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Short Communication

Observation of the relation between uniaxial creep and stress relaxation of filled rubber

S. Oman*, M. Nagode

University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, Ljubljana SI-1000, Slovenia

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ABSTRACT

This paper presents an experimental evaluation of the stress relaxation and creep of filled rubber. A detailed study of the influence of different test programs, where the main variable was the load sequence on the creep and relaxation processes, is discussed. The final goal of the research is to find a method to predict stress relaxation from known creep, or vice versa, in a simple way that would give sufficiently accurate results over both primary and secondary creep regions. Therefore suggestion for converting the creep test result into a stress relaxation curve and vice versa is presented. The idea is based on the assumption that both processes (creep and stress relaxation) are the result of the same viscoelastic mechanism and that the stress relaxation can be treated as creep under decreasing stress. Experimental data shows these assumptions to be correct. For the conversion of the creep parameters into stress relaxation parameters a reverse stress-strain curve is needed, therefore factors affecting the unloading stress-strain curve are also presented. Finally, the transition from the suggested conversion to the final method will be discussed.

1. Introduction

In contrast to metals, rubber-like materials are subject to a relaxation process when constant deformation is applied, or to a creep process when constant stress is applied at room temperature. As early as 1962, A.N. Gent established that both phenomena are the outcome of the same viscoelastic mechanism that takes place inside a material when it is deformed [1]. He assumed that both phenomena were the result of a single relaxation process. Regarding these findings, he proposed a model for describing the relation between the relaxation and creep processes. The model is built on the assumption of a constant creep and relaxation gradient if time is plotted logarithmically. Therefore it is not suitable for very short time periods since the creep and the relaxation gradient is far from constant at the very beginning of the process (even if the logarithm of time is taken). Many other investigations [2-6] have also been performed to predict stress relaxation from creep tests. For example, Lay and Findley [2,3] built a model that uses an inversion of the function obtained from a multiple integral equation describing the creep data. Touati and Cederbaum [4,5] transformed Schapery creep model into a set of first order nonlinear differential equations. By solving these equations the nonlinear stress relaxation curves for different strain and temperature levels are established. Al-Haik, Hussaini and Garmestani [6] used artificial neural network to predict the stress relaxation from known creep. Common to all these models is that they are designed only for predicting stress relaxation from known creep and are relatively complex to use. Therefore a different approach to defining stress relaxation parameters from known creep and vice versa is taken in this work.

In contrast to Gent, who assumed that both phenomena are a result of a single relaxation process, it can be said that both creep and stress relaxation are the result of a creep process. Searching for the correct relation between the creep and stress relaxation of filled rubber, it will be assumed that the stress relaxation is actually creep under decreasing stress. This statement follows the assumption that creep is the outcome of a viscoelastic mechanism resulting mainly from molecular slipping [7] and disentanglement [8]. In both processes, creep and relaxation, molecular slipping and disentanglement occur during loading and result in time dependant deformation once the load is removed [3].

The research presented here deals with the experimental evaluation of the creep, stress relaxation and other phenomena of filled rubber.

The experimental methods are described in Section 2 and include details of the materials and measuring equipment used. To evaluate the influence of the viscoelastic mechanism on the

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* Corresponding author. Tel.: +386 14771506.
E-mail address: simon.oman@fs.uni-lj.si (S. Oman).

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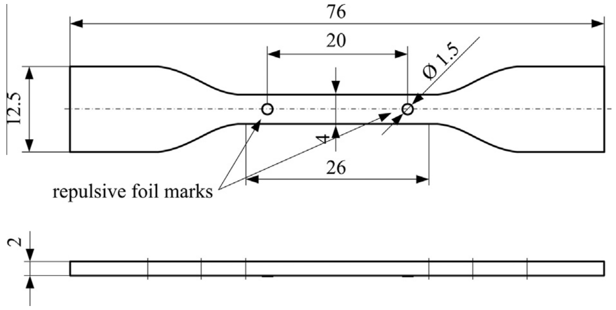

Fig. 1. Shape of specimens used in all experiments.

results of stepwise relaxation tests and cyclic uniaxial tension tests, monotonic tensile test curves are compared to both cyclic and relaxation σ-ε curves (Section 3). In order to treat stress relaxation as creep under decreasing stress, the behaviour of filled rubber during unloading needs to be understood. Hence the influence of creep and stress relaxation on the unloading stress-strain curves is discussed (Section 4). To predict stress relaxation from known creep parameters, changes in creep of a material when stress decreases must be known. For this purpose stepwise creep tests are made with decreasing stress levels (Section 5). This is followed by the results of creep and stress relaxation measurements (Section 6). Finally, the idea of how to predict the stress relaxation from known creep and vice versa is discussed (Section 7).

2. Experimental details

Industrial rubber for producing air springs is used for all measurements. The rubber is a blend of filled natural rubber, polybutadiene rubber and styrene butadiene rubber. A vulcanized plate was prepared from which dumbbell test specimens (Type S2 from DIN 53504 [9]) were cut (Fig. 1). The specimens were then suitably conditioned to prevent the influence of ageing for the duration of the measurements.

The measurements were carried out on the Zwick/Roell Z005 device equipped with a load cell with the range of 0 to 5kN, and an optical extensometer. The specimens were therefore equipped with repulsive foil marks, as shown in Fig. 1. Measuring the specimens, the recommendations of ASTM: D3767-03(2008) standard were taken into account.

Static stress-strain curves were obtained according to the standards DIN 53504 [9] and ASTM: D412-06a(2013). Creep and stress relaxation measurements were done under the recommendations of the standards ASTM: D2990-09 and ASTM: D1646-07(2012) respectively.

3. Influence of viscoelastic behaviour on stress relaxation and cyclic test results

A comparison of the stress relaxation results gained by using one specimen for several strain levels (strain levels are applied in an increasing sequence) with results gained by using a new specimen at each strain level was made in [10] where all the tests were carried out at a constant strain rate of 200 mm/min. The results show that the stress relaxation curves are practically identical at each strain level for both cases.

The same can be said for cases when the stress relaxation time is zero (Fig. 2A) using a uniaxial cyclic tensile test with increasing strain levels. In this case the unloading curves would be expected to be identical to the unloading curves measured on a new specimen at each strain level. This argument can be furthermore justified by reference to the Mullins effect [11], where it is stated that when the extension exceeds the maximum extension previously applied, the material stress-strain response returns to the original path of the monotonous uniaxial tension test stress-strain response after a transition. The diagrams in Fig. 2 show that the statements written above are not completely correct since, in addition to the Mullins effect, there also exists some viscoelastic behaviour that influences the maximum stress level at each imposed strain level. The same effect was also observed by Hanson [12] and Diani [13].

Regarding these findings it can be concluded that the equilibrium stress during the stress relaxation process is the same whether using a new specimen for each strain level or the same specimen for all strain levels (Fig. 2A). On the other hand, the maximum stress at the same strain level is not the same when using a new specimen or a specimen previously loaded with a lower strain level. Since the rate of stress relaxation is far more rapid at the beginning of a test (primary region) than it is in later times (secondary region), the difference in maximum stress does not have any influence on the stress relaxation curves. In reality the stress relaxation curves are shifted relative to each other by less than a second, however this shift is considered negligible. Therefore, the stepwise stress relaxation test with an increasing strain level can be used to define the stress relaxation curves without introducing any significant errors.

A similar effect can also be observed in the case of uniaxial cyclic tension tests with increasing strain levels as shown in Fig. 2A. Although the hold time in this case is zero, a viscoelastic effect that influences the maximum stress level is also present. The reason for the viscoelastic effect to appear in this case is the limitation of the loading speed that makes it impossible to load and unload the specimen in zero time. Consequently, the viscoelastic mechanism has some influence on the stress-strain curve during loading and unloading of the specimen. Since the viscoelastic mechanism is the most intense at the beginning of the process its effect can also be seen in the cyclic tensile test.

Moreover, it can be concluded from Fig. 2 that the viscoelastic mechanism attributable to creep of material is present in both the stress relaxation and uniaxial cyclic tests [7]. The creep is represented by permanent deformation. Therefore our introductory statement that stress relaxation can be treated as creep during decreasing stress is confirmed.

4. Influences on unloading stress-strain curve

If stress relaxation is to be treated as creep under decreasing stress conditions, changes in stress due to creep need to be known. Since the presence of creep reduces elastic strain that causes the stress, the stress-strain curve during unloading (the unloading stress-strain curve) is also required. The influence of creep on elastic strain can be described with Eq. 1.

$$\varepsilon(t) = \varepsilon_{el}(t) + \varepsilon_c(t) \Rightarrow \varepsilon_{el}(t) = \varepsilon(t) - \varepsilon_c(t) \qquad (1)$$

where $\varepsilon_{el}(t)$ is elastic strain, $\varepsilon(t)$ total strain and $\varepsilon_c(t)$ creep strain.

Therefore it is important to be aware of all the possible influences on the unloading stress-strain curve in order to predict stress relaxation from known creep or vice versa.

The shape of unloading curves gained by different tests is independent of whether the specimen had been stressed prior to the measurement or not (Fig. 3). The only variable is the starting point of the unloading stress-strain curve in that it is slightly lower for previously stressed specimens.

Moreover, a single cycle unloading curve was compared with those unloading curves gained from relaxation and creep tests (Fig. 4). The comparison shows that at first sight the unloading curves obtained during the single cycle, relaxation and creep test