Mechanical Testing and Material Modeling of Thermoplastics: Polycarbonate, Polypropylene and Acrylonitrile-Butadiene-Styrene

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Résumé :

Les résultats présentés dans ce travail concernent la mise en place d'une base de données matériau pour trois différents thermoplastiques: le polycarbonate, le polypropylene et l'acrylonitrile-butadiene-styrene. Des essais mécaniques de compression et traction ont été menés à différentes vitesses de déformation afin de caractériser leur comportement mécanique. Une loi de comportement viscoelastique-viscoplastique basée sur les modèles existants [2; 7-13] a été développée et implémentée dans le code éléments finis ABAQUS afin de prédire le comportement mécanique de ces polymères.

Abstract :

The work presents some results of an ongoing research program aimed at building a material database and material models for specific types of polymers. Results for three thermoplastics are the focus of the present article: polycarbonate, polypropylene, and acrylonitrile-butadiene-styrene. Uniaxial compression / tension tests at room temperature and different strain rates have been performed to characterize their mechanical response. A rate-dependent material model has been developed and implemented in a finite element code ABAQUS to predict such mechanical behavior. The model predictions have shown good agreement with the tests results.

Mots clefs: thermoplastiques, essais mécaniques, modelisation numerique

1 Introduction

The automotive industry is currently interested in using lighter and impact resistance materials in vehicular systems, as they would make vehicles more fuel efficient without compromising safety standards. In this context, polymeric materials are a good option for this application. In fact, currently polymers represent 20% of the total weight of a car, with thermoplastics and thermosets being about 10% to 15% of this weight. Based on these statistics, it has been found that by substituting 10lb of other materials using polymers, the fuel efficiency can be improved by 0.11 to 0.14%, an important aspect that makes polymers a material of choice in the automotive industry [1].

In the present study, mechanical characterization tests were performed on three thermoplastics largely used in the automotive industry. The goal was to capture their structure-property relationships under different loading conditions. The particular results (stress-strain curves) presented here were obtained at room temperature and at low to medium strain rates. Also, material modeling efforts were started to capture the experimentally determined mechanical behavior. The current material model used an internal state variable formalism, and followed closely a widely used theory for amorphous polymers [2] but framed in a thermodynamic setting [3]. The model was implemented in the finite element code ABAQUS and applied to predict the strain-rate dependent response of the three thermoplastics.

2 Experimental Procedure

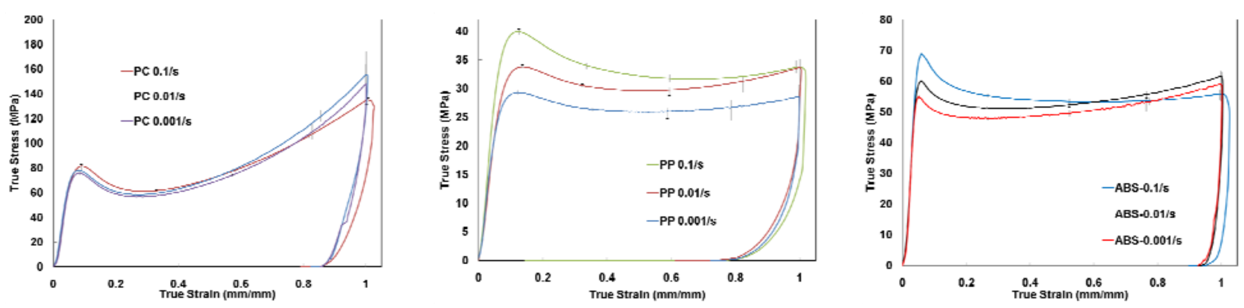
The three thermoplastics selected for the study are: (i) an amorphous polycarbonate (PC) known under the trade name Hyzod® from Sheffield Plastics, (ii) an isotactic polypropylene (PP) provided by Poly Hi Solidur Inc., (iii) a copolymer acrylonitrile butadiene styrene (ABS) supplied by King Plastic Corp. The compressive and tensile specimens were cut from sheets of 1" thickness.

Low and medium strain rate tests were conducted at room temperature (RT) on an INSTRON 5882 electro-mechanical load frame machine. The tests were strain-controlled, with the strain measurements being performed using an INSTRON 2630-110 extensometer. For the compression tests, the extensometer was attached directly to the compression platens. A feedback loop between the extensometer and the machine was used to ensure a constant engineering strain rate over the duration of the tests. Friction and specimen barreling were minimized using thin Teflon sheets placed between the INSTRON platens and specimen surfaces, with a three-in-one lubricant employed between the Teflon sheets and platens. This procedure ensured uniaxial loading conditions. The specimens were right circular cylinders, with a diameter of 12.7 mm and a length of 6.35 mm. The tensile tests, on the other hand, followed ASTM D638-03 on 'Standard Test Method for Tensile Properties of Plastics', using the Type-I specimen geometry.

3 Experimental results

Fig. 1(a), 1(b) and 1(c) present the true strain-true stress responses under compressive loading for PC, PP, and ABS, respectively, determined at RT and for three different strain rates: 0.001/s, 0.01/s and 0.1/s. The curves for PC, Fig. 1(a), show the expected features of its mechanical response at temperatures below the glass transition: an initial linear elastic response followed by a non-linear transition curve to global yield, then strain softening and subsequent strain hardening. The stress response also exhibits an increased yield peak value with increasing applied strain rate, a behavior observed by many other authors [4-6]. Some dispersion in the test results can be observed due to different sources of uncertainty (test instrumentation, testing machine, and material microstructure). Such uncertainty seems to be accentuated as the deformation level increases. For the case of PP, Fig. 1(b), all the curves show an initial linear elastic response followed by a non-linear transition curve to global yield and then some strain softening. At a strain of 0.6, the material exhibits only some slight strain hardening as compared to PC. The stress response also exhibits an increased yield peak value and a decreased strain hardening with increasing applied strain rate. This last phenomenon can be directly related to heat generation due to the applied strain rate. The figure also shows an increased softening effect with increased strain rate. Finally, for ABS, Fig. 1(c), the response exhibits similar features as the other plastics, i.e., a linear elastic regime, strain softening and strain hardening. An important time-dependent effect can be observed on the yield peak and on the residual strain at a strain rate of 0.1/s. Also, the strain hardening is observed to decrease as the strain rate increases.

The RT true stress-true strain curves for PC, PP, and ABS under tensile loading at different strain rates are presented, respectively, in Fig. 2(a), 2(b), and 2(c). For all tensile tests, when the softening behavior ensues, necking begins, and hence, the stress in the specimen is no longer homogeneous (the presented curves should only be valid up to the yield peak). Note that the yield peak of the three polymers increases with an increase in strain rate.



(a) (b) (c)

FIG. 1 – True stress-true strain behavior of PC (a), PP (b), and ABS (c) in uniaxial compression at RT for different strain rates (0.001/s, 0.01/s, and 0.1/s).

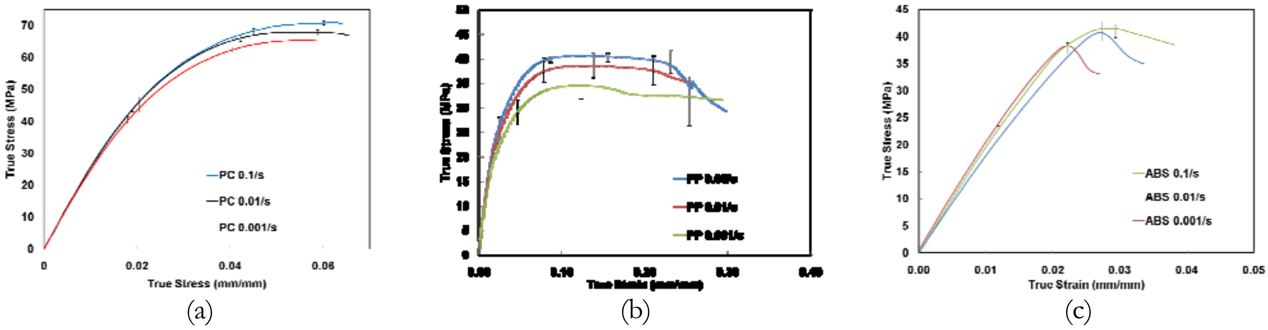


FIG. 2 – True stress-true strain behavior of PC (a), PP (b), and ABS (c) in uniaxial tension at RT for different strain rates (0.001/s, 0.01/s, and 0.1/s).

4 Constitutive model

Polymers exhibit a rich variety of material behavior, which is very temperature and rate dependent. Such behavior is mainly due to their particular microstructures. To capture such a wide range of responses, a number of constitutive models have been developed in the open literature. In particular, many physically-based constitutive equations based on differential formulations using internal state variables have been proposed [2, 3, 7-13]. In the present study, the formulation of a constitutive framework focused on modeling the response of thermoplastics under isothermal deformations at temperatures below and close to the glass transition temperature has been developed and implemented in the finite element code ABAQUS. The framework follows closely the developments presented in [2, 3]. Details of the framework have been given elsewhere [12], and a summary of the constitutive equations is shown in Table 1.

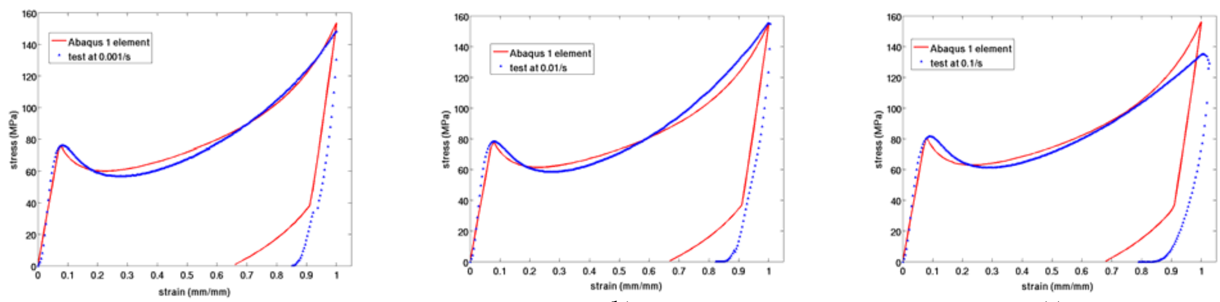
TAB 1 – Summary of the Model Equations for Thermoplastics

Term	Description
$\hat{\psi}(\overline{\mathbf{C}}^e, \mathbf{C}) = \hat{\psi}_{\overline{C}^e}(\overline{\mathbf{C}}^e) + \hat{\psi}_C(\mathbf{C})$	Free energy
$\boldsymbol{\sigma} = J^{-1}\boldsymbol{\tau},\ J = \det\mathbf{F}$ $\boldsymbol{\tau} = \boldsymbol{\tau}_1 + \boldsymbol{\tau}_2$	Cauchy Stress Kirchhoff Stress
$\boldsymbol{\tau}_1 = \mathbf{R}^e\overline{\mathbf{M}}_1\mathbf{R}^{eT}$ $\overline{\mathbf{M}}_1 = \left[2\mu\,\overline{\mathbf{E}}^e + \left(K - \frac{2}{3}\mu\right)\mathbf{tr}\left(\overline{\mathbf{E}}^e\right)\mathbf{I}\right]$ $\mathbf{F} = \mathbf{F}^e\mathbf{F}^p,\ \mathbf{F}^e = \mathbf{R}^e\mathbf{U}^e,\ \overline{\mathbf{E}}^e = \ln(\mathbf{U}^e)$	Kirchhoff Stress (elasto-viscoplastic part) Elastic Law (Mandel Stress) Deformation Gradient
$\boldsymbol{\tau}_2 = \frac{\mu_R\lambda_L}{3\overline{\lambda}}L^{-1}\left(\frac{\overline{\lambda}}{\lambda_L}\right)\mathbf{devb}^* + \frac{1}{2}K_B\left(J^2-1\right)\mathbf{I}$	

$\mathbf{b}^* = \mathbf{F}^*\mathbf{F}^{*T}$ and $\mathbf{F}^* = J^{-\frac{1}{3}}\mathbf{F}$	Kirchhoff Stress (hyper-elastic part) Left Cauchy-Green tensor
$\dot{\mathbf{F}}^p = \overline{\mathbf{D}}^p\mathbf{F}^p$ $\overline{\mathbf{D}}^p = \frac{1}{\sqrt{2}}\dot{\gamma}^p\,\overline{\mathbf{N}}^p$ with $\overline{\mathbf{N}}^p = \frac{\mathbf{dev}\overline{\mathbf{M}}_1}{\lVert\mathbf{dev}\overline{\mathbf{M}}_1\rVert}$ $\dot{\gamma}^p = \dot{\gamma}_0\left(\frac{\overline{\tau}_1}{\kappa+\alpha\overline{\pi}_1}\right)^{\frac{1}{m}}$ with $\overline{\tau}_1 = \frac{1}{\sqrt{2}}\lVert\mathbf{dev}\overline{\mathbf{M}}_1\rVert$ and $\overline{\pi}_1 = -\frac{1}{3}\mathbf{tr}\overline{\mathbf{M}}_1$ $\dot{\kappa} = h_0\left(1-\frac{\kappa}{\kappa_s}\right)\dot{\gamma}^p$	Flow rule Equivalent plastic shear strain-rate Molecular resistance to plastic flow
$\{\mu, K, \dot{\gamma}_0, \alpha, m, \kappa_s, \kappa_0, h_0, \lambda_L, \mu_R, K_B\}$	Material constants

5 Numerical results

Fig. 3 through 6 present the comparison between model prediction and experimental data for uniaxial compression and tension at RT and different strain rates for PC, PP, and ABS. As noted from the figures, the model is able to predict reasonably well the experimental data for the three thermoplastics. Note that for the case of PC in compression, the model captures the expected features of its mechanical response below the glass transition. Similar features are also observed for the other two thermoplastic, where the strain hardening is much less. Note also that the model predicts in all cases the increased yield peak value with increasing applied strain rate.



(a) (b) (c)

FIG. 3 – Comparison between model prediction and experimental data of PC in uniaxial compression at RT for different strain rates ((a) 0.001/s, (b) 0.01/s, and (c) 0.1/s)

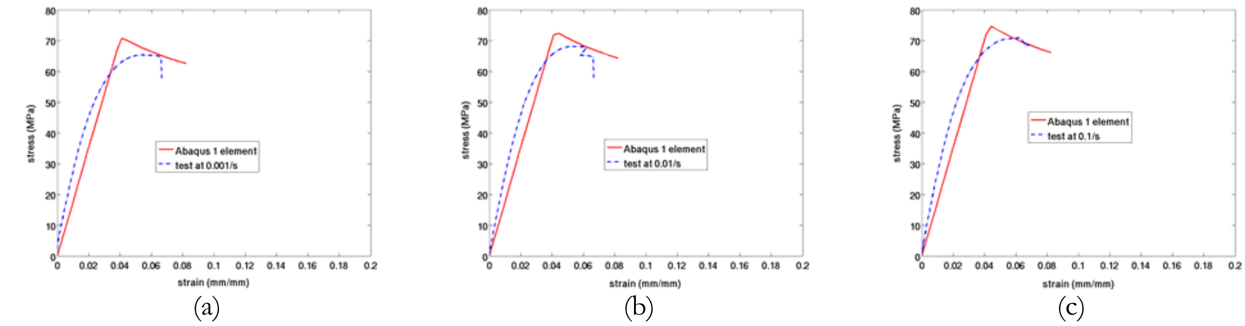


FIG. 4 – Comparison between model prediction and experimental data of PC in uniaxial tension at RT for different strain rates ((a) 0.001/s, (b) 0.01/s, and (c) 0.1/s)

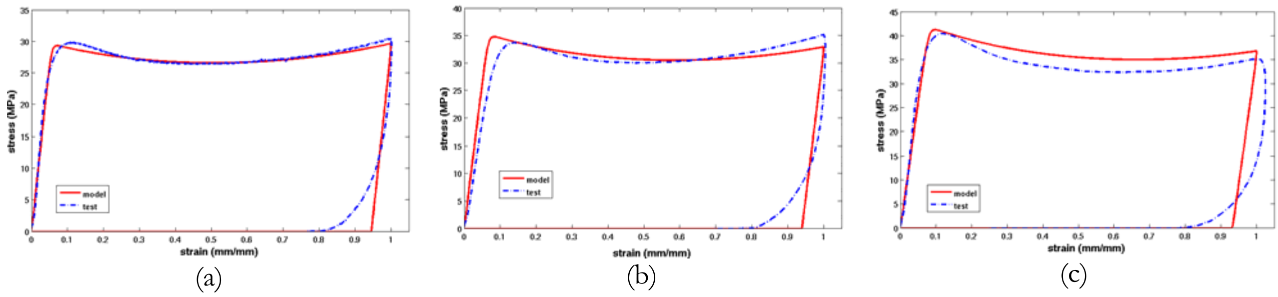


FIG. 5 – Comparison between model prediction and experimental data of PP in uniaxial compression at RT for different strain rates ((a) 0.001/s, (b) 0.01/s, and (c) 0.1/s)

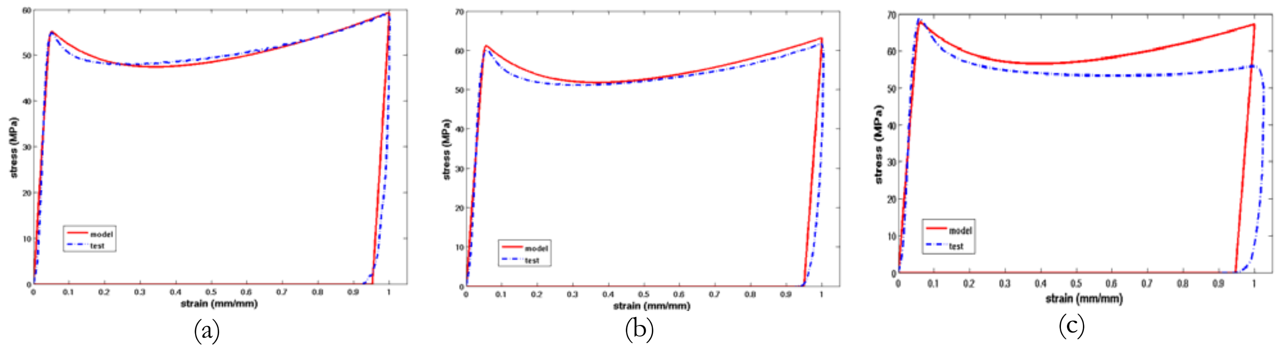


FIG. 6– Comparison between model prediction and experimental data of ABS in uniaxial compression at RT for different strain rates ((a) 0.001/s, (b) 0.01/s, and (c) 0.1/s)

6 Conclusion

The present study examined and modeled the RT rate-dependent mechanical behavior of three different thermoplastics: polycarbonate (PC), polypropylene (PP), and acrylonitrile-butadiene-styrene (ABS). Mechanical tests were performed in compression and tension for three different strain rates: 0.001 s-1, 0.01 s-1, 0.1 s-1. The determined stress-strain curves showed (i) typical features commonly observed for thermoplastics, and (ii) a strong rate-dependent mechanical behavior. A constitutive model for thermoplastics was developed and implemented to capture their mechanical behavior. The model predicts well the RT rate-dependent mechanical response of PC, PP, and ABS in compression and of PC in tension.

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