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Influence of the temperature on the hyper-elastic mechanical behavior of carbon black filled natural rubbers

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ABSTRACT

This paper investigates the temperature and filler effects on the hyper-elastic behavior of reinforced rubbers. Firstly, mechanical tests are carried out on a series of natural rubbers with different volume fractions of carbon black particles at different temperatures. A non-contact optical technique with high precision of measurement is employed to obtain displacement fields, and the stress-strain responses are consequently achieved. In the studied temperature range, the unfilled rubber exhibits a well known entropy-related behavior, while the filled rubbers behave as a complex temperature-dependent characteristic in addition to enthalpy-related behavior. Test results also show that the filler effects on the hyper-elastic properties of rubber elastomer, such as material stiffness and "S" shaped nonlinear response, are seriously influenced by the increase in temperature. Based on these experimental observations, a thermo-mechanical model is developed to describe the hyper-elastic response of filled rubbers over a wide range of temperatures. In addition, the prediction ability of this proposed constitutive model is verified by comparison with test data issued from the mechanical experiments, which shows that the model is suitable to characterize the large deformation behavior of filled rubbers at different temperatures at a certain degree.

1. Introduction

Rubber elastomers are commonly used for manufacturing various products in the automotive, aeronautical, and electronic industries. The large variety of applications must be coupled with a wide range of service temperatures (Yavayi et al., 1993). Additionally, under some typical operating conditions, for instance cyclic loading, the rubber materials usually experience self-heating due to their viscous-related features in connection with the thermo-mechanical coupling process (Willett, 1974). If the material properties depend on temperature, the change in service temperature or the exhibition of self-heating undoubtedly has a drama effect on the mechanical behavior, and evidently influences the operating performance of the rubber products. This leads to a complicated thermo-mechanical coupling problem.

Generally, rubber elastomers are filled with filler particles such as carbon black (CB) in order to improve their overall properties (Fukahori, 2003; Leblac, 2010). In this case, CB fillers greatly complicate the mechanical behavior of elastomer by altering: the stress-strain response, the stress softening effect, the cyclic hysteresis, etc. Besides, the addition of CB particles seems to modify the thermo-mechanical response of elastomer, because the filler-rubber and filler-filler interactions have a strong effect on the thermal behavior and vice versa. Considered the material properties depend both on the filler content and on the temperature, the development of understanding and modeling capable to explicitly explain and describe both

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characteristics, in parallel with the strong non-linearity of this composite under large deformation, is an important issue to be addressed.

In the past years, some efforts have been made to investigate the basic features of the elastomeric mechanical behavior of rubber materials, and to examine the filler effect on their mechanical properties. However, it is important to emphasize that most of these studies only considered the hyper-elastic response of unfilled and filled rubbers at room temperature (Bergstrom and Boyce, 1999; Badawy, 2000; Bouchart et al., 2008). In fact, relatively few works are attempted to the additional influence of temperature and the complex thermo-mechanical behavior of rubber composites. Several scholars (Lion, 1997; Drozdov and Christiansen, 2009; Li et al., 2011; Rey et al., 2013) have experimentally found a stress-softening of filled rubbers with increasing temperature, being distinguished with the well known stress-hardening of unfilled rubbers with increasing temperature. However, they did not discuss how the temperature variation influences the reinforcement effects of filler particles upon elastomer matrix, and never revealed the micromechanisms related to the test results. Since the change in temperature possibly affects the filler-rubber and filler-filler interactions (Rothon, 2001), it is essential to make further studies on both filled and unfilled rubbers at different temperatures. Furthermore, even though some thermo-mechanical models that take into account the temperature effect on the mechanical properties, without the filler effect, it is of theoretical as well as practical interest to develop an effective modeling approach to capture the temperature-dependent hyper-elastic response of filled rubbers at large deformations.

This paper aims, therefore, at investigating the influence of temperature on the hyper-elastic mechanical behavior of filled rubbers systematically. As described in Section 2, CB particles are used as fillers in different volume fractions and natural rubbers are used as matrix. By employing a non-contact optical method with high precision to measure large strain data of soft materials, samples of the rubber composites are submitted to tensile loads at different temperatures. Correspondingly, Section 3 presents different hyper-elastic stress-strain curves of unfilled and filled rubbers with varied CB content at different temperatures, and then makes discussions on the comparisons between them. This permits further understanding on the reinforcement effects of filler particles and micromechanisms involving temperature variation. Using this information, Section 4 proposes a hyper-elastic constitutive model to describe the temperature dependent behavior of filled rubbers. The effect of the filler is included by the notion of the first invariant amplification, and the influence of the temperature is included by a non-linear damping evolution of the filler effect deduced from preceding experimental investigations. Finally in Section 5, some concluding remarks end the paper.

Table 1
Formulation of filled NR materials.

Ingredients	NR-0	NR-A	NR-C	NR-E
NR (phr)	100			
CB (phr)	0	25	45	65
Sulfur (phr)	3.5			
Zinc oxide (phr)	3.5			
Others (phr)	8.34			
Total (phr)	115.34	140.34	160.34	180.34
CB volume fraction (%)*	0	10.3	17.1	23.0

* The CB volume fraction can be calculated from: $v_f = phr[\rho_f(100/\rho_m + phr/\rho_f)]^{-1}$, where $\rho_f = 1.8 \times 10^3 kg/m^3$ is the CB density, $\rho_m = 0.96 \times 10^3 kg/m^3$ is the matrix density, and $phr = [0, 25, 45, 65]$.

2. Materials and experimental setup

The materials used in this study are a series of natural rubbers (NR) reinforced with different contents of CB filler, so as to characterize the filler effect on the hyper-elastic mechanical response of rubber elastomer. The details on material ingredients, provided by the manufacturer (Grandtour Tire Corporation), are given in Table 1. All the studied NR materials are filled with the same CB type and prepared under the same vulcanizing condition.

The hyper-elastic mechanical tests are conducted on a non-contact optical testing system employing the Automated Grid Method (AGM) (Sirkis and Lim, 1991). As illustrated in Fig. 1, this experimental setup is made of a

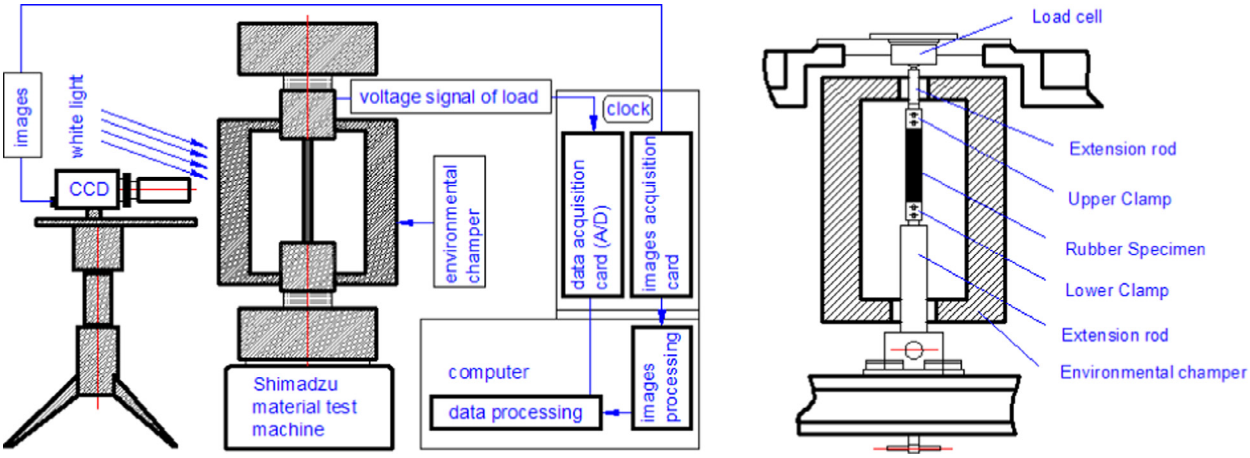

Fig. 1. Illustration of the non-contact AGM experimental setup.