MECHANICAL BEHAVIOUR NUMERICAL INVESTIGATION OF COMPOSITE STRUCTURE, CONSISTING OF POLYMERIC NANOCOMPOSITE MAT AND TEXTILE

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Abstract. The nanocomposite mat employed in this research is made of composite polyethylene nanofibers (nanocomposite mat) that have been strengthened with silver nanoparticles and electro spun to a linen fabric (plain-woven). The goal of this research is determining the mechanical behavior numerical investigation of the composite structure, consisting of the polymeric nanocomposite mat and textile. To achieve this, in this research was created a 3D model of the plain-woven fabric with the nanocomposite mat and extracted a single unit element from it used to identify the mechanical properties of the nanocomposite mat with the woven fabric. The 3D model of the woven fabric was developed as per Hearl's lenticular section geometry with an elliptical form of the linen yarn created in SolidWorks with sizes of the cross section of the woven fabric of 0.375 mm major axis and 0.075 mm minor axis. This single unit was bonded with nanocomposite mats of various thicknesses such as 0.01 mm, 0.015 mm, and 0.02 mm. Using ANSYS static structural simulation on the unit cell model, the longitudinal Young's modulus of the various nanocomposite mat thickness layers with the linen fabric were determined. Young's modulus values changed within the limit of the 0.002 GPa with the thickness of the nanocomposite mat. The numerical simulation corresponds with the experimental results within a margin of error of 2.8%. Practical application: back support belts can be constructed with this reinforced nanocomposite mat affixed to a linen cloth. Silver nanoparticles embedded in the nanocomposite mat enhance the material strength and antibacterial characteristics, making it suitable for use in luxury automotive and back support belts.

Keywords: nanocomposite mat, linen fabric, Young's modulus, polyethylene, silver nanoparticles.

Introduction

A composite material is a mixture of two or more materials that outperforms each component when handled separately. The features of the finished substance are often distinct from those of any of its elements. Injecting appropriate fillers into polymer-based composites has been shown to be a viable method for enhancing the characteristics of polymer materials, allowing for the use of novel composites in current applications [1].

Nanocomposite fibres may be collected using a number of techniques, including electrospinning and melt spinning. Each device has a specific function and lowering the diameter of nanofibers improves their mechanical properties [2; 3]. When silver nanoparticles are mixed with nanofibers, a nanocomposite is generated, altering the nanofibers' overall features (physical and mechanical). These nanocomposites are mostly used in biological applications owing to the antibacterial and antiviral characteristics of silver ions [4].

The development and mass production of more efficient materials across all industrial sectors has been one of the decade's key technical challenges. By employing short, discontinuous fibres, we may strengthen and toughen such materials [5; 6]. Now, there is an active search for novel reinforced metal-matrix composites with reduced density for use in the construction sector [7; 8], automotive, and aerospace industries [9]; novel reinforced metallic-ceramic-matrix composites with novel designs [10], [11]; and novel reinforced metals-crystals-polymer composite fibres with electromagnetic field protection properties for use in office applications [12; 13].

Polymer fibres must have a diameter ranging from a few nanometres to over 1000 nm to be termed nanofibers [14; 15]. As a consequence, nanofibers have a high surface area to volume ratio, a high porosity/aspect ratio, a very small pore size, a low density, and superior mass transfer capabilities. Numerous processes for the fabrication of polymer nanofibers are currently accessible, including drawing, phase separation, template synthesis, freeze-drying, self-assembly, interfacial polymerization of nanofibers, and electrospinning [16]. Nowadays, electrospinning is widely acknowledged as one of the most successful procedures for fabricating nanofibers on an industrial scale [17; 18]. Electro spun nanofibers have a broad range of applications due to their multiple benefits, including air filtration, antibacterial characteristics, oil/water separation, tissue engineering scaffolding, drug delivery [19], reinforced polymer composites [20], and sensors [21; 22].

Polyethylene (PE) is synthetic resin that is lightweight and flexible. It is made by polymerizing ethylene [23]. Polyethylene is a polyolefin resin belonging to the family of basic polyolefin resins. It is the most frequently used plastic on the planet, used in everything from transparent food wrap and supermarket bags to detergent bottles and automobile fuel tanks. Polyethylene (PE) is one of the most widely used thermoplastic polymers due to its good mechanical qualities [24]. Table 1 summarises the mechanical characteristics of polyethylene. Silver nanoparticles have been shown to have antifungal, antibacterial, anti-inflammatory, and antiviral properties [25]. Therefore, they are ideal for reinforcing the fibres in polymer nano fibrillated membranes. At the same time, the combination of the nanocomposite mat with natural fabrics also has a number of advantages, e.g., linen fabric is one of the most extensively used forms of textile on the Earth. Linen yarns are constructed from staple fibres that have a smooth, elastic, and robust structure [26].

The goal of this research is to determine the mechanical behaviour numerical investigation of the composite structure, consisting of the polymeric nanocomposite mat and textile. As well, the influence of the nanocomposite mat thickness on the mechanical characteristics of a composite construction consisting of the nanocomposite mat connected to linen fabric is investigated. To achieve this, a 3D model of the plain-woven fabric was developed in Solid Works, and the mechanical properties of one unit were analysed using ANSYS simulation and experimental investigation was performed.

Materials and Experiment

Prior to performing numerical modelling of the composite structure, a practical experiment was conducted in which the nanocomposite mat was laminated to a linen textile and its mechanical properties were determined using a method specified in ISO 1421:2016 for determining the tensile strength of fabrics coated with rubber or plastics.

The polyethylene (PE) (Sigma-Aldrich chemicals, Merck KGaA, Darmstadt, (64287) Germany; $(C_2H_4)_n$ (low-density); molar mass 280,000 g/mol; CAS number 9002-88-4) solution was prepared in dimethylbenzene solvent (Sigma-Aldrich chemicals, Merck KGaA, Darmstadt, (64287) Germany; (CH3)2C6H4; molar mass 106.16 g/mol; viscosity 0.34 cP at 30 ºC (86ºF); CAS number 106-42-3; RTECS number ZE2625000) with 15% w/w of polyethylene and 1% w/w silver nanoparticles (CD Bioparticles, Shirley, NY 11967, USA; Silver Nanoparticles, Nano Ag Powder CAS 7440-22-4) ranging in size from 50 ± 5 nm (95% correspond 50 nm) by mixing it for 6 hours with the magnetic stirrer (Thermo Scientific™ Cimarec + ™ Stirring Hotplates Series, USA) under + 85 ºC (where room temperature was 22 ± 1 ºC; moisture content, 60%). In the electrospinning setup (Fisherbrand™ Single Syringe Pump, a needle-based electrospinning machine, Danbury, (CT06811), USA), with a spinning-chamber temperature of 22 ± 1 ºC and 36% relative humidity, using a 20 Ga needle, a rotating drum collector (Shenzhen Tongli Tech Co LtD, (D-608) Shenzhen, China; Rotating Collector RC-5000, D140, L50) was used to electro spin the nanofiber mat at 800 rpm directly onto the revolving drum and wrap in linen fabric (Fabric Art. 31107/00/col.19, manufactured by AB "Linas" (LT-35114) Panevezys, Lithuania; plain weave, warp – linen – 33 Tex, weft linen – 33 Tex; surface density 130 ± 9 $g \cdot m^{-2}$). Prepared samples (24 h was technological deposit, room temperature 22 ± 1 ºC; moisture content, 60%) are precisely cut to 140 mm × 20 mm x 0.2 mm (thickness with the nanocomposite mat of 0.015 ± 0.0075 mm) dimensions for mechanical testing. The linen fabric used to cover the spinning drum is 0.15 mm thick and has the weave structure depicted in Figure 1.

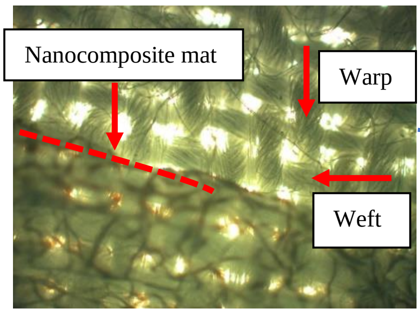

Fig. 1. **Linen fabric (Leica microscope, Mx40)**

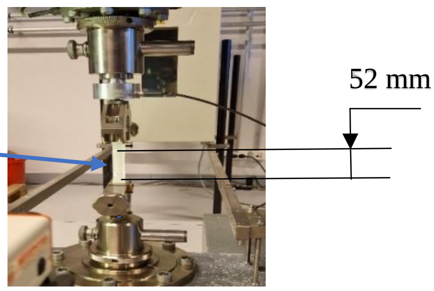

Fig. 2. **Mechanical tensile testing on Zwick/Roell 150**

Mechanical testing was performed using the video extensometer and the Zwick/Roell 150 (Germany) tensile testing machine (x-axis movement was 0.5 mm/min). Figure 2 shows the tensile testing of specimens made from the nanocomposite mat with textile reinforcement. At a distance of 52 mm, black strips are attached to the material to allow the extensor video metre to examine the material's elongation. Five samples were analysed, and the force versus elongation findings are given in the graph along with the average value in Figure 3.

In the graph elongation between 3 and 3.5 is a linear graph that was used to calculate the elastic modulus of this composite nanofiber mat using Hook's law. Calculations are performed on a linear curve with an elongation of between 3 and 3.5 mm and a force detected on the x-axis. The average modulus of elasticity calculated from the experiment was 1.495 GPa.

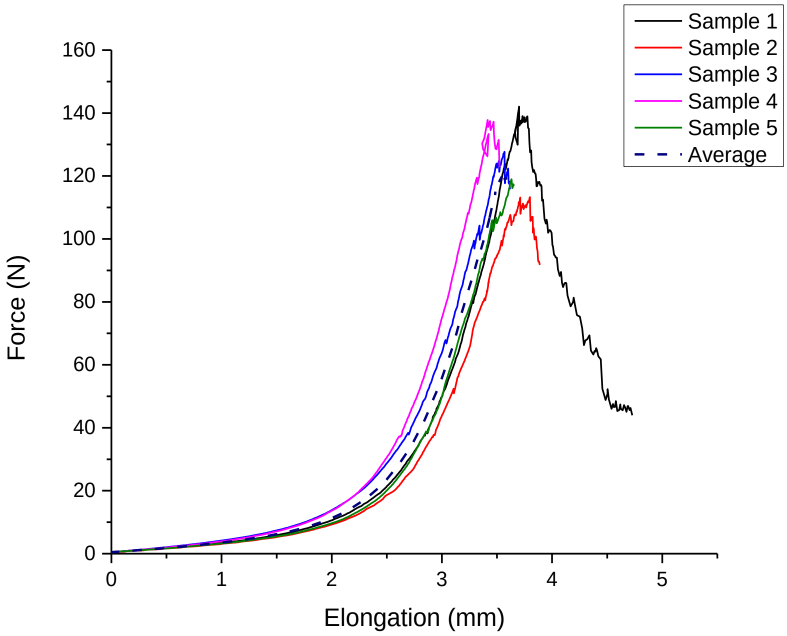

Fig. 3. **Elongation of the nanocomposite mat with textile**

Numerical Simulation

The woven structure of the linen fabric was constructed in SolidWorks using Hearl's lenticular section geometry and an elliptical shape of the linen yarn [27; 31]. The cross section of the woven fabric has a major axis of 0.375 mm and a minor axis of 0.075 mm. As depicted in Figure 4, the layer of silver nanoparticles embedded in a PE nanofiber mat is attached to the woven fabric, to evaluate the material's mechanical characteristics.

In ANSYS, a static structural analysis is performed on the singe unit cell model. The nanocomposite of silver nanoparticles in PE with the thicknesses of 0.05 mm, 0.10 mm, and 0.15 mm is shown in Fig. 5.

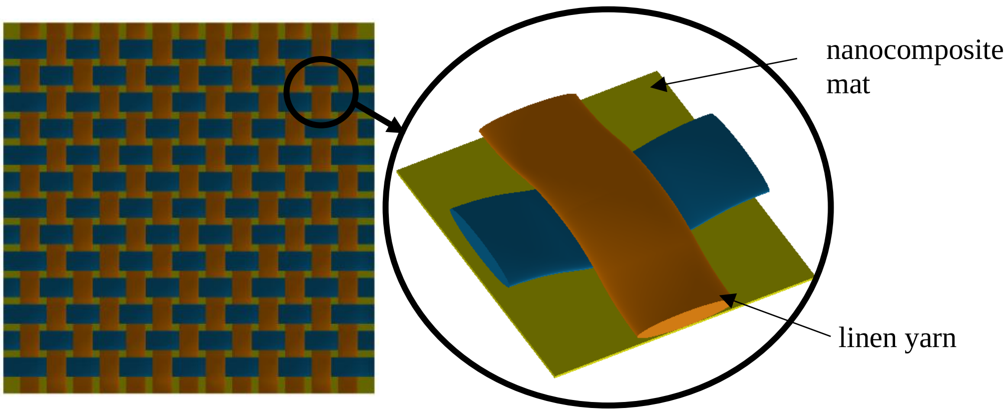

Fig. 4. **Woven fabric with nanocomposite mat**

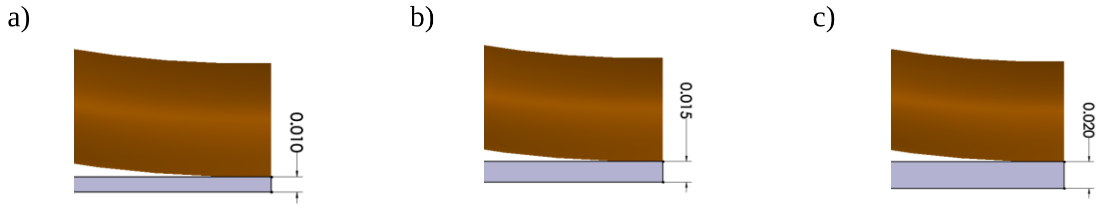

Fig. 5. **Nanocomposites PE embedded with silver nanoparticles with different thicknesses of 0.01 mm, 0.015 mm, 0.02 mm – respectively (a), (b) and (c)**

Due to the fact that the polyethylene solution contains just 1% silver nanoparticles, it is unlikely that the strength of the nanocomposite would be compromised. Thus, the elastic modulus of the polyethylene nanocomposite implanted with silver nanoparticles is regarded comparable to the elastic modulus of polyethylene. Given below, Table 1 represents the material properties assigned to the nanocomposite mat and linen fabric.

Table 1

Mechanical properties of polyethylene and linen fabric

Properties	Polyethylene nanocomposite mat [28]	Linen fabric [29;30]
Young's modulus (GPa)	1.400	1.600
Tensile strength (GPa)	1.100	0.293
Poisson ratio	0.350	0.300

Boundary conditions: in the FE model, boundary conditions were applied to the face of the unit cell to generate stress. Nodes on one of two opposing faces were restricted from out-of-plane displacement and rotation, whilst nodes on the other face were allowed to move freely with the plane. This limitation was achieved by specifying a frictionless support for each face. Faces in the opposing face were uniformly displaced by 0.1 µm in the direction perpendicular to the restricted face. The surface displacement of 0.1 micrometre on the right face normal to the right plane was specified for the longitudinal Y direction, as indicated in the preceding figure. The bottom surface and the left surface are both frictionless supports. A boundary condition is specified to ensure that stress is distributed evenly across the geometry and that the geometry retains its symmetry.

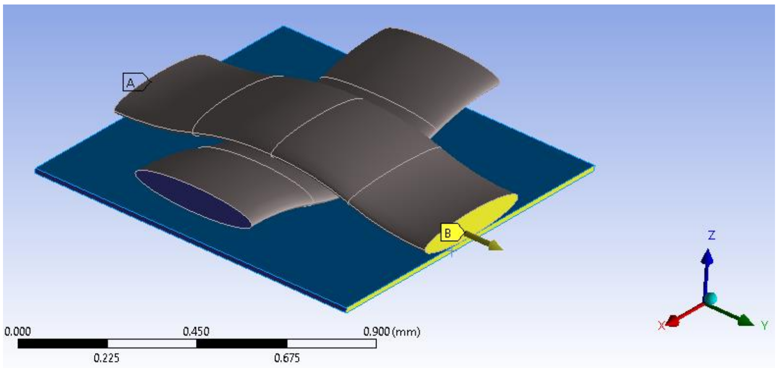

Fig. 6. **Applied constraints to the unit cell model to calculate elastic modulus in longitudinal direction**

In the simulation, the nanocomposite mat is stuck to the fabric (due to electrospinning on the fabric) to create a rigid contact that is specified in the boundary conditions. After applying the necessary boundary conditions, a static analysis in both the x and z axes was done to calculate the longitudinal and transverse Young's moduli. The analysis and processes for various thicknesses of the nanocomposite mat are repeated to compare the results.

As seen in Figure 7 (a), both ends of the top yarn in the weave loop will be linked to the nanocomposite mat. While the weave structure underneath the loop is connected to the nanocomposite mat through the central section of the linen yarn.

a) b)

Fig. 7. **Rigid joint between the nanocomposite mat and the fabric (a) upper yarn (b) bottom yarn (Geometry scaled)**

Results and Discussion

Fig. 8 illustrates the comparable stress results for a 0.015 mm thick nanocomposite attached to the linen weave fabric.

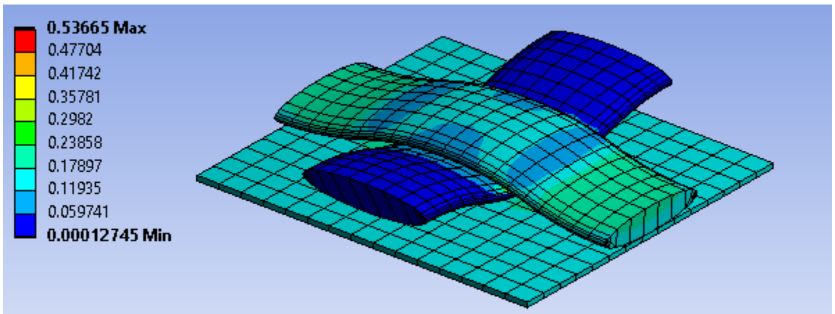

Fig. 8. **Stress analysis of 0.015 mm thickness nanocomposite in longitudinal direction**

Strain is determined manually since the beginning displacement is set to 0.1 µm. The equivalent stress is defined as the average value of the applied displacement in the direction of the displacement. Table 2 compares and summarises the longitudinal stress values of nanocomposites of increasing thickness, as well as the estimated Young's modulus values.

Table 2

Comparing the average stresses of nanocomposites with various thickness

Thickness, mm	Longitudinal stress, MPa
0.010	0.1535
0.015	0.1537
0.020	0.1539

Table 3

Comparing the Young's modulus values of nanocomposites of various thickness with experimental results

Thickness, mm	Longitudinal Young's modulus, GPa
0.010	1.535
0.015	1.537
0.020	1.539
Experimental result	1.495

When the yield strength of the textile nanofiber mat is exceeded, the mat begins to delaminate from the linen fabric. As with the weave structure, yarns begin to break when subjected to tensile loading. Since nanocomposite mats constructed of PE have a higher elongation than textile fabrics, nanocomposite mats stay unbroken under loading conditions. By incorporating silver nanoparticles into the nanofiber mat, the antimicrobial property of linen fabric reinforced with the nanofiber mat is enhanced [32].

Conclusions

1. A 3D model of the woven fabric was developed in SolidWorks to undertake the numerical simulation investigation. The fabric is elliptical in form, with a major axis of 0.375 mm and a minor

axis of 0.75 mm. The thickness of this nanocomposite was varied between 0.01 mm, 0.02 mm, and 0.15 mm. The experimental results show identical results with a 2.8% margin of error.
2. For composites, the effect of the nanocomposite mat thickness on the linen fabric varies by 0.002 GPa in longitudinal directions.
3. Due to the presence of silver nanoparticles, this novel reinforced nanocomposite mat made of linen fabric is suitable for use in luxury automobiles and back support belts.

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Author contributions:

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