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Material behaviour

Influence of the temperature and strain rate on the tensile behavior of post-consumer recycled high-density polyethylene

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ABSTRACT

The tensile behavior of post-consumer recycled high-density polyethylene (HDPE) was studied. The experiments were conducted under a wide range of temperatures (from 25 °C to 100 °C) and strain rates ($7.25 \times 10^{-5}\ s^{-1}$ up to $7.25 \times 10^{-3}\ s^{-1}$). Temperature and strain rate greatly influence the mechanical response of the recycled HDPE. In particular, the stiffness and the ultimate tensile strength are found to increase with decreasing temperature and with increasing strain rate. Also, a one-dimensional viscoelastic phenomenological model able to yield a physically realistic description of temperature sensitivity and damage observed in tensile tests that can be used in engineering problems is proposed. Just three tests performed at different constant temperatures are needed to identify the material parameters that appear in the model. The experimental results are presented and compared to model estimations of damage progression and show good agreement.

1. Introduction

Over the last two decades, the developments in science and technology have increased the amount of synthetic polymers produced worldwide. Polymers have substantial benefits in terms of their low weight, durability and lower cost relative to many other material types [1,2]. Worldwide polymer production was estimated to be 280 million metric tonnes per annum in the year 2011 for all polymers including thermoplastics, thermoset plastics, adhesives and coatings [3]. China is the biggest manufacturer, 23% of the production worldwide, followed by Europe with 21% and NAFTA countries with 20%. Latin America countries comprise 5% of the total production.

Approximately 50 per cent of plastics are used for single-use disposable applications, such as packaging, agricultural films and disposable consumer items, between 20 and 25% for long-term infrastructure such as pipes, cable coatings and structural materials, and the remainder for durable consumer applications with intermediate lifespan, such as in electronic goods, furniture, vehicles, etc. Post-consumer plastic waste generation across the European Union (EU) was 25.1 million tons [3] and in the US was 32 million tons in 2011 [4].

This confirms that packaging is the main source of waste plastics. The main polymer used for packing is high-density polyethylene (HDPE) [3]. After use, polymer containers are disposed of in landfill and only 14.9 millions tons were recovered in the EU and 2.6 million tons in the US [4]. Recycling of plastics is one method of reducing environmental impact and resource depletion. Fundamentally, high levels of recycling, as with reduction in use, reuse and repair or re-manufacturing can allow for a given level of product service with lower material input than would otherwise be required. Recycling can, therefore, decrease energy and material usage per unit of output and so yield improved eco-efficiency.

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Generally, waste polymer packaging is recovered when it is diverted from landfill or littering. Polymer packages, of both flexible and rigid plastics, are by nature lightweight, and are particularly noticeable as litter. Many actions can be made to reduce the use of virgin materials in products and, therefore, reduce the amount of material going into the waste-management system. Designing products to enable reusing, repairing or re-manufacturing will result in fewer products entering the waste stream.

The use of recycled HDPE is a reality nowadays and, therefore, a better understanding of the behavior of this material is necessary. Many researchers have studied the behavior of recycled HDPE [5–11].

The purpose of this study is to experimentally investigate the behavior of recycled HDPE when tested at different temperatures and strain rates. Also, to propose a one-dimensional phenomenological damage model for describing the elasto-viscoplastic behavior of recycled HDPE in tensile tests at different temperatures and strain rates. The model equations combine enough mathematical simplicity to allow their application to engineering problems with the capability of describing complex nonlinear mechanical behavior. The material constants that appear in the model can be easily identified from just three stress-strain curves obtained at two different temperatures and three prescribed strain rates. Previous work performed by da Costa Mattos et al. [12–14] describes the thermodynamic context displayed in the model equations.

2. Material and methods

2.1. Materials

Post-consumer HDPE motor oil containers were obtained from SEPAN Services (Niterói, RJ, BR). The containers were drained and washed with biodegradable soap to eliminate any residue. The containers were dried at 90 °C for 3 hours and then shredded into pellets to produce the recycled HDPE test specimens.

The shredded recycled HPDE was compression molded in a steel frame according to ASTM D 638-08 [15].

2.2. Methods

Mechanical tensile tests at different temperatures and strain rates were performed using a Shimadzu® AG-X universal testing machine with an attached thermostatic chamber and electro-mechanical sensors for the control of longitudinal strain in the active zone of the test specimens. Tensile tests at 4 different constant isothermal temperatures, 25 °C, 50 °C, 75 °C and 100 °C and five different prescribed engineering strain rates, $\dot{\varepsilon}_1 = 7.25 \times 10^{-5}\ \mathrm{s}^{-1}$, $\dot{\varepsilon}_2 = 1.45 \times 10^{-4}\ \mathrm{s}^{-1}$, $\dot{\varepsilon}_3 = 7.25 \times 10^{-4}\ \mathrm{s}^{-1}$, $\dot{\varepsilon}_4 = 1.45 \times 10^{-3}\ \mathrm{s}^{-1}$ and $\dot{\varepsilon}_5 = 7.25 \times 10^{-3}\ \mathrm{s}^{-1}$, were performed to quantify the temperature dependency when recycled HDPE was tested at different strain rates. The strain rate dependency at room temperature was evaluated and confirmed according to previous work by the authors [16]. Fig. 1 displays the recycled HDPE tensile test inside the thermostatic chamber.

3. Results and discussion

3.1. Experiments

Fig. 2 presents the true stress vs. strain curves for recycled HDPE obtained from the controlled-strain tensile tests at different temperatures, 25 °C, 50 °C, 75 °C and 100 °C and constant engineering strain rates: $\dot{\varepsilon}_1 = 7.25 \times 10^{-5}\ \mathrm{s}^{-1}$, $\dot{\varepsilon}_2 = 1.45 \times 10^{-4}\ \mathrm{s}^{-1}$, $\dot{\varepsilon}_3 = 7.25 \times 10^{-4}\ \mathrm{s}^{-1}$, $\dot{\varepsilon}_4 = 1.45 \times 10^{-3}\ \mathrm{s}^{-1}$ and $\dot{\varepsilon}_5 = 7.25 \times 10^{-3}\ \mathrm{s}^{-1}$.

The curves display a significant temperature dependency and also strain rate dependency in which the maximum strength and modulus of elasticity decrease as temperature increases. It is also observed that higher strain rate results in higher stiffness and maximum strength. At 25 °C, as strain rate increases, ductility decreases. Increasing temperature to 50 °C, 75 °C and 100 °C also serves to increase the limiting extensibility (formability) of the recycled HDPE. Fig. 3 presents the temperature influence on the tensile tests performed at constant strain rate according to an ASTM standard [15], $\dot{\varepsilon} = 7.25 \times 10^{-4}\ \mathrm{s}^{-1}$.

According to Fig. 3, at $\dot{\varepsilon} = 7.25 \times 10^{-4}\ \mathrm{s}^{-1}$, a strong temperature dependency can be seen. A decrease in the stiffness and in the tensile strength is observed as temperature increases. This aspect of the observed behavior is the result of the competing effects of continued thermal softening and the commencement of strain hardening, which is occurring due to the evolution of chain orientation with plastic stretch.

3.2. Modeling

The experiments of the previous section carefully identified the important effects of temperature and strain rate. Below, we modify a previously studied constitutive model of the strain rate dependency of recycled HDPE at room temperature [16]. The various details of the existing model and motivations for its development can be found in this earlier work, but the essential features of the model will be reviewed here to introduce the addition of temperature dependency to the model.

The following equation is proposed to model tensile tests of recycled HDPE at a variable temperature (θ) and strain rate ($\dot{\varepsilon}$):

$$\sigma_t = [a(\dot{\varepsilon},\theta)[1 - \exp(-b(\theta)\ \varepsilon_t)]] \tag{1}$$

where σ_t and ε_t are termed true stress and true strain stress defined as follows:

$$\sigma_t = \sigma(1+\varepsilon); \quad \varepsilon_t = \ln(1+\varepsilon) \tag{2}$$

and σ and ε are classically designated engineering stress and engineering strain. The functions $a(\dot{\varepsilon},\theta)$ and $b(\theta)$ are defined as:

$$a(\dot{\varepsilon},\theta) = a_1(\theta)\dot{\varepsilon}^{a_2} \tag{3}$$

where

$$a_1(\theta) = a_{11}\theta - a_{22} \tag{4}$$

and