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Non-linear creep of polypropylene utilizing multiple integral

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ABSTRACT

Multiple integral representation (MIR) has been used to represent studying the effect of temperature on the amount of nonlinear creep on the semi-crystalline polypropylene (PP) under the influence of axial elastic stress. To complete this research, the kernel functions were selected, for the purpose of performing an analogy, and for arranging the conditions for the occurrence of the first, second and third expansion in a temperature range between 20 °C-60 °C, i.e., between the glass transition and softening temperatures, within the framework of the energy law. It was observed that the independent strain time increased non-linearly with increasing stress and non-linearly decreased with increase in temperature, although the time parameter increased non-linearly with stress and temperature directly. In general, a very satisfactory agreement between theoretical and practical results on the MIR material was observed.

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Nomenclature:

e in	Strain tensor
e (t)	Tensile strain
e_o	Time independent strain
F_{ij}	Non-linear continues functional
F_i	Kernel functions
F_{oi}	Time independent component of kernels
F_{mi}	Time dependent coefficients of kernels
m	Time dependent coefficient
N	Time exponent
σ	Tensile stress
ξ	Time parameter (s)

1. INTRODUCTION

After polymers have been widely used in various industrial and commodity fields, polymeric materials are now widely used in structural and construction applications, as its performance meets the necessary maximum mechanical requirements, hence the importance of research and study. Another parameter of paramount importance is that the creep resistance is uniform when under the influence of a long-term load, as it changes from linear to non-linear behavior. Chronological and historical sequences can be linked to reasonably and acceptably determine the non-linear behavior of the polymer material [1]-[4].

Brinson and Brinson [5], Torrens and Castellano [6] used a one-dimensional equation containing first and third order integrals to describe the mechanical behavior characterized by the second function of kernel and up to the third function, for polypropylene (PP) material [7]-[10]. Touati and Cederbaum [11], Lai and Findley [12] identified nine kernel functions to describe the behavior of polyvinyl chloride (PVC) under the influence of both tensile and twisting stress. For further work, only the first and second kernel order of pure tension was assumed, and only the first and third order of pure twist [13]-[17]. When studying the properties of polietilena (PE), "the second kernel arrangement suffices to describe the effect of pure shear distortion and the third kernel order to characterize the effect of pure tensile strength" [18]-[24]. Others researches use multiple integral representation (MIR) and power law to describe the large distortion occurring in nylon-6, in which the mechanical behavior changes from one mode to another, and in each mode the mechanical behavior remains subject to the power law and for all kinds of different loads [25]-[36]. The goal of all of this is to think using a combination of MIR and power law to investigate how temperature affects the mechanical behavior of viscous materials (0.909 g/cm3 at 20 °C) under the influence of uniaxial load.

2. RESEARCH METHOD

For the purpose of developing a suitable characterization of nonlinear behavior, it is assumed that the material elongation rate with respect to time (t) depends mainly on the values of the load rate previously placed on the material or sample. In other words, the elongation that occurs in the sample is a function of the rated loads [1].

$$e_{ij} = F_{ij}\left[\frac{d\sigma(\xi)}{d\xi}\right]_{-\infty}^{t} \tag{1}$$

Where F_{IJ} is represent the continuous nonlinear function. The F function can be represented as indicating the degree of precision within the multiple integration equation [5], [6].

$$e(t) = \int_{-\infty}^{t}(t-\xi_1)\frac{d\sigma}{d\xi_1}d\xi_1 + \int_{-\infty}^{t}\int_{-\infty}^{t}F(t-\xi_1 . t-\xi_2)\frac{d\sigma}{d\xi_1}\frac{d\sigma}{d\xi_2}d\xi_1 d\xi_2 + \int_{-\infty}^{t}\int_{-\infty}^{t}\int_{-\infty}^{t}F(t-\xi_1, t-\xi_2, t-\xi_3)\frac{d\sigma}{d\xi_1}\frac{d\sigma}{d\xi_2}\frac{d\sigma}{d\xi_3}d\xi_1 d\xi_2\, d\xi_3 \tag{2}$$

According to (2), the time dependent elongation produced by uniaxial tensile loading applied at time $\xi_1 = \xi_2 = \xi_3 = 0$ is given by the expression (3).

$$e(t) = F_1(t)\sigma + F_2(t)\sigma^2 + F_3(t)\sigma^3 \tag{3}$$

By substituting the responses obtained from three tensile tests at different levels of stress, (3) becomes a system of simultaneous algebraic equations with the three unknowns, F_1, F_2, and F_3. These equations have been solved for each step time using "Gaussian elimination" to find these kernels in the form of Findlay's power [8] as (4a), (4b), and (4c).

$$F_1 = F_{01} + F_{m1}t^N \tag{4a}$$

$$F_2 = F_{02} + F_{m2}t^N \tag{4b}$$

$$F_3 = F_{03} + F_{m3}t^N \tag{4c}$$

The equation of tensile strain can be obtained by substituting (4) into (3).

$$e(t) = (F_{01} + F_{m1}t^N)\sigma + (F_{02} + F_{m2}t^N)\sigma^2 + (F_{03} + F_{m3}t^N)\sigma^3 = e_0 + m_0 t^N \tag{5}$$

Where e_o and m_o are time independent strain and time dependent coefficient respectively, and both are functions of stress and material constants. N is constant (5) emphasizes that creep reaction of non-linear viscoelasticity materials can be partitioned into time, stretch, and temperature reliance components.

A "creep test" is performed on a sample using a creep meter (note the device in Figure 1). In simple terms, the sample is heated to a temperature. Once the temperature set point is reached, a constant load is applied to exert a longitudinal force on the material's grain structure. Pregnancy is maintained for the duration of the test or until the sample is ruptured. During testing, data is continuously monitored and recorded to qualify for temperature stability, load, and sample elongation.

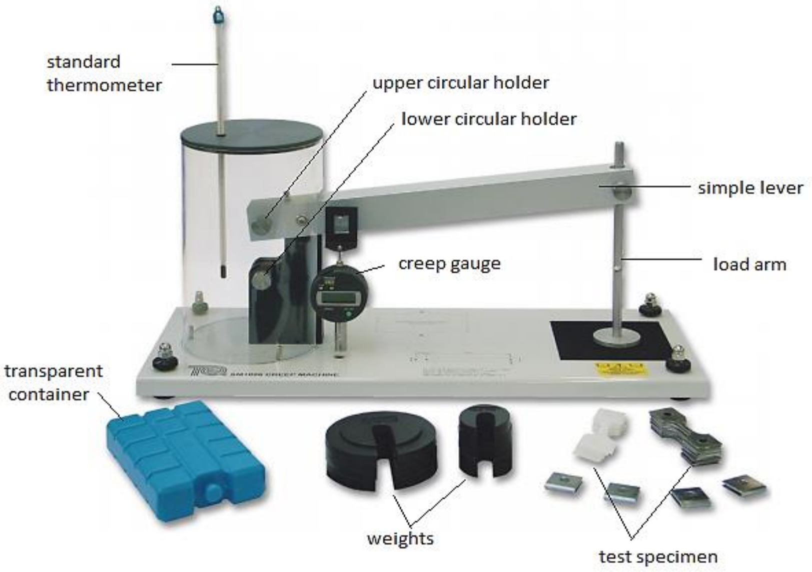

Figure 1. SM1006 creep test device

3. RESULTS AND DISCUSSION

The deformation behavior available at 20 °C and 60 °C only and linear interpolation between them can be made to obtain the deformation at 30, 40, and 50 °C [8]. Kernel functions have been determined at each temperature using three different stress levels (σ = 1.378, 4.136, and 6.897 MPA) in the form of power law, in which the value of time exponent is valid for all levels of loading. From Table 1 it can be noted that the time exponent increases as temperature increases. Kernel functions given in Tables 2, 3, and 4 are presented in Figures 2, 3, and 4. These figures show that, first and third kernels increase non-linearly with time, whereas the second kernel decreases non-linearly. This result is emphasized by the presence of negative values of time dependent coefficients in Table 1. This behavior was observed at each temperature. Also, it was found that temperature increasing caused a shift in values of all kernels. It is critical here to specify that non-linear viscoelasticity can be related to the time dependent on terms of these parts, since the time autonomous terms allude to starting reactions.

Table 1. Variation of time exponent with temperature

Temp. °C	N
20	0.070
30	0.0765
40	0.0817
50	0.086
60	0.090

Table 2. First kernel at different temperature

Temp. °C	F1 (M Pa^{-1})
20	-0.0141241 + 0.132254 t N
30	-0.01284681 + 0.162771 t N
40	-0.007553014 + 0.1886007t N
50	-0.008763126 + 0.2219725t N
60	-0.1184285 + 0.2514425t N

Table 3. Second kernel at different temperature

Temp. °C	F2 X 10-3 (M Pa^{-2})
20	2.320227 – 9.034076 t N
30	1.992685 – 6.130732 t N
40	1.269982 – 2.563623 t N
50	2.1936700 – 1.05282 t N
60	5.290401 – 0.3867674 t N

Table 4. Third kernel at different temperature

Temp. °C	F3 X 10-3 (M Pa^{-3})
20	-0.5189451 + 1.540565 t N
30	-0.4471407 + 1.608113 t N
40	-0.2774595 + 1.613862 t N
50	-0.3519898 + 1.8840761 t N
60	-0.3637092 + 2.077798 t N

Non-linearity degree can be related to the temperature increase since time subordinate coefficients are shifted with temperature. From Tables 2, 3, and 4, time dependent coefficients of first and third kernels are increased as temperature increases, whereas decreased for second kernel. Thus, the non-linearity degree increases for first and third kernels, and decreases for second kernel shown in Figures 2, 3, and 4.

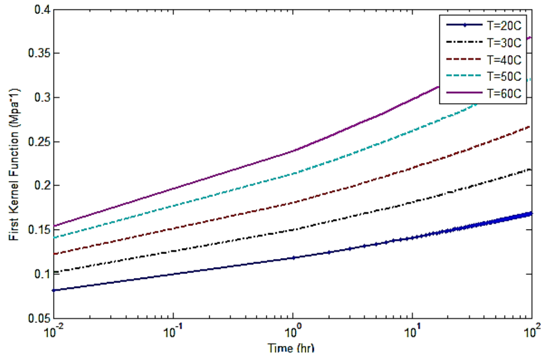

Figure 2. First kernel function of PP for axial tensile loading at different temperature

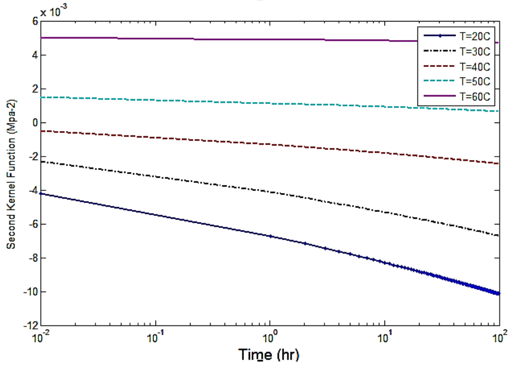

Figure 3. Second kernel function of PP for uniaxial tensile loading at different temperature

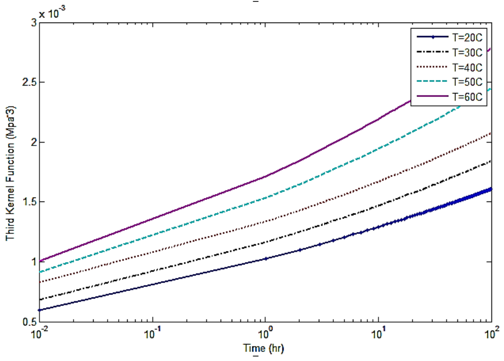

Figure 4. Third kernel function of PP for uniaxial tensile loading at different temperature

From these figures, it can be noted that, effects of F1 and F2 are opposite that of F2 up to 40° C. Beyond this temperature, Figure 3 shows that the values of F2 change from negative to positive (i.e., effects of all kernels are gathered). As temperature, the crystalline degree diminishes and causes a decrease in solidness and tensile quality [37], which increases the inclination of materials to deform (strain rate expanding). This change in properties happens due to the holding powers between the atomic chains ending up weaker. As strain rate increasing, the molecular chain is gradually aligned closer together and oriented in the direction of applied stress, thus, the capacity of these adjacent closer chains to bond again increases and causes increasing tensile and stiffness (strain rate decreasing). Crystalline behavior characterized by α and γ relaxation. Local twisting of atomic chains is represented by γ relaxation, which related with non-linear defects occur in the crystal phase inside the crystal and then move in the form of distortions in the amorphous phase associated with F1 and F2, which increases the tensile strength and reduces the strain rate. This deformation is related to alpha relaxation, and can be represented by F1 and F2. The change in the value of the kernel function agrees with the results of Seeker [37]. Figures 5, 6, 7, 8, and 9 show the results of this representation. Contributions of F1 and F3 at (σ = 1.378 MPA) to total F2 opposite strain up to 40 °C. Beyond this temperature, this behavior does not hold up due to distortion of most of the molecular bonds. It was also found that, over a full timescale, F1 contributed significantly to total stress. With reference to Figures 2, 3 and 4, and based on the equation of temperature and time, the effect of time on the kernel function is similar to that of temperature.

For each temperature, substituting time exponent and kernel functions given in Table 1 and Table 2 in (5), creep strain at different stress levels is shown in Figures 10, 11, 12, 13, and 14. Comparison of MIR and experimental results shows that agreement between them was very satisfactory. Also, it was found that, for each temperature, the strain increases non-linearly with time (since the time exponent is not equal to 1) and stress increment causes a shift in these curves. Net impacts of these parts are given in Figure 15 and Figure 16 through the behavior of time free strain e o and time subordinate coefficient m. Figure 15 appears that, for each temperature, e_o increment non-linearly with stress, and temperature expanding caused a reduction move.

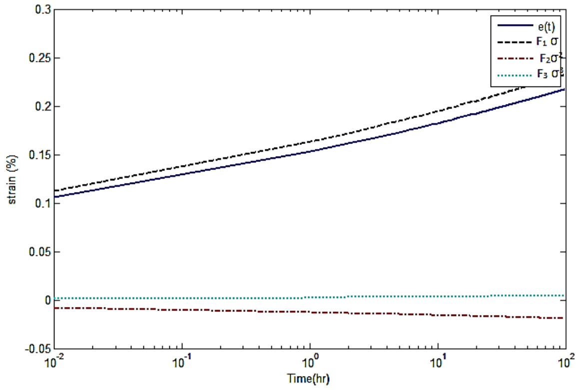

Figure 5. Contribution of kernel function of PP to total strain at σ = 1.3788 MPa and T = 20 °C

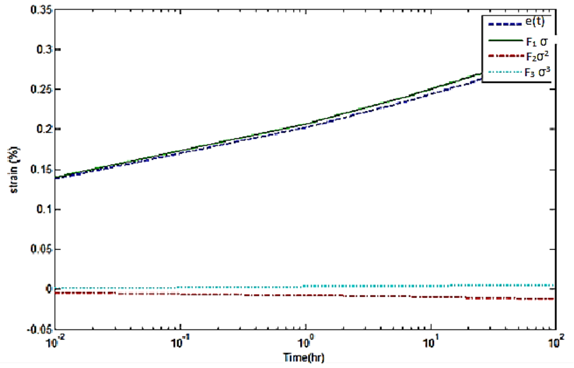

Figure 6. Contribution of kernel function of PP to total strain at σ = 1.3788 MPa and T = 30 °C

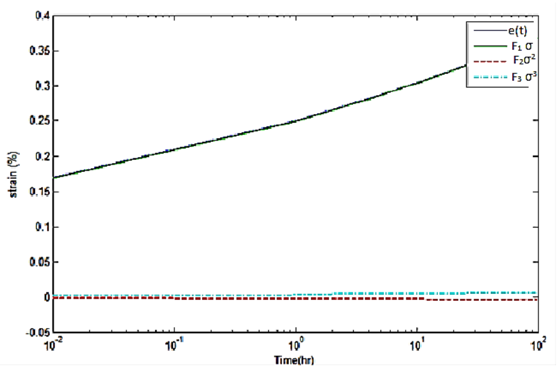

Figure 7. Contribution of kernel function of PP to total strain at σ = 1.3788 MPA and T = 40 °C

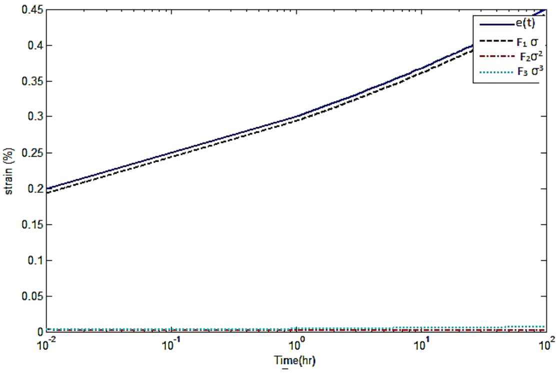

Figure 8. Contribution of kernel function of PP to total strain at σ = 1.3788 MPa and T = 50 °C

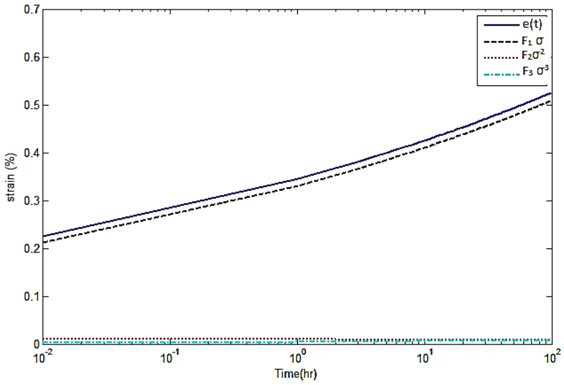

Figure 9. Contribution of kernel function of PP to total strain at σ = 1.3788 MPA and T = 60 °C

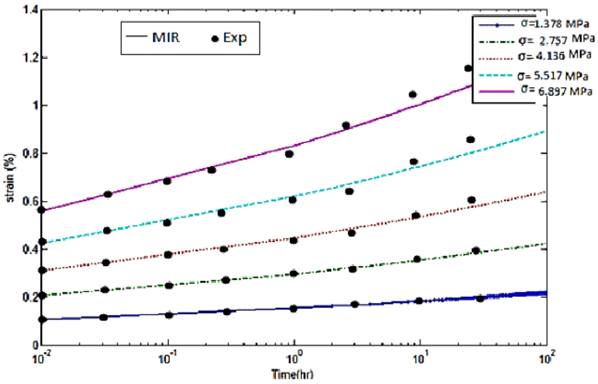

Figure 10. Creep curves of PP in different uniaxial tensile loading at 20 °C

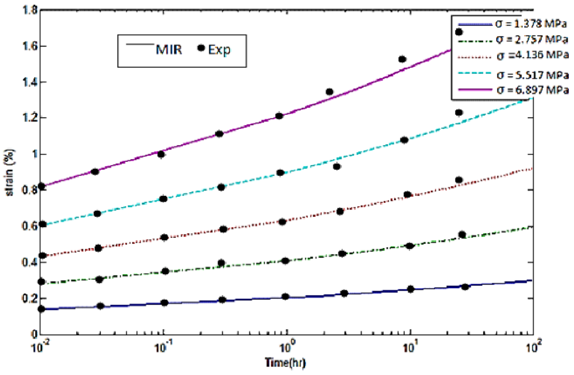

Figure 11. Creep curves of PP in different uniaxial tensile loading at 30 °C

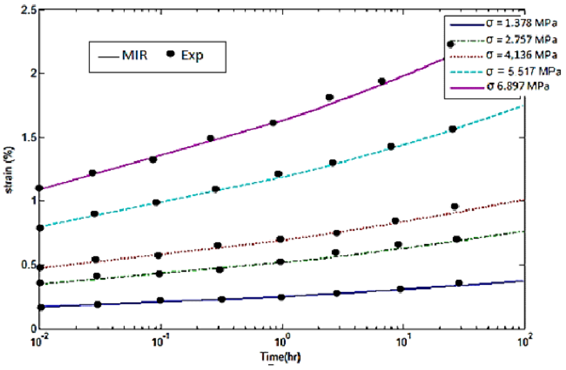

Figure 12. Creep curves of PP in different axial tensile loading at 40 °C

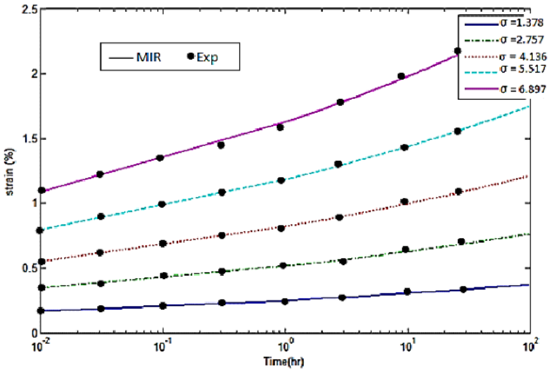

Figure 13. Creep curves of PP in different uniaxial tensile loading at 50 °C

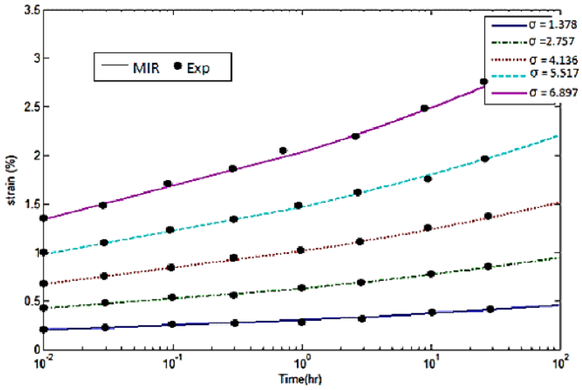

Figure 14. Creep curves of PP in different axial tensile loading at 60 °C

Figure 16 shows that m increases non-linearly with stress and temperature increasing caused a shift in m vs stress curves. The great shift occurred between 30 °C and 40 °C, which insulates more in Figure 17 and reflects the effect of temperature on molecular structure. The reduction of e_o (which represent initial strain) between 30 °C and 40 °C, is related to decreasing of stiffness due to network deformation. Figure 18 show that m is linearly increments with temperature and its effect with increased stress. These results emphasize that PP exhibits nonlinear viscous-elasticity for any deformation of practical importance [13]. Figure 19 shows that time exponent (N) is increasing non-linearly with temperature.

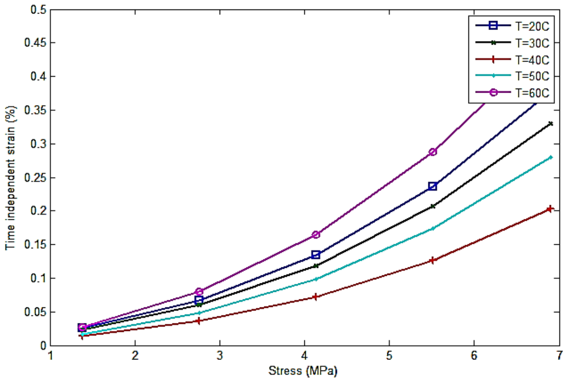

Figure 15. Tensile component of time independent strain e_o % vs stress at different temperature

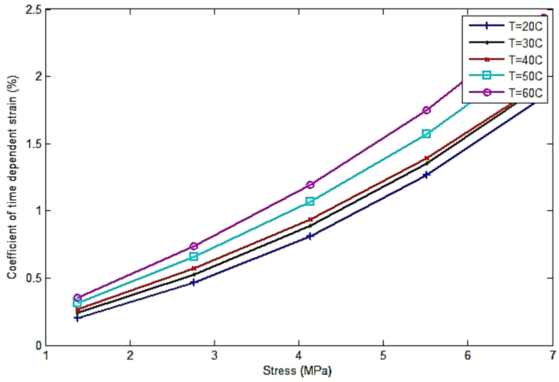

Figure 16. Coefficient of time dependent strain mo% vs stress at different temperature

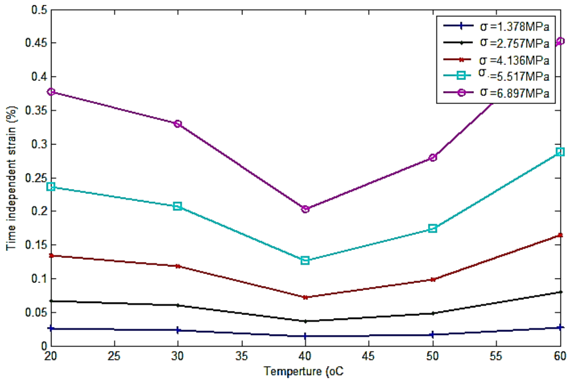

Figure 17. Tensile component of time independent strain e_o% vs temperature at different tensile stresses

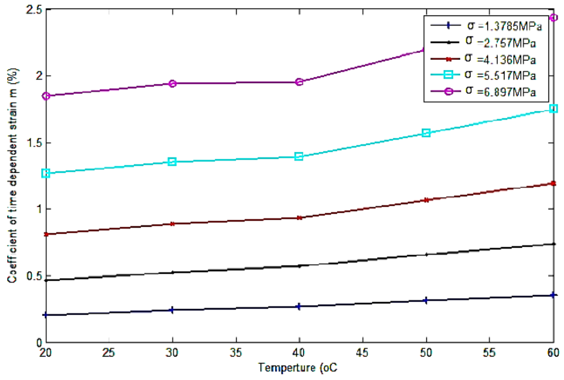

Figure 18. Coefficient of time dependent strain mo% vs temperature at different tensile stresses

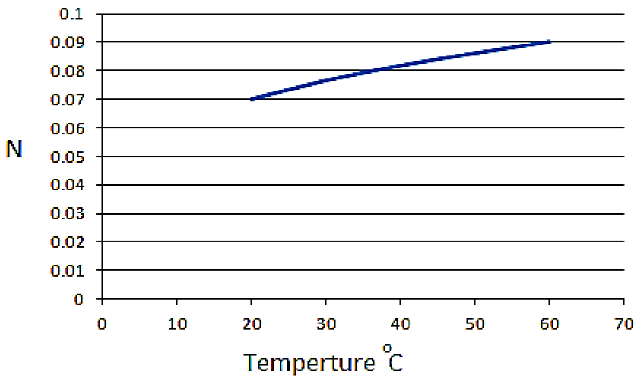

Figure 19. Time exponent (N) vs temperature

4. CONCLUSION

From the above discussion, we can draw: a) The non-linear behavior of PP is adequately described by power law, which the time exponent is valid for all stress levels; b) Non-linear creep of PP is enough spoken to by the first, second, and third arrange stretch of MIR; c) Time exponent n increase as temperature increases; d) First and third kernels increase non-linearly with time whereas F2 decreases non-linearly; e) All kernels increase non-linearly as temperature increases; f) First and third kernels can represent the deformation of non-crystalline phase, whereas second represent that of crystalline phase, which both occur beyond 40 °C; g) Stress increasing caused non-linearly increases in time independent strains and time dependent coefficients; h) Temperature increases cause non-linearly decreases in time independent strains and linearly increases in time dependent coefficient; and h) The time exponent (N) increases non-linearly with temperature.

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