The influence of physical ageing on yielding and failure of unplasticised poly(vinyl chloride) pipes

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Physical ageing can cause significant changes of the mechanical properties of unplasticised poly(vinyl chloride) pipes during service life. A model is presented which incorporates these changes and can predict long-term failure times quantitatively, based on short term tests.

Introduction

From the 1960's onwards polymer pipes have been installed in the Dutch gas distribution network. Unplasticised poly(vinyl chloride) (uPVC) was the first polymer used for this application. The pipes were initially installed with an estimated service life of 20 years, which was extended to 50 years after inspection of the residual quality. Currently, still about 22,500 km of uPVC pipes distribute natural gas to Dutch households at a pressure of 100 mbar. The amount of "spontaneous" failures is negligible even after nearly fifty years of service. Third party damage is still the most common cause of failure.
However, it is know that the mechanical properties of the pipes change during their service life as a result of physical ageing [1]. Physical ageing is a process during which the polymer chains in glassy polymers settle towards their thermodynamically favourable positions. The secondary bonds increase in strength as the chains reposition themselves, resulting in a higher resistance against deformation, thus increasing the yield stress. The kinetics and the quantitative relation between physical ageing, yield and deformation kinetics are studied here. A model is presented which includes the effects of ageing and enables long-term failure predictions based on only short term tensile tests.

Theory

The deformation kinetics of glassy polymers can be described with an Eyring type relation. Here, a pressure modified Eyring relation [2] is employed, which enables description of various loading cases with one set of parameters.

$$\dot{\bar{\gamma}}(T,\bar{\tau},p) = \dot{\gamma}_0 \exp\left(\frac{-\Delta U}{RT}\right)\exp\left(\frac{-\mu p V^*}{kT}\right)\sinh\left(\frac{\bar{\tau}V^*}{kT}\right) \quad (1)$$

In this equation R and k are the universal gas and Boltzmann constant, respectively. The definitions for the equivalent strain rate ($\dot{\bar{\gamma}}$), the equivalent shear stress ($\bar{\tau}$) and hydrostatic pressure (p) can be found in e.g. [3]. The parameters ΔU, V^* and μ were determined using tensile test data from various temperatures, strain rates and superimposed hydrostatic stresses. As an hypothesis a constant equivalent strain ($\bar{\gamma}_{cr}$) is taken as a failure criterion. With the use of equation (1) the time-to-failure (t_f) follows from:

$$\bar{\gamma}_{cr} = \int_0^{t_f} \dot{\bar{\gamma}}(T,\bar{\tau},p,t)\,\mathrm{d}t\,. \quad (2)$$

Incorporating the influence of physical ageing

The pre-exponential factor ($\dot{\gamma}_0$) in equation (1) is a function of the thermodynamic state of the polymer. As this state changes with physical ageing, the pre-exponential factor is a function of the ageing time, temperature and applied stress during this ageing period. A similar approach as presented by Klompen et al. [4] will be used here to describe the influence of physical ageing on the pre-exponential factor:

$$\dot{\gamma}_0\left(T,\bar{\tau},t\right) = \dot{\gamma}_{0,rej}\exp\left(-c_0 - c_1\log\left(\frac{t}{a_T a_\sigma} + t_a\right)\right). \tag{3}$$

In this equation t_a is the initial age of the polymer and t is the ageing time. The parameters $\dot{\gamma}_{0,rej}$, c_0 and c_1 are determined using yield stress data for tensile tests specimens with a range of thermodynamic states. It is well known that aging is accelerated both at elevated temperatures and stresses, as the mobility of the polymer chains is enhanced under these circumstances. The temperature and stress induced acceleration factors a_T and a_σ are given by the following relations:

$$a_T\left(T\right) = \exp\left(\frac{\Delta U_a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right), \tag{4}$$

$$a_\sigma\left(T,\bar{\tau}\right) = \frac{\bar{\tau}\upsilon_a}{RT}\left[\sinh\left(\frac{\bar{\tau}\upsilon_a}{RT}\right)\right]^{-1}. \tag{5}$$

The aging activation energy (ΔU_a) and the specific aging activation volume ($\overline{\upsilon}_a$) are the parameters which determine the influence of temperature and stress on aging. Combining equations (1-5) gives a direct relation between the time-to-failure and the applied equivalent stress, including physical ageing effects. The model will be validated with experimental data.

Experimental

The uPVC tensile specimens were taken out of an excavated uPVC gas distribution pipe (Ø160 mm) that had been in service for several decades. With a band saw a semi-circular section was cut from the pipe material. The section was sawed in axial direction and both parts were pressed into flat plates in a press at 100°C. Tensile bars with a parallel gauge section of approximately 30×5×4 mm^3 were milled from the plate material. All uni-axial tensile and creep measurements were carried out on an MTS Elastomer Testing System 810, equipped with a 25 kN force cell and a temperature controlled chamber. All yield stress, applied stress and strain rate data in this abstract are engineering values.

Results

The parameters which serve as input for equation (1) of the model are obtained using non-linear least squares fitting routines on tensile yield stress data at various temperatures and strain rates as shown in figure 1. The markers represent experimental data, whereas the lines represent the models best fit. The value for the critical equivalent stress ($\bar{\gamma}_{cr}$) in equation (2) is obtained using one of the data points shown in figure 2. The three lines in figure 2 are model predictions based upon this value. The excellent agreement with the experimental data supports the use of a constant critical strain as a failure criterion.

Incorporating ageing kinetics

The parameters related to the ageing kinetics of uPVC are determined using tensile yield stress data for specimens which received various ageing treatments. The circular markers in figure 3 are the result of measurements on the specimen which were aged at four different temperatures. The data were shifted to one master curve using time-temperature superposition using equation (4). The shift results in a value for the parameter ΔU_a, while the best fit of the master curve gives the parameters in equation (3). The triangular markers represent yield data

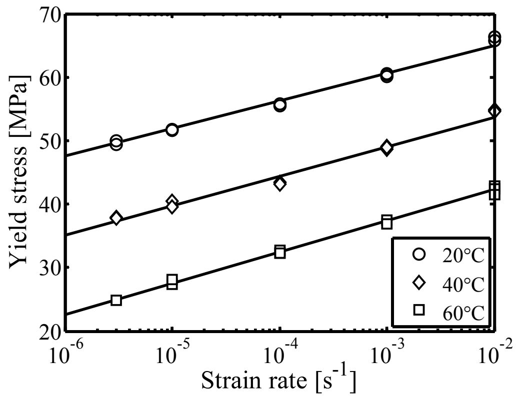

Figure 1: Tensile yield stress data for a range of strain rates and temperatures.

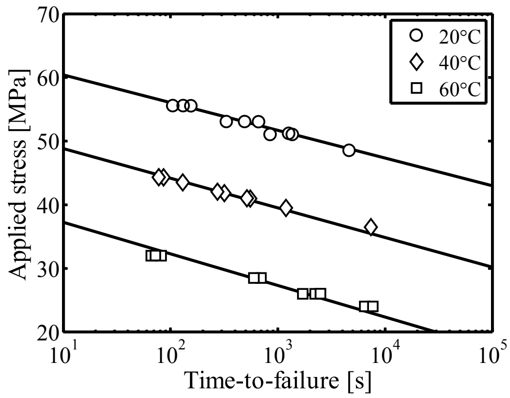

Figure 2: Time-to-failure for a range of applied stresses and temperatures.

for specimens which were aged at a uni-axial tensile stress of 25 MPa. Applying stress clearly accelerates the ageing kinetics. The triangular markers can be shifted towards the solid black master curve using equation (5). From this shift the parameter $\overline{\upsilon}_a$ can be determined. The influence of the thermal history is also indicated in figure 3. The yield stress remains constant for a certain ageing time, after which ageing becomes apparent. Both the length of the "inactive" period and the yield stress level are higher with increasing initial age (t_a).

Time-to-failure predictions including ageing kinetics

With the use of only short term tensile test data as presented in figures 1-3, all the parameters of the model are determined. The accuracy of failure time predictions for short term tests is demonstrated in figure 2. The model should, however, be capable of predicting failure times on longer time scales as well. Therefore, a batch of tensile specimens with a low initial age ("as received") and a higher initial age ("aged") was subjected to a range of constant tensile engineering stresses. The initial age (t_a) of both batches of specimen was determined using the average tensile yield stress at a strain rate of $1{\cdot}10^{-3}$ s^{-1} of three specimens. The resulting predictions are shown in figure 4 as solid lines (including the influence of physical ageing) and dashed lines (without the influence of physical ageing). The experimentally obtained times-to-failure are shown as circular and diamond shaped markers. The model successfully predicts the failure of both batches, and shows to hold for different thermodynamic states. The results of the as received specimens are of special interest as physical ageing has a significant contribution for failure times above 10,000 seconds. It is clear that the model quantitatively predicts the failure times very well, also on a longer time scale.

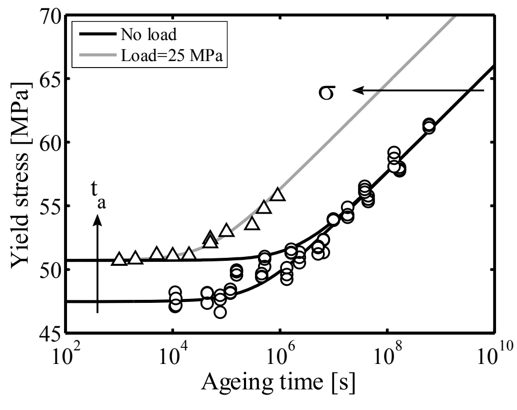

Figure 3: Master curve constructed using time-temperature superposition on experimental yield data (circles) and the influence of applied load and initial age.

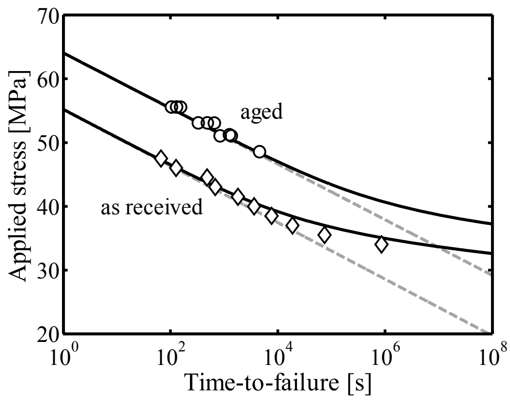

Figure 4: Time-to-failure for tensile bars under constant uni-axial tensile stress. The markers are experimentally obtained values, the lines are model predictions.

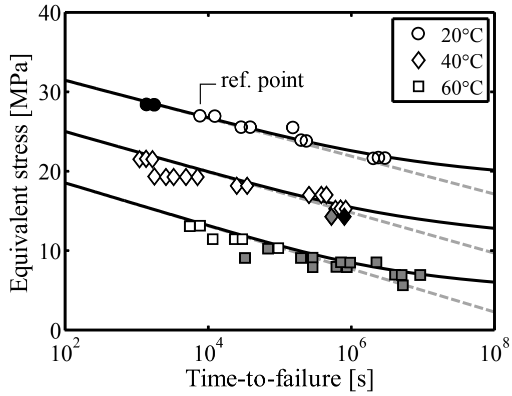

Figure 3: Failure times burst tests on uPVC pipes, reproduced from [5]. The unfilled, grey and black markers represent ductile tearing, hairline cracking and brittle fracture respectively. The lines are model predictions.

Time-to-failure prediction for pipes at a constant internal pressure

The model proves to be capable to predict the failure times for uni-axially loaded specimen accurately. However, more complicated loading cases are encountered in practise. One commonly known example is a pipe which is loaded at a constant internal pressure. Burst tests are carried out to qualify the polymer and to study its long term failure behaviour. By pressurising pipe segments a three dimensional stress field is induced in the pipe wall. The equivalent stress and hydrostatic pressure in equations (1) and (5) are calculated for this stress state and used to predict burst test data for uPVC as measured by Niklas et al. [5] and shown in figure 3. Three failure modes were encountered: ductile tearing (unfilled markers), hairline cracking (grey markers) and brittle fracture (black markers). Niklas et al. noted that there was no change in kinetics observed for the experimental data in spite of the different failure modes. The solid line predictions are based upon one reference point, which is used to determine the initial age of the pipe sections. Again an excellent quantitative prediction is obtained with the model, for all three failure types. The initial age appears to be relatively high (about $2 \cdot 10^8$ s), which explains why physical ageing has an insignificant effect in the experimental data. This is confirmed by the model predictions.

Conclusions

The presented model is capable to quantitatively predict the long-term time-to-failure for structures under both uni-axial and more complex loads. The model is based upon prediction of the deformation kinetics of uPVC, incorporating the influence of physical ageing and applying a critical equivalent strain criterion to determine the onset of material failure. The input parameters can be determined using only short term tensile tests.

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