water distribution system which contains PVC pipes produced in the nineteen seventies and nineteen eighties.

Passive approach
The residual lifetime of the PVC water pipe systems is investigated after this system experienced a major leakage using a passive approach. The investigation is then performed to reveal whether the leakage was due to an incident or due to the fact that the lifetime of the corresponding pipe has been consumed under the conditions experienced and that the probability for failure in neighbour pipes of the same production in the near future is considerable high.

The active and passive approach is shown schematically in the figures 7.1 and 7.2.

Active approach

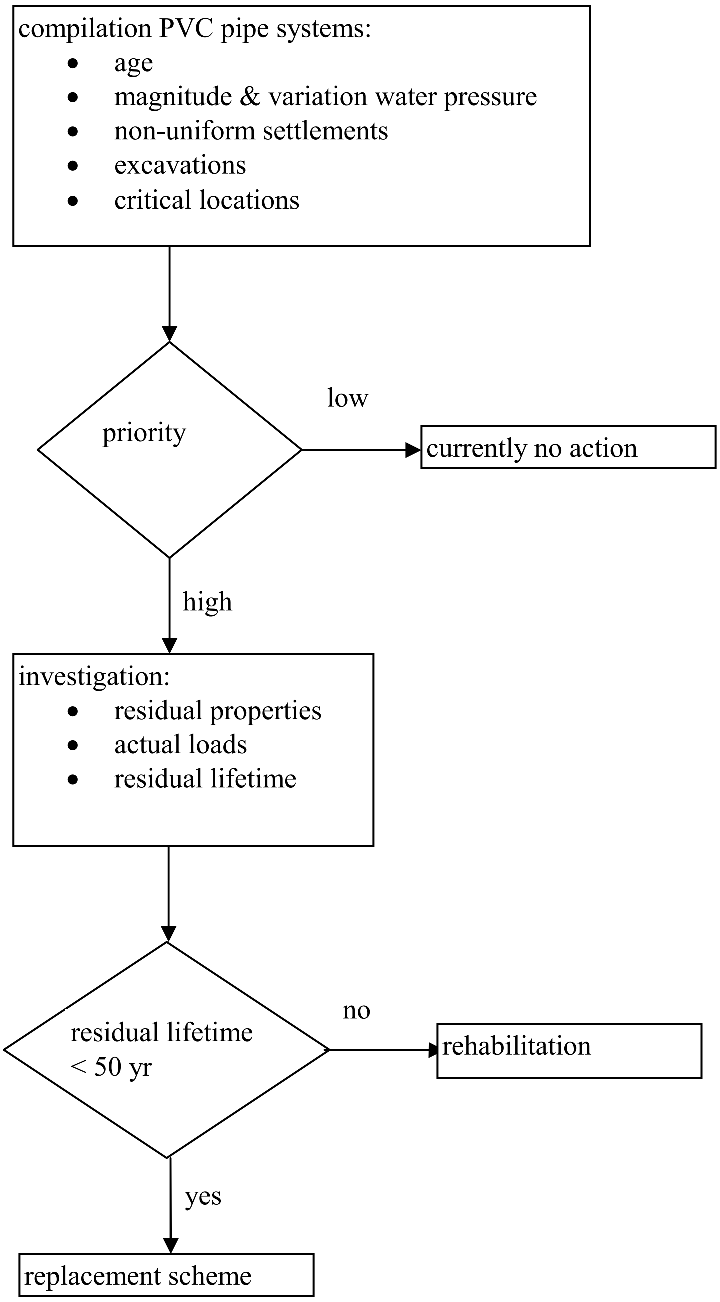


Fig. 7.1 Flowchart for active approach.

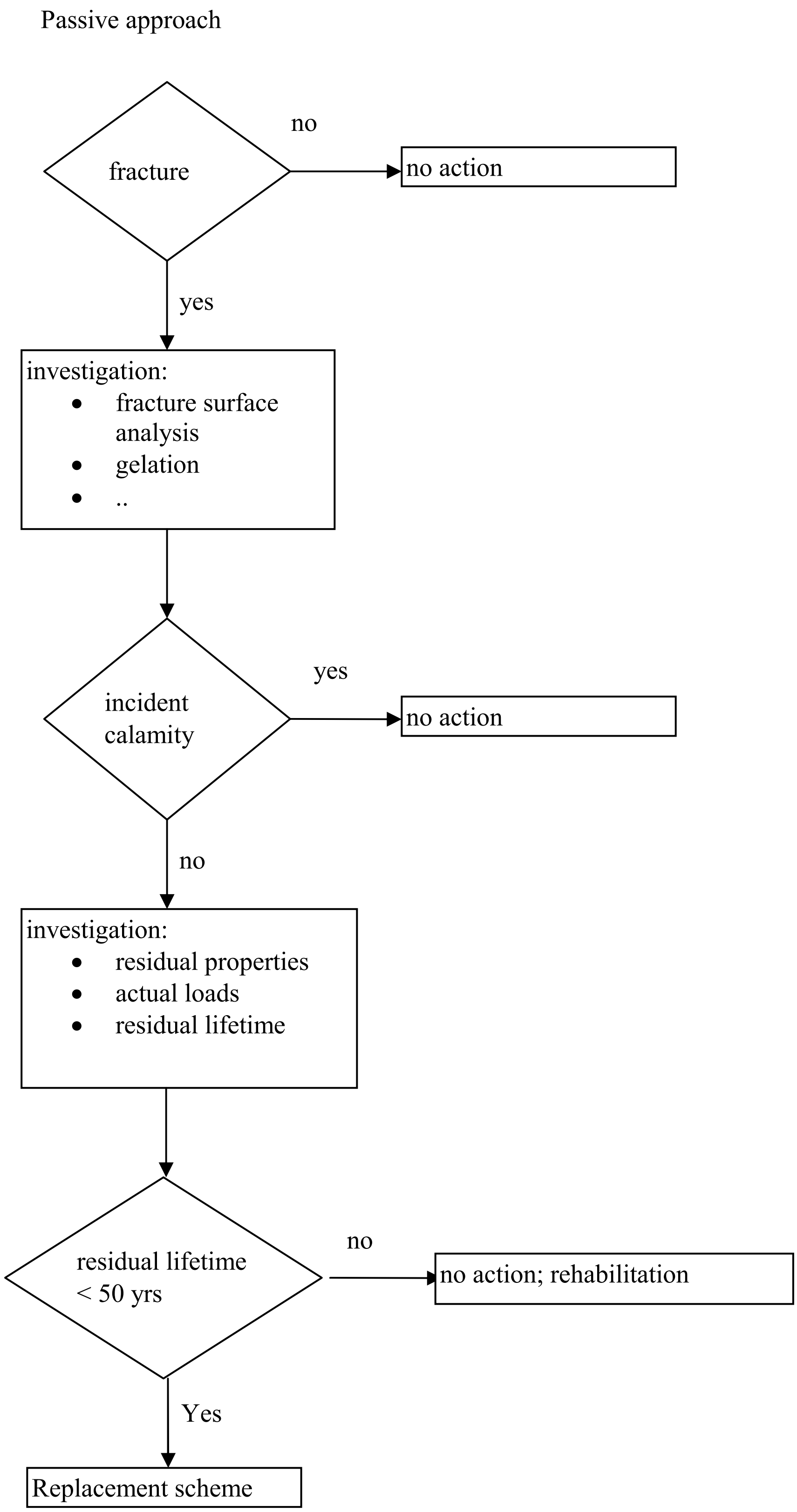


Fig. 7.2 Flowchart for active approach.

8 Publications

Lecture & paper: A.Boersma, J. Breen, “Long term performance of existing PVC water distribution systems”, 9th Int. Conf. PVC, Brighton, April 2005

Lecture: J. Breen, “Restlevensduur PVC leidingen”, meeting FKS, 24-1-05

Lecture & paper: J. Breen, A.Boersma, “Long term performance of existing PVC water distribution systems”, Plastics Pipes XII, Milano, April 2004

Lectures: A. Boersma, J. Breen, “Restlevensduur PVC leidingen”, meeting water companies at KIWA, 23-11-05

Lectures: J. Breen, “Levensduurverwachting PVC waterleidingsystemen”, Waterforum, 4-11-2003

9 Signature

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