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Effects of strain rate and temperature on the mechanical behavior of carbon black reinforced elastomers based on butyl rubber and high molecular weight polyethylene

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ABSTRACT

The influence of the mechanical property and morphology of different blend ratio of Butyl rubber (IIR)/ high molecular weight polyethylene (PE) by temperature and strain rate are performed. Special attention has been considered to a ductile–brittle transition that is known to occur at around 60 °C. The idea is to explain the unexpected phenomenon of brittleness which directly related to all tensile mechanical properties such as the strength of blends, modulus of elasticity of filled and unfilled IIR-polyethylene blends. In particular, the initial Young's modulus, tensile strength and strain at failure exhibit similar dependency on strain rate and temperature. These quantities lowered and increased with an increment of temperature, whereas the increased with increasing of strain rate. Furthermore, the tensile strength and strain at failure decreases for all temperatures range with the increase of PE content in the blend, except Young's modulus in reverse. The strain rate sensitivity index parameter of the examined polymeric materials is consistent with the micro-mechanisms of deformation and the behavior was well described by an Eyring relationship leading to an activation volume of ~1 nm^3, except for the highest value of unfilled IIR ~8.45 nm^3.

Introduction

High molecular weight polyethylene material (PE), which is a subject of many studies, has been considered subset of the thermoplastic polyethylene. This polymer is known to have extremely long chain that helps in moving load more effectively to the polymer backbone. This is can be done by strengthening intermolecular interactions. The very high molecular weight of these materials provides the ability to make tie molecules which is the responsible for making an exceptional toughness for the polymers [1,2]. Utilizing from these facts, a very tough material has been successfully made of any thermoplastic material ever known.

The high durability and versatility of the (PE), makes it a favorite material for industry. Modification polymers through the polymer blending are used to tune its properties. PE is used to blend with IIR, as a bearing material. This will highly change its biomechanical properties to better ones. However, one of the limitations of these blends is the effect on the lifetime of the prosthetic devices [3]. Thermoplastic elastomers (TPEs) have been widely considered and used for their extra technological beneficial importance. Most of the TPEs are heterogeneous in their morphology that consists of hard and soft domains. This is what highly provides the material its elastomeric characteristics [4,5]. Of great interest for the effect of the mechanical properties of polymers by strain rate and temperature have been studied and known to significantly change the properties and tune the effect of these polymers. Characterizing the mechanical polymer behavior affected by the temperature and strain rate has been a subject of numerous experimental studies. Among these studies, Govaert [6] who investigated the strain rate, temperature and humidity effects on the tensile yield behavior of aliphatic polymers.

Detailed investigation of the tensile deformation of polyamide 6 (PA6) by strain rates and temperatures was performed by Gui-Fang Shan [7] has shown that the relationship between the first yield stress and temperature is nearly linear. On the other hand, the strain-rate shows a logarithmic dependence. Shih-Kai Cheng el al. [8] investigated the strain-rate effect of EVA/PMMA and its effect on the mechanical properties of the polymer. The measurements were carried out in situ polymerization for different blends. In these investigations, several mechanical properties were found to be higher for EVA/PMMA blends than those for pure PMMA. Chaves et al. [9] Roberto et al. [10], and Richeton et al. [11] conducted

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different experiments on phenolic resin blended with PP-EPDM-NBR, ethylene-propylene-diene rubber (EPDM) and (PC, PMMA and PAI) respectively. The previous studies were done to examine the mechanical properties effect by changing the blends. Also, Blumenthal et al. [12] had examined the response of PMMA deformation whereas Cady et al. [13] studied the mechanical effect of different polymers at relatively high temperatures. Bronnikov et al. for Polyethylene (PE), They found that the yield stress and elastic modulus decreased with increasing temperature and decreasing strain rate [14].

In the light of the above facts and studies, a new type of elastomer blends based on butyl rubber (IIR) and HMWPE are made. The effect of PE added amount on the change of the network structure, mechanical properties are studied and correlated. Also, the effect of strain rate and temperatures on the mechanical behavior of IRR-PE blend are reported and discussed. One of the critical steps to develop constitutive modeling is the testing of these materials over a wide range of strain rates and temperatures. These measurements have been done to precisely predict the mechanical effect of these molecules for different applications. The microstructure of butyl rubber filled with different concentrations of high molecular weight polyethylene are examining by scanning electron microscopy (SEM).

Experimental

Materials and preparation of composites

Butyl rubber (IIR) was manufactured by Transport and Engineering (rubber manufacturing) (TRENCO, Alexandria, Egypt) and had density 0.94 g/cm^3. PE powders with molecular weight (M_W =3.5 x 10^6 g/mol and isotacticity of 97% were kindly provided by Tokuyama Co. Ltd., Japan). The furnace carbon black (CB) with a commercial name of porous black was supplied by Asahi Carbon Co. Ltd. (Niigata, Japan) with a particle size of 1 μm and a surface area of (290 m^2g^{-1}) used as reinforcing fillers. The mixing was accomplished in a home made two-roll mixing mill (length 0.3 m, radius 0.15 m, speed of slow roll 18 rpm and gear ratio 1.4) was used. The formulations of the blends are given in Table 1. The blends of IIR and PE were prepared in ratios of 100/0, 90/10, 80/20, 70/30, and 60/40 (wt%) and are designated PE0, PE10, PE20, PE30, and PE40 respectively, where the numbers indicate the weight percentages of PE in the blends. The mixing occurred for 40 min at a temperature of 25 °C, with same sequence of mixing of all compounding ingredients to avoid the effect of processing on mechanical properties. The vulcanization was conducted under a heating press (KARL KOLB, Germany). Compression molded plaques were prepared by sandwiching the polymer between Mylar sheets, heating at 155 ± 2 °C for 30 min under minimal pressure 0.40 MPa. Plaques were rapidly cooled to ambient temperature. The vulcanized samples were shelf aged for 48 h before testing. The mixing time and vulcanization conditions were fixed for all samples.

Mechanical techniques

Tensile tests of various compositions of IRR-PE blends were tested at 30, 50, 70 and 80 °C and strain rates of 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2} sec^{-1}, on a tensile testing machine (AMETEK, USA). The test samples were strips of 2 cm working length and of ~4 mm^2 cross-sectional area. A digital force gauge (Hunter Spring ACCU Force II, 0.01 N resolution, USA) connected to a microprocessor was used to measure extension force (F). A home made motor attachment was used to control the strain rate through a gearbox. The strain rate was preset using a variable DC power supply, and was measured using a micro-switch attached to the apparatus wheel. The accuracy of strain measurement was about 0.1 mm. Tensile tests of PE20 blend were carried out at a constant (strain rate: 1 s^{-1}) over a temperature range between 30 °C and 80 °C. All the tests were repeated for several samples for each temperature, strain rate, and composition conditions. The samples were kept in oven of the tensile testing machine at the definite temperature of the drawing experiment through a K-type thermocouple for about 5 min before starting the experiments. True stress and strains were calculated as shown by Eqs. (1) and (2) respectively:

$$True\ Stress = \frac{F}{A_o}(1+\varepsilon) \tag{1}$$

$$True\ Strain = \ln(1+\varepsilon) \tag{2}$$

where $\varepsilon = \Delta l/l_o$, is the tensile strain, and A_o is the original cross-sectional area. The data obtained from tensile tests provide information on the tensile strength, elastic modulus and fracture strain as well as toughness modulus. This information is used in the present study to investigate the effect of strain rate and temperature on tensile properties of IRR-PE blends.

Scanning electronic microscopy (SEM)

The microstructure of the polymer samples was examined by scanning electron microscopy (SEM) instrument (model 8650, JEOL, Tokyo, Japan) with an acceleration voltage of 30 kV. A very thin coating film of sample was deposited onto the surface of SEM sample stub which is mounted inside the SEM instrument to get the measurements. Fig. 1(a-c) shows the SEM micrograph of IIR system for samples PE0, PE20, and PE40, respectively. It can be seen that there are remarkable differences between unfilled and filled IIR composites as to grain distribution. For unfilled PE

Table 1
Different Loadings of PE in IIR Blends.

Ingredients (phr)	Samples				
	PE0	PE10	PE20	PE30	PE40
IIR[a]	100	90	80	70	60
PE	0	10	20	30	40
ZnO	5	5	5	5	5
Stearic acid	2	2	2	2	2
Glycerol	10	10	10	10	10
CB	25	25	25	25	25
TMTD[b]	1	1	1	1	1
CBS[c]	1	1	1	1	1
Sulfur	2	2	2	2	2

[a] The ingredients are arranged in the same order used during preparation.
[b] Tetra methyl thiuram disulfide.
[c] *N*-cyclohexylbenzethiozole sulphenamide.