

MODELING OF THE THERMOPHYSICAL AND THERMOMECHANICAL PROPERTIES OF FIBRE REINFORCED POLYMER (FRP) COMPOSITES UNDER ELEVATED TEMPERATURES

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Abstract

As the range of applications for fibre-reinforced polymer (FRP) composite materials in material engineering constantly increases, there is more and more concern with regard to their performance in critical environments. The behavior of composite materials in high temperature environments is especially important since complex physical and chemical processes such as the glass transition and decomposition occur when these materials are subjected to elevated and high temperatures possibly leading to considerable loss of stiffness and strength. The stiffness and strength degradation in composite materials under elevated temperatures is the result of changes in polymer molecular structures. When polyester thermosets are subjected to elevated and high temperatures they undergo three transitions (glass transition, leather to rubbery transition and rubbery-to-decomposed transition) corresponding to four different states (glass, rubbery, leathery and decomposed). At elevated temperatures a composite material can therefore be considered a mixture of materials that are in different states. As the content of each state varies with temperature the polymer composite exhibit temperature dependent properties and this forms the basis for the development of property sub-models for composites at elevated temperatures. The result show that the elastic modulus, E reduces with increase in temperature fig 1: the thermal conductivity, K also decreases with increase in reciprocal temperature fig 2.

Keywords: Polymer Matrix Composite, Thermo Physical Property, Thermo Mechanical Property, Thermal Response, Mechanical Response.

1.0 Introduction

The increasing use of fibre-reinforced polymer (FRP) composites in many load bearing structures presents material scientists and structural Engineers with many challenges. One of the challenges is the understanding and meticulous prediction of the changes in thermo physical responses of FRP composites under elevated (30-200°C) and high (>200°C) temperatures. The progressive changes that occur in the thermo physical and thermo mechanical properties of FRP composites with increasing temperature result from the alteration of the molecular structure of the polymer component (Bo, 2003) and (Gregar, 2003). The bonds existing in thermoset polymers which have frequently been used as the resin in composite materials can be divided into two main groups: Primary and Secondary. The first group is the strong covalent intra-molecular bonds in the polymer chains and cross-links. The dissociation energy of such bonds varies between 125.6 and 837.4 kJ/mol. Secondary bonds include much weaker bonds eg hydrogen bonds (dissociation energy 12.6-29.3 kJ/mol) dipole interactions (6.3–12.6 kJ/mol) and van der waal's interaction (2.09–8.4 kJ/mol) consequently secondary bonds can be much more easily dissociated (Konstantions, 2010) and (Odegard, 2002). When temperature increases, secondary bonds are broken during glass transition and the material state changes from glassy to leathery. As temperature is raised further, the polymer chains form entanglement points where molecules, because of their length and flexibility, become knotted together (Ya, 2008) and (Yu, 2007). This state designated the rubbery state is also characterized by intact primary and broken secondary bonds but in an entangled molecular

structure. When even higher temperatures are reached, the primary bonds are also broken and the material decomposes, which is known as the decomposition process. Consequently four different states (glassy, leathery, rubbery and decomposed) and three transitions or processes (glass transition, leathery to rubbery transition and decomposition) can be defined when temperature is raised in accordance with statistical mechanics, since an aggregation of a large population of molecules (or other functional units) changes continuously from one state to another (Yu, 2008) and (Yu, 2008).

These physical and chemical processes lead to an obvious degradation of the material stiffness and strength of FRP Composite materials. The increasing application of FRP materials in structures requiring extended excessive heating resistance such as building structures, necessitates a study of the changes that occur in the thermo physical and thermo mechanical properties and resulting thermo mechanical responses of large scale and complex composite structures over longer time periods.

2.0 Research Objectives

The research paper focuses on the changes that occur in the thermo physical and thermo mechanical properties and the resulting thermo mechanical responses of FRP composites under elevated and high temperatures. Anchoring on this analysis the objectives of the research include:

To understand and model the progressive changes in states of composite materials in the temperature range 20 -600°C based on statistical mechanics and kinetic theory covering the glass transition, leathery-to-rubbery transition and decomposition process for the thermoset resin (polyester matrix).

To model progressive changes in the thermo physical properties (density, thermal conductivity, specific heat capacity) and thermo mechanical properties (elastic modulus, viscosity and strength) of the composite materials at elevated temperatures by the use of appropriate distribution functions.

To predict the thermal response of composite material at elevated temperature by the use of thermo physical property sub model in the heat transfer equation.

To predict the mechanical responses of composite materials at elevated temperature by the use of thermo mechanical property sub model in the statistical analysis.

3.0 Development of the Thermo Mechanical/Thermo Physical Model

The thermo physical parameters of interest in the modeling and analysis of unsaturated polyester matrix reinforced with musa acuminata fibre behavior at elevated and high temperatures include the thermal conductivity $K(T)$, specific heat capacity $C_p(T)$ and the bulk density $\rho(T)$ which has the following empirical relationship with temperature

$$K = \alpha_0 + \alpha_1 T^{-1} \quad \dots(1)$$

$$\rho = \alpha_0 + \alpha_1 T^{-2} + \alpha_2 T^{-3} \quad \dots(2)$$

$$C_p = \alpha_0 + \alpha_1 T^{-1} + \alpha_2 T^{-2} \quad \dots(2)$$

Where α_0 , α_1 , and α_2 are empirical constants to be determined from the Differential scanning calorimetric (DSC) experimental data and the plots are shown fig 1, fig 2 and fig 3. The Temperature dependence of the elastic modulus of polyester resin reinforced with musa acuminata fibre (banana) is given by

$$\frac{\partial E}{\partial t} = \alpha_0 \frac{\partial^2 E}{\partial X^2} \quad \dots (4)$$

Where E is elastic modulus of the composite, x is the temperature and t is time (minutes) and the associated boundary and initial conditions include

$$t=0, E=E_0, \text{ all } X \quad \dots(5)$$

$$t \geq 0, E=E_1 \text{ at } X = 0 \quad \dots(6)$$

$$t \geq 0, E = E_0 \text{ as } X \rightarrow \infty \quad \dots(7)$$

In order to obtain the E-modulus profile from equation 4 we recast the second order differential model into dimensionless forms as

$$\theta = \frac{E - E_0}{E_1 - E_0} \quad \dots (8)$$

Hence equation 4 is converted to

$$\frac{\partial \theta}{\partial t} = \alpha_0 \frac{\partial^2 \theta}{\partial X^2} \quad \dots (9)$$

With the boundary and initial conditions as

$$t=0, \theta = 0, \text{ all } X \quad \dots(10)$$

$$t \geq 0, \theta = 1.0 \text{ at } X = 0 \quad \dots(11)$$

$$t \geq 0, \theta = 0 \text{ as } X \rightarrow \infty \quad \dots(12)$$

Utilizing laplace transformation technique to equation (9) we have

$$S\bar{\theta} = \alpha_0 \frac{d^2 \bar{\theta}}{dx^2} \quad \dots (13)$$

With the transformed boundary and initial conditions as

$$t=0, \bar{\theta} = 0, \text{ all } X \quad \dots(14)$$

$$t \geq 0, \bar{\theta} = \frac{1}{S} \text{ at } X = 0 \quad \dots(15)$$

$$t \geq 0, \theta = 0 \text{ as } X \rightarrow \infty \quad \dots(16)$$

equation 13 is a second order ordinary differential equation (ODE) whose solution is

$$\theta(x,t) = A_1 e^{-rX} + A_2 e^{rX} \quad \dots(17)$$

where $r = \sqrt{s/\alpha_0} x$ and $\alpha_0 = K/\rho C_p$

K = thermal conductivity, W/m°C, ρ is bulk density, kg/m³ and C_p is the specific heat KJ/kgC. Evaluating the physical constants A_1 and A_2 using the boundary and initial conditions (14) to (16) we have $A_1 = 0$ and $A_2 = 1/s$ hence

$$\theta(x, t) = \frac{1}{s} e^{-\sqrt{s/\alpha_0} x} \quad \dots (18)$$

Using an inverse transform table we have

$$\theta(x, t) = \text{erfc} \left[\frac{x}{\sqrt{2\alpha_0 t}} \right] \quad \dots (19)$$

Using equation (8) we have for the original variable

$$E(x, t) = (E_1 - E_0) \text{erfc} \left[\frac{x}{\sqrt{2\alpha_0 t}} \right] + E_0 \quad \dots (20)$$

Where E_0 is the initial elastic modulus before differential heating process and erfc is error function compliment

4.0 Results and Discussion

The plots of the experimental data obtained in the differential scanning calorimetric analysis of polyester matrix reinforced with *musa acuminata* fibre (banana fibre) are shown in fig 1.0, fig 2.0 and fig 3.0 respectively for the plot of elastic modulus as function of temperature, plot of thermal conductivity as a function of reciprocal temperature and the plot of specific heat as a function of reciprocal temperature. The plots show a decreasing profile as the temperature increases which imply a degradation in the thermo mechanical property ie elastic modulus E and also in the thermo physical property ie Thermal Conductivity (k), bulk density (ρ) and specific heat capacity (C_p).

4.1 Materials and Method

The polyester resin reinforced with *musa acuminata* (banana fibre) fibre were subjected to high temperatures by differential heating using the differential scanning calorimeter (DSC) in the temperature range 20°C to 700°C and the thermo physical properties - thermal conductivity k, bulk density, ρ , specific heat C_p measured at fixed time interval. The thermo mechanical property ie elastic modulus was also determined and an appropriate model developed from first principles whose solution were determined. Experimental data obtained from the DSC measurements were fitted into the model solution, Implemented via the MATLAB Software and run on a desktop HP 590-XP micro computing device housed in software laboratory of the department.

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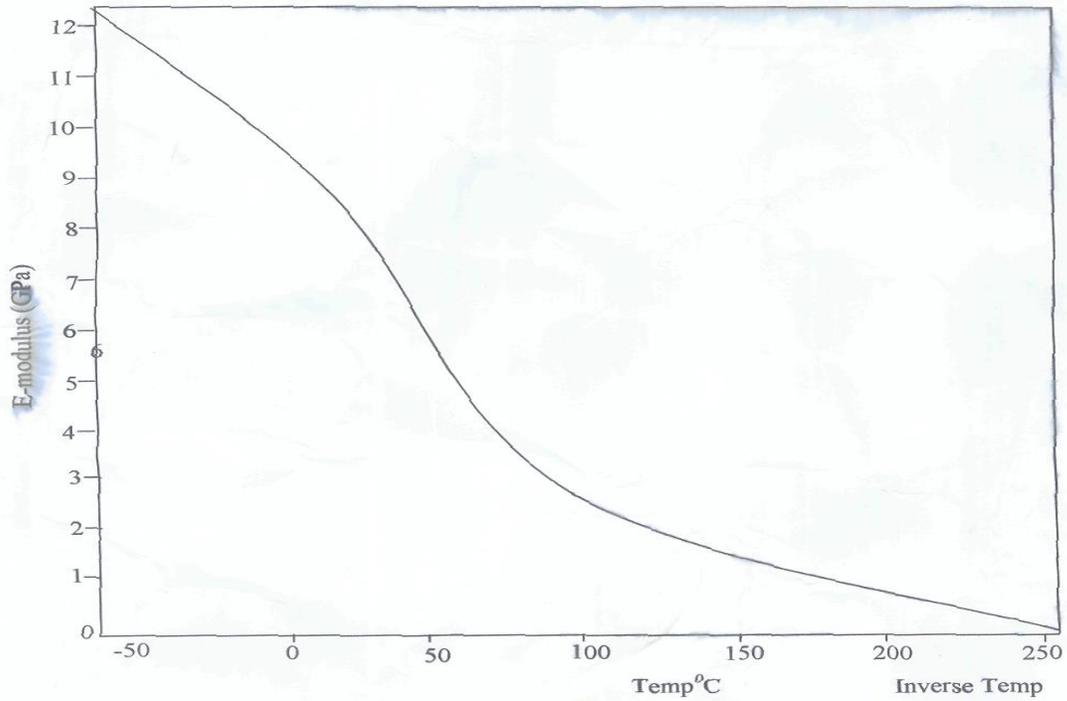


Fig. 1.0: E-modulus degradation of FRP composites at elevated Temperatures

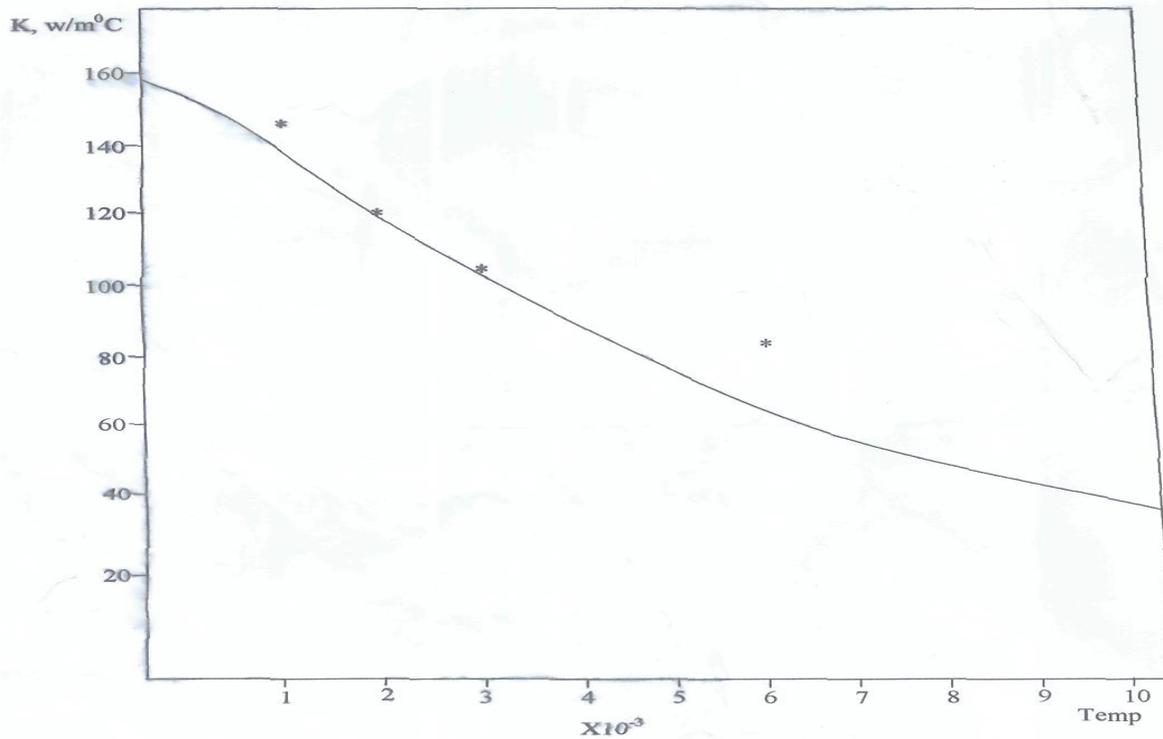


Fig. 2.0: Plot of thermal conductivity as a function of temperature inverse

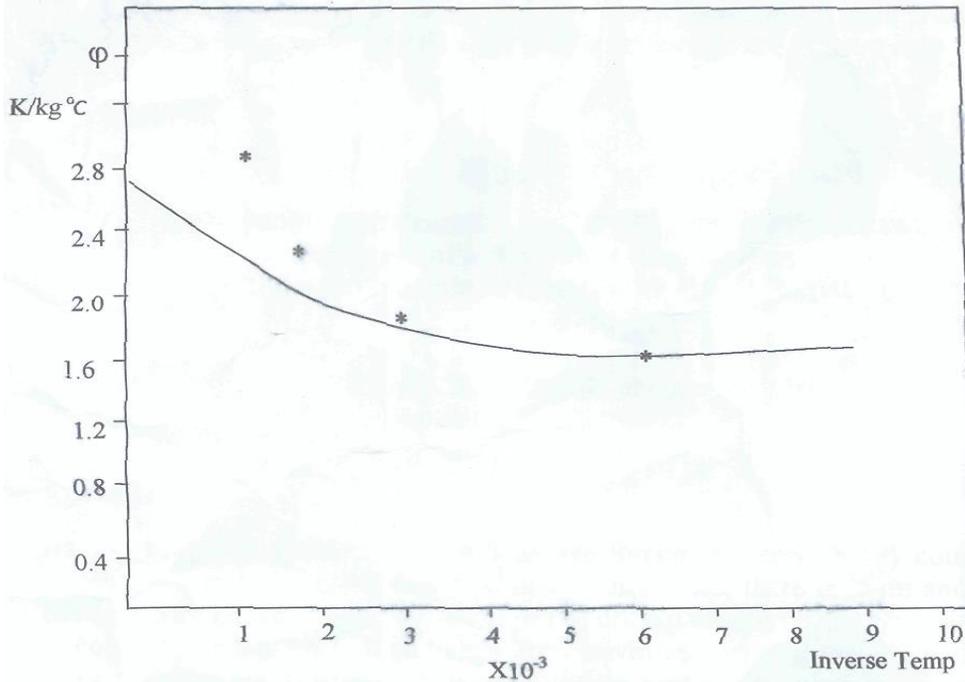


Fig. 3.0: Plot of specific heat as a function of Reciprocal of Temperature