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Experimental Investigation of the Relief Time for Fiberglass/Epoxy Composites with Volume Fraction 30% and 40%

Mahmoud, M.F. [1] *and Abdel Elnaby M.A.*[2]

ABSTRACT

This paper deals with an experimental study of a relaxation behaviour of fibreglass/epoxy composite material subjected to tensile stress. The small tensile testing machine including the heating chamber with temperature controller is designed and manufactured to perform the stress relief testing at different operating conditions. The influence of the operating temperature onto both the relief time and the number of the loading cycles is considered. The test specimens having a different number of layers of fibreglass tissues are prepared in the laboratory. Furthermore, the effect of the fiberglass tissue volume fraction on the relief behaviour of the fibreglass/epoxy composite material is investigated. The constant of the relief time is evaluated for various volume fraction and operating temperature. The obtained results showed that the relief time and the number of relaxation cycles are highly increased by increasing the fibreglass layers. The total number of relief cycles was increased by about 34% when increasing the volume fraction of the fibreglass tissue by about 15%. The relief time of the first cycle was increased by about 83% when increasing the volume fraction of the fibreglass tissue from 30% to 45 % at operating temperature equal to 60^oC. The time taken to fracture the specimens decreased significantly by increasing the operating temperature as it decreased by about 88% and 73% for volume fraction 30% and 40% respectively when raising the operating temperature from the room temperature to 60^oC. The material relief time constant is strongly affected by both the operating temperature and the volume fraction of the fibreglass tissue.

KEYWORDS: Relaxation modulus, material models, composite materials, polymeric materials, creep

1. INTRODUCTION

Plastics have become an essential part of our life's. Thus, it is essential for engineering applications to determine the mechanical features of the plastic and its composites, such as their relaxation conduct [1]. Many studies were performed to investigate the mechanical and thermal properties of the polymeric materials and their composites by different parameters. Even so, there are little studies had been focused on the relief or relaxation characteristics of the polymer composites. Whereas the creep deals with the growth of the strain with time under constant stress, the stress relief is a measure of the attenuation of stress with time with a constant strain [2-5]. The engineering components are often subjected to a constant strain such as the screw and sealing parts, as a result, many of the automotive manufacturers have begun to perform relaxation examinations for the critical parts in their products. Some theoretical and experimental studies were performed to estimate the relief behaviour of polymeric materials at different operating conditions [6-10].

[1]Department of Mechanical Design, Faculty of Engineering (Elmataria), Helwan University, Egypt. mf.fahmy@gmail.com

[2]Department of Production and Design Engineering, Faculty of Engineering, Minia University, Egypt.

Viscoelastic materials, such as amorphous polymers, semi crystalline polymers, and biopolymers, can be modelled in order to determine their stress or strain interactions as well as their temporal dependencies.

These models, which include the Maxwell model, the Kelvin-Voigt model, and the Standard Linear Solid Model, are used to predict a material's response under different loading conditions. Viscoelastic behaviour has elastic and viscous components modelled as linear combinations of springs and dashpots, respectively. Each model differs in the arrangement of these elements. Nutting- Struik relationships and Kohlrausch-Williams-Watts (KWW) functions were applied to estimate which of them could be a better model to simulate the stress relief behaviour of the polymeric materials [11-16]. Obaid et al. [17] studied the effect of adding an interfacial coupling agent on the stress relaxation characteristics of the fibreglass/ polypropylene composites. George et al. [18, 19] investigated the stress relief behaviour of the short pineapple-fibre reinforced polyethene composites. They found that the addition of natural fiber has reduced relaxation of stress and the interface between fiber and matrix has a major impact on the general behaviour. Gutman et al. [20] studied the

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influence of the chemical environment on stress relief in the polyester-fibreglass composite material, they observed an increase in relief when the material was subjected to the acidic or basic environment. Nouri [21] studied the creep and stress relaxation of a polypropylene-based copolymer. The obtained results showed that Struik- Nutting model was proper to simulate creep experiments while the Maxwell model was sufficiently suitable to predict the relief time. Tang et al. [22] proposed a mathematical model based on the variational asymptotic method to describe the stress relaxation of the polymeric composites. Their results were in a good agreement with the finite element findings using ABAQUS software.

This paper presents an experimental study for the stress relief of the fibreglass/epoxy composite materials in order to contribute for a better understanding of the relaxation behaviour of the polymeric composite materials under uniaxial tensile stress. The mechanical relaxation testing machine is designed and manufactured to perform and measure the relief of the polymeric materials. The required specimens from fibreglass tissue/epoxy composite material are produced in laboratories by using vacuum bagging method. The effects of the fibreglass layers and the environment temperatures on the stress relief behaviour of the fibreglass/epoxy composite are studied. The relief time constant is evaluated for several volume fractions and environment temperatures.

2. MATHEMATICAL MODELL

This section explains the mathematical model that uses to derive the necessary equations. The rheological properties of the viscoelastic materials are nonlinear and time-dependent due to the influence of the nonlinearity of both elastic and damping functions. The Maxwell model is utilized to determine a fibreglass/epoxy composite response at various loading conditions. . The Maxwell model predicts that stress decays exponentially with time, which is accurate for most polymers. In the Maxwell model, the viscoelastic material is modelled by a viscous damper and a spring connected in series. With this arrangement, the force on each element is similar and equal to the acting force. In addition, the total strain is equal to the summation of the strain of the two elements [21]. The total strain acting on the viscous damper and the spring can be written as following:

$$\varepsilon_t = \varepsilon_e + \varepsilon_v \tag{1}$$

In addition, the stress - strain relation for the plastic materials can be expressed as:

In an elastic region

$$\sigma = E\varepsilon_e \tag{2}$$

In a plastic region

$$\sigma = \eta \, d\varepsilon_v/dt \tag{3}$$

Where ε_t is the total strain, σ is the applied axial stress , E is the modulus of elasticity, ε_e is the elastic strain in the spring, ε_v is the viscous strain in the damper , t is the time and η is the material coefficient of viscosity.

By differentiating Eq. (1) regards to time The strain rate under uniaxial stress can be expressed as follow:

$$\frac{d\varepsilon_t}{dt} = \frac{d\varepsilon_e}{dt} + \frac{\sigma\varepsilon_v}{dt} \tag{4}$$

Replacing the stress term from Eqs. (2, 3) into Eq. (4), therefore

$$\frac{d\varepsilon_t}{dt} = \frac{d\sigma}{Edt} + \frac{\sigma}{\eta} \tag{5}$$

For constant strain as in the case of the relaxation, thus

$$\frac{d\varepsilon_t}{dt} = 0 \qquad \text{and} \qquad \frac{1}{E}\frac{d\sigma}{dt} = -\frac{\sigma}{\eta}$$

Hence

$$\frac{d\sigma}{\sigma} = -\frac{E}{\eta}dt \tag{6}$$

The integration of the Eq. (6) leads to:

$$\ln\sigma = -\frac{Et}{\eta} + C \tag{7}$$

Using the initial conditions, where at the beginning of the relief test, t = 0 and the stress σ equal to the initial stress σ_o , therefore the Eq. (7) can be rewritten as follow:

$$\ln\sigma - \ln\sigma_o = -\frac{E}{\eta}\, t \tag{8}$$

Based on Eq. (8), the relation between the relief stress and the time can be expressed as:

$$\sigma(t) = \sigma_o e^{-(\frac{Et}{\eta})} \tag{9}$$

By introducing the relief time constant as:

$$\lambda = \frac{\eta}{E}$$

Hence, Eq. (9) can be written as:

$$\sigma(t) = \sigma_o e^{-(t/\lambda)} \tag{10}$$

Equation (10) offers an acceptable qualitative show of the relaxation stress and time that can be utilized under distinct circumstances to forecast relaxation behaviour.

3. MATERIALS

Thin sheets of the Fibreglass /epoxy composite material are manufactured from fibreglass tissue utilizing the vacuum bagging process. Where the fiberglass fabric is placed in the form of successive layers separated by epoxy material. Table 1 summarizes the physical and mechanical properties of the resin used. Almost every composite fibreglass/epoxy sheet is 10 cm wide and 2 mm thick with a length of 30 cm.

Table 1: Mechanical and physical properties of the utilised resin.

Density (kg/m^3)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Failure Strain (%)
1200	60	1.3	1.8

Two types of composite material sheets have been manufactured based on the number of fibreglass tissue layers with a fibre volume ratio (volume fraction) of vf = 30% and vf = 45% respectively. Lastly, from these sheets, the test specimens with dimensions of 1.2 cm wide and 12 cm long are cut from these sheets. The fibreglass / epoxy composite maximum tensile strength σ_u is shown in Table 2 for a varying volume fraction.

Table 2: the Maximum tensile strength at different volume fractions

v_f %	30%	45%
σ_u (MPa)	74	81

4. TEST MACHINE DESCRIPTION and EXPERIMENTAL PROCESSES

Figure 1 shows the tensile testing machine, which was designed and manufactured to perform uniaxial tensile stress relief tests. The test machine consists of a steel frame where the upper base is used to suspend a digital load cell used to measure the variation of force applied over time. The middle base can move along the side guides to adjust the space needed to place the controllable oven and sample. The testing specimen is fixed from both sides by special jaws. The upper jaw tip is pinned with the force gauge and the other lower jaw is pinned with the loading shaft. The loading shaft consists of a power screw can move freely vertically through the loading hand, which is used to rotate a special nut installed on a self-aligning roller bearing was fastened to the middle base. In addition, the test machine is equipped with a controllable isolated oven that allows test specimen to be placed inside it during the test procedure. The isolated oven is completely controllable to maintain the inside temperature in a range of $\pm 2\%$ from the set temperature through a special temperature control unit. The oven is fixed on the left side guide through a movable frame made from steel ducts.

At the beginning of each test, the stress equal to 10% from break stress is applied to the test specimen and allow the test specimen to relax to stress equal 8% from break stress. The variation of the affecting stress on the specimen is recorded over time until the lower limit of the stress is reached. Sequentially, the specimen is loaded again to the upper limit of the stress. The same process is reiterated until the specimen breaking. Each experiment is conducted on a new specimen.

Fig. 1. Uniaxial relief tensile stress test machine with a controllable oven

5. RESULTS and DISCUSSIONS

The variation of the affecting stress on the test specimen with the time for each load and reload cycle at ambient temperature ($T \cong 30^{o}C$) is shown in Fig. 2. The time is taken by the specimen to relax from the upper-stress limit to the lower stress limit is called a relaxation or relief time. Referring to Fig. 2, the relief time of the primary cycle is greater than the successive cycles and it is decreased through the successive cycles until the fracture has taken places. The specimen takes about 810 min to achieve the first relaxation cycle and this time is decreased to about 758 min and 103 min in the second and the sixth cycles respectively.

Figure 3 displays the variation of the relief stress cycles in the time domain for a specimen with vf = 30 %. It can be noticed that about nine loads/ reload cycles is achieved until the fracture of the specimen. The specimen was taken about 2882 min to reach to the fracture.

As shown in Fig. 4, the same trend is observed with increasing the percentage of the fibreglass tissue to vf = 45%. Where the first cycle has greater relief time and this time is gradually decreasing throughout each of the successive cycles until the rupture of the specimen. On another hand, increasing the volume fraction of the fibreglass tissue from vf = 30% to 45% leads to an increase in the total number of relief cycles from nine to twelve cycles.

As shown in Fig. 5, it can be observed that the specimen fracture time due to the load/reload cycles is reached to about 3147 min by reinforcing epoxy with vf = 45 % of fibreglass tissue. The fracture time increases significantly compared with the case of vf = 30% which meant that the fibreglass tissue performs an essential function to increase the relaxation resistance of the epoxy composites.

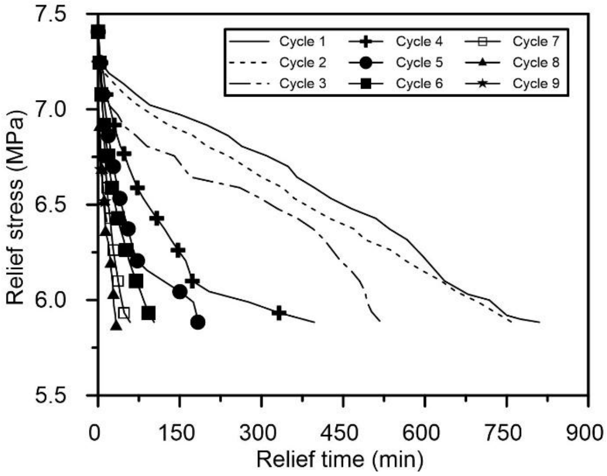

Fig. 2. The variation of the relief stress with time for the different relief cycles at vf =30%

Fig. 6 displays a comparison of the relief time of first relief cycle at the volume fraction of the fibreglass tissue vf = 30% and 45 %. It can be noticed that the relief time of the first cycle is increased from 810 min to 850 min by increasing the volume fraction of the fibreglass tissue from vf = 30% to vf = 45 %. The increasing of the fibreglass tissue percentage plays an essential role in increasing the relief time of fibreglass/epoxy composite. Also, its influence is noticed in both the successive relaxation cycles and the total number of the relaxation cycles which the specimens performed until the fracture.

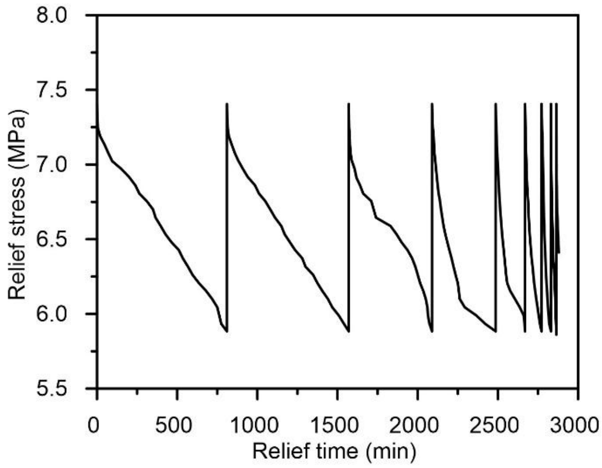

Fig. 3. Relief cycles in the time domain for vf =30%

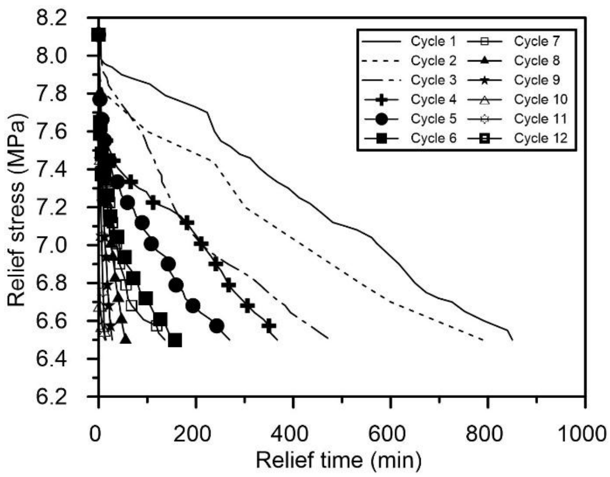

Fig. 4. The variation of the relief stress with time for the different relief cycles for vf =45%

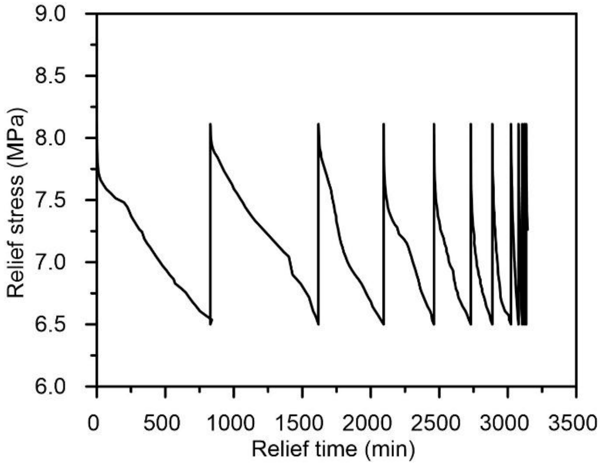

Fig. 5. Relief cycles in the time domain for vf =45%

Figure 7 demonstrates the variation of the relief stress in the time domain for various relaxation cycles for the reinforced epoxy composite with vf = 30% at the operating temperature T=60 °C. it can be observed that the test specimen performed only seven relaxation cycles until the fracture reached, compared with nine cycles were achieved in the ambient temperature case. Else that, the general relief behaviour of the fibreglass/epoxy lamella is still consistent with its behaviour in ambient temperature.

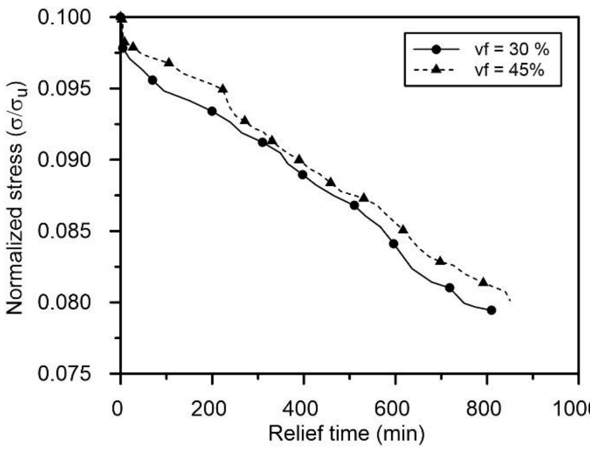

Fig. 6. Variation of the normalized stress for the first relaxation cycle at vf =30% and 45%

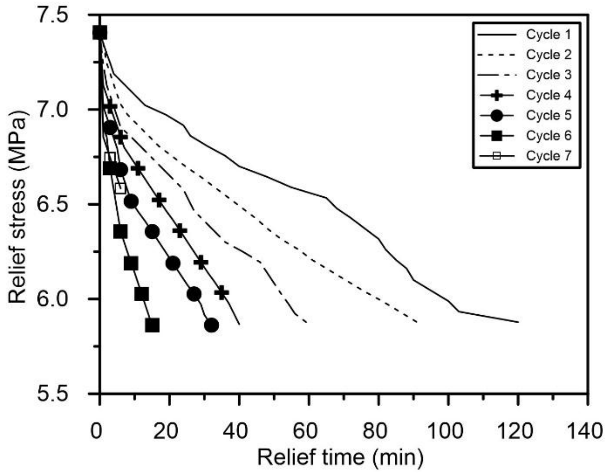

Fig. 7. The variation of the relief stress with time for the different relief cycles at vf =30% at T= 60°C.

Fig. 8 shows, the variation of the relief stress cycles of the fibreglass/epoxy composite material for vf = 30% at operating temperature T= 60 °C. It can be observed that the specimen was taken about 364 min to reach the fracture. Therefore, increasing the operating temperature leads to dramatically drop in the fracture time, which is dropped from 2282 min to 364 min with raising the temperature from ambient temperature to 60°C.

Figure 9 demonstrates the variation of the relief stress in the time domain for various relaxation cycles for the reinforced epoxy composite with vf = 45% at the operating temperature T=60 °C. it can be observed that the test specimen performed only nine load/reload cycles until the fracture reached, compared with twelve cycles were achieved in the ambient temperature case. Else that, the general relaxation behaviour of the fibreglass/epoxy lamella is still consistent with its behaviour in ambient temperature. Furthermore, the relief time of first relief cycle was decreased by about 75% from its value at the ambient temperature.

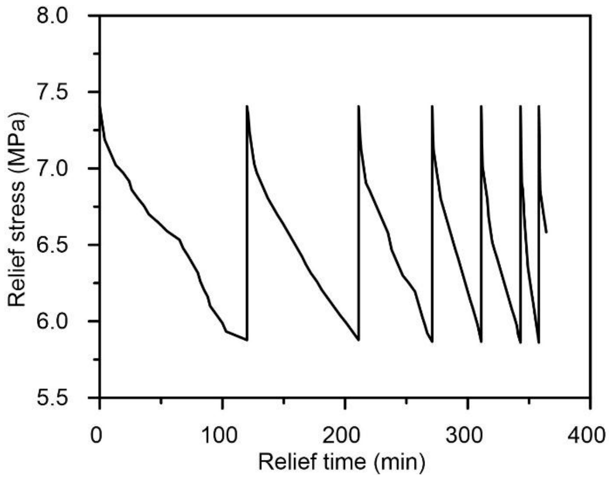

Fig. 8. Relaxation cycles in the time domain for vf =30% at T= 60°C.

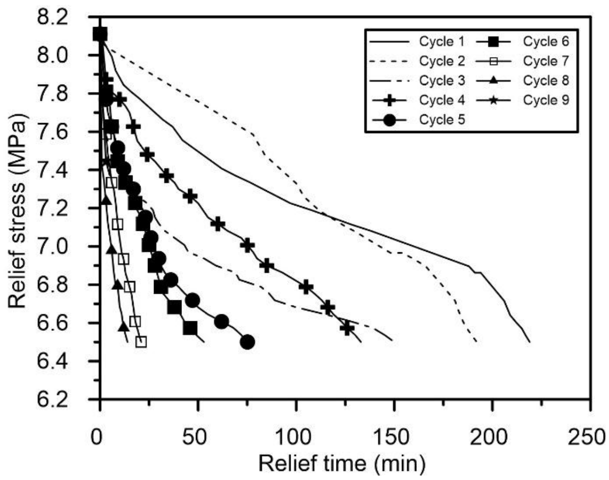

Fig. 9. The variation of the relief stress with time for the different relief cycles for vf =45% at T= 60°C.

Figure 10 displays the variation of the relief stress cycles in the time domain for the reinforced epoxy by vf = 45% from fibreglass tissue at operating temperature T= 60 °C. It can be noticed that the fracture time is reached to about 862 min with a percentage increase of about 140% over than that in the case of vf=30% and T= 60 °C. On another side, the increasing of the operating temperature leads to a drop of the fracture time by about 73 % compared with that at ambient temperature.

Figure 11 displays a comparison of the relief time of first relaxation cycle at the operating temperature of T= 60 °C for the volume fraction of the fibreglass tissue vf = 30% and 45 %. It can be noticed that the relief time of the first cycle is increased by about 83% by increasing the volume fraction of the fibreglass tissue from vf = 30% to 45 %. This shows that the percentage of the fibreglass tissue plays an essential role in increasing the relief time of the fibreglass/epoxy composite. In addition, the influence of the operating temperature on the contraction of the relief time is noticed from the first relief cycle and continue in the successive cycles. This high difference of the relief time of the first relief cycle was not recorded for the cases at the ambient temperature. Therefore, the dramatically dropping of the relief time can be interpreted by the relatively deboning of the fibreglass fabric and the epoxy matrix with increasing the operating temperature.

On another side, and referring to Eq. (10), the relief time constant has great importance where it can be defined as the time taken to reach the stress affecting on the specimen to 1/e (0.368) of its primary value (*e* is the base of natural logarithm).

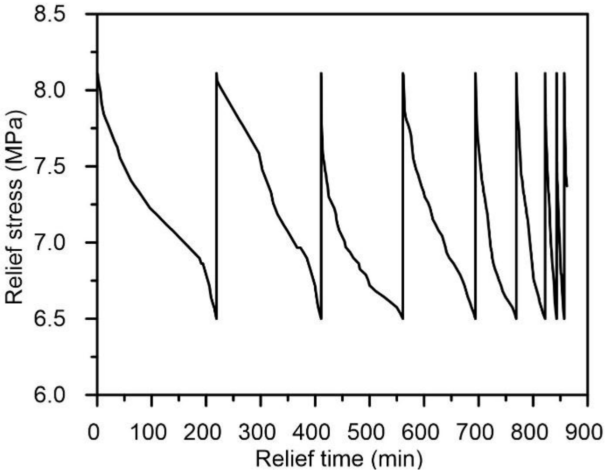

Fig. 10. Relaxation cycles in time domain for vf =45% at T= 60°C.

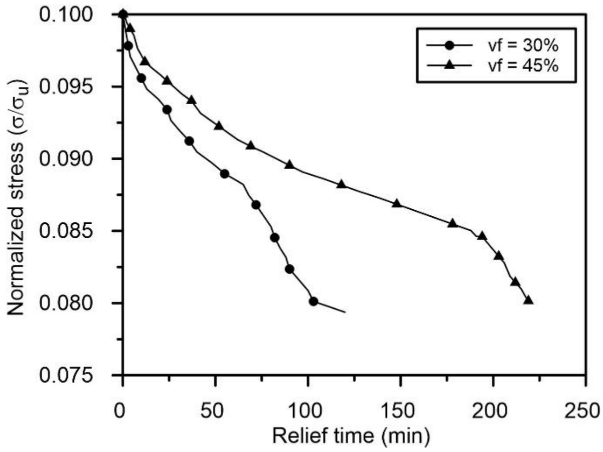

Fig. 11. Variation of the normalized stress for the first relaxation cycle for vf =30%, 45% at T= 60°C

Figures 12 and 13 shown the exponential fitting curves of the experimental findings of the first relief cycle for the fibreglass tissue/epoxy composite for the different volume fractions at ambient temperature and 60°C respectively. Furthermore, the relief time constant values for fibreglass tissue/epoxy composite for vf =30% and 45% at the operating temperature T= 30°C and 60°C are summarized in Table 3. According to the obtained values of the relief time constant, it can be observed that the relief time constant of the reinforced epoxy composite is extremely influenced by the percentage of the fibreglass tissue and substantially dependent on the operating temperature.

6. CONCLUSIONS

The obtained results show that the first load/reload cycle have the highest relief time compared with the successive cycles. The lower operating temperate extending the relief time of the fibreglass tissue /epoxy composite several times. Where the relief time for vf =30% and 45% was decreased by about 3.8 times and 6.75 times respectively when increasing the temperature from T=30° **C** to T= 60° **C**. Furthermore, the fracture time is affected by the percentage of the fibreglass tissue where it was increased by about 1.1 times and 2.4 times at T=30° **C** and T=60° **C** respectively when increasing the volume fraction from 30% to 45%. Subsequently, the relief stress of the fiberglass tissue/epoxy composite material can be obtained directly using the presented relief time constant for different operating temperatures and volume fractions.

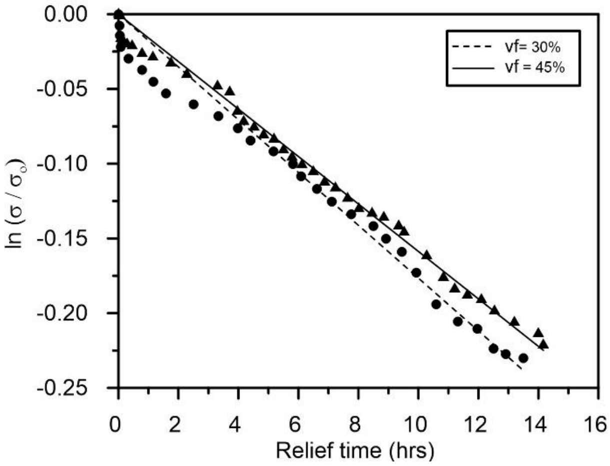

Fig. 12. Curve fitting of the first relief cycle at ambient temperature.

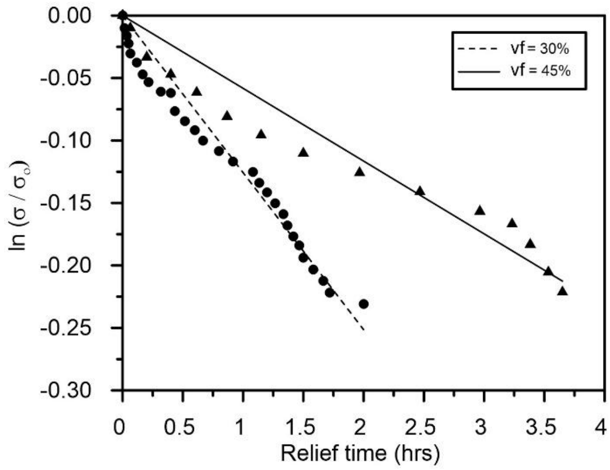

Fig. 13. Curve fitting of the first relief cycle at T = 60° C

Table 3. Relief time constant λ for fiberglass tissue/ epoxy composite material

	Ambient Temperature		**T= 60° C**	
$\mathbf{v_f}$	30%	45%	30%	45%
λ	56	63	8	17

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