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Steady-State Creep Behaviour of Functionally Graded Silicone Rubber with Cellulose Addition

Manal H. Jasem[1*], Esraa A. Abbod[1], Tamara A. Jassim[2], Zainab Y. Hussien[3], Ehsan Omaraa[4]

[1]Material Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq
[2]Applied Sciences Department, University of Technology, Baghdad, Iraq
[3]Project and Construction Department, Mustansiriyah University, Baghdad, Iraq
[4]University of South AuStralia,UniSa, Australia
[*]Email: manalatheer79@uomustansiriyah.edu.iq

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Abstract

This study investigates the steady-state creep behaviour of functionally graded silicone rubber with cellulose addition. Functionally graded materials (FGMs) have a composition that gradually changes based on their volume, resulting in properties such as strength, thermal conductivity, and stiffness that vary from point to point. This work aims to examine the creep and thermal behaviour of silicone rubber with cellulose and determine the effect of cellulose content on the properties of this FGM. Different amounts (by weight) of cellulose (0%, 3%, 6%, 9%, and 12%) were added to a silicone rubber matrix, and creep tests were conducted on FGM samples. The results showed that as the amount of cellulose increased, creep resistance and heat conductivity improved. It follows that FGMs with a higher cellulose content are better able to withstand high temperatures and deformation when subjected to load, as opposed to those with a lower cellulose concentration. The viscoelastic behavior of the FGM samples was characterized using the Kelvin-Voigt model. This study shows that adding cellulose to silicone rubber increases its creep resistance but decreases its ultimate strength, making it more brittle and prone to cracking under abrupt loads. FGMs whose composition changes gradually.

Keywords: Cellulose; Functionally Graded Material; Kelvin–Voig; Silicone Rubber; Steady State

1. Introduction

Materials classified as functionally graded materials (FGMs) have compositions that change progressively over their volume. This means that their thermal conductivity, stiffness, and strength are all material qualities that change over time [1],[2]. FGMs are used because they can improve performance and have many uses, particularly in polymer materials. Polymer materials greatly benefit from FGM processing, wherein FGMs can confer heat resistance, durability, corrosion resistance, and flexibility [3]-[5]. Polymer-based functional gradient composite materials have unique properties because the properties of FGMs change in a specific direction to meet the desired purpose. FGMs are a perfect combination of two distinct materials that inherit the properties of their original components and have become a fashionable trend in materials engineering science [6]-[8]. Some studies have explored the medical and construction applications of FGMs [9],[10]. For example, FGMs can be prepared to confer external flexibility and internal stiffness to parts that are insecure to wear, thus increasing the service life of polymer materials in harsh environments [11]. FGMs face several challenges in environments where temperatures might change; therefore, understanding how temperature affects them is an important field of study. FGMs are a good choice for uses that need strong thermal resistance because they perform better in hot or cold environments than traditional materials. The automobile, aviation, and aerospace sectors are among those that make use of such applications [12]. In recent years, investigators have used quenching and centrifugation to create property gradients in corrosion - and impact-resistant polymers [13].

Amirova et al. studied the applications, properties, and processing methods of functionally graded polymer materials (FGPMs) made from mixes of epoxy resins that don't match well [14]. Their study investigated these mixes' ability to create FGPMs with different properties. They concluded that the unique features of these materials make them appropriate for various applications.

Andrianova et al. [15] developed a novel technique for making FGMs utilizing poorly compatible epoxy oligomers. Their method permits spontaneous settling based on differences in density, resulting in a composition gradient throughout the material. Their conclusion highlighted that the resulting FGMs appeared to have variations in glass temperature, microhardness, thermal expansion, and elasticity, suggesting that these materials have a wide range of potential applications.

In their research, Devada et al. [16] highlighted how FGPMs are becoming increasingly paramount. Their study focused on the multifield uses, processing methods, characterization, and characteristics of FGPMs. According to their feedback, FGPMs have more potential than regular composites, which makes them significant for many high-tech applications.

Teacher and Velu executed a thorough estimate of FGMs [17]. Their review reviewed additive manufacturing's potential and traditional fabrication methods for making complicated structures. Their conclusion emphasized the need to comprehend the interrelationships between characteristics, FGM structures, materials, and modeling. Further study and improvement in this area are needed, as their analysis also tackled the FGM production difficulties and processing.

There usually are three stages to testing creep: primary, secondary, and tertiary. In the first stage, the strain rate falls; in the second, sometimes called the steady-state stage, it is constant. As demonstrated in Fig. 1, the tertiary stage is characterized by progressively increasing the strain rate until failure occurs.

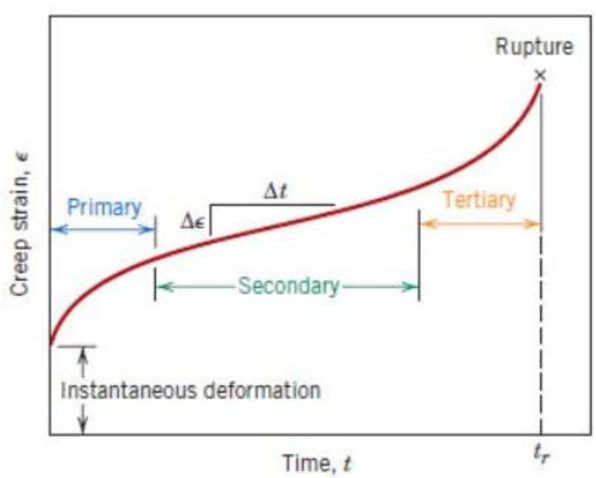

Figure 1. Creep Stages [18]

The steady-state stage is of particular interest in creep studies because it is the stage wherein the properties of materials are relatively constant. The relationship between the strain rate, stress, and temperature in this stage can be explained by the following equation [19]:

$$68\ \dot{\varepsilon} = A\sigma^n e^{\frac{-Q}{RT}}, \quad (1)$$

where

$\dot{\varepsilon}$ is the strain rate, σ is the stress, A is the constant of a material, Q is the activation energy, and n is the stress. The present work aims to obtain a good strain rate and strength FGM and identify mathematical relationships that show the utilization of graded materials at certain temperatures. FGMs are materials with compositions that vary spatially. This variation can be in the form of a gradient, step change, or random distribution.

2. Materials and Methods

The silicone rubber used in this study, supplied by Shenzhen Inno Silica Co., Ltd, with a Shore A hardness of 50 and a tensile strength of 7 MPa, was mixed with cellulose sourced from BIOSYNTH Co. Ltd, with a particle size of 25 µm and a purity of 99%, using a mechanical mixer operating at 1500 rpm for 10 minutes to ensure thorough and uniform distribution and prevent agglomeration. Different weight fractions of cellulose (0%, 3%, 6%, 9%, and 12%) were added to the silicone rubber matrix to prepare five different groups of FGM samples, as shown in Table 1. The first layer without cellulose (pure silicone rubber) was cast, and before it fully solidified, subsequent layers with increasing cellulose content were cast, resulting in a functionally graded material with a gradual change in composition. This study investigated the creep behavior of these cellulose-filled silicone rubber FGMs.

The creep of the FGM samples was measured through a creep and stress relaxation test, using a creep testing machine. The tensile properties of the FGM samples were measured using a tensile testing machine.

Table 1: Composition of FGM Samples Containing Cellulose and Silicone Rubber

Groups	% Cellulose
A	0
B	3
C	6
D	9
E	12

2.1 Tensile Test

Tensile specimens were prepared for all five groups in accordance with the global standard ASTM D412 Type C [20]. They were cut using a mould in the shape of a tensile specimen, as shown in Fig. 2. The tensile test was conducted using a tensile testing machine (Tinius Olsen–100 kN). The FGM samples were stretched at a constant strain rate of 20 mm/min until failure. The tensile strength and elongation at break were measured.

(a)

(b)

Figure 2 a. Cutting Specimen b. Tensile Specimen

2.2. Creep Test

The creep test was performed using an Elastocorn creep and stress relaxation testing machine, as illustrated in Fig. 3. As shown in Fig. 4, the samples were subjected to a constant load of 2.8 N for 160 min at 50 °C. The creep strain was measured as a function of time in accordance with the ISO 899- 1:2017(E) standard [21].

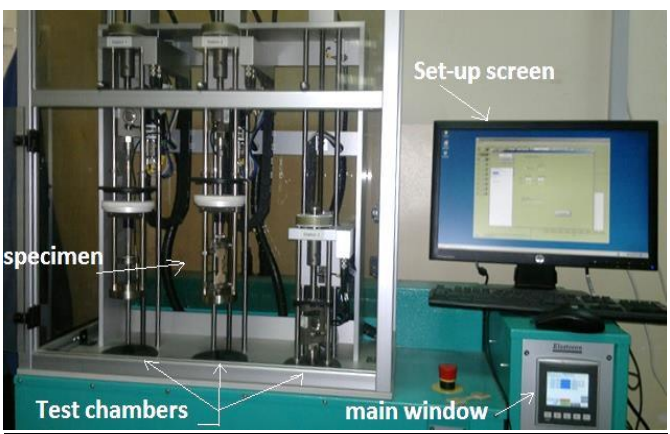

Figure 3. Stress Relaxation/Creep Machine

Figure 4. Creep Specimens

2.3. FGMs and Creep Characteristics

The thickness of layers influences the relationships between the mechanical and physical properties of FGMs. These properties vary across different layers. The general equation for these properties can be adapted and transformed into a specific equation for the strain rate in the steady-state creep phase [22]:

$$P(z) = (Pt - Pb)\left(\frac{z}{h} + \frac{1}{2}\right)^n + Pb, \quad (2)$$

P(z) is the properties at z point, P_t is the properties at the top, P_b is the properties at the bottom, **z** is the variable point, h is the thickness of the beam, and n is a parameter that dictates the material variation profile.

The general equation for the parameter of FGMs was modified to accommodate the strain rate in creep tests. The modified equation was then verified experimentally, and the results are presented below:

$$\dot{\varepsilon}(z) = (\dot{\varepsilon}t - \dot{\varepsilon}b)\left(\frac{z}{h} + \frac{1}{2}\right)^n + \dot{\varepsilon}b. \quad (3)$$

In this research, the Kelvin–Voigt model, as shown in Fig. 5, was adopted to describe silicone rubber with varying cellulose additions. This choice reflects the parallel connection between the spring and dashpot elements in the model, allowing for the derivation of the following equations:

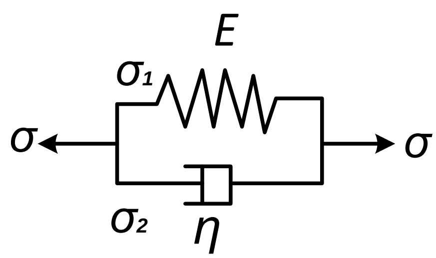

Figure 5. Kelvin–Voigt Model

$$\sigma_1 = E.\varepsilon, \quad (4)$$

$$\sigma_2 = \eta.\dot{\varepsilon}, \quad (5)$$

$$\sigma = \sigma_1 + \sigma_2, \quad (6)$$

$$\dot{\varepsilon} + \frac{E}{\eta}\varepsilon = \frac{\sigma}{\eta}. \quad (7)$$

To solve Equation (7),

$$\varepsilon(t) = \frac{\sigma_o}{E}\left(1 - e^{\frac{-Et}{\eta}}\right). \quad (8)$$

4. Results and Discussion

4.1 Tensile Test Results

The tensile test results of the five groups of silicone rubber materials with different cellulose addition ratios, wherein the particle size of cellulose was 25 µm, reveal that ultimate strength decreases with the increase in the modulus of elasticity (Fig. 6).

The addition of cellulose particles to silicone rubber decreases ultimate strength due to stress concentration and increases the modulus of elasticity due to the reduced mobility of polymer chains and increased network rigidity; this finding is consistent with the results of Karger-Kocsis et al. [23].

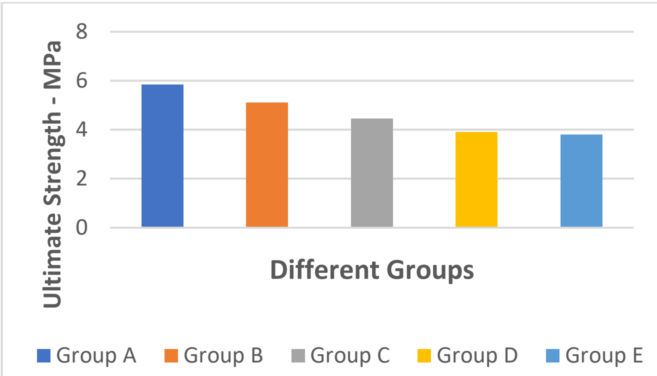

Figure 6. Ultimate Strength of Different Groups

4.2. Creep and Strain State Results

Fig. 7 shows that when cellulose is not added to the silicone rubber, all five samples have a high strain rate in the steady-state region due to the high initial strain. The slope represents the strain rate. However, the strain in the first stage and strain rate in the second stage begin to decrease when 3% cellulose is added, as illustrated in Fig. 8, because the thermal properties of cellulose lead to a reduction in thermal conductivity and an increase in the modulus of elasticity, subsequently decreasing the strain rate in the steady-state region. This behavior becomes increasingly pronounced as the cellulose addition ratio increases (6%, 9%, and 12%), albeit to a low extent (Fig. 9 – Fig. 11).

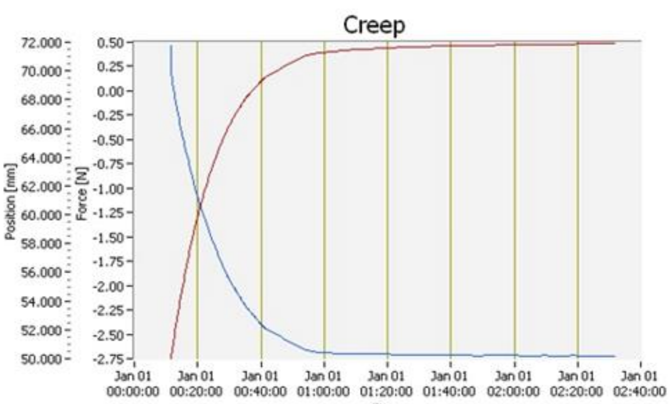

Figure 7. Creep of the Silicone Rubber Specimens

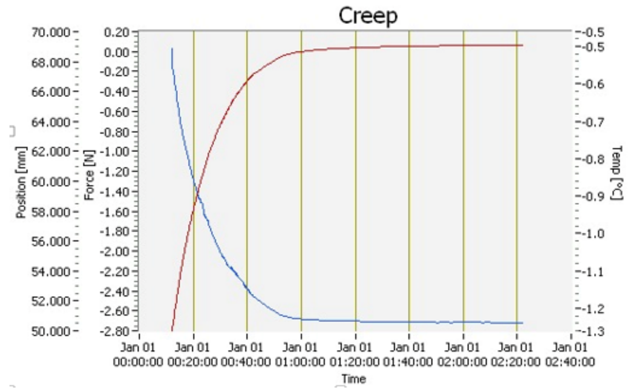

Figure 8. Creep of the Silicone Rubber Specimen with 3% Cellulose

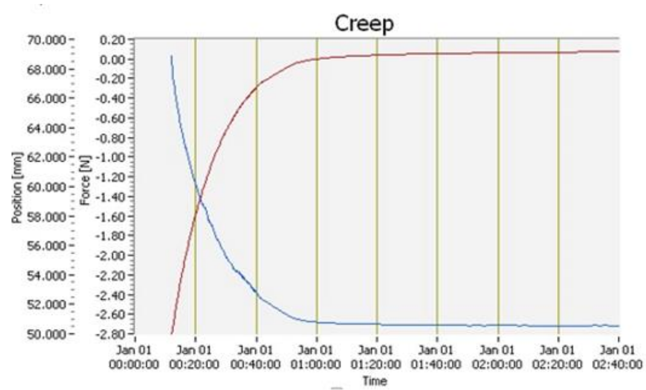

Figure 9. Creep of the Silicone Rubber Specimen with 6% Cellulose

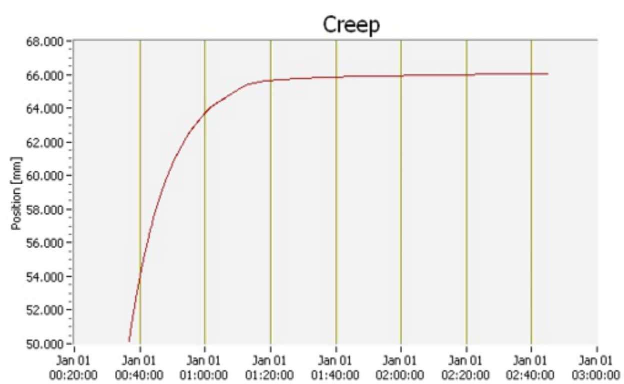

Figure 10. Creep of the Silicone Rubber Specimen with 9% Cellulose

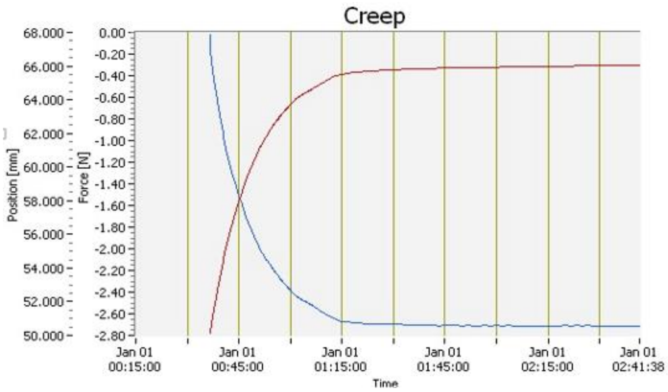

Figure 11. Creep of the Silicone Rubber Specimen with 12% Cellulose

The presence of cellulose particles disrupts the material's homogeneity, introducing potential sites for crack initiation and propagation under high stress, leading to a decrease in ultimate tensile strength.

Cellulose also improves performance under load and high temperatures by lowering thermal conductivity and increasing creep resistance. The viscoelastic behavior is accurately predicted for this sample using the Kelvin-Voigt model. There appears to be a compromise between thermal characteristics and strength, as the final stress decreases as the cellulose percentage increases. These findings demonstrate that FGMs have great promise for use in materials with excellent heat resistance under load and resistance to deformation. The aerospace and automobile sectors are two examples of such fields that use such applications. The homogeneity of the material is disrupted by cellulose particles, which could lead to a decrease in the final tensile strength. The findings of this study highlight the significance of material structure balance in achieving optimal performance in many contexts.

5. Conclusion

When added to silicone rubber, cellulose increases creep resistance; the effect is most noticeable between 0% and 12% cellulose concentration. A decrease in heat conductivity is another result of increasing cellulose content, suggesting that thermal insulation characteristics have been enhanced. However, the material's ultimate tensile strength decreases with the further increase in cellulose content, making the material susceptible to fracture under conditions of sudden loading. Balancing cellulose content is crucial to meet specific application requirements, suggesting that an optimal cellulose content for achieving the desired balance between creep resistance and ultimate tensile strength exists. The findings of this work underscore the potential of FGMs to address the trade-offs between different material properties.

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Conflicts of Interest

The authors declare no conflict of interest.

Author Contribution Statement

All authors contributed to writing and editing this manuscript. Manal H. Jasem and Esraa A. Abbod proposed the research problem and supervised this work. All authors developed the introduction, organized the manuscript, discussed the results, and contributed to the final manuscript.

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