Polymer Testing 50 (2016) 292–296

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Short communication: material behaviour

# Time-strain rate superposition for relaxation behavior of polyethylene pressure pipes

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A R T I C L E  I N F O

*Article history:*
Received 27 October 2015
Accepted 23 December 2015
Available online 28 January 2016

*Keywords:*
Polyethylene pipe
Superposition
Strain rate
Relaxation

A B S T R A C T

A new superposition principle based on time and strain rate is suggested as an alternative approach to construct a master curve of relaxation modulus versus time for polyethylene (PE) pressure pipe. The new approach uses results from a series of relaxation tests that reach the same relaxation strain at different strain rates (by varying the crosshead speed). Construction of the master curve for the relaxation modulus is first through horizontal shift using an expression similar to that for the time–temperature superposition principle. Then, a vertical shift is applied to generate a smooth curve profile. Such a time-strain rate superposition principle can serve as an alternative approach to construct a master curve for the long-term behavior of PE. The master curve shows two transitions for the rate of decrease of the relaxation modulus, instead of one transition reported before. The additional transition occurs within a short period after the relaxation strain is reached, and is detectable only if the initial strain rate is sufficiently low. Discovery of the new transition offers an additional perspective for studying mechanisms involved in the PE deformation.

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## 1. Introduction

Over 90% of newly installed gas pipeline systems are now made of polyethylene (PE) [1], which are expected to have lifetime of at least 50 years. Because of such a long service time, assurance of mechanical performance of the PE pipes has been a major challenge for pipe design, especially when the short-term mechanical properties are considered for characterizing the long-term behavior of PE, due to the complication caused by the significant viscous deformation. Various test methods have been developed to overcome this problem. Those test methods are often based on creep deformation or load relaxation mode [2–7]. Currently, time–temperature superposition (TTS) is a popular approach to construct a master curve for the long-term behavior for polymers [8–10], of which the majority is concerned with creep deformation, e.g. Refs. [11–15]. Much less work is about the load relaxation counterpart, e.g. Ref. [16]. Nevertheless, none of the previous work has considered the strain rate used to reach the targeted creep stress or relaxation strain as a variable for constructing the master curve for the creep deformation or load relaxation, respectively.

With recent understanding of the damage development in PE and dependence of the damage level on the tensile strain rate [17], we started an investigation to explore the possible change in the load relaxation behavior by varying the strain rate used to reach the relaxation strain. This technical note is to summarize the discovery from a preliminary study, to show the trend of change of the relaxation modulus with time by varying the strain rate used to reach the relaxation strain. Based on the test results, the paper describes a new approach to construct a master curve of the relaxation modulus versus time, for a period that is comparable to or longer than the service time required for the PE pipe.

## 2. Experimental details

### 2.1. Materials and specimens

All specimens used in this study were prepared from commercial PE4710, Cell classification 445576C HDPE pipe, with inner diameter and nominal wall thickness of 52.5 mm and 5.84 mm, respectively, manufactured by Endot Industries. Resin for the pipe is PE-100 which has the minimum required strength (MRS) of 10 MPa. Notched pipe ring (NPR) specimens were prepared from one pipe section, with dimensions following those recommended in ASTM: D2290-12, except that the notch profile was flat, instead

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http://dx.doi.org/10.1016/j.polymertesting.2015.12.014
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of round, to have a relatively uniform stress distribution in the ligament region. Note that ligament length for the specimens was chosen to be 5.84 mm, close to wall thickness of the pipe, so that the initial aspect ratio of width to thickness is nearly 1 in order to generate similar contraction in the two directions under tensile loading [18]. Details of the specimen dimensions are given in Ref. [19].

### 2.2. Mechanical testing

All tests were conducted at room temperature using a universal test machine (QUASAR 100). The specimens were stretched using the set-up for D-split tensile test, first proposed for characterizing mechanical properties of composite materials. Set-up for the D-split test used here is also described in Ref. [19].

The test scheme has three phases, as shown in Fig. 1 which is similar to that used before [17], consisting of monotonic tension, relaxation and unloading phases. During the test, each of the NPR specimens was first stretched to the predefined relaxation strain level, followed by 3-h load relaxation and then unloading. Four crosshead speeds of 0.01, 1, 10 and 100 mm/min were selected to vary the strain rate. A series of finite element (FE) simulation, following the procedure used before [20], was performed to determine the strain rates generated at a given crosshead speed. The results are presented in Fig. 2, which suggests that the maximum strain rates are $7 \times 10^{-5}$, $7 \times 10^{-3}$, $7 \times 10^{-2}$, and $7 \times 10^{-1}$ $s^{-1}$ for the above four crosshead speeds, respectively. Fig. 2 also suggests that the strain rate did not remain constant during the initial stretch of the relaxation test. Rather, the above maximum strain rates are about 20–30 times of the initial strain rates generated at a given crosshead speed. Nevertheless, in view of the maximum strain rates showing a linear relationship with the crosshead speed used, and the ranges of strain rate variation for the four crosshead speeds are clearly distinguishable, crosshead speed is used to represent the rate of deformation experienced by each specimen, based on which, the amount of horizontal shift is determined for constructing the master curve, as will be shown later.

Note that, similar to the work reported previously [19], strain is based on two times the logarithmic ratio of the original ligament length to the deformed ligament length, also known as area strain. Totally, five relaxation strain levels, namely, 5%, 10%, 20%, 30%, and 40%, were used to monitor the load relaxation at the crosshead speeds of 0.01, 1 and 10 mm/min. However, at the crosshead speed of 100 mm/min, the relaxation strains considered were only 5% and 10%, due to difficulties encountered in manual control of the test machine to generate the desired relaxation strains at such a high crosshead speed, and sensitivity of the specimens to the presence of foreign particles [19].

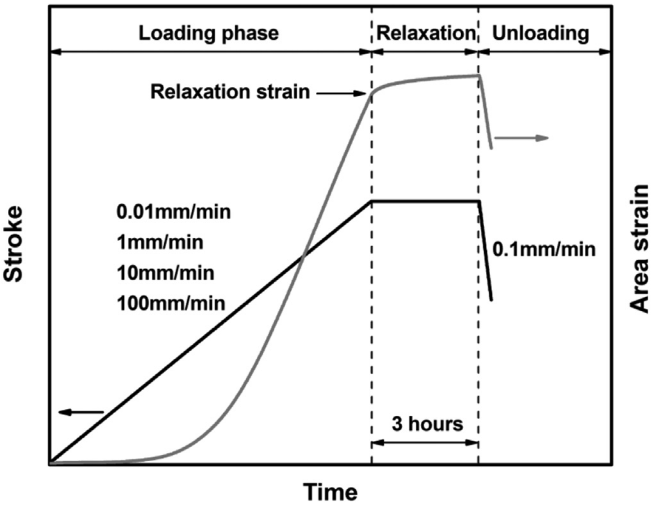

**Fig. 1.** Schematic description of relaxation tests conducted in this study.

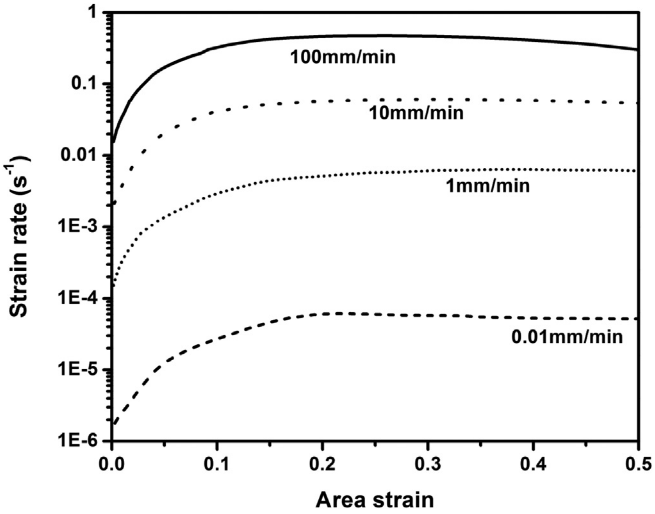

**Fig. 2.** Variation of strain rate as a function of area strain during the tensile deformation at crosshead speeds of 0.01, 1, 10 and 100 mm/min.

## 3. Results and discussion

Relaxation modulus is defined here as the ratio of engineering stress to the relaxation strain, similar to the definition in the literature [16] except that strain is expressed in terms of area strain, due to the short gauge length of the NPR specimens. Each of the plots in Fig. 3 summarizes variation of relaxation modulus as a function of time for NPR specimens that were stretched to the targeted relaxation strains at the same crosshead speed, that is 0.01, 1, 10 or 100 mm/min. The figure clearly shows that, at a given time, the relaxation modulus decreases with the increase of the relaxation strain, consistent with that reported before [16].

Fig. 3 also suggests that curve profile from the relaxation test is affected by the crosshead speed used to reach the relaxation strain. That is, by increasing the crosshead speed from 0.01 to 100 mm/min, the curve profile changes from concave downward to concave upward. The latter has been reported many times in the literature [16,21,22] but the former, to the best of our knowledge, has never been observed before, possibly because a very low crosshead speed, i.e., at or below the strain rate of $7 \times 10^{-3}$ $s^{-1}$, is needed to introduce the initial stretch in order to generate such a concave–downward curve profile.

Fig. 4(a) gives an example of the curves of relaxation modulus from the experimental testing, and Fig. 4(b) the corresponding master curve constructed using the superposition principle. All curves in Fig. 4(a) are with the relaxation strain of 5%, but using different crosshead speeds to generate the initial stretch. The master curve in Fig. 4(b) is also for the relaxation strain of 5%, with the initial stretch generated at the crosshead speed of 0.01 mm/min.

The master curve in Fig. 4(b) is constructed by first horizontally shifting each curve in Fig. 4(a) by a time duration $a_{\dot{\varepsilon}}$, calculated using an expression similar to the WLF equations [23] except that the governing variable is changed from temperature to crosshead speed. That is,

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