LONG TERM PERFORMANCE OF EXISTING PVC WATER DISTRIBUTION SYSTEMS

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ABSTRACT

In co-operation with the PVC producers, pipe manufacturers and waterworks companies in the Netherlands, a study is carried out by the research institute TNO Industrial Technology on the current status of the existing PVC water distribution system and on the prediction of its residual lifetime. The prediction of the residual lifetime of PVC water distribution systems is complicated as a result of the variations in production quality, of the installation process, of the service conditions, of the traffic load, etc. Moreover, material degradation processes occur during the whole history of the PVC systems. The consequences for the long-term behaviour were studied starting from the degradation processes in the PVC products in combination with the processing, installation and service conditions. Procedures to accelerate the relevant degradation processes in PVC materials with a service life of several decades are proposed.

INTRODUCTION

The total length of PVC drinking water pipes in the Netherlands was about 55000 km in 2000 and is still increasing (1). The first PVC pipes were installed in the nineteen-fifties. About 2000 km of PVC water pipes were installed in 1960. Experimental and extrapolation procedures have been developed to guarantee the lifetime of PVC pipes since the first installation. The guideline, BRL K502, is applied in the Netherlands for newly produced PVC pipes (2). The guideline is based on European standards and guarantees a lifetime of approximate 50 years when the PVC pipes are installed and used properly. The 50 years period will be reached within some years for the PVC pipes installed in the nineteen-fifties. Currently, the discussion started on procedures to quantify the residual lifetime of existing PVC water distribution systems.

The objective of this study is to develop reliable methods for the prediction of the residual lifetime of PVC water distribution systems based on a thorough understanding of the underlying degradation processes which is accepted within the PVC pipe industry and PVC water pipe users. The prediction of the lifetime of newly produced PVC systems using those methods will be included. Moreover, the design hoop stress of PVC water pipes will be reviewed based on the results obtained in this study.

The activities started with the compilation and evaluation of the possible degradation processes in PVC. Field failures together with information of the sponsors (Kiwa, Dyka, LVM, Pipelife, Shin-Etsu, Solvin and Wavin) were discussed to elucidate the most probable causes and mode of failure. A model was developed to deal with the different degradation processes. Some introductory experiments were performed on small pieces of excavated PVC water pipes. Methods were developed for the acceleration of the different degradation processes to obtain a reliable prediction of the residual lifetime of existing PVC water systems. Some of the results obtained so far are presented in this paper.

DEGRADATION PROCESSES AND CONSEQUENCES

Three degrees of degradation are considered in the PVC material, namely chemical degradation, physical degradation and mechanical degradation. The more dominant chemical degradation processes in PVC are dehydrochlorination, oxidation and photo-oxidation (3). Physical ageing is an important physical degradation process (4). Mechanical degradation stands for the distribution of crazes, cracks, flaws and other microscopic damages.
The degrees of chemical, physical and mechanical degradation together with the molecular weight distribution, the morphology of the PVC matrix and the internal stresses determine the functional properties that are related to the critical strain or stress for further craze, crack initiation and growth under the service conditions met by the PVC distribution system. The critical strain or stress is defined here as the strain at which failure occurs. This strain or stress level depends on the strain rate experienced, for example during drilling or under constant hoop stress, the temperature and the interaction with chemicals.

An illustration of the failure by craze initiation, craze growth, crack initiation and crack growth under a constant stress is shown in figure 1. The time dependence of the yield stress, the craze initiation curve and the brittle failure curve are shown schematically on a logarithmic time scale. The arrows represent the change between a newly produced and an old PVC material. The yield stress will increase with the ageing time due to physical ageing. The stress for craze initiation can increase with the yield stress or decrease when mechanical damage occurred during the ageing. The craze growth, the transition into a crack and the crack growth till failure will occur faster in aged PVC pipes.

The craze initiation curve is a material property which is affected by physical ageing. The craze growth and crack growth are determined by the level of gelation and less by the molecular weight, provided that the molecular weight exceeds a critical minimum value.

The degree of mechanical degradation can be quantified in first approximation by the brittle-ductile transition temperature. The chemical degradation is characterised by a change in infrared spectrum and a change in molecular weight distribution.

The external factors related to stresses and strains are summarised in table 1. Unfortunately, the internal and external factor can vary significantly among different PVC pipes, depending on wall thickness, extrusion rate, installation, etc. It is therefore needed to study the variations in ultimate strength of PVC pipes as a function of these parameters.

The variation in chemical degradation, physical ageing and external and internal conditions can be dealt with using a probabilistic approach. A simple situation is shown in figure 2 for a product of which the lifetime is determined by mechanical strength. The product has to withstand a load S, which is subject to some variations for example due to water pressure variation and traffic load. The strength, R, of the product is supposed to decrease due to the degradation processes active in the product material. The distribution of the load S is related to the service conditions. The distribution of the strength R is related to the variation in the PVC materials used.

EXPERIMENTAL PART

Pipe materials

The introductory study was performed using small parts of excavated PVC pipes and some recently produced pipes from 2002. The pipes studied are presented in table 2. The variation in wall thickness is rather high for the older pipes.

Lead stabiliser

The lead stabiliser reacts with the hydrochloric acid, which is released as a result of the chemical degradation of PVC at higher temperatures, especially during the residence in the extruder. The total lead content was measured by atomic absorption spectroscopy. The chloride ion bonded to the lead ions was first released from the PVC matrix using solution and extraction methods and finally quantified by high pressure liquid chromatography.

Gelation

The degree of gelation was determined using DSC (differential scanning calorimetry). A small piece of the inside of a PVC pipe was used. The inside wall was chosen because the craze initiation and environmental stress cracking experiments were conducted on the inside of the pipe. The degree of gelation can be obtained by the ratio of two areas in the DSC thermogram separated by the processing temperature (5).

Craze initiation

Tapered specimens were applied to follow the craze initiation front as a function of the loading time (6).When a constant tensile force is applied on the sample, the stress in the smallest part of the sample is a factor of two larger than the stress in the widest part. Surface crazes were observed with a light microscope (magnification × 50-100) in oblique light. The craze initiation experiments were conducted in a conditioned room at 23 °C and 40 % RH.

Fatigue

Fatigue measurements were performed using ring compression load combined with a rotation of the ring at 1 Hz (see figure 3). The rings were cut from the pipe. The width of those rings was 30 mm. The maximum tensile stress in the inner layer was calculated from the compression load applied.

RESULTS

The results of a limited number of experiments are presented in this chapter.

Stabiliser content

The results for the consumption of the lead stabiliser is included in table 3 for two 110 mm diameter PVC pipes studied. A lead stabiliser consumption up to about 15 % was found for the 315 mm diameter pipes studied. The higher lead stabiliser consumption of about 23 % was found for the 500 mm PVC pipe produced in 1973.

The larger amount of lead stabiliser consumption occurs during the extrusion process. As a consequence of the longer residence time in the extruder, more lead stabiliser is consumed for the larger diameter pipes.

Gelation

The degrees of gelation obtained by DSC and the processing temperatures are presented in table 3. The degree of gelation is the highest for the newest pipe (Pipelife) produced. The pipes from the nineteen sixties (1964/1965) show a similar degree of gelation and a comparable processing temperature. The oldest pipe (Tilburg) from 1950 has a processing temperature comparable to that of the new pipe and has a slightly lower degree of gelation. The pipe (Gouda) of unknown age is processed at the lowest temperature and has a very low degree of gelation. This pipe is probably produced in the early 1970's.

Craze initiation

The craze initiation experiment was performed loading the specimens in length direction of the pipe. Craze initiated during installation, which will be parallel to the length direction will therefore not interfere with this measurement. Figure 4 shows that the craze initiation time versus the loading leads to the same craze initiation curve for the three samples investigated.

Fatigue

Some preliminary measurements were performed on the pipe rings failed in the fatigue test. Results obtained on 110 mm diameter PVC pipes are shown in figure 5. Again all PVC pipes studied showed within the scatter a similar curve. The PVC pipe excavated in Haarle showed some crazes in the surface, which resulted in an acceleration of the failure. The failure found in the fatigue tests is brittle. A craze-crack growth mechanism is observed in the facture surface.

DISCUSSION AND CONCLUSIONS

Stabiliser consumption

From the data presented, it is concluded that no clear dependence of the consumed lead stabiliser and the age of the PVC pipes exists. Modelling based on thermal activated processes shows that most of the degradation of PVC takes place during processing and not during its service life in the soil at 5-20 °C. Variations in stabiliser consumption are associated with variation in the production process and or longer residence times in the extruder.

There is a high amount of effective stabiliser left (~70%) in all PVC pipes studied, which seems sufficient to protect those PVC pipes at least for another 50 years. Currently, the rate of consumption of the lead stabiliser is quantified under service conditions.

Gelation

The degree of gelation is an important parameter where it concerns the craze stability, craze and crack growth and the impact resistance. A lower degree of gelation results in a smaller time to failure at stress levels exceeding the critical stress level for craze initiation. PVC pipes with a lower level of gelation are prone to failure under dynamic situations caused by e.g. drilling new connections, water hammer and traffic loads.

Craze initiation

It was found that the craze initiation curve (stress versus time to craze initiation) is the almost the same for all pipes investigated. The craze initiation stress in the PVC pipes is thus affected to a small amount by the evolution of the degradation and ageing processes. As a result of the small increase in stiffness of PVC with increasing degree of physical ageing, the critical strain level for crazing will decrease to some extent.

Fatigue

The maximum stress versus cycles to failure curves found for the PVC pipes studied is similar to the constant stress versus the time to craze initiation. However the stress level is lower for the fatigue tests compared to the craze initiation tests by about 5 MPa. This stress difference is thought to be caused partly by the internal tensile stress in the inner wall of the PVC pipe due to the cooling from the outside of the pipe in the extrusion line and partly by a stimulation of the craze initiation process due to the fatigue loading. The failure curve obtained under fatigue loading is applied to quantify the number of water hammer acceptable for the PVC pipe under study.

The compilation, the experiments and the modelling performed up till now lead to the following preliminary conclusion that the lifetime of existing PVC drinkwater systems in The Netherlands will be exceeding 50 years and possible 100 years provided that the material is well processed, well installed and applied under relative mild service conditions. A founded prediction of the behaviour of an existing PVC system within the coming years requires some experiments focussed on the more dominant degradation processes.

ACKNOWLEDGEMENT

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REFERENCES

1. P.G.G. Slaats, J.H.G. Vreeburg, A. Boersma, J. Breen, *H_2O*, 2003, **36** (16), 25.
2. BRL K502, *“Water systems of PVC-U”*, Kiwa, 1998.
3 B. Dolezel, *“Die Beständigkeit von Kunststoffen und Gummi“*, Hanser Verlag, München, 1978.
4 L.C.E. Struik, *“Physical aging in amorphous polymers and other materials”*, Elsevier, Amsterdam, 1978.
5 M. Gilbert, J.C. Vyoda, *Polymer*, 1981, **22**, 1134.
6 J. Breen, *J. Mater. Sci.*, 1993, **28**, 3769.

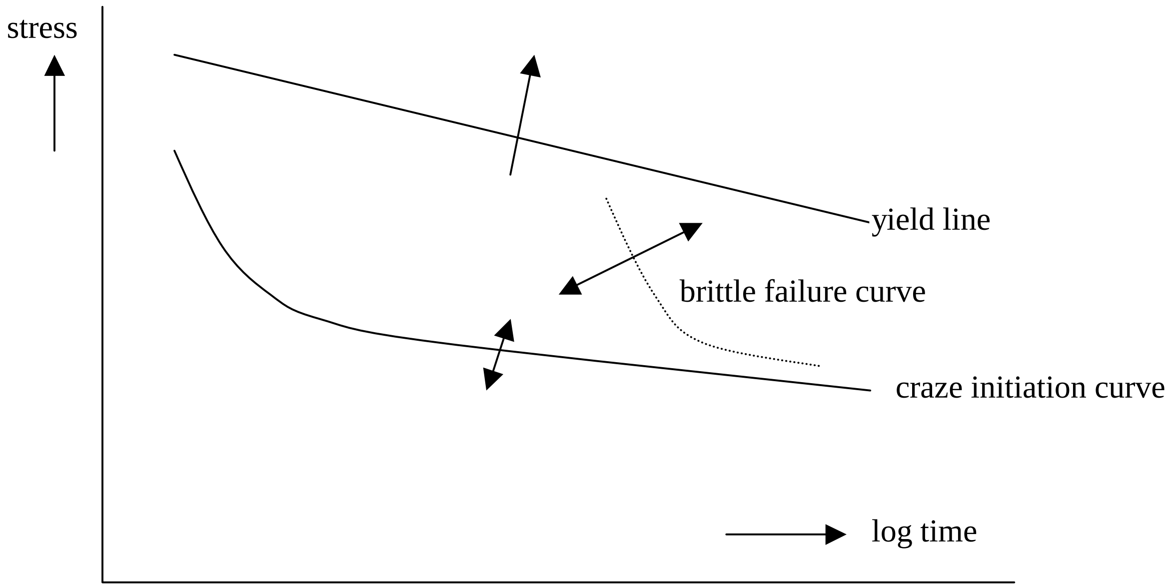

Figure 1 The time dependence of the yield line, the craze initiation curve and the brittle failure curve are shown schematically on a logarithmic time scale. The arrows in the yield line, the craze initiation curve and the brittle failure curve represent the change with the ageing. Notice that the change can be towards longer or shorter times given a certain stress.

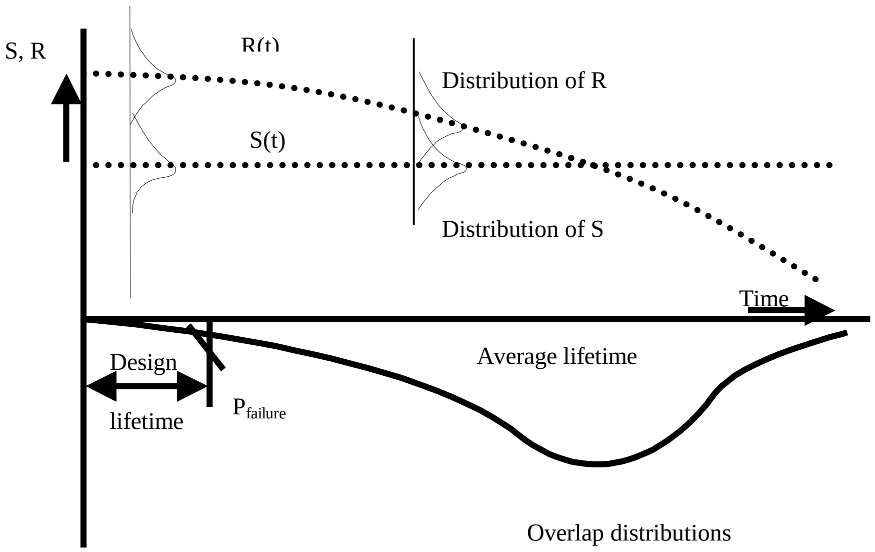

Figure 2 Schematic illustration in which the lifetime of a product is defined as the moment when a certain probability for failure is exceeded.

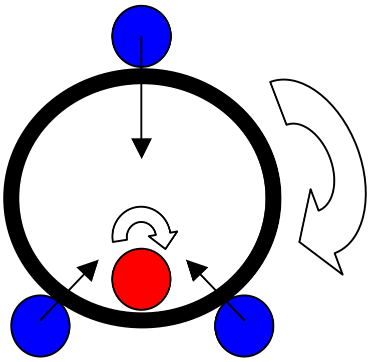

Figure 3 Schematic illustration of the fatigue by rotating a ring from the PVC pipe under compression loading.

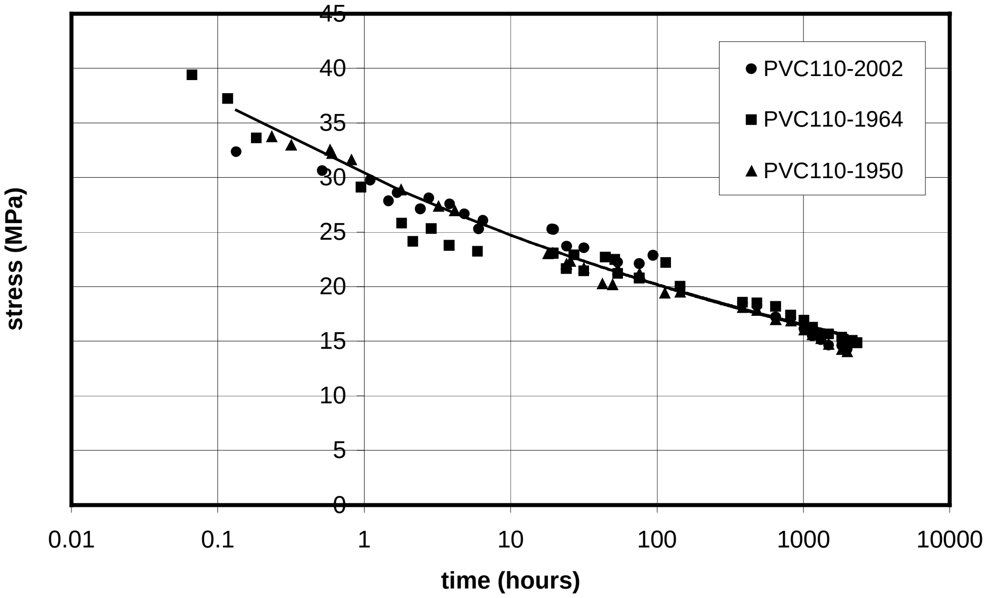

Figure 4 Craze initiation curves for specimens taken from PVC 110 mm pipes (Tilburg 1950; Haarle 1964; Pipelife 2002).

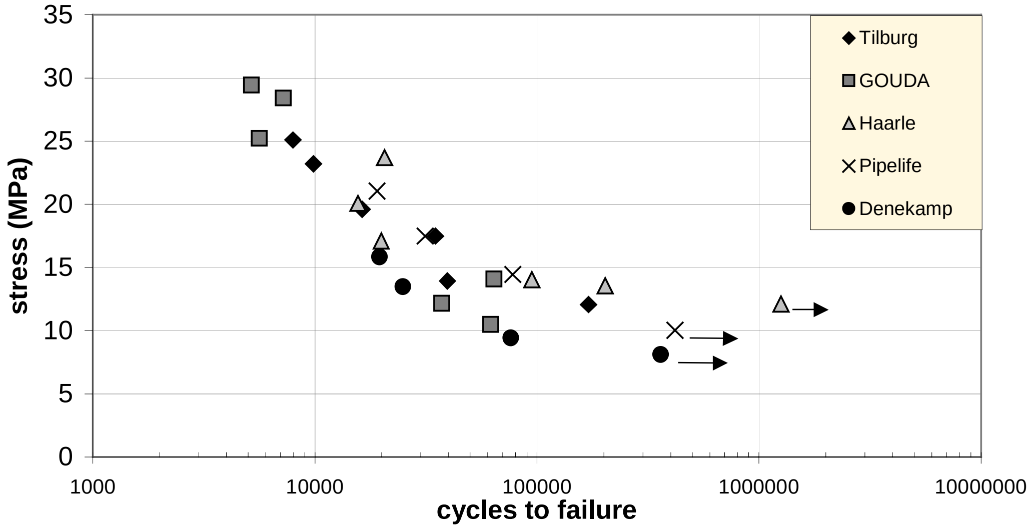

Figure 5 Fatigue curves (maximum stress versus cycles to failure) for specimens taken from PVC 110 mm pipes (Tilburg 1950; Haarle 1964; Denekamp 1965, Pipelife 2002). An arrow is added when the specimen did not fail.

Table 1 External stress or strain related factors in the different stages in the life of a PVC pipe.

Stage	**Process**	**External factors**
Cooling	Internal stress	Cooling rate
Installation	Pipe deformation	Soil load; up to 0,7 % local strain
Service period	Water pressure	Water pressure (about 5 bar)
Service period	Water hammer	Water pressure variations (0 – 7 bar)
Service period	Drilling new connections	Local stress peaks

Table 2 Summary of excavated and new PVC pipes studied.

Pipe code	Year of production or installation	Diameter (mm)	Wall thickness (mm)
Tilburg	1950	108	3.3-3.6
Haarle	1964	108	2.9-3.4
Denekamp	1965	108	3.6-4.0
Gouda	Unknown	108	3.2-3.5
Pipelife	2002	110	4.4-4.5
Tilburg-315	1975	315	9.0-11.1

Table 3 Consumed lead stabilised, degree of gelation and processing temperatures of five PVC pipe samples.

Pipe code	Consumed lead stabiliser (%)	Degree of gelation (%)	Processing temperature (°C)
Tilburg		75	196
Haarle		64	186
Denekamp	10	62	185
Gouda		51	182
Pipelife	13	81	195