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Effect of Fiber Length on the Short-Term Flexural Creep Behavior of Polypropylene

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***Abstract*— Injection molded long fiber thermoplastic components are being used in recent days as a viable replacement for metals in many applications .Present work focus on the effect of fiber length on the short-term flexural creep performance of fiber reinforced thermoplastic polypropylene. Unreinforced polypropylene, 20 wt % short and 20 wt % long glass fiber reinforced polypropylene materials was injection-molded into flexural test specimens. Short-term flexural creep tests were performed for 2 h duration on molded specimen at various stress levels with the aid of in-house developed flexural creep fixture. Experimental creep performance of polypropylene composites for 2 h is utilized to predict the creep performance with the aid of four parameter HRZ model and compared with 24 h experimental creep data. Creep strain was found to be increased with respect to time for all the test materials and found to be sensitive with respect to the stress level. Test results also revealed that long fiber reinforced thermoplastic material possessed enhanced creep resistance over their counter parts and HRZ model is sufficient enough to predict creep performance of polypropylene composites over wide range of stress.**

***Keywords-* Injection molding, flexural creep, thermoplastic, creep, strain**

I. INTRODUCTION

Due to the mass production requirement in the automotive industries, discontinuous long fiber reinforced thermoplastics (LFRT) have shown significant role in replacing metals, short fiber reinforced thermoplastics, thermoset sheet molding and bulk molding composites [1]. The common problem associated with unreinforced thermoplastics is creep under moderate to severe stress at elevated temperature. Creep resistance of thermoplastic composites is significantly improved by increase in fiber loadings [2]. Dynamic mechanical analysis (DMA) was utilized to investigate the viscoelasticity of injection-molded nylon 6/6 material reinforced with short and long glass fibers by Sepe[3] and reported an increase in creep resistance for long glass fiber reinforced nylon composites. Challa and Progelhof [4] investigated the effect of temperature on the creep characteristics of polycarbonate and developed a relationship based on Arrhenius theory to develop creep master curves. Pegoretti and Ricco [5] studied the propagation of crack under creep for varying temperature conditions for polypropylene composites and observed that speed with which the crack progresses was dependent on the test temperature. Krishnaswamy [6] performed extensive creep rupture testing on high density polyethylene pipes at various hoop stress levels and temperatures and observed the dependency of density and crystallinity towards failure. Houshyar [7] reported the improvement in creep properties with the addition of long polypropylene fibers in propylene-co-ethylene (PPE) matrix and visualized the improvement in interfacial properties. Trans-crystallization of the polypropylene matrix was observed in the PPE samples due to the thin layer of matrix on the reinforcement, which was attributed to good impregnation and wetting of the fibers. Greco et al. [8] investigated the flexural creep behavior for compression molded glass fiber reinforced polypropylene at various applied stress level. The effect of matrix crystallinity was highlighted for the improvement in creep properties for glass fiber reinforced polypropylene in their work. Acha et al. [9] studied the influence of interfacial adhesion in discontinuous jute fiber reinforced polypropylene. Relation between interfacial properties and creep deformation were investigated. Higher creep resistance was observed for polypropylene composites with good interfacial bonding which was confirmed by the observation of the composite fractured surfaces.

Findley and Khosla [10] conducted creep tests for unreinforced thermoplastics; polyethylene, polyvinyl chloride and polystyrene. Approximation was carried out for the linear viscoelastic region by power law and compared the creep performance by estimating the power law coefficient and power law exponent. Liou and Tseng [11] used Findley power law to estimate the creep compliance of carbon fiber nylon composites in hygrothermal condition. Power law model was modified by Hadid et al. [12] by incorporating the time and stress dependence during creep loading of polyamide specimens and estimated four parameters for describing the deformation occurring in the material and used stress–time superposition principle to predict long-term material creep behavior of injection molded fiber glass reinforced polyamide.

Master curves were developed and a perfect superposition of the curves at various stress levels was visualized. Novak [13] used strain energy equivalence theory and developed a creep predictive model to predict the creep behavior of talc filled polypropylene. Banik et al. [14] reported the improvement in creep resistance due to unidirectional reinforcement for polypropylene-polypropylene composites. Burger and Findley power law model were used to predict the short term creep behavior and the underlying deformation mechanisms were also investigated. Liu et al. [15] used multi-Kelvin element theory and power law functions to predict creep compliance in polyethylene material and compared with the tensile creep experiments.

Even though a lot of works were carried out in the past pertaining to the experimental creep behavior of plastics and composites, estimation and prediction of creep data using mathematical and numerical modeling is limited. Hence in this work the influence of reinforced fiber length on the creep performance of thermoplastic composite at various stress levels at room temperature condition was carried out. The results obtained through flexural creep test were analyzed using Findley power law model and empirical model proposed by Hadid *et al* [12]. Short term experimental creep results were used to predict long term creep behavior of the molded specimen.

II. Theorectical Background

A. Findley's Power Law Model

Mechanical behavior of polymeric material under constant stress was developed by Findley and Khosla [10]. The general form of the power law equation is given as

$$\varepsilon(t) = \varepsilon_t^{'} t^n \qquad (1)$$

where $\varepsilon(t)$ is the time dependent strain, $\varepsilon_t^{'}$ is power law coefficient which is stress and temperature dependent coefficient, n is the power law exponent and t is the time after loading.Power law model is simple in approach and successfully predicted nonlinear viscoelastic creep behavior of thermoplastic composites over large range of stress[10-13]besides this model is also recommended by American Society of Civil Engineers (ASCE) for structural plastics design manual in the analysis of composite materials for long term structural behavior [16].

B. HRZ Model

Findley's power law was unsuccessful in accounting for the stress effect on the mechanical behavior of polymeric material. The two power law parameters in the Findley-Khosla model $\varepsilon_t^{'}$ and n are significantly influenced by the applied stress level. Hadid *et al*. [12] modified the Findley's power law to incorporate time and stress dependence in the model where the power law coefficient ($\varepsilon_t^{'}$) and power law exponent (n) were plotted with respect to stress level (σ). The best fitting curve proposed the relation between $\varepsilon_t^{'}$ and σ as

$$\varepsilon_t^{'} = a(\sigma)^b \qquad (2)$$

Similarly the best fitting curve proposed between n and σ value takes the form

$$n = c\, exp(e.\sigma) \qquad (3)$$

Eqs. (2) and (3) are used in eq. (1) and strain at any particular time (t) can be calculated using the following HRZ equation

$$\varepsilon(t) = a\sigma^b t^{c exp(e.\sigma)} \qquad (4)$$

where a, b ,c ,e are the curve fitting parameters obtained from the regression analysis. Chevali *et al*. [17] used the four parameter HRZ model to fit the experimental data obtained from flexural creep investigation for nylon 6/6, polypropylene and high-density polyethylene based long fiber thermoplastic composites.

III. Experimental Creep Performance of Polypropylene Composites

A. Specimen Fabrication

In the current investigation, 20 wt % short glass fiber reinforced polypropylene (SFPP), 20 wt % long glass fiber reinforced polypropylene (LFPP) and unreinforced polypropylene (UFPP) obtained from Saint Gobain were used for injection molding the specimens. In general, lengths of the reinforced fibers in the short and long fiber reinforced pellets are 1 mm and 12.5 mm respectively [18]. Weight average fiber length of the reinforced fibers after injection molding for the chosen SFPP and LFPP materials are 0.440 mm and 1.251 mm respectively [19]. The base resin of LFPP and SFPP materials were having same molecular weight with a melt flow index of 40 g/10 min. According to the material supplier's data, silane type coupling agent has been used for the manufacturing of SFPP and LFPP materials. Since both the investigated materials used the same type and amount of coupling agent, material behavior discussions were limited only to the reinforced fiber length. Developed injection molding dies and molded specimens are shown in Figs 1a and 1b. Raw materials were initially preheated for two hours at 353 K and during molding, screw speed of 50 rpm and a low back pressure of 0.25 MPa were kept to retain the residual fiber length. Process parameters used for injection molding are listed in Table I. Due to the presence of reinforced fibers in LFPP and SFPP materials, temperature in the three zones were kept higher than unreinforced material.

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Fig 1a .Die for preparing specimens

Fig 1b. Injection molded specimens for flexural creep testing

TABLE 1
INJECTION MOLDING PARAMETERS FOR THE SPECIMENS

Screw diameter	35 mm
L/D	20
Screw speed	50 rpm
Barrel temperature Zone 1 Zone 2 Zone 3	 255 °C 250 °C 240 °C
Injection speed	50 mm/sec
Mold temperature	40 °C

IV. EXPERIMENTAL METHODOLOGY

A fixture is developed in house to evaluate the creep performance of molded specimen according to ASTM D2990 standard. The specimen is kept in between the supports as shown in Fig 2a and the load is applied at the centre of the test specimen with the means of steel rod attached with dead load. When the load is applied at the center the specimen is deflected and the deflection is recorded in the dial gauge as shown in Fig 2b. Test specimens were loaded with respect to various stress levels for 2 hrs. Constant load is maintained and test specimen deflection ($\delta(t)$) is continuously measured and recorded. Creep strain at instantaneous time ($\varepsilon(t)$) is computed using the relation (5) [20].

$$\varepsilon(t) = \frac{6\delta(t).d}{l^2} \qquad (5)$$

where, $\delta(t)$ is the deflection at instantaneous time , d is the thickness and l the test specimen length. The corresponding stress is calculated using the relation

$$S_{max} = \frac{3Pl}{2wd^2} \qquad (6)$$

Where S_{max} is the stress and P is the load, l is the length and w is the width and d is the thickness of the specimen .The length, width and thickness of the specimen is 70mm, 13 and 3mm respectively.

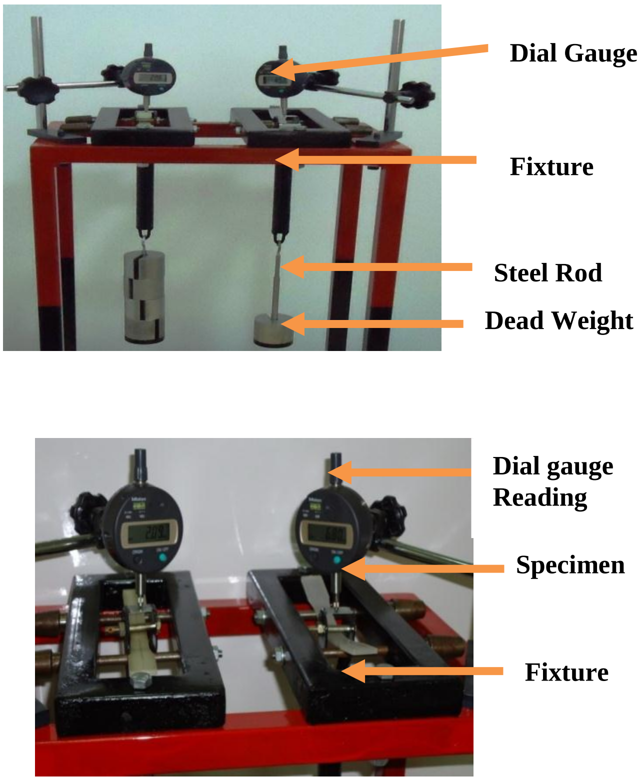


Fig 2(a-b). Assembled view of the flexural creep fixture

V. RESULTS AND DISCUSSIONS

A. Creep Behavior of Polypropylene Thermoplastic Composites

Creep performance evaluation was carried out at various loading levels ranging from 18.84 N/mm^2 to 47.17 N/mm^2 for all the materials. Fig 3 shows the 2h creep response of the chosen test specimens. A raise in creep strain was observed with the time period for all the specimens. Subsequent to the preliminary rapid increase in creep strain, the rate of creep strain decreases. Three trails were conducted for calculating creep strain for all the molded materials and the deviation for LFPP, SFPP and UFPP were found to be 2.5 %, 3.2 % and 1.5 % respectively Improved creep resistance behavior of long fiber reinforced polypropylene is observed is due to the improved load transfer from the matrix to the reinforced fibers and the matrix constriction to deformation. Chevali *et al*. [17] also observed a similar behavior with the increase in loading of glass fiber reinforcement in the nylon composites.

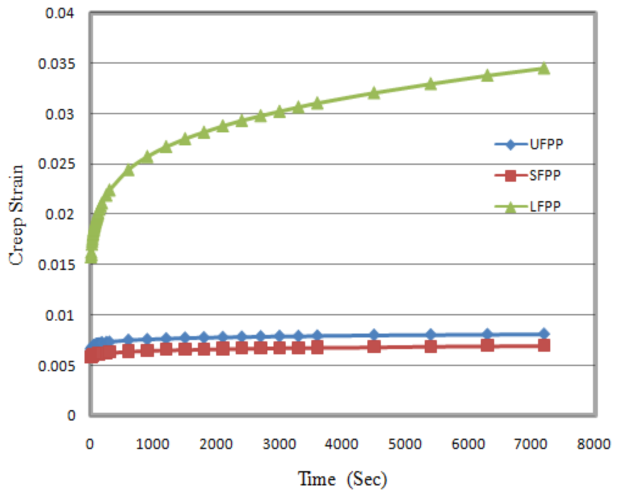
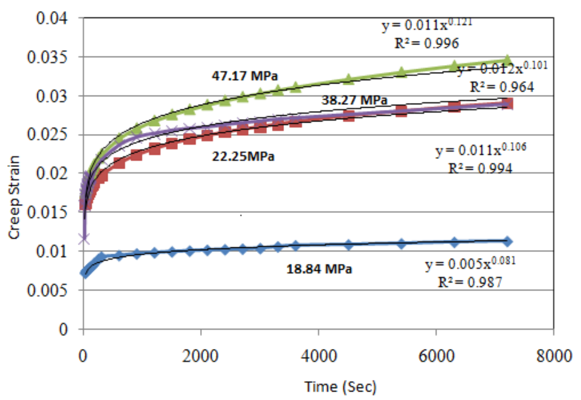


Fig 3. Comparison of creep strain for three materials for a stress of 22.5N/mm²

Due to the increase in reinforced fiber length, stiffness retention is more pronounced in LFPP. Due to the substantial time requirement for the creep investigation, an empirical model is made use in the subsequent section to predict the creep strain for a specific period of time.

B. Empirical Model for Predicting Short Term Creep Behavior

The creep performance of molded specimens was experimentally investigated for 2h duration for the stress range varying from 18.84, 22.25, 38.27 and 47.17 N//mm² and the test results are shown in Fig (4a-4c) .It is vivid from the results that for all the tested materials, creep strain increases with time and found to be increased with applied stress level. Power law function is fitted using eq. (1) for each and every stress levels thereby power law coefficient ($\varepsilon_t^{'}$), power law exponent (n) and correlation index (R^2) are determined.



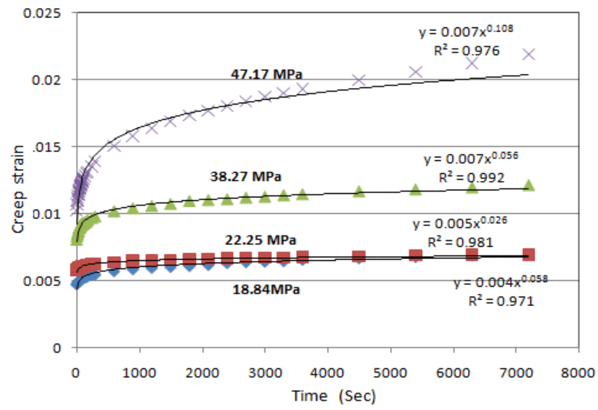


Fig 4b. Creep strain for SFPP

The correlation index, R^2 indicates that power law function provides a good approximation to the visco elastic behavior at every stress levels. It is vivid from Figs (4a-4c) that the power law coefficient ($\varepsilon_t^{'}$) and power law exponent (n) are dependent on the stress level and increases with the increase in stress level

Since the power law coefficient ($\varepsilon_t^{'}$) and power law exponent (n) are sensitive to the stress level, a methodology adopted by Hadid *et al*.[12] was used to establish the dependence of power law coefficient ($\varepsilon_t^{'}$) (Fig5a) and power law exponent (n) (Fig 5b) on applied stress level. Fig 5a shows the best fitting curve using eq. (2) and depicts the influence of applied stress (σ) on power law coefficient ($\varepsilon_t^{'}$) for the test specimen . The constant curve fitting parameters (a, b from eq. 2) are also shown in Fig 5a. In general the constant parameters a and b are dependent on glass transition temperature, degree of crystallinity, and fiber orientation in the composite[20] . These parameters represent the instantaneous strain normally visualized during the initial period of load application. Fig 5b shows the best fitting curve using eq. (3) and elucidates the influence of applied stress (σ) on power law exponent (n) for the test specimen. The constant curve fitting parameters (c, e from eq. 3) are also shown in Fig 5b. The constant parameters c and e are dependent on the time period of testing and relaxation mechanisms involved for the composite. These parameters represent the viscous response visualized during the secondary creep process. Eq. (4) is used to predict creep performance of molded specimen and compared with the 24 h experimental data as shown in Fig 6 (a-c). It is found that HRZ model predicted well with the experimental creep performance of the chosen thermoplastic composite specimen.

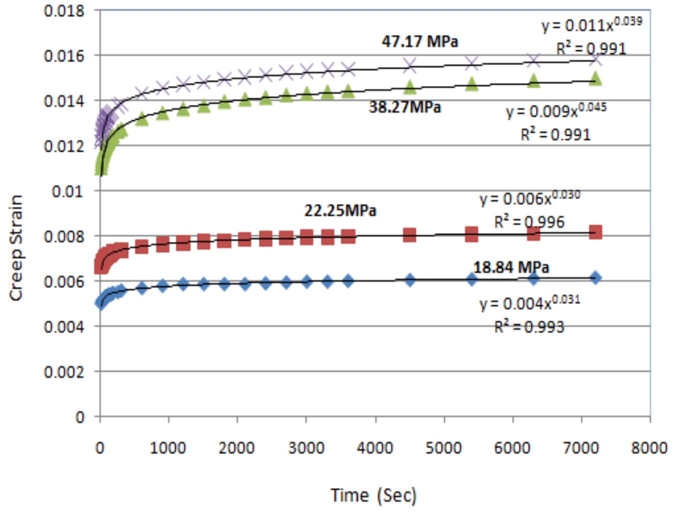


Fig 4c. Creep strain for LFPP

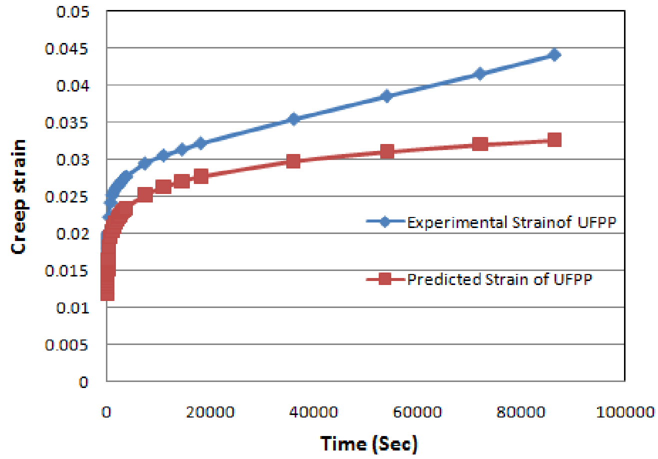


Fig 6a Experimental and predicted creep performance of UFPP for 55MPa

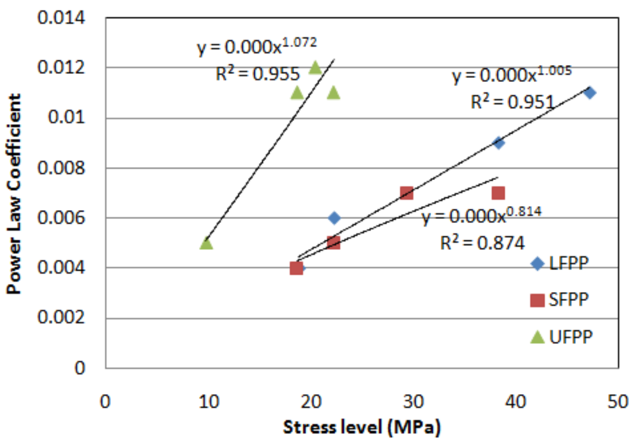


Fig 5a. Variation of power law coefficients over stress

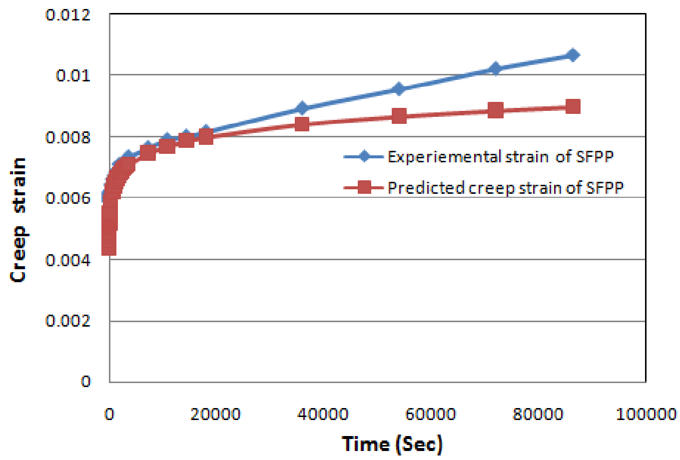


Fig 6b Experimental and predicted creep performance of SFPP for 40MPa

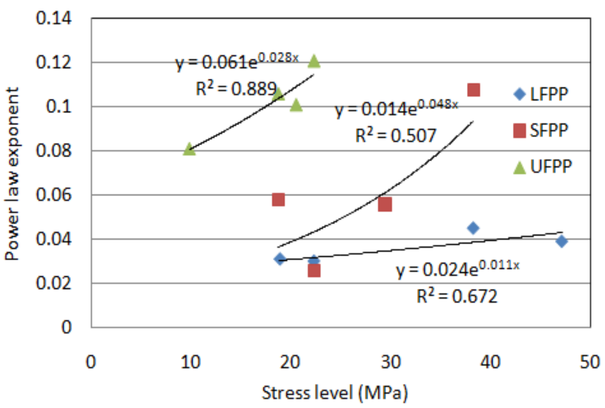


Fig 5b. Variation of power law exponents over stress

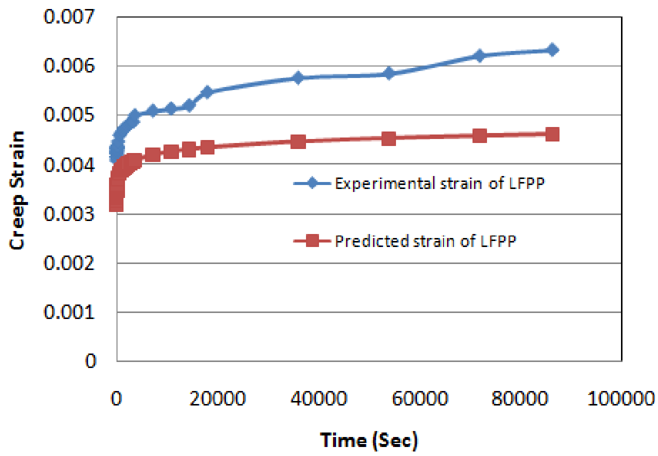


Fig 6c Experimental and predicted creep performance of LFPP for 20MPa

VI. Conclusions

Discontinuous fiber reinforced polypropylene composites were injection molded and its short term flexural creep performance is investigated. Due to the extensive time requirement for the creep performance evaluation, HRZ model was used in this work. Creep performance of the molded specimens was experimentally evaluated for 2 h and short term creep performance (24 h) was predicted with the aid of HRZ model over wide range of stress. The predicted performance was compared with 24 h experimental results and found to be satisfactory. From the present investigation, HRZ model was found to be useful in predicting the short-term creep performance of viscoelastic engineering material. Experimental results confirmed that long fiber reinforced thermoplastics possessed enhanced creep retention characteristic. HRZ model parameters were also utilized to correlate investigated material characteristics.

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