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Numerical study of mechanical behaviour of a polypropylene reinforced with Alfa fibres

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| | |

Numerical study of mechanical behaviour of a polypropylene reinforced with Alfa fibres

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Abstract

The main purpose of this work consists of the mechanical characterization of a copolymer PolyPropylene (PP) filled with natural Alfa fibres. The elaboration of the PP-based composite reinforced with these natural fibres is explained. The mechanical behaviour of these composite blends has been analysed. Contrary to classical studies of the mechanical characterization of these kinds of materials which focus only on monotonic tensile tests, cyclic loading/unloading tests and loading/unloading tests interrupted by relaxation steps have been investigated. These tests enable us to compare the mechanical response of the virgin PP and the PP filled with Alfa fibres (Alfa/PP). Reinforcement by these natural fibres shows an impact in the improvement of the mechanical properties of this composite. All these experimental results constitute a data base used to identify the material parameters of a phenomenological constitutive Hyperelasto-Visco-Hysteresis (HVH) model. These tests also provide indications about the hyperelastic, viscous and hysteretic stress contributions of the HVH model with these materials during cyclic loading.

Keywords

Polymer-matrix composites, Polypropylene, Alfa fibres, Mechanical properties, Finite element analysis

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1 Introduction

Composite materials are increasingly used in daily life due to their low production cost, light weight and efficient performance. Among these materials are the thermoplastics reinforced with natural fibres such as Bamboo, Jute, Kenaf, Flax, Sisal, Hemp, Alfa, etc. Their use has gained significant interest during the last decade because of their biodegradability. These natural fibres offer a number of advantages over other conventional fibres in the form of: abundance, renewability, and relatively low cost. These benefits present an opportunity to make an environmentally friendly material with excellent mechanical properties [1, 2].

Nevertheless, the manufacture of these materials is difficult due to poor compatibility between the hydrophobic polymer matrix and the hydrophilic cellulose fibres. This poor compatibility affects the mechanical properties that strongly depend on the interfacial adhesion between components. Therefore, a number of studies in the modification of the fibre's surface properties were introduced to improve their adhesion with a different polymer matrix [3]. Some of these treatments have a physical nature and some are of a chemical nature. These days, more and more natural fibre resources for products are being studied for polymer reinforcement, and the number of the studies and researches that have been published during the last decade reflects the growing importance of these new bio-composites [3, 4, 5, 6, 7]. Since the use of these materials is growing, studying their mechanical properties and behaviour becomes necessary to ensure that their characteristics will be reliable and predictable.

The aim of the present paper is to study the mechanical behaviour during cyclic tests of a thermoplastic reinforced with chemically treated natural fibres extracted from the Alfa plant. Alfa fibres are available in large quantities in North Africa. They have good mechanical properties compared to other natural fibres [8] and they are mostly used to produce paper. Paiva et al. [9] have studied the tensile properties of an single filament of Alfa fibre, resulting in values of approximately 20 GPa and 250 MPa for tensile modulus and yield strength, respectively. Arrakhiz et al. [10] have investigated the effect of chemical modification (alkali treatment, etherification treatment and esterification treatment) on the Alfa fibre's surface, and its impact on mechanical and thermal properties of composites. However, they only analysed the Young's modulus and tensile strength. To improve the mechanical knowledge of this kind polymer rein-

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6 30 forcement, it is important to analyse their mechanical responses during more complicated tests,
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8 31 such as loading-unloading cyclic tests.

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10 32 In this study, to characterize the mechanical performance of a PP filled with Alfa fibres, a
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12 33 commercial grade of copolymer polypropylene PPC7712 is used as a matrix. In our previous
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14 34 works, this material was studied in static tensile tests [11], dynamic tensile tests [12] and under
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16 35 multiaxial loading conditions [13].

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18 36 Monotonic tensile tests, cyclic loading/unloading tests and loading/unloading tests inter-
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20 37 rupted by relaxation steps (multi-step relaxation test) were carried out to investigate the me-
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22 38 chanical behaviour of the Alfa/PP composite. The first objective of these tests is to have a
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24 39 full characterization of the stress-strain responses of the PP and Alfa/PP during the uniaxial
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26 40 tensile cyclic tests. Thus, the second objective of this study is to analyse the mechanical impact
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28 41 of the reinforcement with these natural fibres on these complicated cyclic tests.

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30 42 Finally, an original phenomenological model, called Hyperelasto-Visco-Hysteretic (HVH) was
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32 43 used to simulate the mechanical behaviour of these materials during these tests. This model,
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34 44 written in 3D and implemented in an in-house code HEREZH++ [14], is based on the super-
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36 45 imposition of three stress components which correspond to linear viscoelastic, hyperelastic and
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38 46 pure hysteresis behaviour. In contrast to previous studies based on the same model [11, 15], a
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40 47 new identification method of material parameters is performed in this paper. This method, pre-
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42 48 sented in [16], but with a fluoro-elastomer, is based only on a cyclic tension test interrupted by
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44 49 relaxation steps (multi-step relaxation test). It does not require an optimization procedure by
45
46 50 a least-square method to minimize the experimental data and prediction of the test. The main
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48 51 advantage of this identification method is that, using only this multi-step relaxation test, hy-
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50 52 perelasticity, hysteresis and viscosity contributions of the HVH model are discriminated, which
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52 53 results in the substantially easy and simple identification process of the material parameters.
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54 54 To verify the suitability of the material parameters obtained, experimental tests that were not
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56 55 used for the identification are simulated. A good performance of the proposed model is shown
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58 56 by a comparative analysis between the predictive solution and experimental data.
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2 Materials and processing of composites

The composites were prepared using a commercial grade heterophasic copolymer polypropylene, named PPC7712, provided by Total-Petrochemicals. This copolymer is recyclable with good mechanical properties, excellent impact strength and is easy to inject. Some thermo-mechanical characteristics of the PPC7712 are listed in Table 1 [11]. The Alfa fibres used, readily available in the dry region of North Africa, were extracted from plants from the central west of Tunisia. The Alfa plant is the Arab name of "esparto grass" or "stippa tenacissima" plant [9]. These fibres were characterized by good thermal and mechanical properties compared to other natural fibres. Characteristics and the composition of Alfa fibres in comparison to other natural fibres can be found in [8, 9, 10, 17, 18].

2.1 Chemical treatment of the Alfa fibres

To improve compatibility with a hydrophobic polymer and eliminate the majority of its non-cellulosic components [19], Alfa fibres were chemically treated according to the standard procedure proposed in [10, 20, 21]. To separate the fibres and clean their surfaces, whole fibres were first immersed in salted water with a salt (NaCl) concentration of 35 g/l at 60° C for a duration of 24 hrs. The fibres were then placed in an aqueous sodium hydroxide solution (NaOH) with a concentration of 1.6 mol/l (corresponding to 64 g/l) for a duration of 48 hrs for each 35 g of fibres, with the objective of eliminating the lignin and pectin elements covering the fibre's surface. Subsequently, to neutralize the sodium hydroxide solution, they were placed in an acetic acid solution (100 ml for each 35 g of fibres).

Finally, the Alfa fibres were washed with distilled water to remove any excess of sodium hydroxide to obtain a final pH=7. Each step of this procedure was followed by a drying period in an oven at 60° C for a duration of 24 hrs.

2.2 Alfa fibres characterization

The tensile strength and Young's modulus of treated Alfa fibres were determined according to the ASTM D3379-75 standard test method for high-modulus single filament materials. Elemen-

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6 83 tary fibres were separated from their fibre bundles by hand, and then mounted on 2 mm thick
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8 84 cardboard mounting cards with 10 mm holes punched into them, such that the punched hole
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10 85 diameters determined the fibre gauge length. Fibres were positioned to bridge the hole, and
11
12 86 were secured in place with glue. This method follows the procedure proposed by the example
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14 87 in [22]. Mounted fibres were inspected under an Olympus BX60F5 metallurgical microscope
15
16 88 to ensure that only a single fibre was present on each card and to determinate the average
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18 89 diameter of the fibre. Thirty fibre samples were analysed. For each fibre, three points were
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20 90 measured: two at the extremities of the fibre and one point on the middle of fibre. The average
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22 91 diameter of the fibres was equal to $185.2 \pm^{39} \mu\text{m}$. **The cross section area was also measured for**
23
24 92 **the thirty fibres. The distribution of this experimental value is given in Figure 1. The average**
25
26 93 **cross section area is of $28110 \mu\text{m}^2$ (green line in Figure 1).**

27
28 94 The mounted single fibre was placed in the grips of an MTS tensile testing machine and
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30 95 the supporting sides of the mounting cards were carefully cut using a hot-wire cutter. Tensile
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32 96 tests were performed until failure at a rate of 5 mm/min using a load cell of 50 N at room
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34 97 temperature (20°C). **With the average cross section area previously given**, an average Young's
35
36 98 modulus of $3.84 \pm^{1.3} \text{GPa}$, a stress and a strain at break of $173.4 \pm^5 \text{MPa}$ and $5 \pm^{0.5} \%$ respectively,
37
38 99 were found.

41 100 **2.3 Elaboration of the composite material**

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43
44 101 Composites reinforced with Alfa fibres were prepared by compounding neat polypropylene.
45
46 102 ~~Short fibres are of a length between 1 and 2 mm.~~ The fibre percentage in the matrix was
47
48 103 fixed at 15 wt.%. The PP and the Alfa fibres were mechanically mixed in, using a single screw
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50 104 extruder at temperature of 190°C . After cooling at room temperature, the strands from the
51
52 105 extruder were pelletized. Then, using these mixed pellets, tensile specimens were moulded
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54 106 using a Battenfeld HM 80 injection-moulding machine. The geometric properties of the tensile
55
56 107 specimen follow the ISO 3167 norm.

2.4 Determination of the diameter and length of fibres after extrusion and after injection

To find out the influence of the extrusion and injection processes on the dimensions of the fibres, a microscopic analysis of the Alfa/PP composites after these two steps of elaboration has been performed. Film samples were prepared using a hydraulic press under a pressure of 3 bars for a duration of 2 minutes at a temperature of 190° C, from (i) the pellets obtained after extrusion and (ii) a portion of a tensile specimen after injection. From these film samples, 250 measurements of diameter and length of fibres were recorded. The dimensions (diameter and length) of the Alfa fibre were reduced after each process. Initially, the raw fibres have an average diameter of 185 μm which decreases from 70.8 μm after extrusion to 40 μm after injection step. The raw fibres have an initial length between 1 and 2 mm which decreases from 444.1 μm after extrusion to 273 μm after injection step.

3 Mechanical characterisation

To compare the mechanical behaviour of the virgin PP and Alfa/PP composite, several tests were performed under tension: monotonic tensile tests, cyclic loading/unloading tensile tests and loading/unloading tensile tests interrupted by relaxation phases (multi-step relaxation tests). The first aim of these tests is to better understand the macroscopic mechanical behaviour of these composites during the cyclic test which is rarely analysed. The second objective is to have a maximum amount of data to compare the simulation results using the HVH model with these experimental tests.

Tensile tests were carried out using the universal testing machine Instron 5560, equipped with a standard load cell of 10 kN and an extensometer with an initial gauge length of $L_0 = 10$ mm. These tests were performed with an engineering strain rate of $\dot{\epsilon} = 4.10^{-4}\text{s}^{-1}$. For each test, at least three specimens are used to check the reproducibility of the results. The curve that passes at the maximum through the middle of the three experimental curves is chosen as representative of the behaviour.

In this paper, when not stated otherwise, all the experimental curves presented were based

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6 135 on the Cauchy stress and Almansi strain. Assuming that the transformation is isovolume, the
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8 136 Cauchy stress is given by: $\sigma_{Cauchy} = \frac{F}{S_0} \frac{L}{L_0}$, with L is the final length of the extensometer, L_0
9
10 137 is the initial length of the extensometer, F is the measured load and S_0 the initial specimen
11
12 138 section. The Almansi strain is obtained by: $\epsilon_{Almansi} = \frac{1}{2} \frac{L^2 - L_0^2}{L^2}$.

139 3.1 Monotonic tensile tests

140 The first experiment performed was the standard monotonic tensile test with a constant strain
141 rate $\dot{\epsilon}$. A comparison of the two material responses is presented in Figure 2. In the case of PP,
142 a break never occurred at a strain of 0.35. Young modulus and the maximum stress have been
143 increased for the Alfa/PP (E=1.103 GPa with PP and E=1.766 GPa with Alfa/PP). However,
144 the Alfa/PP only supports a small deformation (near 0.08) and the break occurs quickly after
145 the maximum stress is reached.

146 A specimen surface of the Alfa/PP was observed by SEM after the break at the end of a tensile
147 test (see Figure 3). **The fibre surface was damaged after the break. This result shows a relatively**
148 **poor adhesion between the polymer matrix and the fibres at this strain level. This adhesion**
149 **can be improved with a stronger chemical treatment but it will be in contradiction with the**
150 **environmental point of view whose the aim is to achieve interesting composite characteristics**
151 **with low-treated fibres.** To compare **experimentally and numerically** the two materials in the
152 same conditions, the maximum strain imposed in the following tests will be restricted to 0.05.

153 3.2 Loading-unloading tests with 50 cycles

154 To study the mechanical behaviour of the two materials under cyclic deformation loads, a
155 further tension test was performed with cyclic loads. During cyclic test presented in Figure 4,
156 the specimen was stretched up to the maximum engineering strain of 4.6% and then unloaded
157 down to zero stress. To clearly compare the mechanical behaviour of PP and Alfa/PP, only
158 the first, the tenth and the last cycle are shown in Figure 4.

159 With the two materials, the responses obtained during loading and unloading are strongly
160 nonlinear. The remanent strain increases after each cycle. The maximum stress also decreases
161 at the end of each cycle for a given strain level. The area of the hysteresis loop is reduced after

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6 each cycle and is almost similar between the two materials.
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9 10 **3.3 Multi-step relaxation tests** 11

12 During an loading-unloading test, the test was interrupted at prescribed levels of axial strain
13 ε_r for a given holding time of 900 s (see Figure 5). It is assumed that the stress evolution as
14 function of time is much lower after 900 s, because of this the evolution was ignored after 900
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20 During this holding time, the load evolution was stored. The loading phase was interrupted by
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22 3 relaxation phases at strain levels of $\varepsilon_r = 1, 2.8$ and 4.6% . The unloading phase is interrupted
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24 by 2 relaxation phases at strain levels of $\varepsilon_r = 3.7$ and 2.8% . The multi-relaxation tests were
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26 performed at a strain rate of $\dot{\varepsilon} = 4.10^{-4}\text{s}^{-1}$.
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28 The results show that the stress decreases during the holding time in the loading path while
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30 an increase is observed during the holding time in the unloading path. Note that, during the
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32 holding time, the stress evolves towards a stabilized value which gives the relaxed-response. This
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34 kind of test constitutes an attractive way of identifying the material parameters corresponding
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36 to the three stress components included in the HVH model (see section 5). The amplitude of
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38 the relaxation phase at a given strain level ε_r is more large for the Alfa/PP than the PP, as
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40 indicated by the distances 1 and 2 in Figure 5(a), which is due ot the fact that during the
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42 loading step, the relaxation phase is higher with the Alfa/PP, whereas during the unloading
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44 step, the relaxation phase is almost similar between the two materials.
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48 **4 Hyperelasto-Visco-Hysteresis behaviour model** 49

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51 The macroscopic behaviour of solid materials is most often the result of simultaneous actions,
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53 at the relevant scales of reversible physical phenomena and irreversible physical phenomena.
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55 To describe the macroscopic properties of the global behaviour related to these physical phe-
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57 nomena, an assumption has been adopted which states that the internal stress power system
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59 results from the decomposition of this power in several contributions in stress. Each of these
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61 contributions is related to a particular physical phenomenon. From the results of the previous

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6 188 tests, the mechanical response of the two materials studied exhibits three classical main phe-
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8 189 nomena, namely a reversible elastic phase which occurs at the onset of the loading (hyperelastic
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10 190 response), a strain rate dependent phase which can be described in terms of the viscosity, and
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12 191 an irreversible plastic phase (hysteresis response) which occurs during the loading-unloading
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14 192 cycles.

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16 193 If the processes of hysteresis, reversibility and viscosity are simultaneous, it is assumed that
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18 194 the stress power or the rate of internal mechanical work \mathcal{P}_{int} , which describes the response of a
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20 195 material domain \mathcal{D} , occupying a volume v , at time t , effected by the stress field $\boldsymbol{\sigma}$ can then be
21
22 196 split into three contributions as, the internal stress powers of the hyperelastic \mathcal{P}_e , viscoelastic
23
24 197 \mathcal{P}_v and hysteresis components \mathcal{P}_h as follows:

$$\begin{aligned} \mathcal{P}_{int} &= \mathcal{P}_e + \mathcal{P}_v + \mathcal{P}_h \\ \int_{\mathcal{D}} (\boldsymbol{\sigma} : \mathbf{D}) dv &= \int_{\mathcal{D}} (\boldsymbol{\sigma}_e : \mathbf{D}) dv + \int_{\mathcal{D}} (\boldsymbol{\sigma}_v : \mathbf{D}) dv + \int_{\mathcal{D}} (\boldsymbol{\sigma}_h : \mathbf{D}) dv \quad (1) \\ &= \int_{\mathcal{D}} ((\boldsymbol{\sigma}_e + \boldsymbol{\sigma}_v + \boldsymbol{\sigma}_h) : \mathbf{D}) dv \end{aligned}$$

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35 198 where $\boldsymbol{\sigma}$ is the Cauchy stress tensor, \mathbf{D} is the strain rate tensor, $\boldsymbol{\sigma}_e$ is the stress associated with
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37 199 the reversible hyperelastic behaviour, $\boldsymbol{\sigma}_v$ is associated with the viscoelastic behaviour and $\boldsymbol{\sigma}_h$
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39 200 with the non-viscous hysteresis behaviour, always irreversible and of the elasto-plastic type.

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41 201 The strain rate \mathbf{D} is independent on these phenomena and the total stress applied to the
42
43 202 material is, therefore, the result of the superimposed hyperelastic, viscoelastic and hysteresis
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45 203 stress components:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}_e + \boldsymbol{\sigma}_v + \boldsymbol{\sigma}_h \quad (2)$$

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49 204 This basic assumption gives our macroscopic approach a strong relationship with the physical
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51 205 processes involved. However, it leads to a conceptual break from constitutive and thermody-
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53 206 namic views compared to the classical elasto-plasticity approach, which advocates the decom-
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55 207 position of the total strain $\boldsymbol{\varepsilon}$ or of the strain rate \mathbf{D} . However, this approach interests more
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57 208 and more authors, as the literature shows that is becoming increasingly common, especially for
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59 209 polymer behaviour modelling [23, 24, 25, 26].

60
210 The fundamental assumption (eq. 2) which involves three basic contributions $\boldsymbol{\sigma}_e$, $\boldsymbol{\sigma}_v$ and $\boldsymbol{\sigma}_h$
211 sets a framework of a phenomenological model of the Hyperelasto-Visco-Hysteresis type (HVH

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6 212 model). The HVH model has been successfully applied to a fluoro-elastomer [15, 16, 27] and
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8 213 the PPC7712 in previous works [11, 12]. In the following, we will briefly recall the three stress
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10 214 contributions used. One of the main contributions of this paper is to give a new method of
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12 215 identification of material parameters in the HVH model.

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14 216 The non-linear behaviour of the polymer requires the establishment of finite deformation
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16 217 formalism for writing and implementing the constitutive laws. To implement the HVH model
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18 218 in a numerical schema, a 3D finite deformation framework has been developed in a finite
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20 219 element software, called HERZ++ [14]. An Eulerian formulation, the Cauchy stress tensor,
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22 220 the Almansi strain tensor and the Jaumann time derivative of the stress are chosen for this
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24 221 purpose.

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26 222 For further details about the Hyperelasto-Visco-Hysteresis model, see [11, 12].
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30 223 **5 Identification of the material parameters**

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33 224 In a previous study [11], the identification method of the material parameters of the HVH
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35 225 model was performed using a numerical procedure by inverse analysis through an experimental
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37 226 database consisting of tensile tests, relaxation tests and cyclic loading-unloading tests. This
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39 227 complicated method using all experimental tests simultaneously, leads unfortunately, to several
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41 228 possible sets of material parameters and cannot really differentiate between the different stress
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43 229 contributions of the HVH model. Finally, this method is difficult to use for industrial purposes.

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45 230 In this paper, a new identification method of material parameters is proposed. It is easier
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47 231 to use and only requires the multi-step relaxation tests, presented in Figures 5 and 6. This
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49 232 identification method, proposed in [16] but with a rubber material, is direct and does not
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51 233 require the use of software by inverse analysis. It is performed in two steps. The first identifies
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53 234 the hyperelastic and hysteretic contributions, considering only the end of the relaxation periods
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55 235 corresponding to the equilibrium hysteretic state (as described by [28]), that is independent
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57 236 of the strain rate (cf blue points in Figure 6). In the second step, the viscous parameters are
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59 237 determined from one relaxation phase of the multi-step tests. Analytical identification is then
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238 used to obtain the characteristic times of the three Maxwell elements.

5.1 Hyperelastic and hysteretic contributions

The viscous stress σ_v , hyperelastic stress σ_e and hysteretic stress σ_h components are presented in Figure 6 at a given strain ε_0 , based on the experimental results shown in Figure 5. The equilibrium state $\sigma_\infty = \sigma_e + \sigma_h$ can be obtained by connecting all the converged asymptotic stress values recorded at the end of the relaxation periods of each corresponding strain level. Assuming that the viscous stress σ_v reaches its steady state at the end of these relaxation phases, σ_∞ will be composed of the hysteresis stress component σ_h and the hyperelastic stress component σ_e and will give the blue curve in figure 6. With this assumption of stress decomposition, identification of the material parameters of hyperelastic and hysteresis contributions is direct using a simple manual identification process through several numerical trials with initial values of material parameters initially obtained in [11]. Experimental boundary and loading conditions are simulated with HERZ++ on a single hexahedral finite element to reproduce the assumed homogeneous state at the centre of the specimen.

The obtained material parameters values are reported in Table 2. The bulk viscosity K is fixed to 2000 MPa for the two materials, as previously used in [11]. Figure 7 show the comparison between experimental equilibrium responses and model predictions in the case of PP and Alfa/PP respectively. The identified material parameters are in the same of order of our previous works in the case of PP [11, 12]. The main contribution in the stress-strain response is still controlled by the hyperelastic part for the PP and Alfa/PP.

5.2 Viscous contribution

Viscous parameters of the three Maxwell elements are analytically calculated from the second relaxation phase for a strain level of 2.8% (Figure 6). First, the characteristic times of each branch τ_i are determined graphically on the experimental relaxation stress-strain curve by removing the loading phase (Figure 8). Each time t_i of the i basic Maxwell elements is taken so that it verifies the relation $4\tau_i < t_{i+1}$ for $i \in [1, k - 1]$ which ensures that each branch is almost independent.

265 The viscous contribution is the sum of the three Maxwell elements:

$$\sigma_v(t) \approx \sum_i^{n=3} \sigma_i(t) \quad (3)$$

266 Knowing that each Maxwell element satisfies: $\sigma_i(t) = \sigma_i \exp\left(\frac{-t}{\tau_i}\right)$ and the value of σ_i is given
 267 by: $\sigma_i = \sigma_{0i} \exp\left(\frac{t_i}{\tau_i}\right)$ where each value of σ_{0i} and slope of the characteristic time τ_i is obtained
 268 graphically from Figure 8.

269 The stiffness E_i and the viscosity η_i of each Maxwell element are then obtained from the
 270 following equation:

$$E_i = \frac{\sigma_i}{D\tau_i \left(1 - \exp\left(\frac{-t_{ch}}{\tau_i}\right)\right)} \text{ et } \eta_i = E_i\tau_i \quad (4)$$

271 where t_{ch} corresponds to the loading time necessary to reach a strain of 2.8% and D is the
 272 strain rate during this loading phase.

273 The viscous parameters of the three Maxwell elements are presented in Table 3. In all
 274 simulations, the Poisson coefficients, necessary for 3D formulation, are arbitrarily selected as
 275 $\nu_1 = \nu_2 = \nu_3 = 0.4$. Comparison between parameters in Table 3 shows that the second and
 276 third viscous parameters are different between the two materials. The results of the viscous
 277 parameter identification are presented in Figure 8.

278 6 Simulations using the HVH model

279 Using the hyperelastic and hysteretic parameters of Table 2 and the viscous parameters of Table
 280 3, comparisons between experimental and model predictions for the tension tests interrupted by
 281 relaxation steps are presented in Figures 9 and 10 in the case of PP and Alfa/PP, respectively.

282 The results of the identification correlated well with the experimental data. A good corre-
 283 lation can be observed during the relaxation steps during the loading and unloading phases.
 284 However, especially in the case of the Alfa/PP, after the first loading and relaxation phase, a
 285 discrepancy is observed between the experimental and numerical results during the two loading
 286 steps. This is probably due to the fact that the viscosity in this material is strongly non-linear

287 whereas in the HVH model, the viscous contribution, using a generalised Maxwell's model is
288 not dependent on the level of strain or stress.

289 To verify the pertinence of the HVH model under various loading conditions, based on the
290 parameters herein identified in the case of the PP and Alfa/PP materials, simulations of ex-
291 perimental tests previously presented in section 3 are performed. The numerical simulations of
292 the complex loading test are carried out in the HEREZH++ software. Experimental boundary
293 conditions are reproduced in a single hexahedral element by imposing experimental loading.

294 Firstly, the numerical results of the monotonous tensile tests are compared with experimental
295 data in Figure 11. In these figures, the effect of the hyperelastic, viscous, and hysteresis
296 contributions are presented. The hysteresis contribution is low whereas the hyperelastic and
297 viscous contributions are the highest. This monotonous tensile test shows that the effect of
298 the viscous part is non-negligible in this kind of test. The discrepancy with the experimental
299 results at the end of the loading is due to the limitations of the linear viscoelastic contribution
300 with Maxwell branches used in the HVH model.

301 The loading/unloading test with 50 cycles is also numerically simulated. Comparisons with
302 experiments are shown in Figure 12. Good agreement was found to exist between the ex-
303 perimental and numerical data obtained in these cyclic tests. In the case of the Alfa/PP,
304 some significant differences were observed during the loading steps, as already observed in the
305 monotonous tensile test, however the hysteresis loops are relatively well described for all tests
306 with the two materials.

307 The identification method developed here has shown its efficiency to be able to simulate the
308 mechanical behaviour in simple and cyclic tensile tests. This method is simple and rapid in
309 comparison with the previous used in [11]. However, it appears that an improvement of the
310 viscosity contribution in the HVH model is necessary to enhance the results obtained.

311 7 Conclusion

312 In this paper, a semi-crystalline polymer (PP) reinforced with natural Alfa fibres was studied.
313 The elaboration and the treatment to improve the adhesion of fibres/matrix in the Alfa/PP
314 blend were presented. Several mechanical tests for different loading targets (monotonic tensile

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6 315 tests, cyclic tensile tests and multi-step relaxations tests) were carried out. The experimental
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8 316 results showed a good adhesion between the polymer matrix and the Alfa fibres and a strong
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10 317 influence of the presence of fibres on the mechanical behaviour of PP. These tests were subse-
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12 318 quently used as an experimental database to identify the material parameters of a Hyperelasto-
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14 319 Visco-Hysteresis model. A new identification method, rapid and simple, already used for the
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16 320 simulation of the elastomers behaviour, has shown its efficiency in simulating the mechanical
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18 321 responses of the PP and Alfa/PP during all the experimental cyclic tests. Some limitations in
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20 322 the viscous part with a generalised Maxwell's model were observed during the loading phases.
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22 323 The improvement of the viscous part of the HVH model seems important due to the fact that
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24 324 the viscosity of polymer material is strongly non-linear as a function of the strain or stress level.
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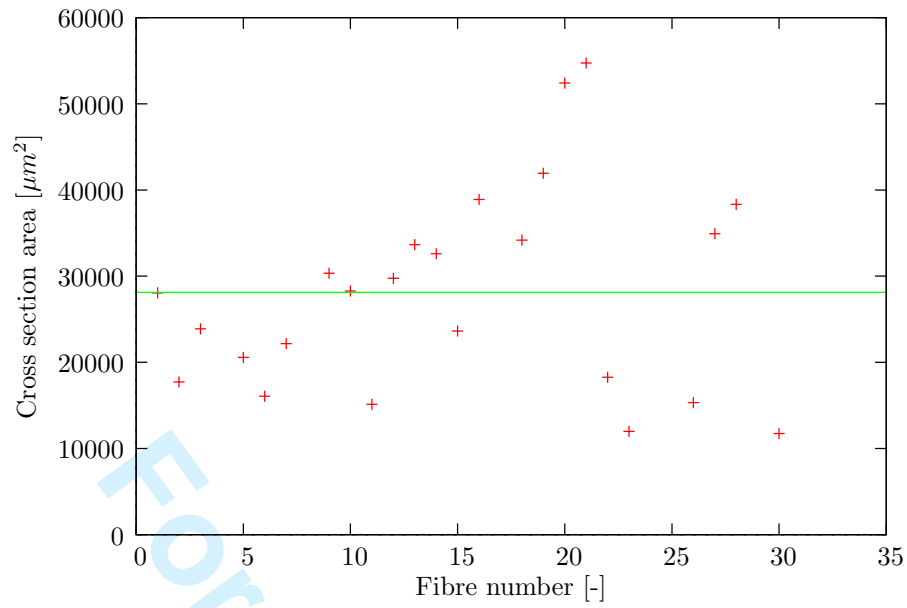


Figure 1: Distribution of the cross sectional area as function as the fibre number (in green the average value).

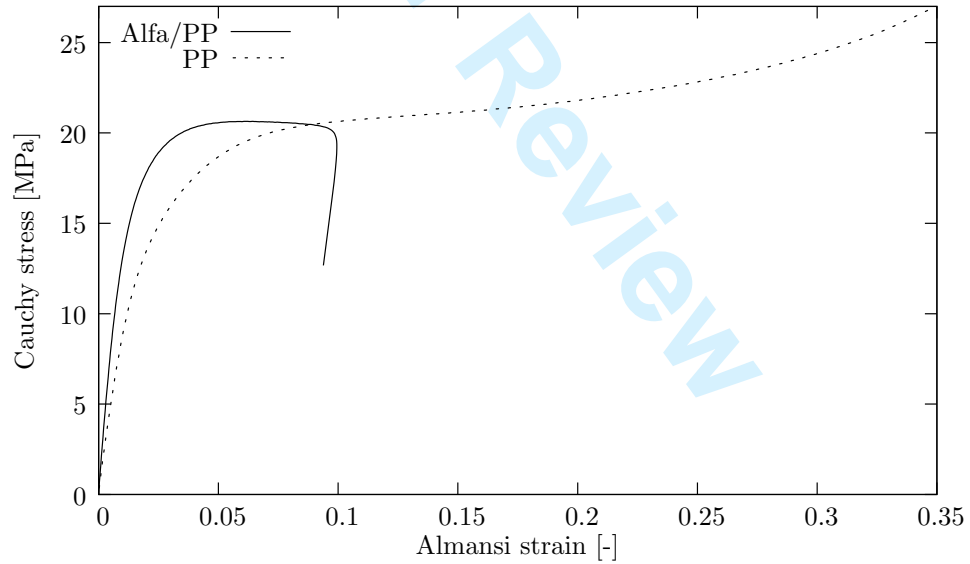


Figure 2: Comparison of PP and Alfa/PP material responses in the monotonic tensile test.

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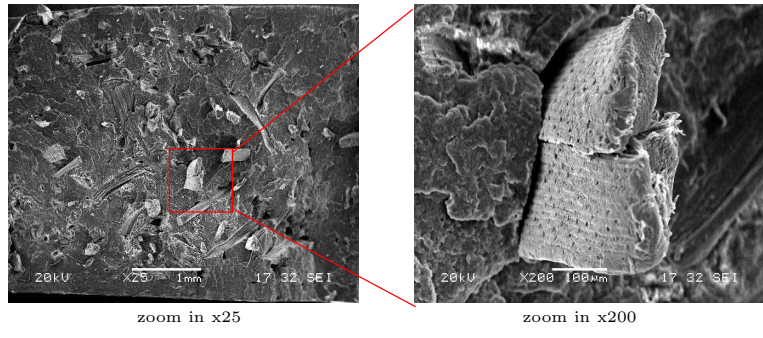


Figure 3: Scanning Electron Microscopic analysis on a specimen surface after the break of a tensile test.

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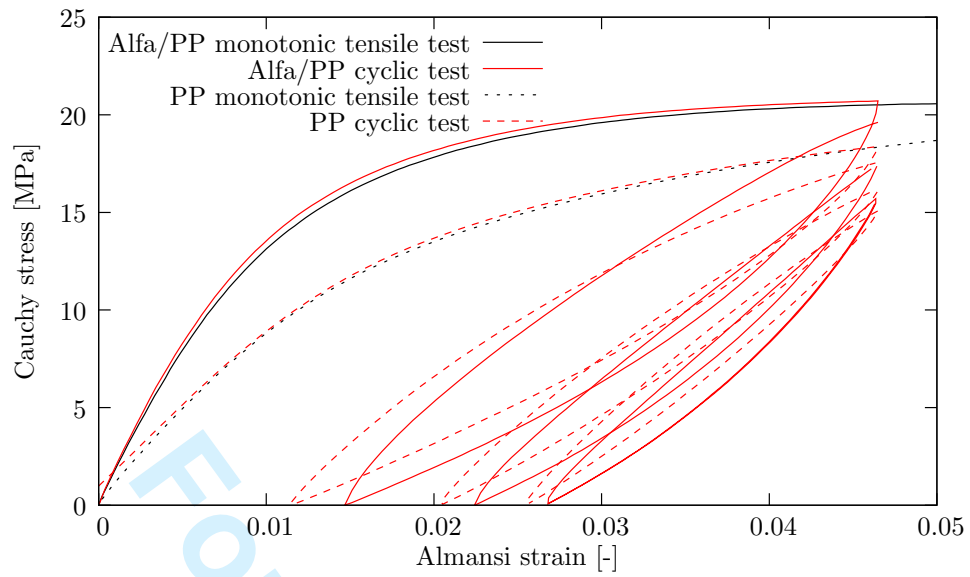


Figure 4: Comparison of PP and Alfa/PP material responses in the loading/unloading test with 50 cycles (only the first, the tenth and the last cycle are presented).

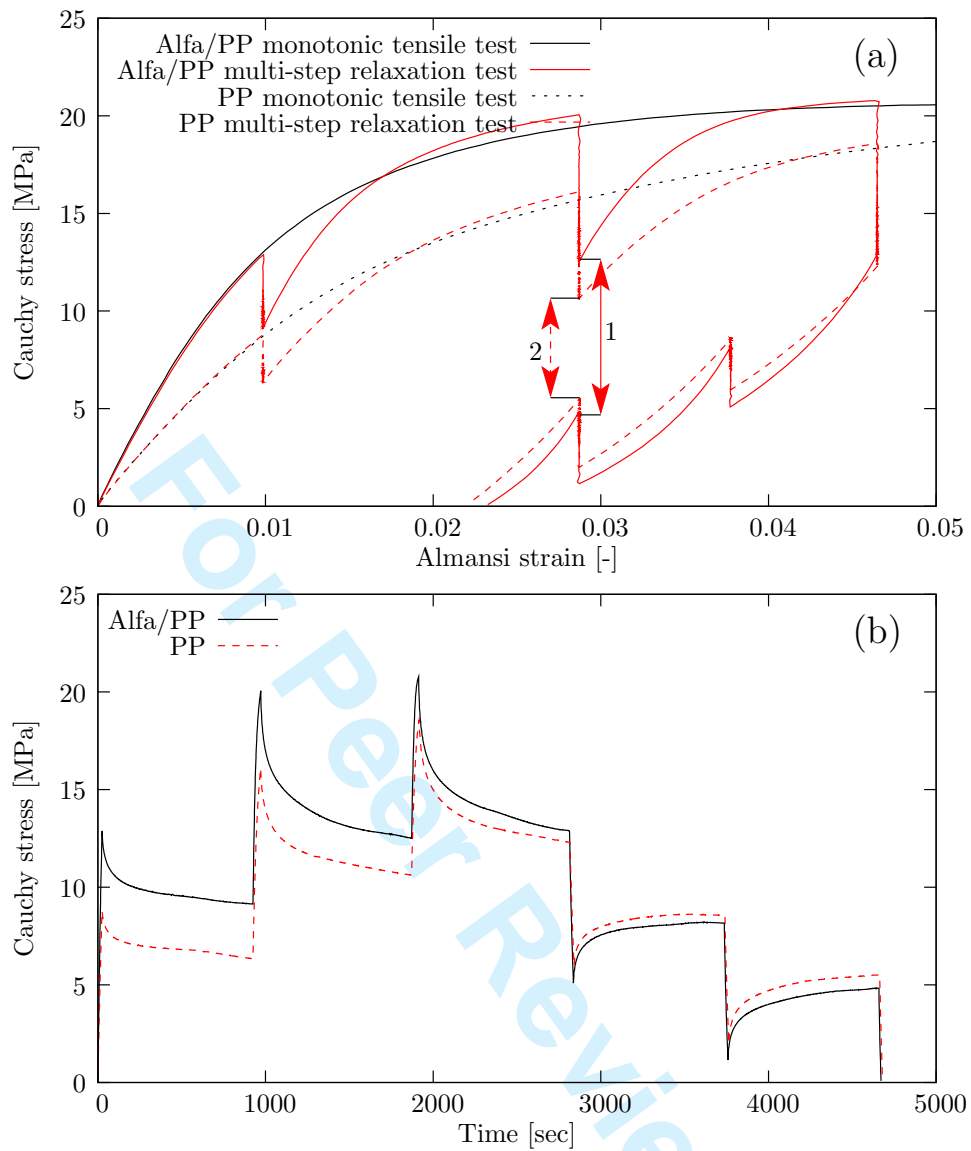


Figure 5: Comparison of PP and Alfa/PP material responses in the multi-step relaxation test.

(a) Stress-strain response. (b) Stress-time response.

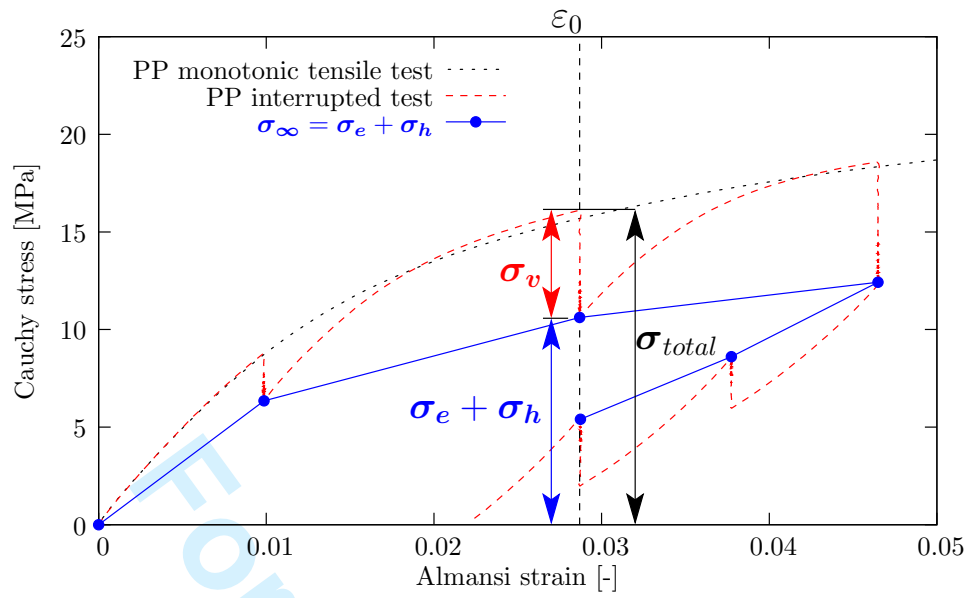


Figure 6: Example of estimated viscous σ_v , hyperelastic σ_e and hysteretic σ_h contributions from the loading/unloading test interrupted by relaxation phases.

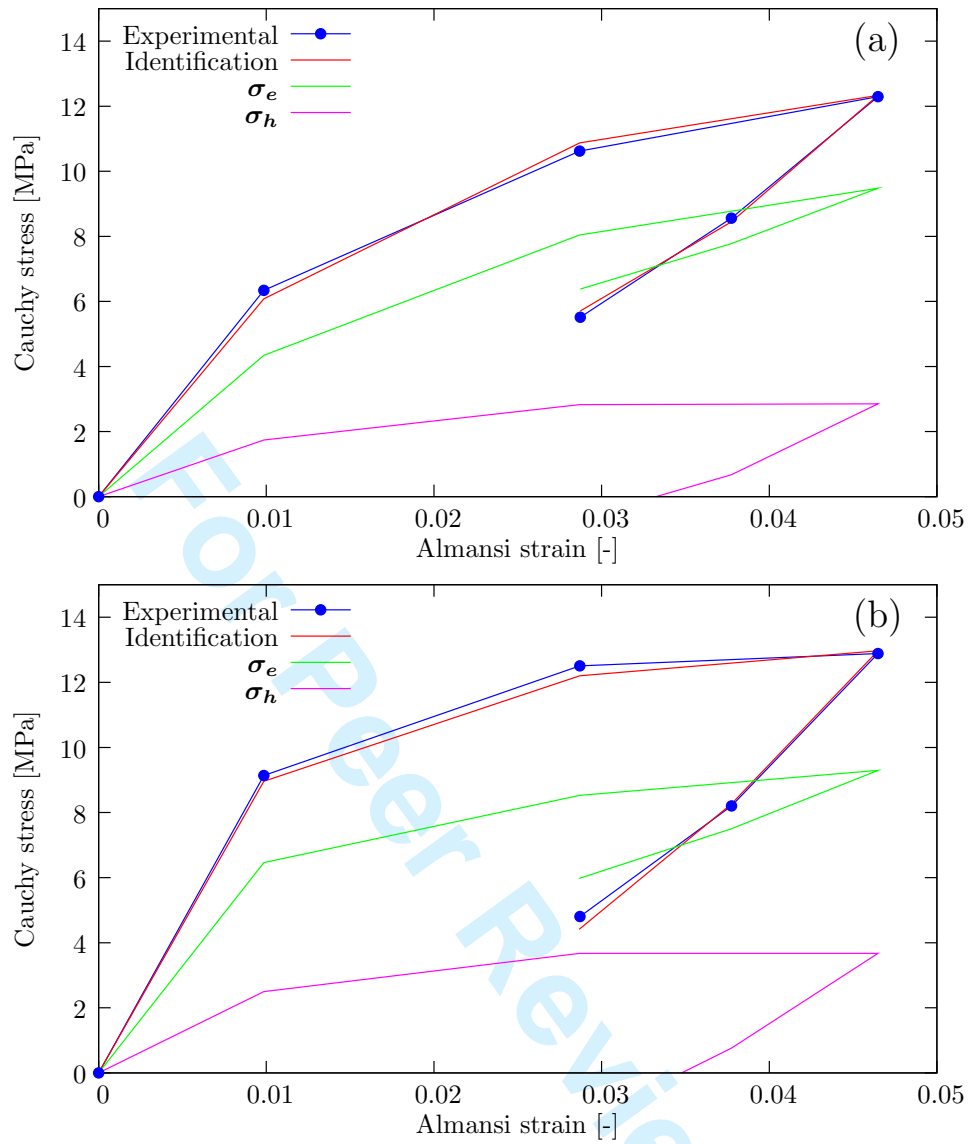


Figure 7: Identification of the hyperelastic and hysteresis contributions from the end points of relaxation phases in the case of : (a) PP and (b) Alfa/PP.

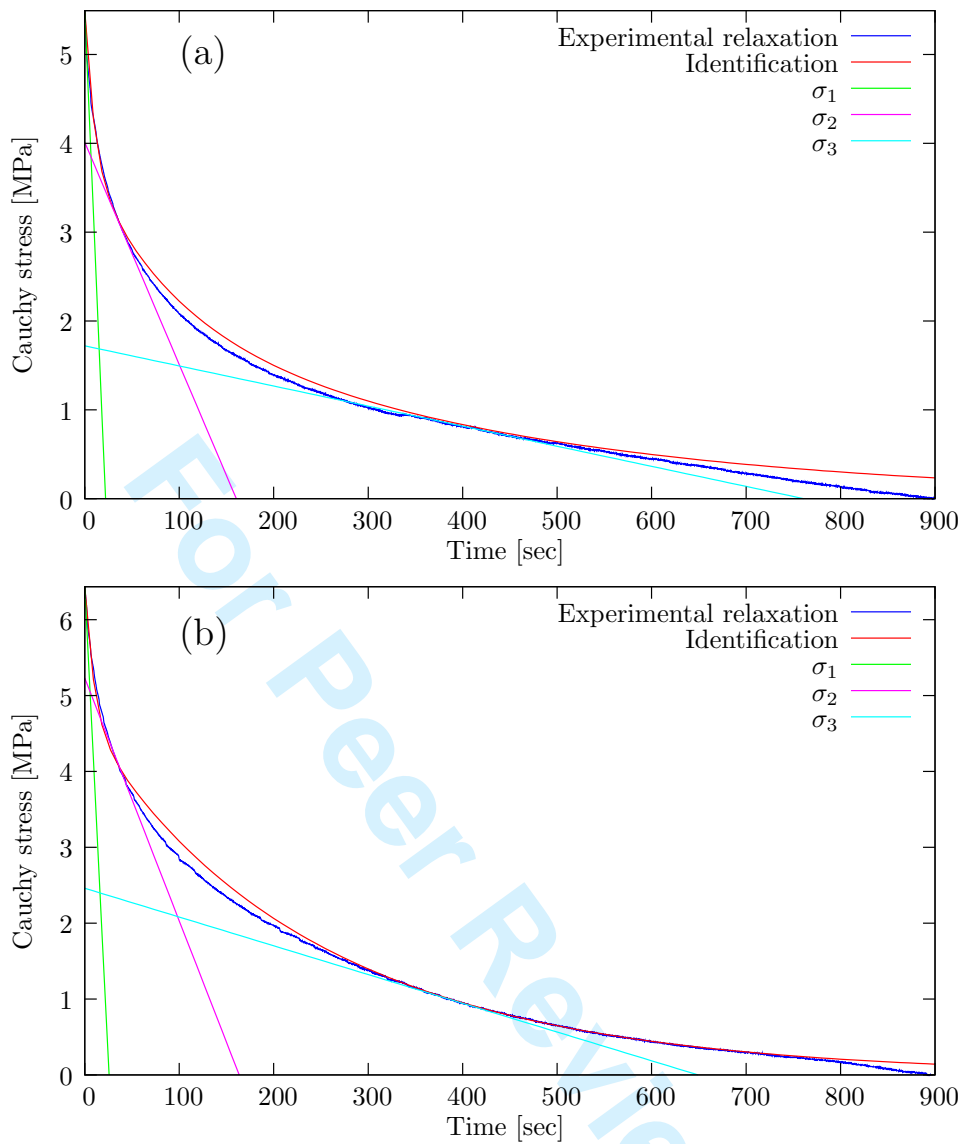


Figure 8: Identification of the slope of the three Maxwell elements and final identification of the viscous contribution during the relaxation phase in the case of : (a) PP and (b) Alfa/PP.

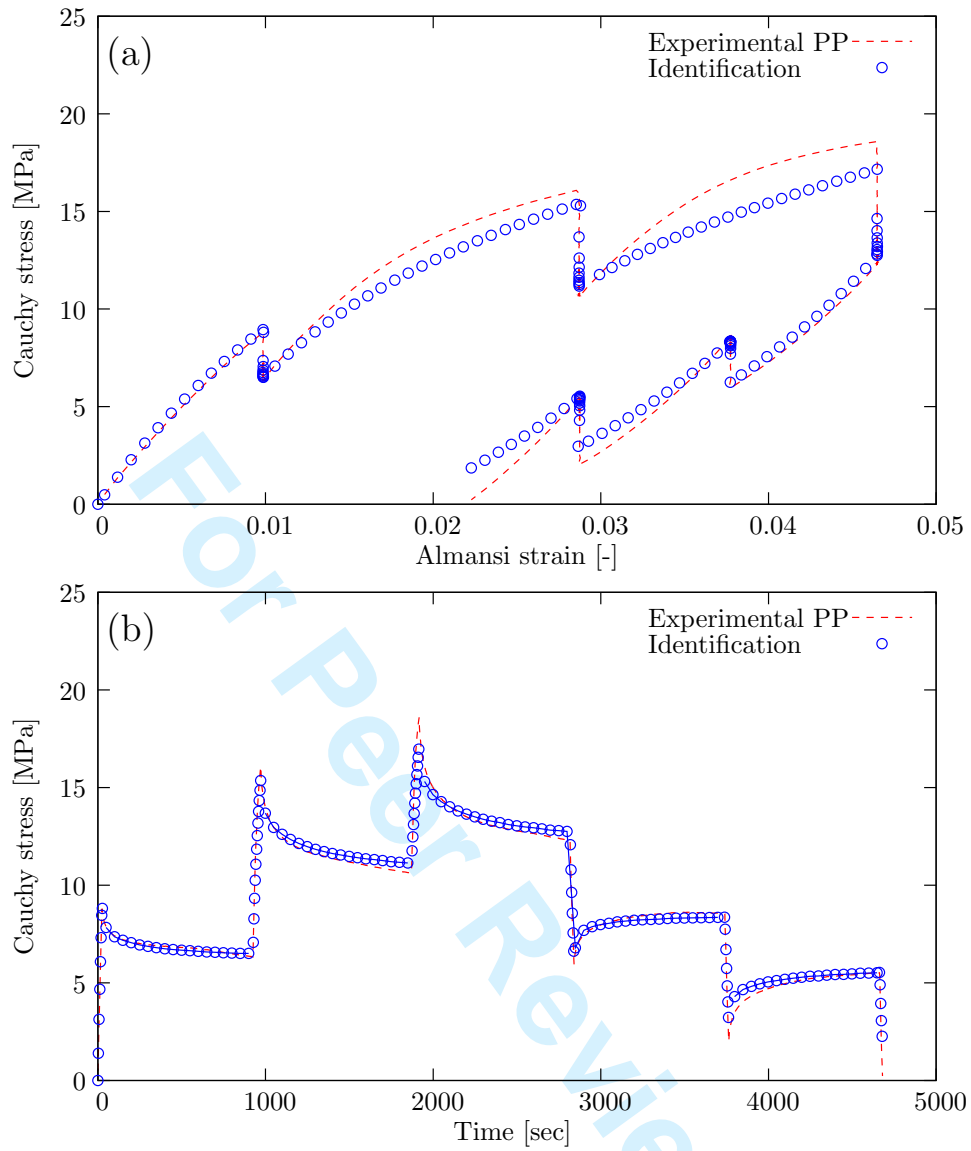


Figure 9: Comparison between experimental and identification in the loading/unloading test interrupted by relaxation steps in the case of the PP. (a) Stress-strain response. (b) Stress-time response.

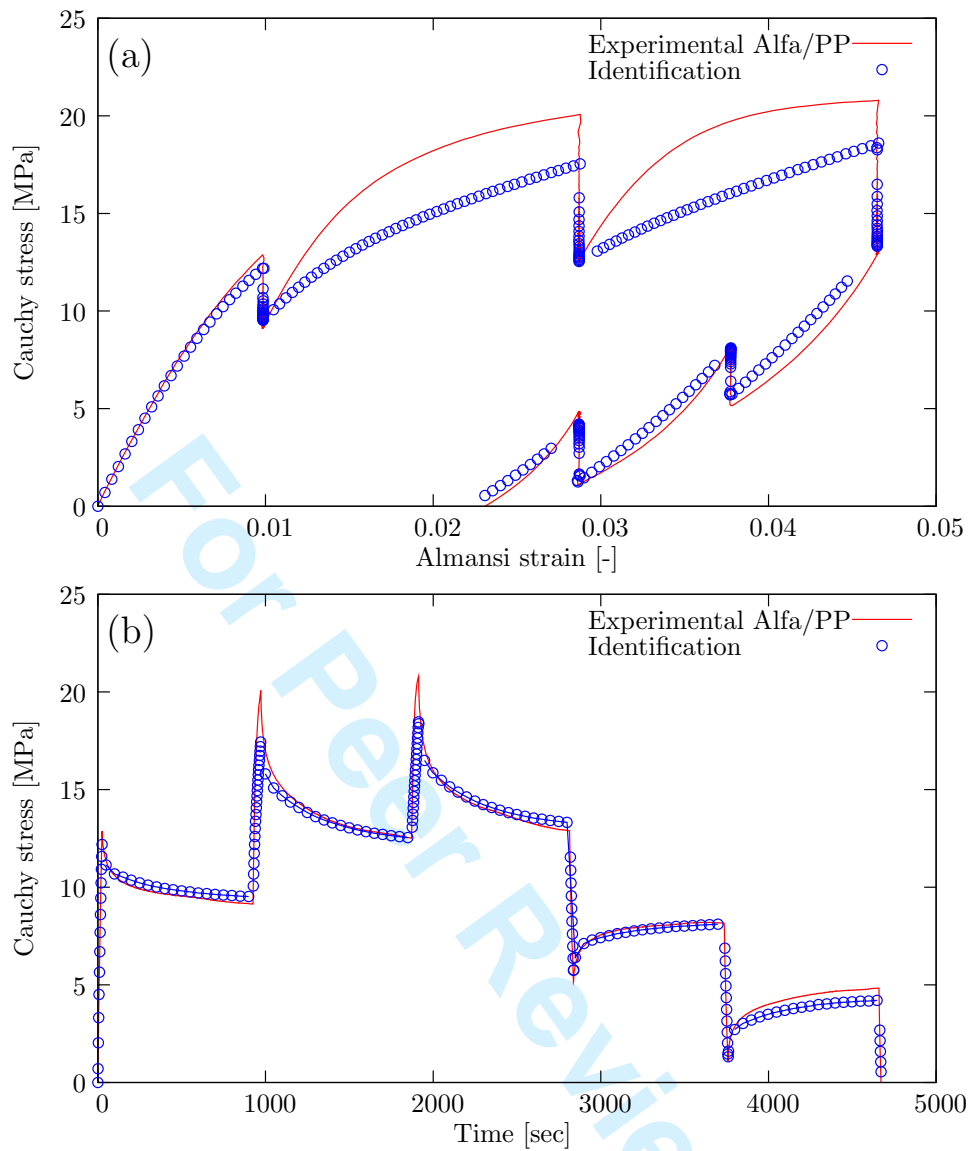


Figure 10: Comparison between experimental and identification in the loading/unloading test interrupted by relaxation steps in the case of the Alfa/PP. (a) Stress-strain response. (b) Stress-time response.

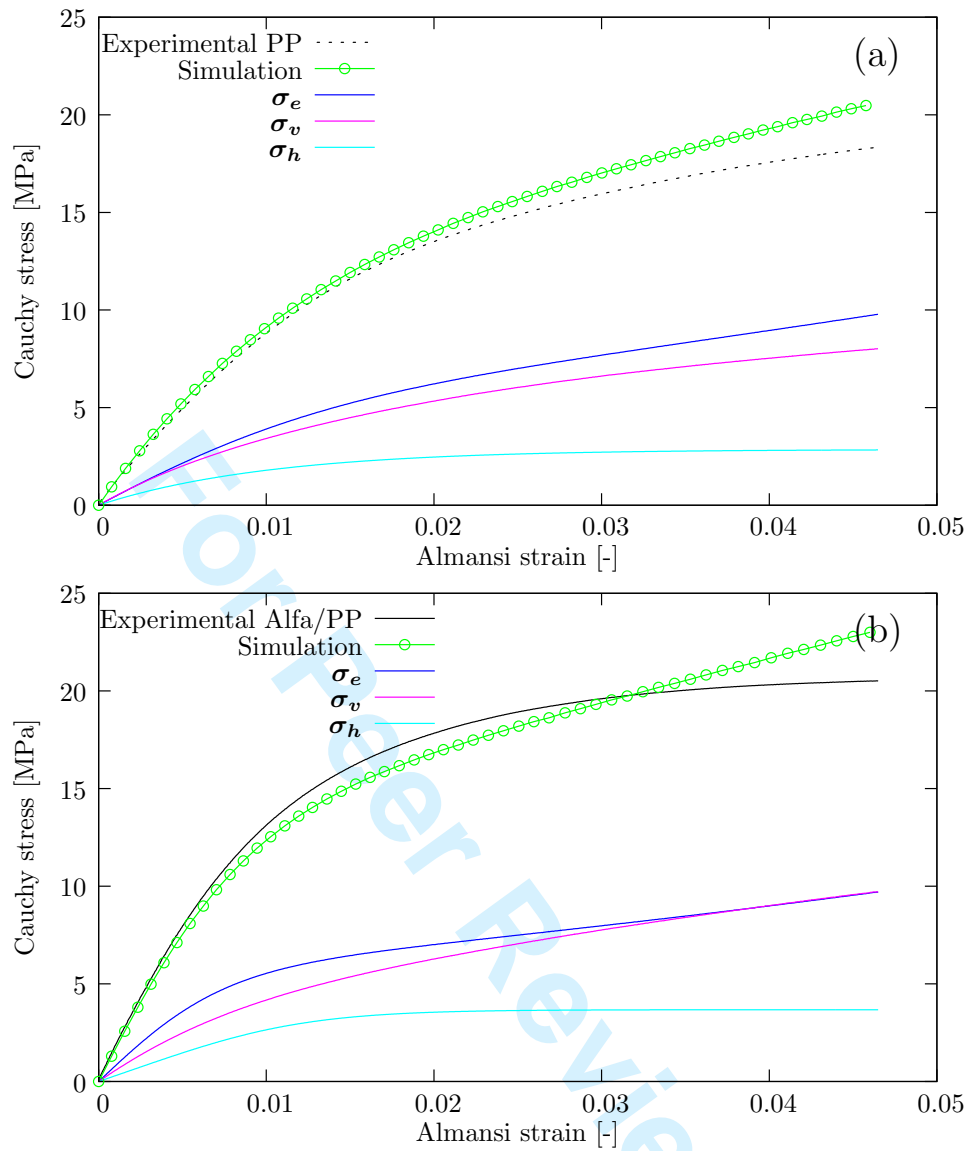


Figure 11: Numerical simulation of the monotonous tensile test in the case of : (a) PP and (b) Alfa/PP. Influence of the hyperelastic stress contribution σ_e , viscous stress contribution σ_v and hysteresis stress contribution σ_h .

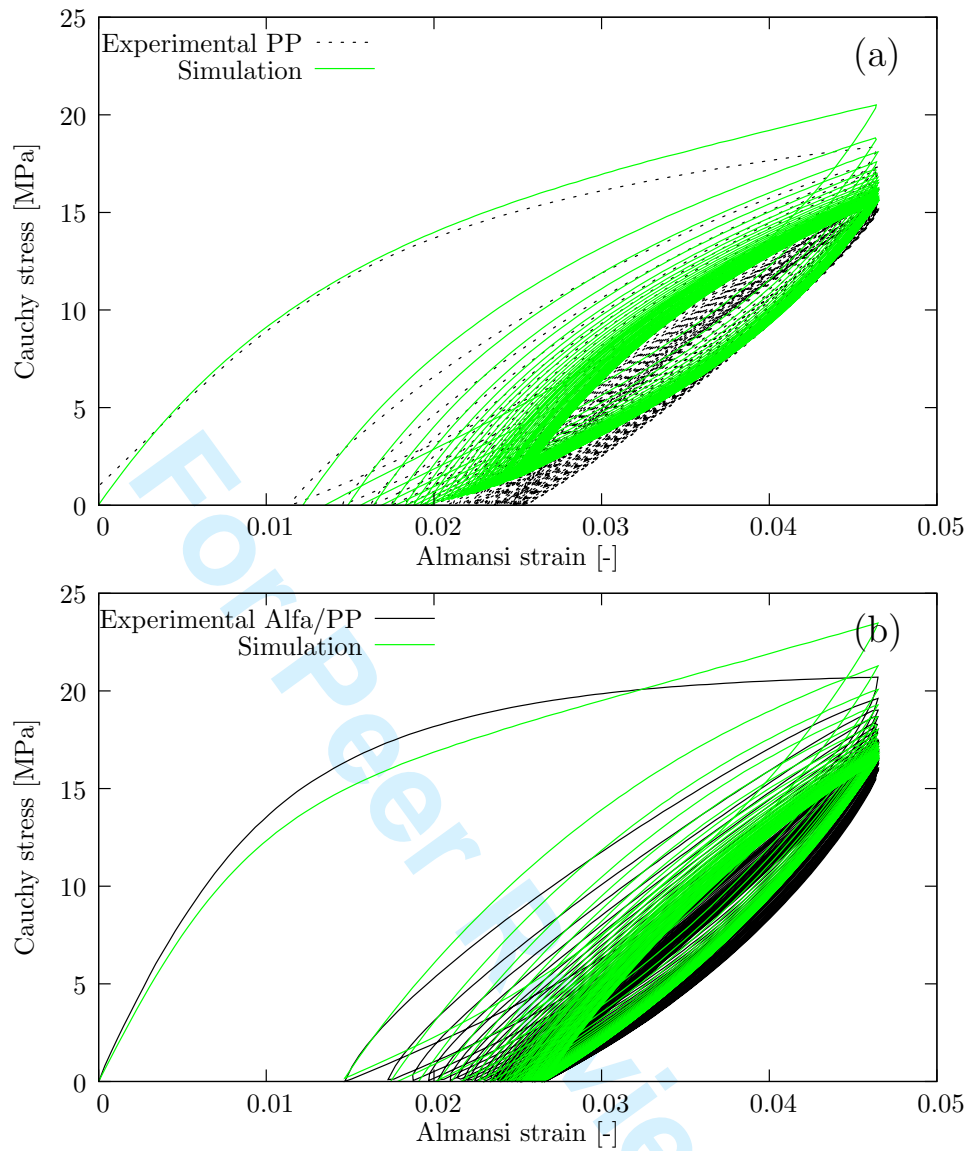


Figure 12: Numerical simulation of the loading/unloading test with 50 cycles in the case of :
(a) PP and (b) Alfa/PP.

| Properties | Values |
|---|--------|
| Melt flow index MFI(g/10 min) | 13 |
| Molecular weight Mw (g/mol) | 229527 |
| Crystallinity ratio (%) | 34.2 |
| Tensile modulus (MPa) | 1280 |
| Yield stress (MPa) | 19 |
| Charpy impact strength (kJ/m ²) | 7 |

Table 1: Thermo-mechanical characteristics of the PPC7712 copolymer at 20° C[11].

| | Hyperelastic parameters (in MPa) | Hysteretic parameters (in MPa) |
|---------|--|---|
| PP | $Q_{0r} = 3.9$ $\mu_0 = 120$ $\mu_\infty = 27$ | $n_p = 0.9 (-)$ $\mu_h = 160$ $Q_0 = 3.5$ |
| Alfa/PP | $Q_{0r} = 4.5$ $\mu_0 = 300$ $\mu_\infty = 17$ | $n_p = 2.5 (-)$ $\mu_h = 170$ $Q_0 = 4.5$ |

Table 2: Hyperelastic and hysteresis parameters identified in the case of PP and Alfa/PP.

| | 1 st Maxwell branch | 2 nd Maxwell branch | 3 rd Maxwell branch |
|---------|--------------------------------|--------------------------------|--------------------------------|
| PP | $E_1 = 277$ (MPa) | $E_2 = 72$ (MPa) | $E_3 = 82$ (MPa) |
| | $\eta_1 = 2764$ (MPa.s) | $\eta_2 = 6043$ (MPa.s) | $\eta_3 = 32942$ (MPa.s) |
| | $\tau_1 = 9.97$ (s) | $\tau_2 = 83.93$ (s) | $\tau_3 = 401.73$ (s) |
| Alfa/PP | $E_1 = 283$ (MPa) | $E_2 = 16.7$ (MPa) | $E_3 = 163$ (MPa) |
| | $\eta_1 = 2812$ (MPa.s) | $\eta_2 = 1537$ (MPa.s) | $\eta_3 = 43184$ (MPa.s) |
| | $\tau_1 = 9.93$ (s) | $\tau_2 = 92.03$ (s) | $\tau_3 = 264.93$ (s) |

Table 3: Viscous parameters of three Maxwell branches obtained in the case of PP and Alfa/PP ($\nu_1 = \nu_2 = \nu_3 = 0.4$).