Assessment of Material Type, Diameter, Orientation and Closeness of Fibers in Vulcanized Reinforced Rubbers

Ali Osman Güney, Bahattin Kanber

***Abstract*—**In this work, the effect of material type, diameter, orientation and closeness of fibers on the general performance of reinforced vulcanized rubbers are investigated using finite element method with experimental verification. Various fiber materials such as hemp, nylon, polyester are used for different fiber diameters, orientations and closeness. 3D finite element models are developed by considering bonded contact elements between fiber and rubber sheet interfaces. The fibers are assumed as linear elastic, while vulcanized rubber is considered as hyper-elastic. After an experimental verification of finite element results, the developed models are analyzed under prescribed displacement that causes tension. The normal stresses in fibers and shear stresses between fibers and rubber sheet are investigated in all models. Large deformation of reinforced rubber sheet also represented with various fiber conditions under incremental loading. A general assessment is achieved about best fiber properties of reinforced rubber sheets for tension-load conditions.

***Keywords*—**Fiber properties, finite element method, tension-load condition, reinforced vulcanized rubbers.

I. Introduction

NATURAL rubber (NR) is not very strong elastomer as much as vulcanized rubber. Therefore, it is generally reinforced with fibers (hemp, nylon, polyester etc.) to improve its mechanical properties. For this reason, the research of mechanical behaviours of vulcanized rubbers reinforced with fibers is important. In this work, various fibers were studied for different diameters, orientations and closeness using 3D finite element models in ANSYS Workbench. Finite element solutions are verified by experimental tests.

In all solutions, fiber materials are supposed to be linearly elastic, and matrix materials are supposed to be hyperelastic. Fiber reinforced elastomers provide an extraordinary strength along fiber directions. Hyperelastic materials are broadly used in car tires, shoes, elastic tubes, seekers, cable coverings, balloons, shock absorbers, conveyor and power transmission belts and are also present in biological tissues (arterial walls, connective tissue, annulus fibrosus), etc. [1]-[2].

Fiber reinforced elastomers were searched by many researchers. In literature, deformations of elastomer matrix uniaxial reinforced with fibers were studied by computational micromechanics [1]. Researchers investigated an analytic system to define the comprehensive fundamental behaviour of elastomers which are reinforced by compatible fibers, and exposed to finite distortions [2]. The deformation of reinforced elastomers exposed to vertical tensile force to the fibers was investigated using computational micromechanics [3]. A radial distortion method was concurrently improved via performing compressive and tensile stretches to a vulcanized rubber specimen [4]. In another work, utilizing the constants of a displacement tensor that depend on a stable strain measure a new strain energy function for cross fiber reinforced rubber is enhanced [5]. Non-linear finite-extensive distortion and wave spread models in anisotropic hyperelastic Mooney-Rivlin type materials were investigated in [6]. In literature, researchers also improved a homogenization-based fundamental model for fiber-reinforced elastomers by irregular microstructures [7]. Uniaxial and biaxial elongation tests are carried out on the same sample which is vulcanized rubber that is constant in y direction and remain vertical in x direction from 1 to 1.4 [8]. In another study, a new hyperelastic material model is intended feasible large deformations for rubber solids by stored-energy function [9]. A novel approach for analysing hyperelastic and rubber-like materials are presented in another paper. This paper explain linear analysis bubble function idea to nonlinear analysis and mention two repetitive methods [10]. Researchers investigated mechanical properties of coir fiber reinforced vulcanized NR which is under water aging, cold, hot [11]. Mechanical properties of an ordinary tyre tread component which reinforced with aramid short fibers were studied to estimate the effects of fibers on tyre tread productions [12].

II. Specimen, Experimental and Finite Element Analysis

In the experimental part of this study, a tensile test is carried out for a fiber reinforced vulcanized NR specimen (FR-VNR). FR-VNR specimen is obtained according to DIN 53504-S2 standard. It was prepared by Instron6054.000 model (Fig. 1). The tension load is applied at 0.5 mm/speed (Fig. 2 shows tested specimen). The tensile test machine is Shimadzu AG-X Plus 250 kN model (Fig. 3). After completing tension test, the same specimen is modelled in ANSYS Workbench as shown in Fig. 4.

The results are shown in Fig. 5. The best agreement between experimental tests and finite element solutions are obtained when fibers are assumed linear elastic and rubbers are assumed as Mooney-Rivlin 3 Parameters.

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Fig. 1 Specimen preparation machine (Instron 6054.000)

Fig. 2 Specimen is tested at 0.5 mm/s

A general solid model of fiber-reinforced rubber composite is shown in Fig. 6 with different layers. Fig. 7 shows a solid model with inclined fibers.

In this study, all solutions were carried out using two layers. Unless otherwise stated, nylon 6.6 was used for reinforcement fibers.

All solutions were carried by applying 1 mm prescribed displacements in vertical directions. It was shown that when the angles between fibers in different layers are selected as zero, the stresses on fibers and rubber matrix are not affected by changes of fiber diameters (8-9) and distances (Figs. 10, 11). However, when the fiber angles are increased to 30°, the normal stresses on fibers are decreased when fiber diameters increased as shown in Fig. 12. They are also increased as fiber distances are increased (Fig. 13). Similar results are obtained when the fiber angles are increased to 45° as shown in Figs. 16 and 17.

Fig. 3 Tensile testing machine (Shimadzu AG-X Plus 250 kN)

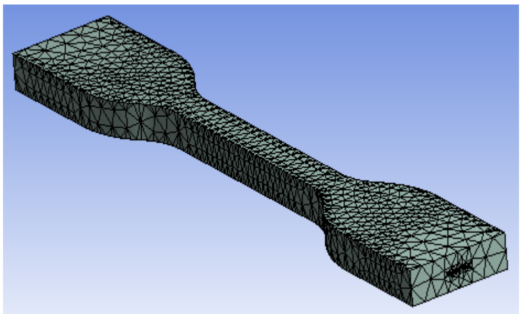

Fig. 4 Finite element model of test specimen

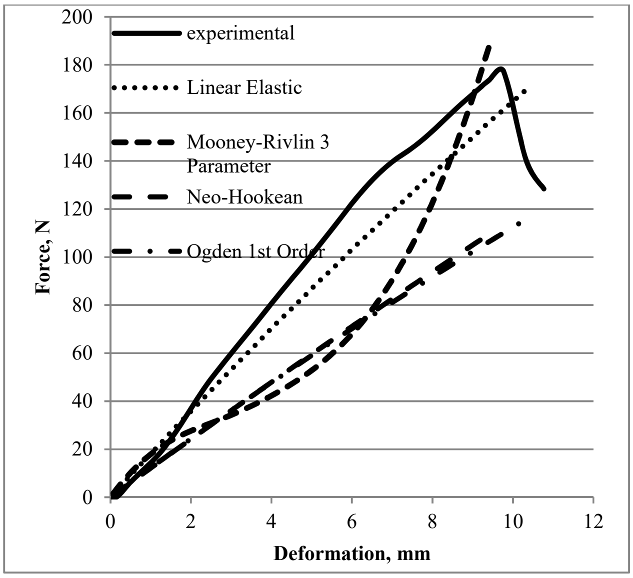

Fig. 5 Comparison of experimental and FEM results

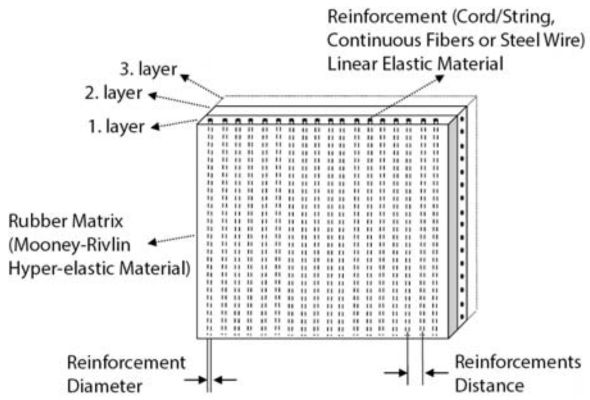

Fig. 6 The general solid model of reinforced rubbers with different layers

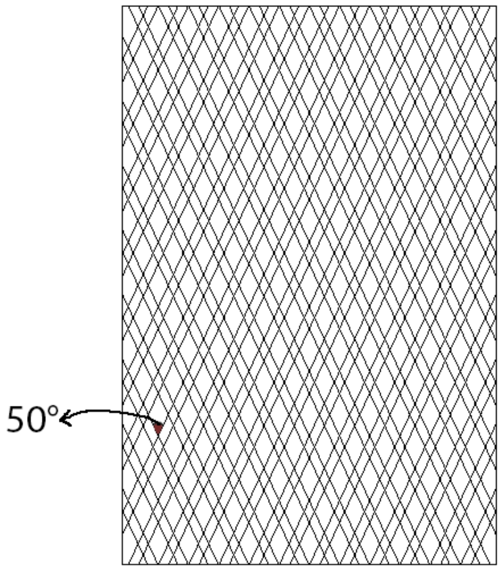

Fig. 7 The solid model sample for inclined fibers

Shear stresses between fibers and rubber are shown in Figs. 18 and 19 for 45° fiber angles. It is shown that when fiber diameters are increased, the shear stresses between fiber and rubber decrease. The normal stresses are increased on fibers when stronger fibers are used as shown in Figs. 20 and 21. As the angles between fibers in different layer are increased, the normal stresses are decreased as shown in Fig. 22.

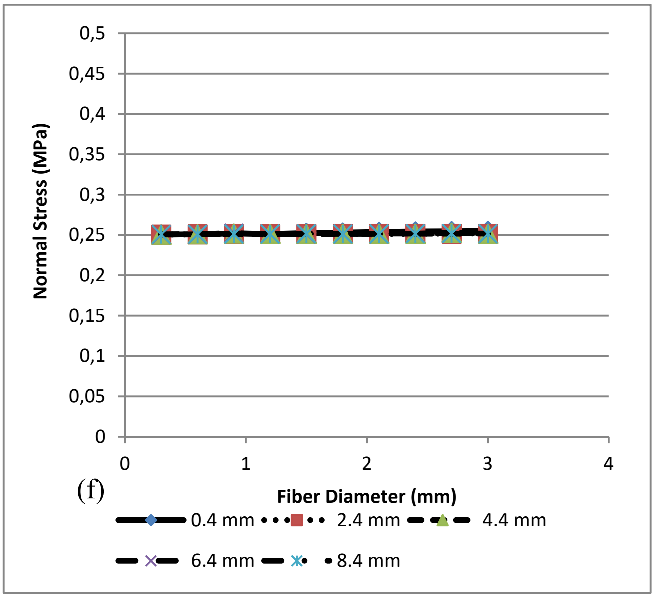

Fig. 8 Normal stresses on rubber for various fiber diameters. Graphic markers show fiber distances (Angle is 0° between fibers)

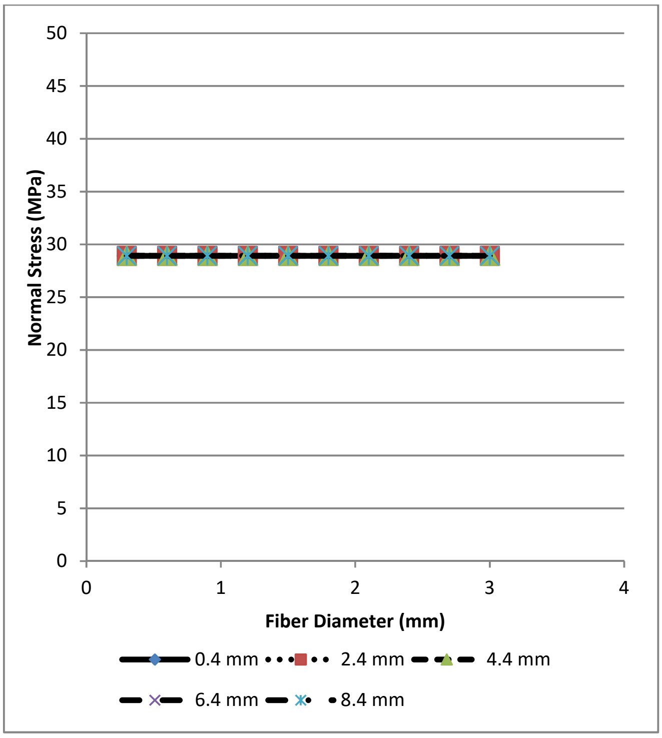

Fig. 9 Normal stresses on fibers for various fiber diameters. Graphic markers show fiber distances (Angle is 0° between fibers)

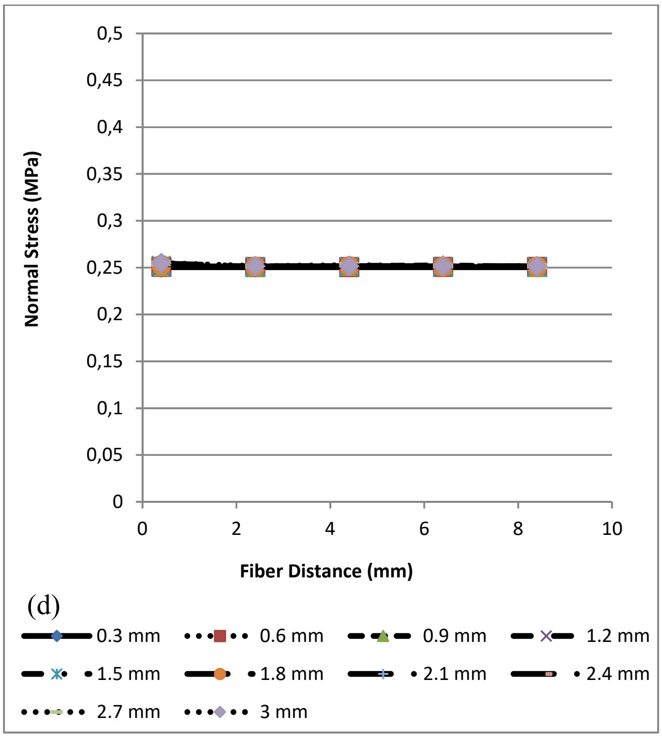

Fig. 10 Normal stresses on rubber for various fiber distances. Graphic markers show fiber diameters (Angle is 0° between fibers)

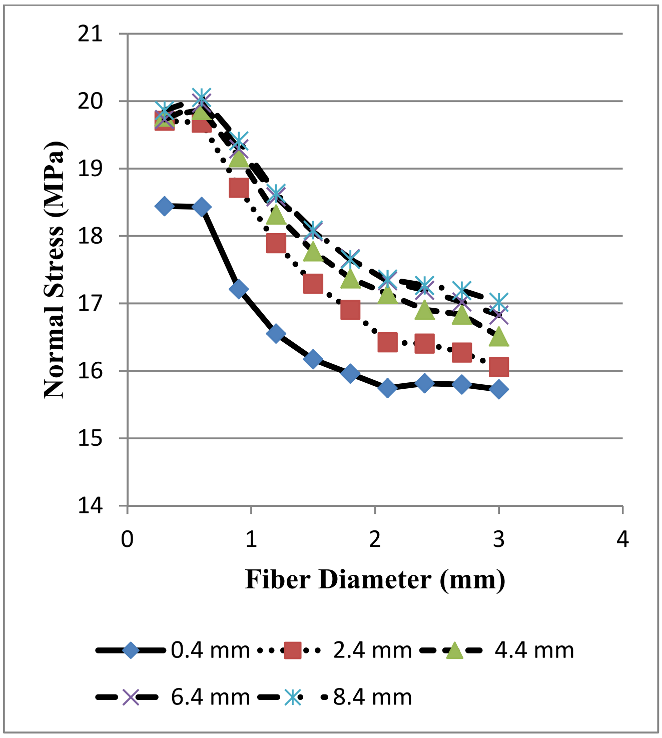

Fig. 12 Normal stresses on fibers for various fiber diameters. Graphic markers show fiber distances (Angle is 30° between fibers)

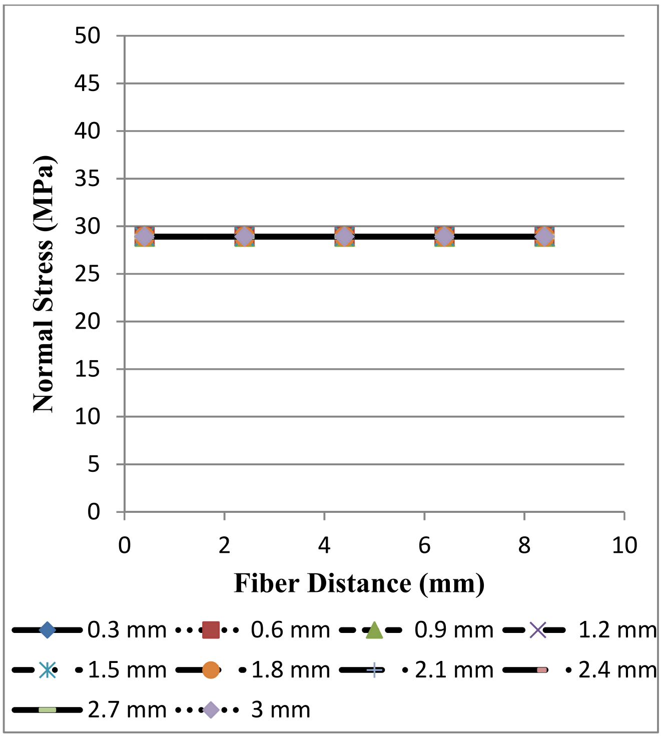

Fig. 11 Normal stresses on fibers for various fiber. Graphic markers show fiber diameters (Angle is 0° between fibers)

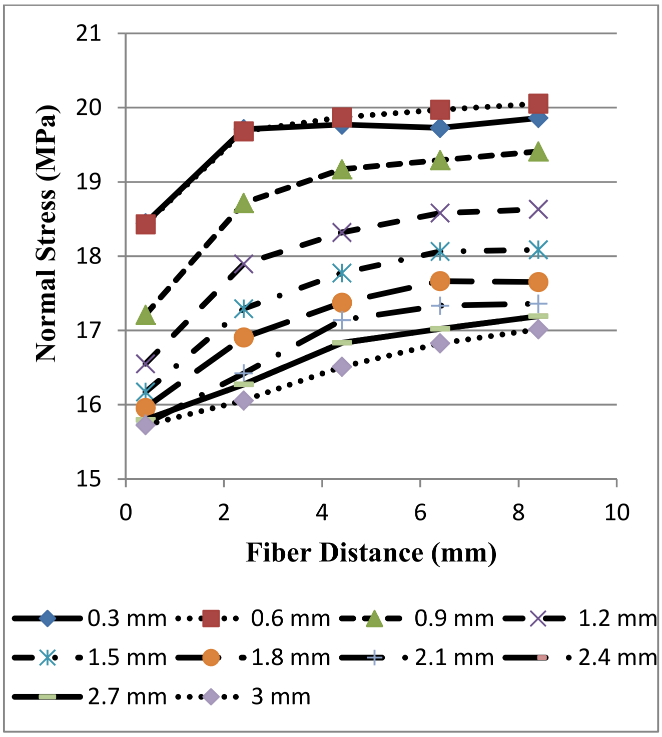

Fig. 13 Normal stresses on fibers for various fiber. Graphic markers show fiber diameters (Angle is 30° between fibers)

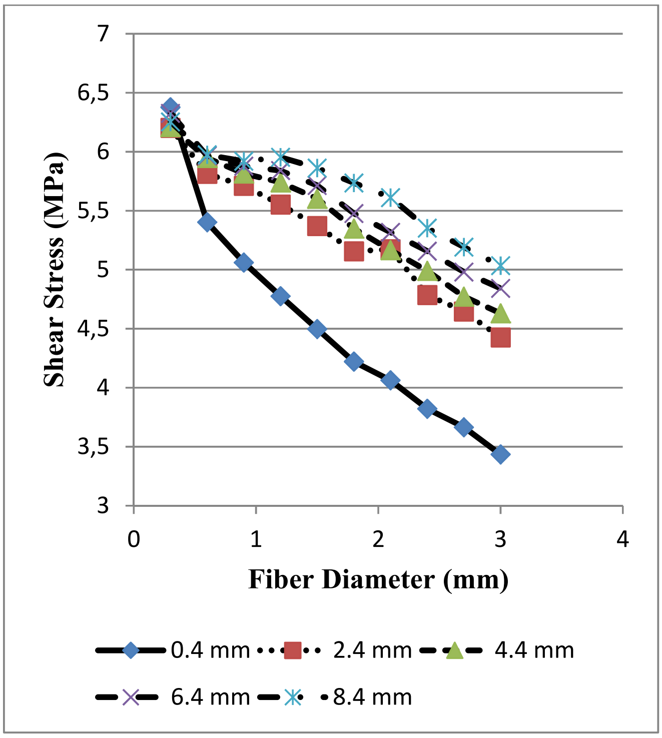

Fig. 14 Shear stresses on fibers for various fiber. Graphic markers show fiber distances (Angle is 30° between fibers)

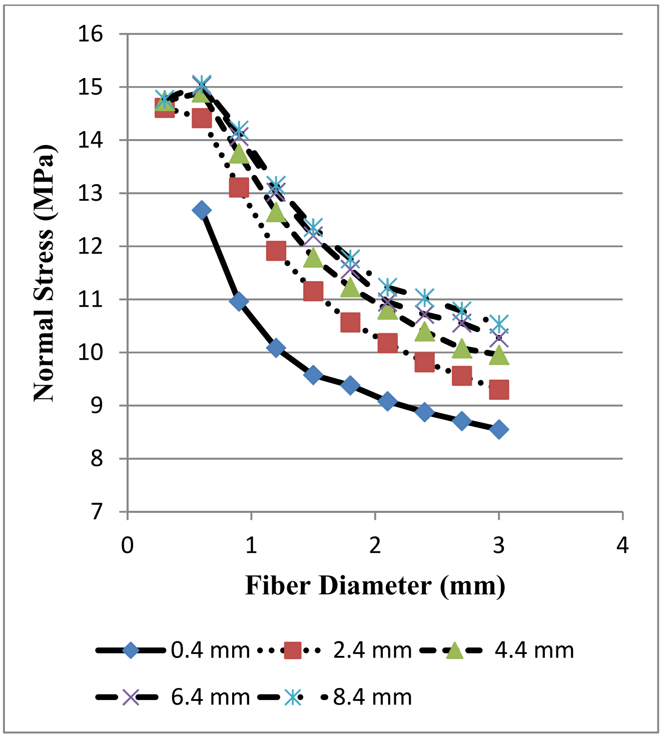

Fig. 16 Normal stresses on fibers for various fiber diameters. Graphic markers show fiber distances (Angle is 45° between fibers)

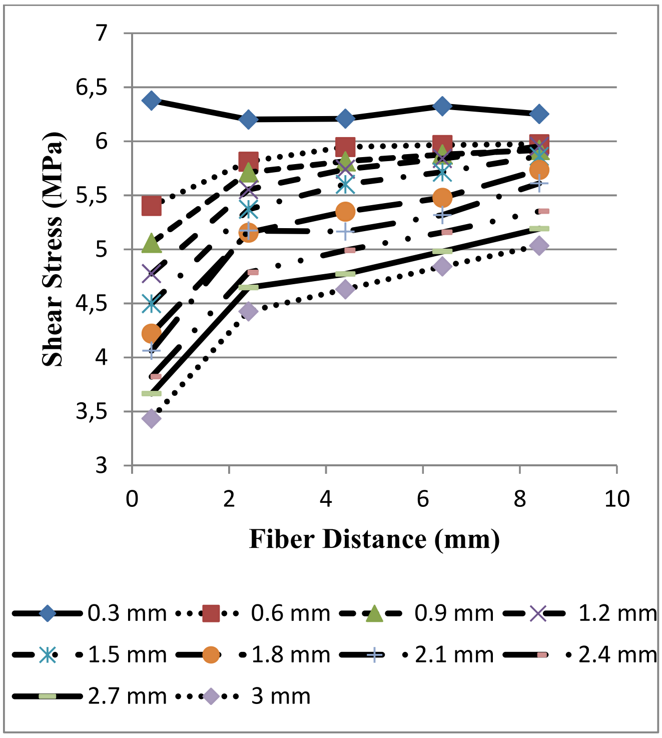

Fig. 15 Shear stresses on fibers for various fiber distances. Graphic markers show fiber diameters (Angle is 30° between fibers)

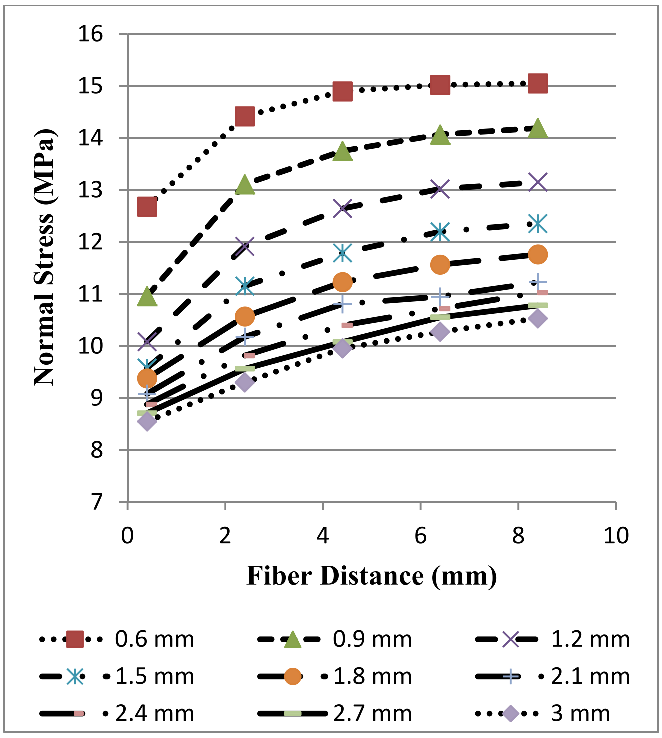

Fig. 17 Normal stresses on fibers for various fiber distances. Graphic markers show fiber diameters (Angle is 45° between fibers)

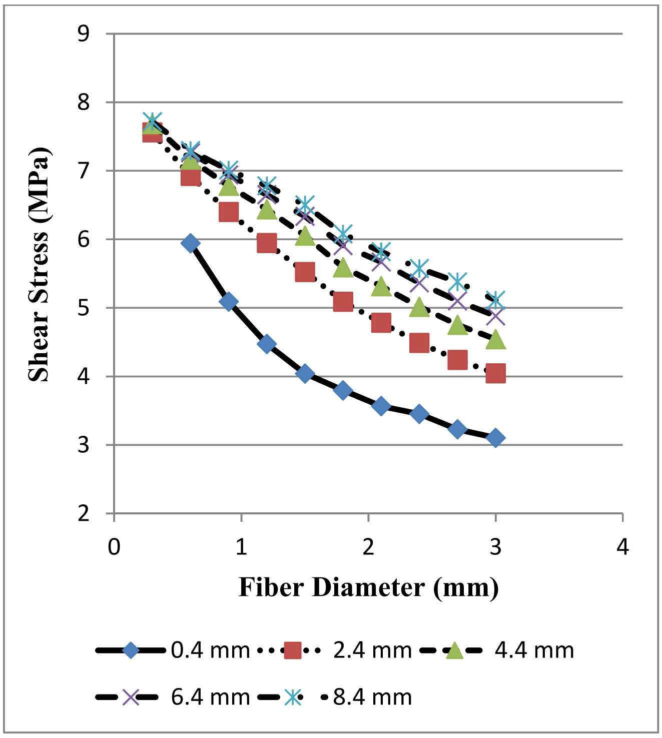

Fig. 18 Shear stresses between fibers and rubber for various fiber diameters. Graphic markers show fiber distances (Angle is 45° between fibers)

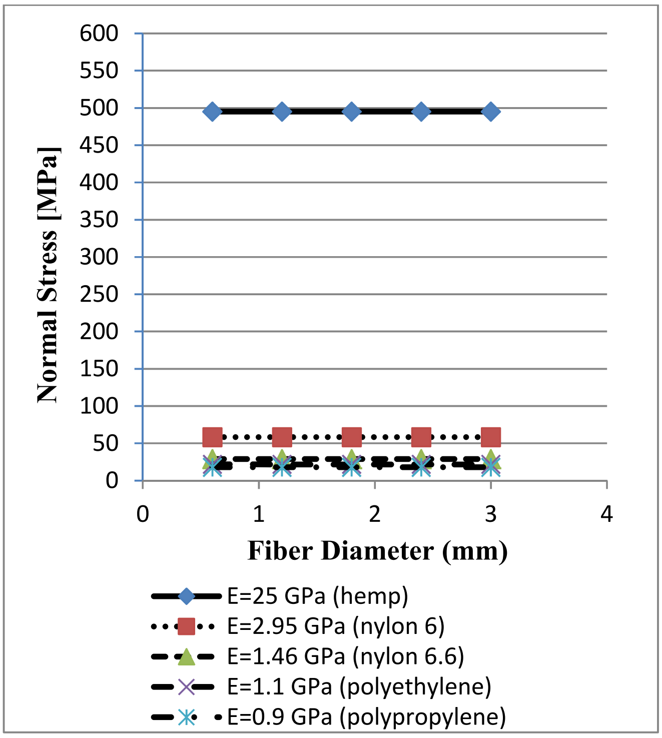

Fig. 20 Normal stresses for various fiber materials and fiber diameters (Fiber distance is 2.4 mm and angle is 0° between fibers) [13]-[20]

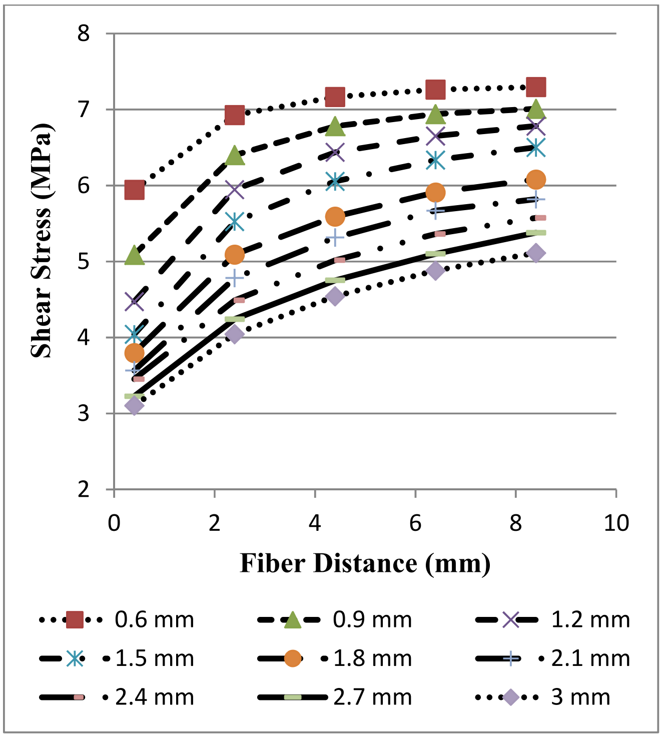

Fig. 19 Shear stresses between fibers and rubber for various fiber distances. Graphic markers show fiber diameters (Angle is 45° between fibers)

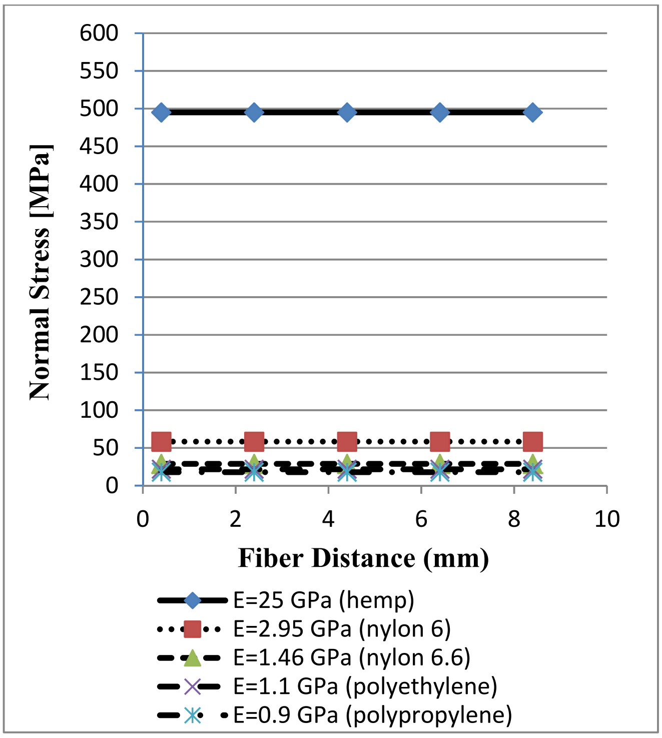

Fig. 21 Normal stresses for various fiber materials and fiber distances (Fiber diameter is 0.9 mm and angle is 0° between fibers) [13]-[20]

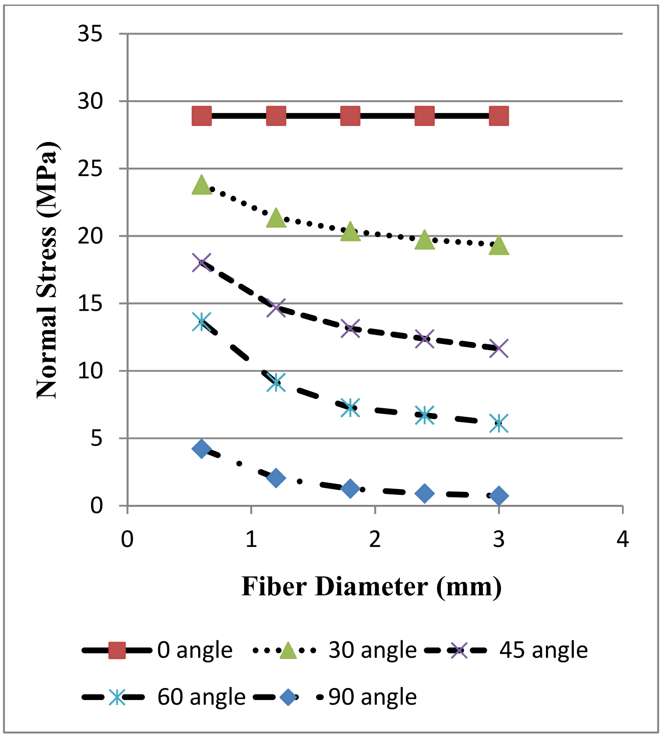

Fig. 22 Normal stresses on fibers for various fibers orientation angles and fiber diameters (Distance is 0.4 mm between fibers)

III. Conclusion

In this study, continuous fiber reinforced vulcanized rubbers are analyzed using finite element method. After verification of finite element solutions with experimental tests, the solutions are obtained for various fiber diameters, distances, angles and materials. All solutions were carried by applying 1 mm prescribed displacements.

It was shown that when the angles between fibers in different layers are used as zero, the stresses on fibers and rubber matrix are not affected by changes of fiber diameters and distances. However, when the fiber angles are increased, the amount of normal stresses is decreased as fiber diameters are increased.

It was also shown that when fiber diameters are increased, the shear stresses between fiber and rubber decrease. The normal stresses are increased on fibers when stronger fibers are used. As the angle between fibers in different layer is increased, the normal stresses are decreased.

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