Finite Element Thermal - Structural Analysis of EPDM Rubber Composites

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Abstract

Polymer Composites are used in many applications of nuclear fields for their strong, stiff, and light structures, however their conduct in fire isn't constantly ideal. In the present work Finite Element method (FE) has been used to analyze rock fiber (RF) reinforced ethylene propylene diene monomer (EPDM). EPDM rubber composites are used as cable insulator in NPP (Nuclear Power Plant). The aim of the work is to determine the stresses and deformation of the rock fiber reinforced EPDM (10 wt. % and 20 wt. % RF) in case of hot gas environment exposure, which lead to temperature range of 100 – 400^{o}C. FE multiphysics package ANSYS has been used throughout the present study. The stresses and deformation in the active temperature range have been evaluated. The results have been indicated that the sample of 20 wt % RF has the lowest stresses and deformation.

Keywords: ANSYS, FE, EPDM, Rock fiber, thermal deformation

Introduction

Ethylene propylene diene monomer (EPDM) is widely used as cable insulation material. This polymer has excellent performances such as prominent electric insulation, outstanding elasticity, and high abrasive resistance, and remarkable slipperiness resistance, excellent resistance to aging owing to heat, light, oxygen and ozone[(1,2)]. However, EPDM is highly flammable, which restricts its further application and development in some important fields, especially cable industry. Thus, fire retardants are generally added into EPDM rubber in order to improve its combustion properties, fire performance and reduce its smoke [(3)].

Rock fiber reinforced the EPDM rubber as a fire retardant due to its good mechanical properties, thermal stability, electrical and sound insulating properties [(4,5)]. The thermal insulating ability of rock is three times that of asbestos [(6,7)], the electrical insulating properties 10 times better than glass[(7,8)], and due to good insulation properties rock fiber is used in the fire protection

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S. Ezhil Vannan et al(9) studied the Coefficient of Thermal Expansion (CTE) of Al7075/basalt short fiber Metal Matrix Composites (MMCs) as a function of temperature (50°C to 300°C) and reinforcement (2.5 to 10 wt. %). The composites were prepared by the liquid metallurgy technique. They used Thermal Mechanical Analyzer (TMA) to record the changes in the linear dimension as a function of temperature as Percent Linear Change (PLC). The results showed that the CTE significantly increased with increasing temperature but decreased with increasing basalt fiber. P. Valentino et alii (10) described the results of tensile tests and finite element (FE) calculations with representative volume elements (RVEs) of basalt fiber reinforced plastic with two different types of fabric reinforcements. The classical theory of micromechanics defines a RVE as the smallest sample region, which behaves in the same way as the whole sample. They determined the stiffness of a fabric reinforced composite in warp and fill direction with numerical investigations.

Total heat release of a polymer is the heat of complete combustion of the pyrolysis gases per unit its initial mass. Microscale combustion calorimetry, an oxygen consumption technique, identifies the total heat release of polymers that is a key parameter for predicting polymer flammability.

Nour F. Attia et al (11) studied a modified rock fiber dispersed in rubbers forming various composites. They polymerize organic polyaniline layer on fiber surface to form a fixed mass shell to improve compatibility, enhance interfacial adhesion between rubber and inorganic fibers, and shield harmful radiation effect. They studied experimentally the flammability, mechanical, and thermal properties due to organic modification. They resulted in significant reduction in peak heat release, total heat release and tensile strength properties compared to blank rubber.

Major of researchers study the effect of adding fire retardant on combustion properties, fire performance, and mechanical properties (E-Modulus and tensile strength). There is lack of research the effect of thermal load (as in fire condition) on the stress, strain and deformation resulted in new composites. FE multi-physics package ANSYS is used to numerically solve multi-physics problem to study the effect of hot environment on structural analysis of new composites.

In this work thermal-structural behavior of EPDM/Rock fiber composites is analyzed in case exposed to hot environment. Large stresses due to hot gases can lead to cable insulator deformation which could lead to insulation failure. ANSYS multi-physics package (12) is used to analyze the case study. The main goal is to reduce as much as possible the resulted plastic deformation in the composite.

Experimental Work

Ethylene–propylene–diene monomer rubber (EPDM) with trade name BUNAR EP T9650 was bought from Bayer AG, Germany, with high molecular weight, with ethylene norbornene as termonomer. Basalt fibers of 6.5 μm diameter and 2.3 mm length were obtained from Egyptian Rock Wool Factory, Cairo, Egypt. EPDM rubber composites were prepared using laboratory two-roll mill (152 mm 9330 mm) at a friction ratio of 1:1.4, according to ASTM D 15-627. Rock fiber with different mass ratios (10 and 20 mass %) was dispersed in the EPDM rubber based on final mass of rubber composites [(11)]. The compositions of blank EPDM rubber (sample A), 10 wt. % reinforced rock fiber (sample B), and 20 wt. % reinforced rock fiber (sample C) are tabulated in Table 1.

Table 1: Composition of various rubber composites in grams

Sample	A	B	C
EPDM	100	100	100
Zinc oxide	5	5	5
Stearic acid	3	3	3
TMTD	1	1	1
CBS	1	1	1
Oil	9.5	9.5	9.5
6PPD	1	1	1
Sulfur	1.5	1.5	1.5
RF	0	13.6	30

TMTD, tetramethylthiuram disulfide; CBS, N-cyclohexyl-2-benzothiazole sulfenamide; 6PPD, N - (1, 3-dimethylbutyl)-N0-phenyl-p-phenylenediamine

Finite Element Model:

Three dimension steady state finite element model is established for three samples, blank EPDM (sample A), 10 wt. % reinforced rock fiber (sample B), and 20wt. % reinforced rock fiber (sample C). The three samples have equal dimension of (40*40*5 mm). The experimental data results of Nour F. Attia et al [(11)] (E-Modulus and tensile strength) are introduced to ANSYS package to simulate composite deformation. Density, thermal conductivity, and thermal expansion coefficient are calculated for the composites by the rule of mixtures equation [(13).] Table (2) represents the data used in FE mode

$$X_c(U)= X_m V_m + X_p V_p \qquad (1)$$

Where, X and V denote the property and the volume fraction. The subscripts c, m, and p represent composite, matrix, and particulate phases.

From elasticity theory [12], an infinitesimal volume of material at an arbitrary point on or inside the solid body can be rotated such that only normal stresses remain and all shear stresses are zero. The three normal stresses that remain are called the principal stresses:

σ1 – maximum, σ2 – middle, and σ3 – minimum. The principal stresses are always ordered such that σ1 > σ2 > σ3.

Equivalent stress is related to the principal stresses by the equation [12]:

$$\sigma_e = \sqrt{\frac{(\sigma 1-\sigma 2)^2+(\sigma 2-\sigma 3)^2+(\sigma 3-\sigma 1)^2}{2}} \qquad (2)$$

Equivalent stress (also called von Mises stress) is often used in design work because it allows any arbitrary three-dimensional stress state to be represented as a single positive stress value. Equivalent stress is part of the maximum equivalent stress failure theory used to predict yielding in a ductile material [12,14].

Thermal strain [12] is computed when coefficient of thermal expansion is specified and a temperature load is applied in a structural analysis.

Each of the components of thermal strain are computed as:

$$\varepsilon^{th} = \alpha^{se} (T - T_{ref}) \qquad (3)$$

Where:

ε^{th} - thermal strain in one of the directions x, y, or z.

α^{se} - Secant coefficient of thermal expansion defined as a material property in Engineering Data.

T_{ref} - reference temperature or the "stress-free" temperature.

The von Mises or equivalent strain ε_e is computed as [12]:

$$\varepsilon_e = \frac{1}{1+\nu'}\sqrt{\frac{(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_3-\varepsilon_1)^2}{2}} \qquad (4)$$

Where:

ν' = effective Poisson's ratio

Sensitivity test for grid number has been conducted for 240999, 374380, and 637578 elements to ensure that results are independent on the number of grids. The model of 637578 3-D elements satisfies the convergence criterion, so the stresses and deformation are independent of the number of grids. The FE model mesh of sample C is shown in Fig. (1)

Table 2: Data used in finite element model

	Elastic-Modulus (MPa)	Tensile Strength (MPa)	Thermal conductivity (W/m.K)	Thermal expansion coefficient
Sample A	2.14	1.79	0.26	$160*10^{-6}$
Sample B	2.23	1.76	0.247	$151.458*10^{-6}$
Sample C	2.23	1.47	0.2334	$142.045*10^{-6}$

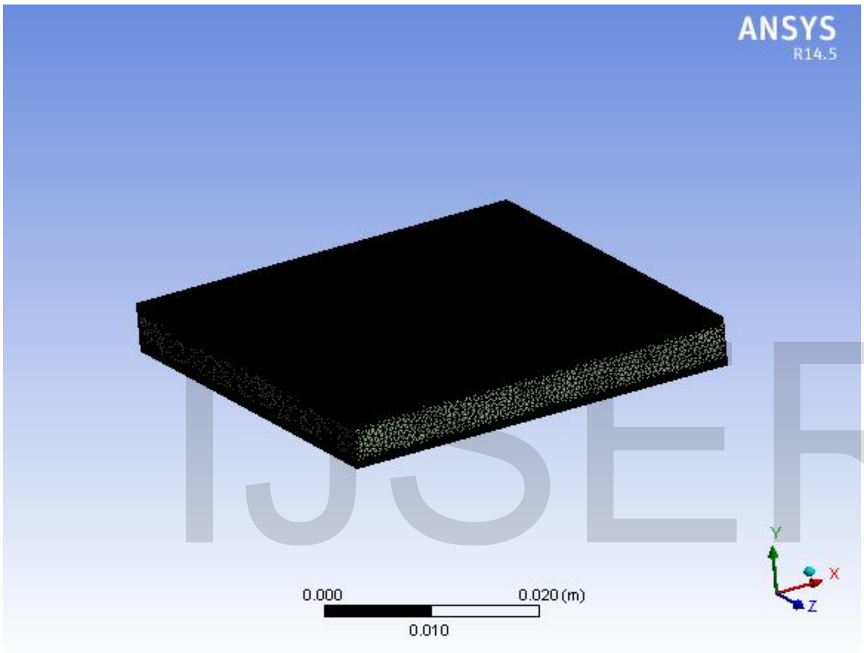

Fig. (1): sample C mesh element.

Thermal structure module analyzes the three sample temperature in hot environment. The resulted temperature is introduced as input in the structural analysis module. Stress, strain, and deformation are obtained for the three samples in the temperature range of 100 – 400°C with temperature step of 50 °C.

Results and Discussion

Stress temperature and deformation temperature curves for the three samples are shown in Fig. (2) and Fig. (3) respectively. Fig. (2) represents elastic performance in the studied temperature range (100 – 400 ^{0}C) for samples B and C and transition from elastic to plastic performance above 150 ^{0}C which is the glass transition point for sample A. For sample A it is obvious to see transition from elastic to plastic performance above 150 ^{0}C which is the glass transition point for blank EPDM.

In Fig. (2), the line represents sample A (blank EPDM) is a straight line before 150°C (elastic response). The line direction is changed above 150°C (plastic performance). This result agrees with the published glass transition point of EPDM (150 ^{0}C). This result is considered as a code validation for the analyzed model.

Stresses as shown in Fig. (2) are lower in case of sample B and C with large difference at temperatures in the range (250 – 400 °C) with maximum difference in stresses of 6.7% at 400°C for sample C from sample B and 12.66% from sample C from sample A. Fig. (3) represents that deformation for the three samples nearly the same in the range (50 – 200 °C) and the difference increases in the range (250 – 400 °C) with maximum difference in deformation of 6.72% at 400 °C for sample C from sample B and 13.44% from sample C from sample A. From the figures we can conclude that sample C has lowest stress and deformation values, sample B has higher stress and deformation values, and sample A has the highest thermal stress and deformation. Since sample C has the best performance in case of fire, more analysis for stress deformation curve has been made for that sample.

Stress–thermal strain curve for sample (C) is shown in Fig.(4). The material performance is elastic in the temperature range (100 – 400 °C). The slope of the line equal to 2.3 which is the young modulus obtained experimentally for sample (C). Fig. (5) represents stress-temperature and thermal strain temperature curves (100-400 °C) for samples (C). The results indicate that stress-temperature has the same response as the thermal strain-temperature curve. The response is linear with nearly the same slope. The stress and strain percentage increase is also the same. The percentage varies from 1.64 % at temperature range 100-150 °C up to 1.15 % at temperature range 350 to 400 °C.

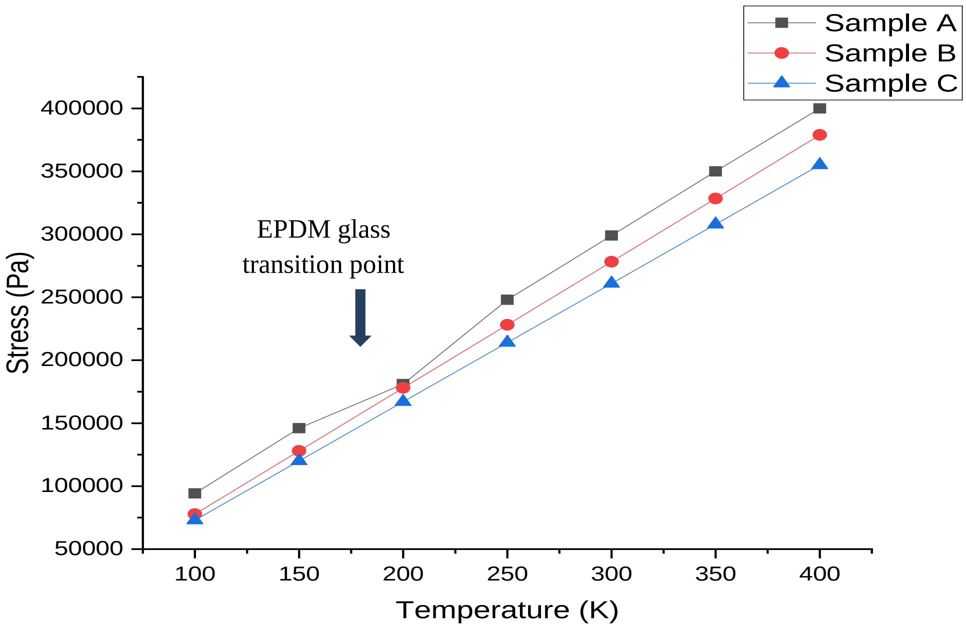

Fig. (2): Stress temperature curve for the three samples.

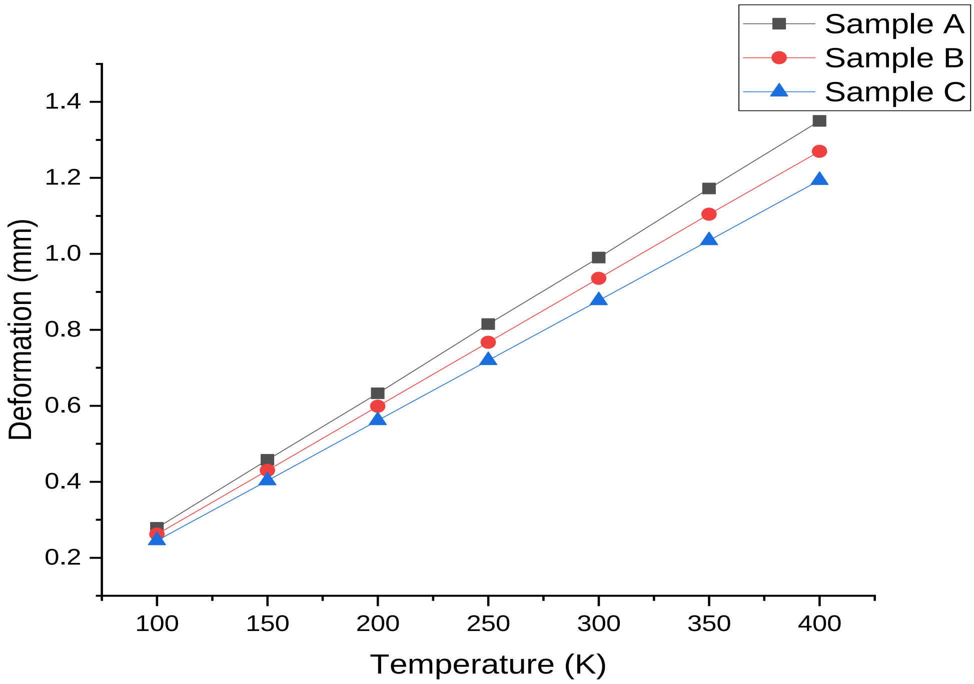

Fig. (3): Deformation temperature curve for the three samples.

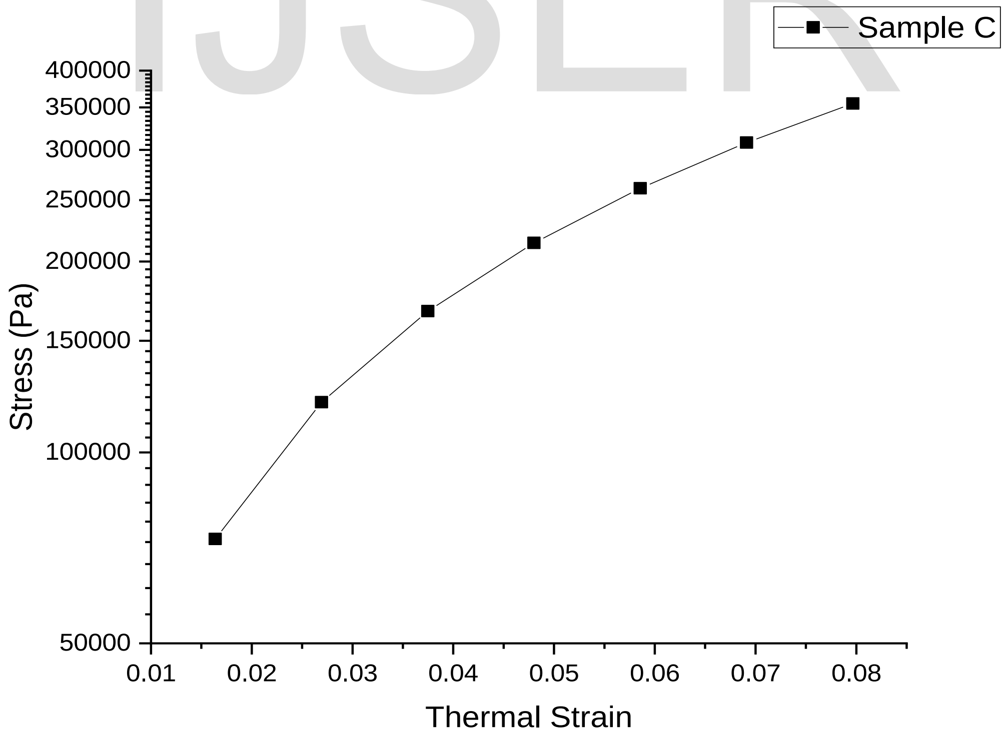

Fig. (4): Stress-thermal strain curve (100-400 °C) for samples (C).

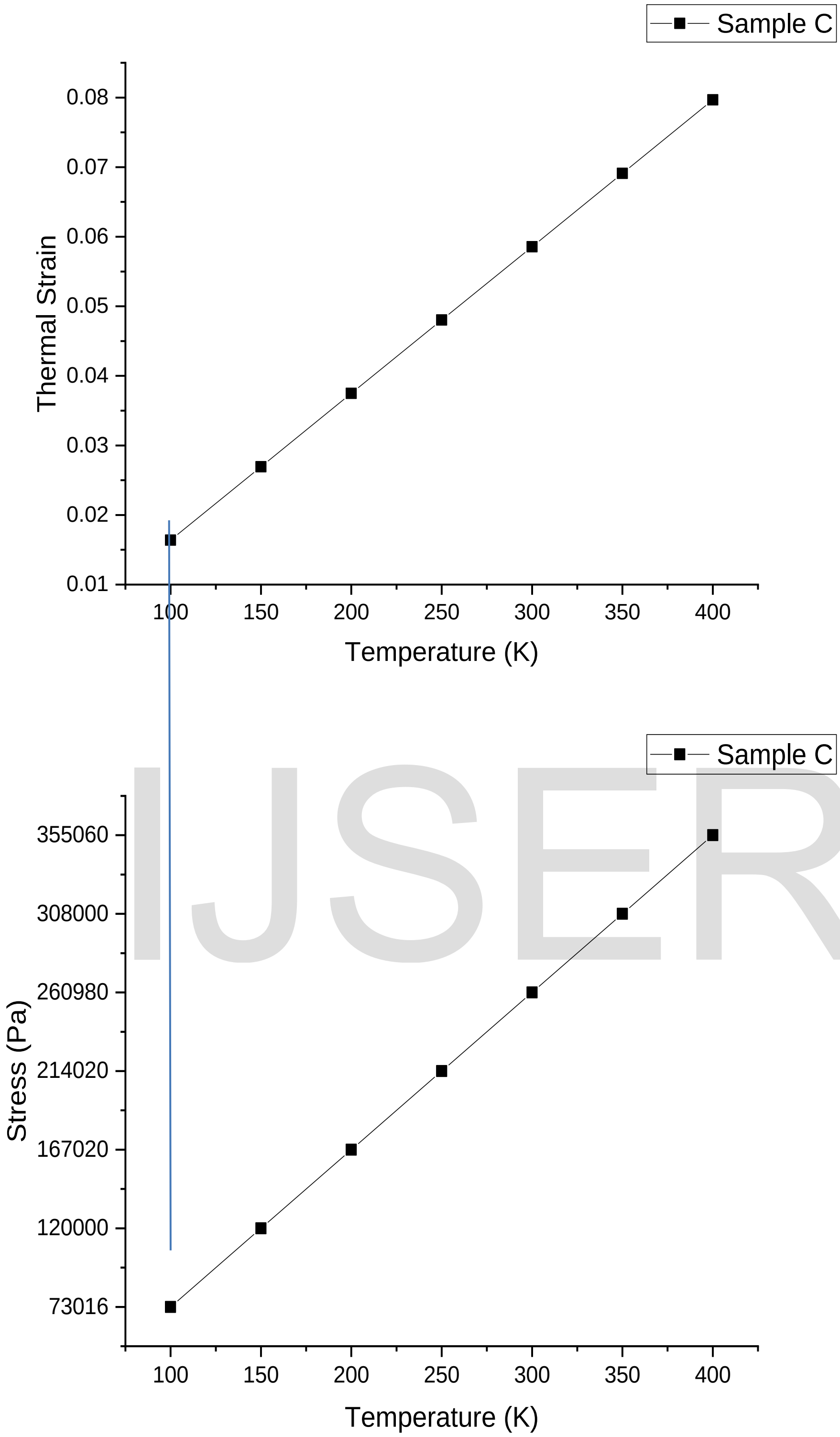

Fig. (5): Stress-temperature and thermal strain temperature curves (100-400 ^{o}C) for samples (C).

Conclusion

- Rock fiber with different mass ratios (10 and 20 mass %) is dispersed in the EPDM rubber based on final mass of rubber composites.
- Three dimension steady state FE model is constructed for three samples, blank EPDM (sample A), 10 wt. % reinforced rock fiber (sample B), and 20wt. % reinforced rock fiber (sample C).
- Stress, strain, and deformation are obtained for the three samples in the temperature range of 100 – 400^{o}C
- Stress and deformation are lower in case of sample B and C with maximum difference in stresses of 6.7% at 400^{o}C for sample C with regard to sample B and 12.66% with regard to C from sample A. The maximum difference in deformation is 6.72% at 400 ^{o}C for sample C with regard to B and 13.44% from sample C with regard to A.
- Sample C has the best performance as it has the lowest stress and deformation in case exposure to hot environment.
- Finite element results agree with experimentally results of flammability, mechanical, and thermal properties that increasing fire retardants mass ratio from 10 up to 20 mass % improve composite performance in case of hot environment.
- FE results ensure safe operation of the studied Rock fiber with different mass ratios (10 and 20 mass %) in case of hot environment with elastic performance in the studied temperature range (100 – 400^{o}C).

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