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STRESS RELAXATION AND RECOVERY FOLLOWING APPLYING AND REMOVING DEFORMATION FOR DIFFERENT RUBBERS

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Abstract—Viscoelastic materials are commonly used for engineering applications due to their unique and useful properties. Namely, when rubbers are subjected to deformation, then the stress response is not linear but increases or decreases similar to a hyperelastic material. Moreover, the significant part of elastomers is that when the deformation is held constant after loading or unloading, the stress response is to relax or recover, respectively. These transient effects are more obvious when the rubbers are saturated and change with the increasing velocity that the material deforms. In the current work, we experimentally examined the viscoelastic behaviour of two different rubbers subjected to tension for three different speeds.

Keywords- stress relaxation; stress recovery; transient effect; viscoelasticity; elastomers

I. INTRODUCTION

Rubbers are materials with a complex composition that exhibit viscoelastic behavior. In several engineering applications, rubbers are used for reducing the vibration when the material is subjected to sudden tension or compression and might fracture or even crack. Rubbers can be divided into several categories depending on their composition. Filled or unfilled, saturated or unsaturated rubbers differ especially when they are subjected to continuous loading cycles as the interaction between the matrix and the embedded material might require more force, speed or repeating cycles for breaking the molecule chains [1-2].

Elastomers' response to deformation is complicated and it can be simulated by more complex nonlinear theories than the classic elasticity. Specifically, hyperelasticity defines the stress-strain relationship using the strain energy density function [3-5]. A significant behaviour of rubbers begins by the end of the loading stage, namely when the desired strain level is achieved and then is held constant for a specific period. The stress response to this cause is known as stress relaxation, as the stress will not remain constant, but it will start decreasing until it approximately reaches a constant value. Several studies have investigated stress relaxation under different conditions and useful results have been obtained [6-7]. We must notice that transient effect is a following procedure of loading and without the latter, stress it is not possible to respond with relaxation. The above significant conclusion raises the question of what the response of the rubber would be if the cause is unloading, meaning removing an applied deformation. In our previous work, we investigated natural rubber's response to removing an applied loading for several strain levels and the material's response was similar to relaxation [7]. Consequently, the transient effect of removing a strain is stress recovery, which constitutes an "opposite" procedure of relaxation. In the current study, we expand this research to rubbers with different consistency and resistance at extreme conditions (e.g. temperature, etc.).

It is known that rubbers, saturated or unsaturated, exhibit a unique change in their mechanical behaviour when they are subjected to repeated tension. It has been noticed that a stress softening occurs upon unloading that follows virgin loading and possibly continues for several cycles. This phenomenon, known as the Mullins effect, was firstly related to the increasing stiffening ability of filled rubbers. However, it has been noticed in unfilled rubbers as well [8-9]. Since the consideration of stress softening is mandatory for achieving accurate results, the mathematical modelling or experimental preconditioning must be followed [10-11]. Although in the bibliography it is suggested to perform approximately six cycles of loading-unloading [11], we noticed that for several rubbers, more preconditioning cycles are necessary.

In the current paper, we performed several experimental tests on different rubbers for investigating rubbers' transient response to applying and removing deformation. We speculated that if we merely change some experimental conditions, the results would vary. Therefore, we repeated the experimental procedure for a lower and a higher speed in order to compare the rubbers' viscoelastic response.

II. MATERIALS AND METHODS

For investigating the transient viscoelastic effects, we selected two representatives, saturated and unsaturated rubbers, namely EPDM (ethylene propylene diene monomer rubber) and natural rubber, respectively. For each material, we cut samples of a so-called dog-bone shape (115mm x 25mm x 3.175mm). All experiments were performed by an MTS machine at room temperature.

Before investigating the transient effect of the selected rubbers, we preconditioned our samples by performing several cycling loadings. Hence, the rubbers were subjected to 12 repeating cycles of loading and unloading until they reached 100% and 20%, respectively. We selected to leave a residual strain during unloading in order to avoid possible folding of the samples, especially if the test is performed at high speed. The above procedure was performed for both rubbers and three crosshead constant speeds, 0.01mm/s, 0.1mm/s and 1mm/s. During the test procedures, we observed and recorded the deformation of a small area of 5mm in the centre of every sample (gage area) which deforms with less speed compared to the constant crosshead's velocity. Specifically, the average speeds of the gage area are approximately 1/10 of the corresponding crosshead's velocities 0.01mm/s, 0.1mm/s, 1mm/s.

After eliminating the Mullins effect by preconditioning the samples, the rubbers were subjected to uniaxial tension until 100% strain was reached. Then it was held constant for 900 sec, and the stress relaxation was recorded for the same period. An approximate constant value of stress was reached, and then the unloading of the sample begun until the 20% level of the maximum strain was achieved. Then it was held constant for 900 sec more and the stress recovery was recorded. The experimental procedure was performed for three different speeds, 0.01mm/s, 0.1mm/s and 1mm/s.

III. RESULTS AND DISCUSSION

Figures 1-2 illustrate the normalized stress response to cycling loading and unloading for 0.01mm/s, 0.1mm/s and 1mm/s applied on natural rubber and EPDM. In order to be more obvious, for all conditions, stress was divided by the maximum stress level required for the sample to reach 100% strain. For both materials and different speeds, the maximum stress was reached during the first cycle. As it is shown in the graphs of Figure 1-2, after 12 cycles of loading and unloading, a new cycle continues by including stress relaxation and recovery. Each of the above transient stages lasted for 900 sec.

Moreover, the stress softening phenomenon is evident in Figures 1-2, as the stress level decreases for several cycles. Consequently, the importance of preconditioning the samples before the main experimental procedure begins is mandatory. The number of the required cycles varies for each material as natural rubber is barely affected by this phenomenon, while EPDM needs more than 10 cycles for the stress value to be stable.

The transient effects of applying and removing 100% strain follow the precondition of the sample. Obviously, stress relaxation occurs more to EPDM compared to natural rubber. The significant result constitutes the fact that recovery occurs similarly to relaxation for each rubber. Moreover, it is observed that for low speed, 0.01mm/s, relaxation and recovery require more time than 900 sec for completing the decreasing and increasing, respectively, until they approximately reach a stable stress value. Namely, the required time for the sample to relax or recover, while the deformation is held constant, depends on the speed that the rubber deforms. For 0.01mm/s, both rubbers needed approximately 5000 sec to reach 100% strain, and thus the relaxation and recovery should be more than this period. However, the current work is not focused on discovering the specific task as it is already proved by several other researchers [12-14].

Furthermore, stress relaxation and recovery are affected by the speed that the crosshead of the machine is stretching the samples. By comparing natural rubber and EPDM in Figures 1-2, it is evident that the amount of stress needed for the rubber to reach 100% strain depends on the consistency of the material. For natural rubber, the required stress is almost the same (5%) for 0.1mm/s and 1mm/s, while in the slower speed, it is considerably decreased (15%). On the contrary, the stress value of EPDM increases for higher speed. Specifically, the highest increase in stress level for stretching the sample until 100% strain is observed for 1mm/s compared with the stress value needed for 0.1mm/s (Figure 2).

According to the statement that recovery is the response to removing deformation that follows loading, the results related to the transient viscoelastic effects are anticipated for all the tested materials. Stress relaxation and recovery are more evident for speeds 0.1mm/s and 1mm/s compared to the lowest speed. Namely, for 0.01mm/s, rubbers are subjected to extremely slow deformation, and consequently, a longer period for responding to loading and unloading for higher speeds is required. However, it is obvious that stress relaxation and recovery occur more in saturated rubber (please see Figure 2). The graphs of EPDM show that this is the case. Moreover, for natural rubber subjected to tension until 100% strain with 0.1mm/s speed, the normalized results shown in Figure 1 almost coincide with the relative results obtained by Gkouti E. et al. [7].

IV. CONCLUSION

When rubbers are subjected to tension until a specific strain level is reached and then held constant, the stress response is relaxation. By removing even partially this deformation, the transient stress effect is similar and is called stress recovery. Both stress relaxation and recovery are affected by the combination of rubber's consistency and deformation speed. For saturated rubbers, the stress recovery as well as the relaxation are more obvious especially when the speed increases. Moreover, both saturated and unsaturated rubbers must be preconditioned before subjecting to viscoelastic deformation as the stress softening occurs during the loading that follows the initial stretching. This phenomenon varies depending on different materials and speeds that a sample is subjected to tension.

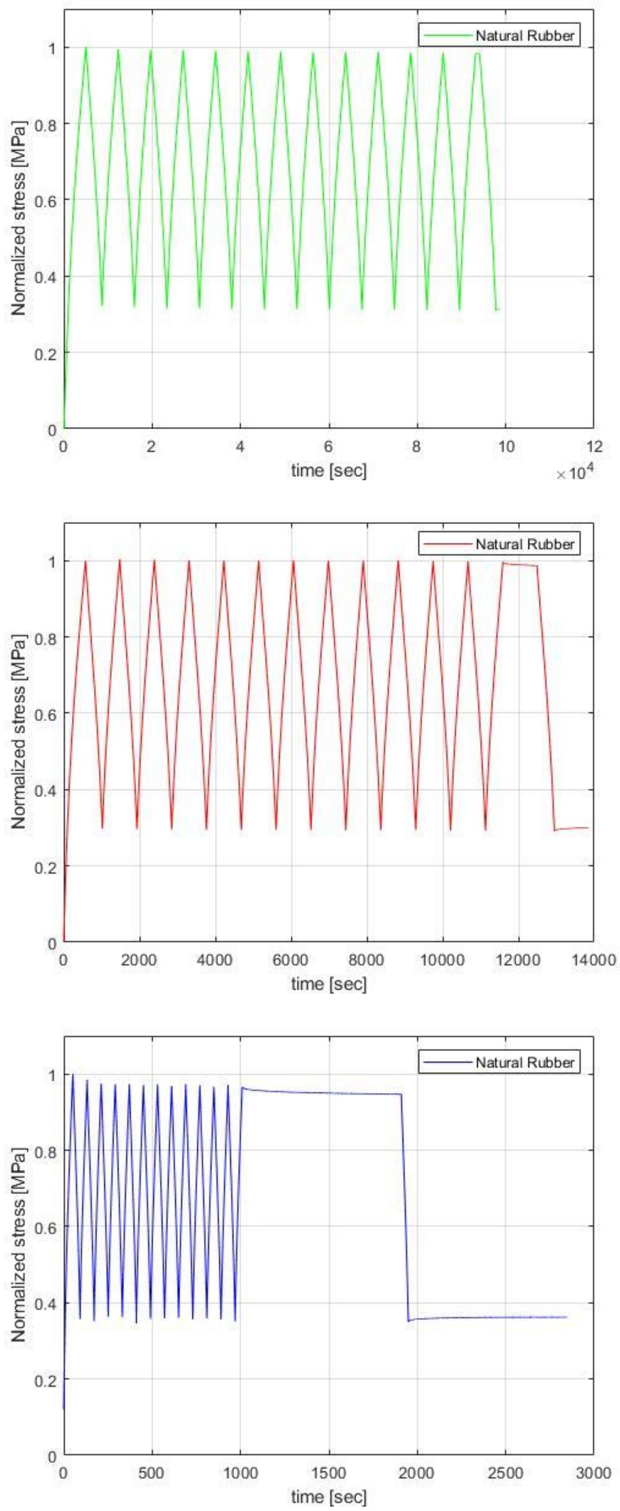

Figure 1: Normalized transient effects of applying and removing 100% and 20% strain, respectively of preconditioned natural rubber, for 0.01mm/s (green line), 0.1mm/s (red line), and 1mm/s speed (blue line).

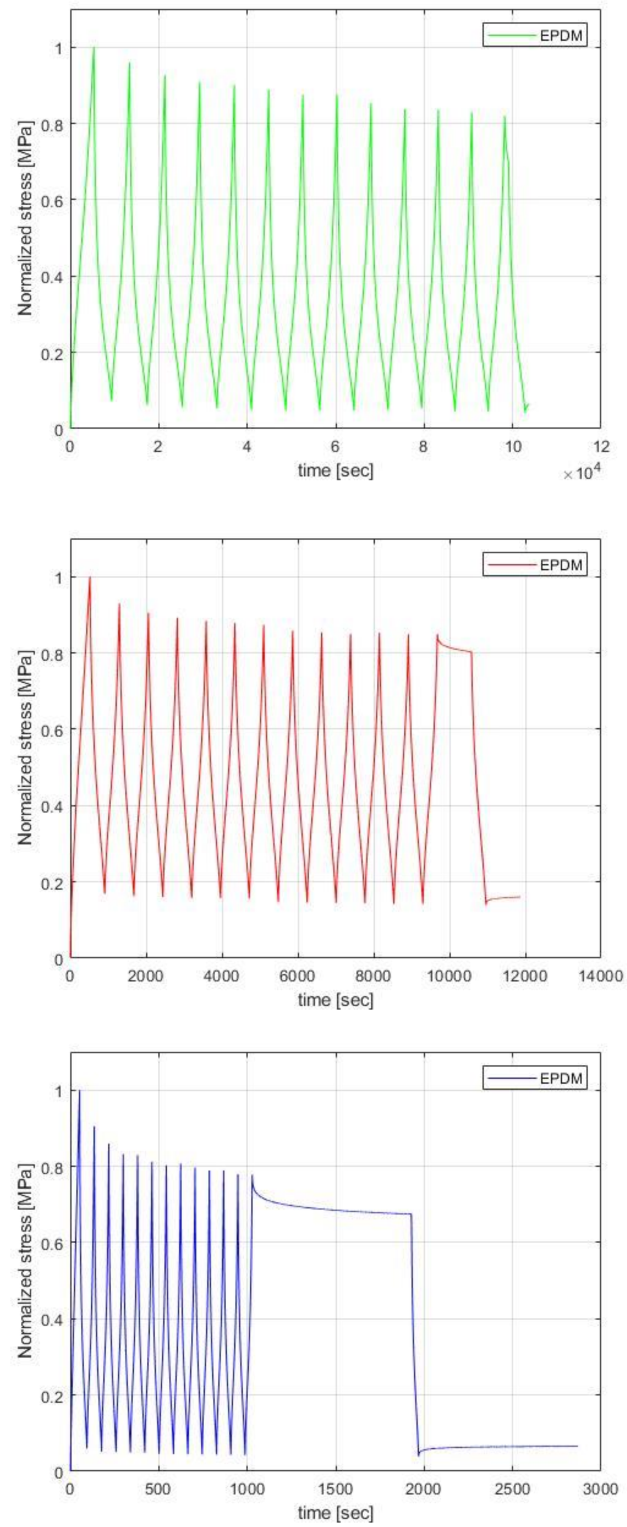

Figure 2 : Normalized transient effects of applying and removing 100% and 20% strain, respectively of preconditioned EPDM, for 0.01mm/s (green line), 0.1mm/s (red line), and 1mm/s speed (blue line).

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