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Effect of Carbon Nanotubes on Characteristics Performance of Non-Pneumatic Tyres

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ABSTRACT
Extensive studies have been proposed for on/off-road light and heavy equipment non-Pneumatic Tyres (NPTs) due to their advantages over the traditional pneumatic tyre in low rolling resistance, flat-proof, low maintenance. Many studies were focusing on the elastomer material asthe primary material using in NPT. In this paper, NPT finite element (FE)model with honeycomb spokes containingpolyurethance/carbon nanotubes (PU/CNTs) is investigated. The NPT static behaviour of vertical stiffness, and contact pressure are studied. Rolling resistance and dynamic shear stress are also studied. The parametric study shows that PU/CNT makes a significant effect on rolling resistance.
KEYWORDS: Non-pneumatic tyre (NPT); rolling resistance; carbon nanotubes (CNTs); FEM.

I. INTRODUCTION

Researchers are still ongoing to developnon-pneumatic tyres (NPTs) made from polyurethane (PU) instead of rubber[1]. PU is significant because it is positively effect on the energy, contact behaviour between the NPT and road, entirely recyclable, and non-vulcanized make it more environmentally friendly unlike the conventional tyre manufacturing methods require[2,3,4,5,6]. Many researchers have attempted to improve the structural performance of the NPTs, Ju et al.[7] reduce NPT rolling resistance by reducing the material volume using porous topology without scarifying stiffness. Kim et al.[8] investigate the contact pressure of hexagonal honeycomb spokes ofNPT and found that it is lower than the similar traditional pneumatic tyre contact pressure as a hexagonal honeycomb spoke has high lateral stiffness. On the other side, many researchers aimed to improve the PU mechanical properties. Thyagaraja.[9] replace the viscoelastic PU shear layer in NPT with linear elastic materials to reduce the corresponding rolling resistance.Ju et al.[10] investigate the influence of the metallic shear band on lunar NPTcontact pressure. In PU research, Xiong et al.[11]have fabricated a chemical compoundof a polyurethane and carbon nanotube elastomer composite, and analyzeit's dynamical mechanical thermal properties, and Thermal stability. The mechanical properties results showed an improvement in the mechanical strength, and thermal stability by adding 2% by weight of CNTs. That's make carbon nanotubes are ideal reinforcing fibers for composites. CNT was used in pneumatic tyres to improve wear resistance, rubber cohesion strength, tensile and tear strength, rolling resistance, and vulcanization dynamic properties[12,13,14]. The increase in Young's modulus and tensile strengths improve the performance of NPTs, which is the hypothesis of this paper. To evaluate the performance of NPT, a rolling resistance, contact pressure, stresses, and stiffness of the NPT with and without CNT on the unpaved soil has been studied at constant velocities approx. to 20, 40 and 60 km/h.

II. MATERIAL AND METHODS

2.1 Material

The NPT outside and hub radii are 277, and 171 *mm*, respectively, and a cross-sectional width is 200 *mm*. Figure 1 shows the tyre components;the rigid hub is made from an aluminum alloy, integrated with the spokes. The flexible honeycomb spokes and shear band are made of PU,and they are the basis of the NPT structure. The two inextensible membranes are made of high strength steel, to strength the shear band, and the three make a shear beam.The rubber is used, like the traditional tyre, to make the NPT tread. Tread, shear band, two inextensible membrane reinforcements, spokes, and hub thicknesses are 5, 20, 0.5, 5, and 1 *mm*, respectively.

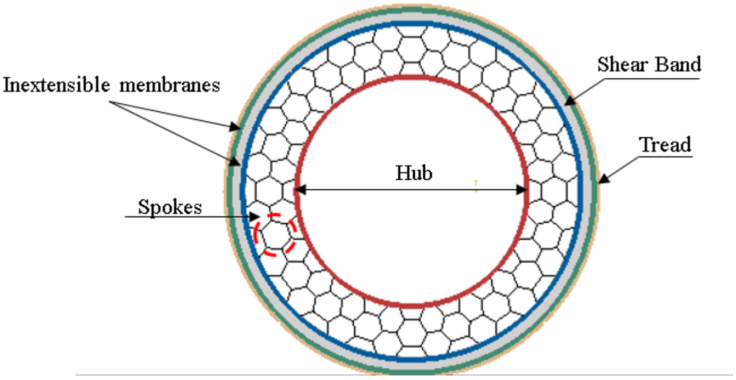


Figure1.NPT components.

Table 1 illustrates the properties of each component material used in this tyre.NPT spokes are designed for materials and structure to be uniform and flexible, to meet the combination of stiffness and resilience requirements[15].Figure 2 illustrates the Hexagonal honeycomb spoke geometry and the honeycomb cell dimensions illustrated in table 2. As shown in Figure 2, horizontalcell length "*h*", cell angle"*θ*", and side spoke length "*l*".

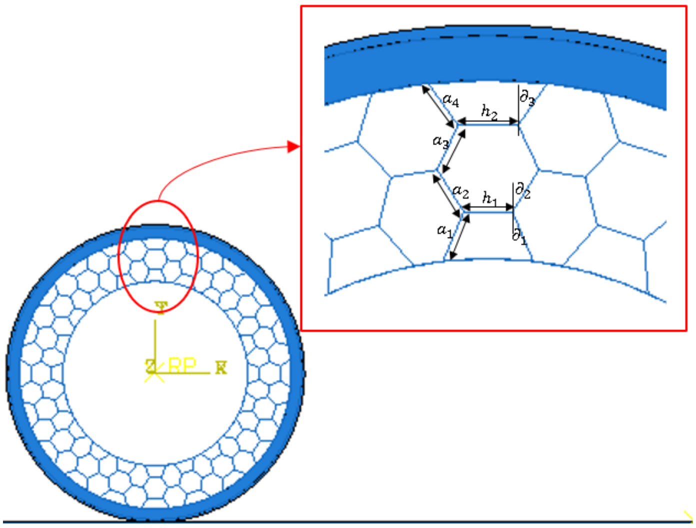


Figure 2.hexagonal unit cell length.

Table 1. Properties of tyre material.

Material	Density, ρ (*kg/m*^{3})	Young's modulus, E (*MPa*)	Poisson's ratio, N	Shear modulus, G (*MPa*)
Aluminum alloy	2800	72x10^3	0.33	——
PU	1200	32	0.49	10.8
ANSI 4340	7800	210 x10^3	0.29	——
Rubber	1043	11.9	0.49	4

Table 2. Dimensions of a hexagonal unit cell.

Geometric parameters	a_1	a_2	a_3	a_4	h_1	h_2	θ_1	θ_2	θ_3
mm (degree)	22.9	21.1	21.3	24.1	26.9	21.8	22	32	35

2.2 Modeling of soil and NPT

To investigate the structural behavior of the model, ABAQUS 2018, a finite element numerical mathematic tool has been used.Structural analysis is conducted in a static, general step, to deform the tyrewith the specified load applied at the center point of the tyre, and a boundary condition of this center is set free in the deform direction to study thedeformation, stress, contact shear, and the contact pressure distributions betweenthe soil and the tyre.While maintaining the previous load applied in the first step,rolling in the second step, are performed at different times, and boundary conditions are set free in y-direction “the direction of the tyre deformation”, and z-direction“the direction of the tyre rotation”. In contrast, the translation in x-direction is set to roll the tyre at constant velocities approx. to 20, 40 and 60 km/h. In this step, the rolling resistance is calculated using the ALLCD ABAQUS function[15,16,17]. Both soil side edges are fixed in y-direction. Besides, the bottom edge in x- direction as shown in Figure 3[18,19].The hub, spokes, and reinforcements are modeled as in-plane quadratic beam elements. “B22” is the naming convention in ABAQUS for these elements. The shear beam and tread are modeled as biquadratic plane stress model with reduced integration. “CPS8R” is the naming convention in ABAQUS for theseelements. The soil is modeled as a plane strain model with reduced integration, named “CPE8R”.

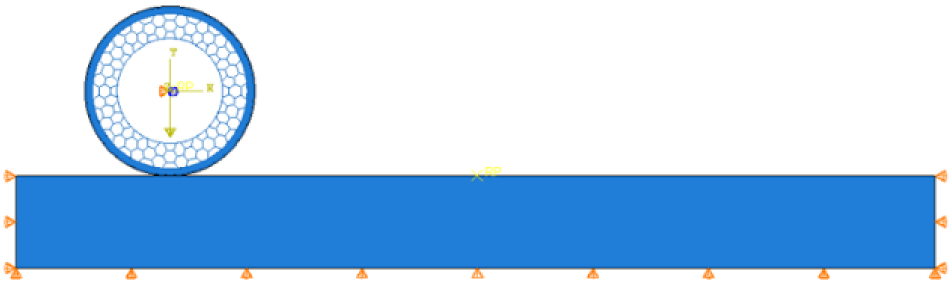


Figure3.soil boundary conditions.

The ground's behavior is represented as the modified Drucker-Prager/cap plasticity model to describe the soil mechanical characteristics under compression specifically, and the FE soil model parameters, and the hydrostatic compression yield stress as a function of the volumetric inelastic strain are displayed in tables 3, and 4, respectively[20.21]. The hyper-elastic strain energy used as an Ogden's hyper-elastic material model input for the pure PU material as in reference[22]. Besides the hyper-elastic strain energy behavior of the rubber used as in reference[23].For a viscoelastic material behavior, PU is defined by the parameters of the Prony series given by equation (1)

$$G_R(t) = G_0 \left(1 - \sum_{K=1}^{N} \bar{g}_i^p (1 - e^{-t/\tau_i}\right)^{23} \quad (1)$$

Table 3. Soil parameters.

Young's modulus $[MPa]$	Poisson's ratio	Cap eccentricity $\boldsymbol{R_s}$	Initial yield surface position
50.5	0.25	0.1	0.001
Soil cohesion $[MPa]$	Friction angle β [°]	Transition surface radius α	Flow stress ratio k_R
0.113	14.56	0.03	1

Table 4. Parameters for soil hardening effect

Yield stress $[MPa]$	0.02	0.025	0.063	0.13	0.24	0.42	0.61	0.93	2.52
Volumetric strain	0	0.005	0.01	0.02	0.03	0.04	0.05	0.06	0.1

Table 5 illustrates the Prony coefficients $\bar{g}_i^p$ and $\tau_i^p$of the PU and rubberfrom the previous equation[24,25,26].The carbon nanotubes (CNTs) used in this research area hollow tube formed by a layer of carbon atoms with 9.5 nm diameter, and 1.5 μm length which makes it ideal reinforcing fibers for PU in this study. The purity of CNT is 90%. Young's modulus, Breaking stress, and fracture of the PU/CNT are summarized in Table 6[27]. From various CNT loading ratios, a 2 wt.% of PU/CNT have been selected in this study. According to the Chinese national standard GB/T 582-1998, the stress-strain curve for PU and PU/CNT are shown in Figure 4. The storage modulus increased while the damping factor decreased with increasing the CNT content in PU[28,29,30,31,32,33].

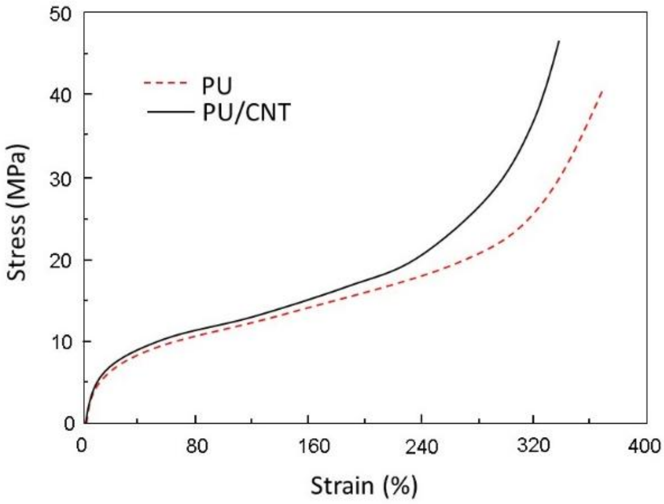


Figure4. Neat PU and 2 wt.% PU/CNT Stress–strain curves[29].

Table 5.PU and rubber three viscoelastic coefficients.

		1	**2**	**3**
PU	g_i	0.125	0.125	0.125
	τ_i	0.002	0.02	0.2
Rubber	g_i	0.2	0.2	0.2
	τ_i	0.002	0.02	0.2

Table 6.PU/CNTmechanical properties.

Sample	Young'smodulus (MPa)	Tensile strength (MPa)	Fracture strain (%)
PU/CNT 0.5%	74.8±3.3	30.5±1.8	510±5.1
PU/CNT 1%	83.2±3.8	29.3±1.6	510±5.5
PU/CNT 1.5%	70.7±3.5	28.4±2.1	482.6±6.4
PU/CNT 2%	74.8±3.1	27.2±1.9	531±5.2

III. RESULTS

The use of CNT in NPT has a significant effect on tyre performance. It is observed in Figure 5 that the maximum contact pressure between the NPT and the soil surfaceis 0.247 *MPa* for PU/CNT at a vertical load of 3000 *N*, higher than that of the PU, which is 0.193 *MPa*. The comparison between the maximum contact pressure at different vertical loads for PU and PU/CNT is shown in Figure 6.It is observed that the PU/CNT increased with the increase of vertical load higher than the case of pure PU.

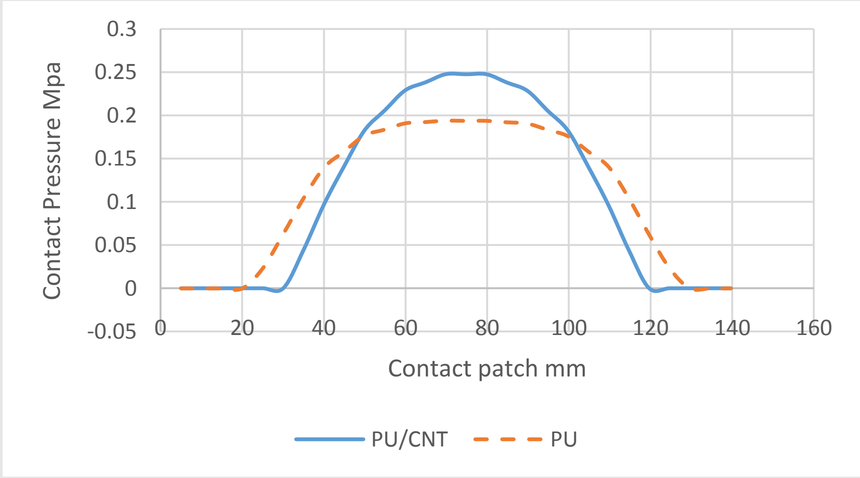


Figure5. Variation in NPT contact pressure for PU and PU/CNT.

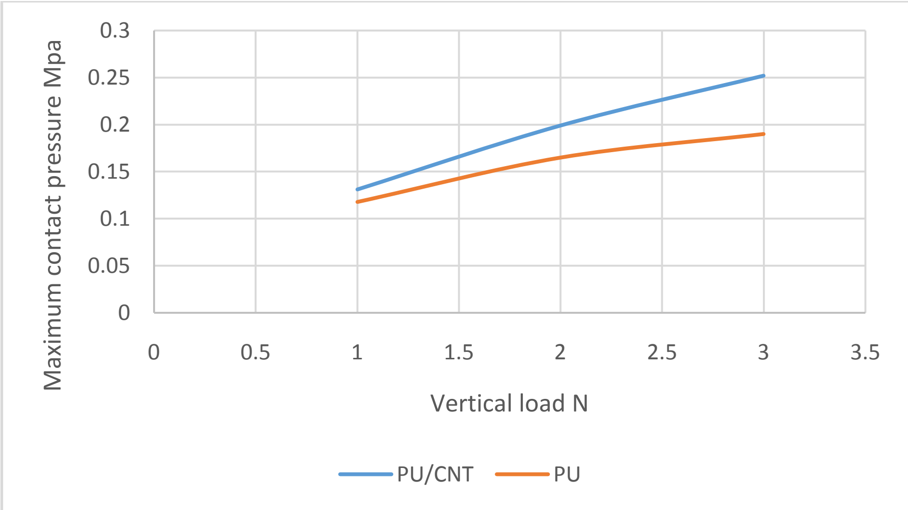


Figure6. Compare between maximum contact pressure with different loads at 20km/h for PU and PU/CNT.

Figure 7 shows the maximum contact pressure at 1000, 2000, and 3000 *N*vertical loads at various speeds for Neat PU and PU/CNT. The maximum contact pressure increasees slightly, with the speed increase at the same vertical load.The increase in maximum contact pressure in PU/CNT from speed 20 to 60 *km/h* at3000 *N* is 1.6%, while the increase from load 1000 to 3000 at speed 60 *km/h* is 48%.

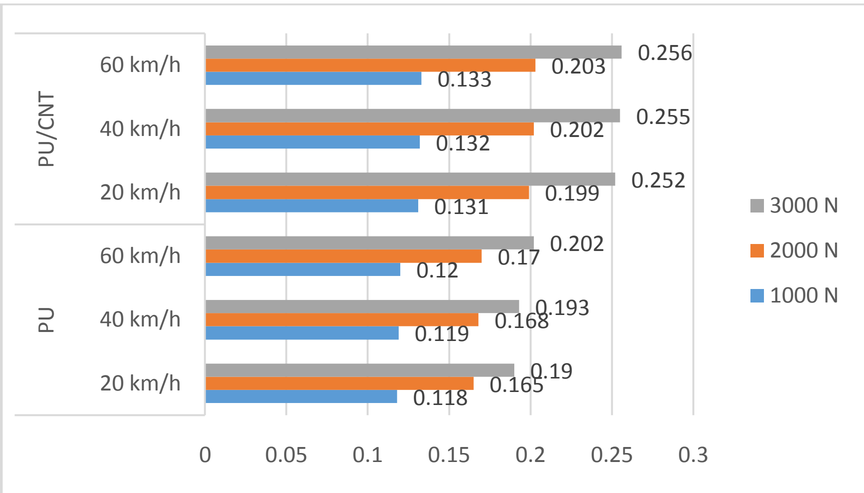


Figure7. Maximum contact pressure at various loads/speeds for PU and PU/CNT.

The average contact shear stress between NPT and the soil forvertical loading of 3,000*N*is analyzed. Figure8 shows the contact shear stress of the NPT at rolling step. It is observed that the shear stress for PU/CNT is higher than that of PU. Figure 9 shows the maximum value of contact shear at vertical loads 1000, 2000, and 3000 *N*at various speeds for PU and PU/CNT. The maximum contact shear stress increased slightly, with the speed increase at the same vertical load. The increase in maximum shear in PU/CNT from speed 20 to 60 *km/h* at 3000 *N* is 6.5%, while the increase from load 1000 to 3000 at speed 60 *km/h* is 66.3%.

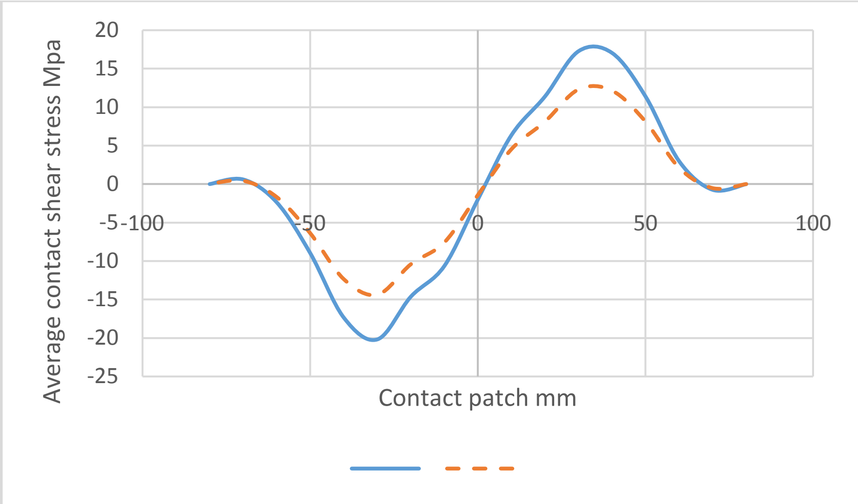


Figure8.shear stress at rolling

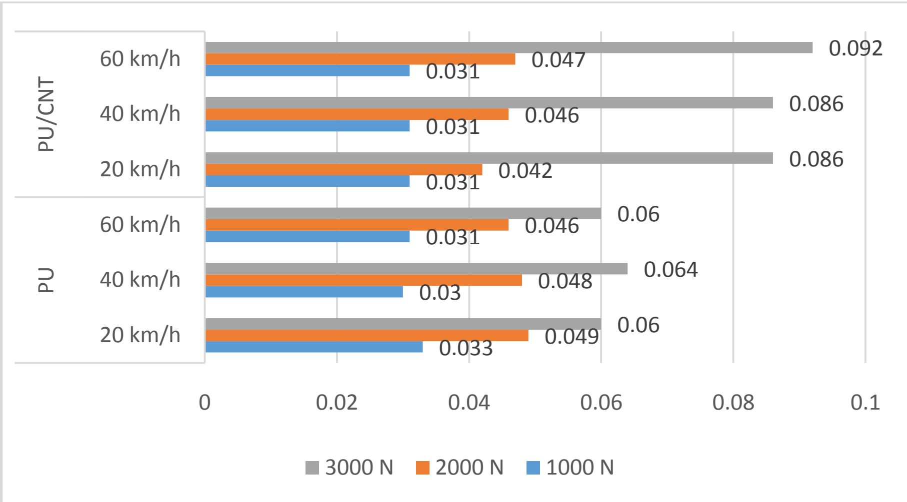


Figure9. Maximum shear stress at various loads/speeds for PU and PU/CNT.

The static load-deflection procedure shown in Figure 10are used to determine the tyre vertical stiffness as shown in Figure 11 by using the relationship between load-deflection (δ)and vertical stiffness (K)at a specified vertical load (F) asdefined in equation 2;

$$K = \frac{F}{\partial} \tag{2}$$

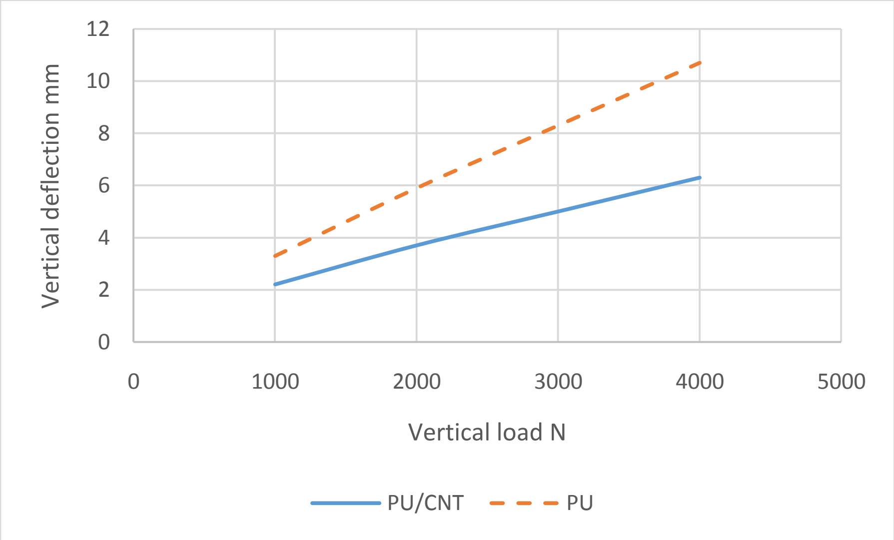


Figure10. Variation in vertical deflection for PU and PU/CNT.

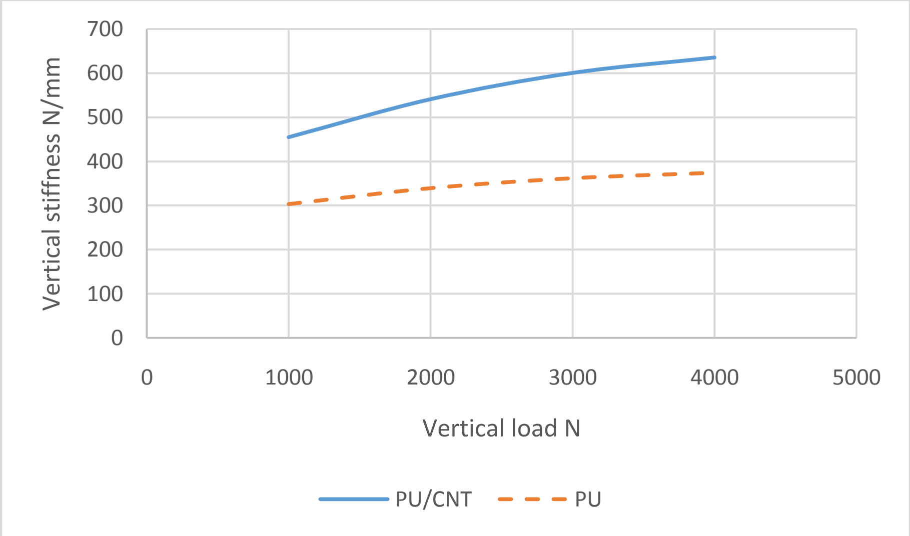
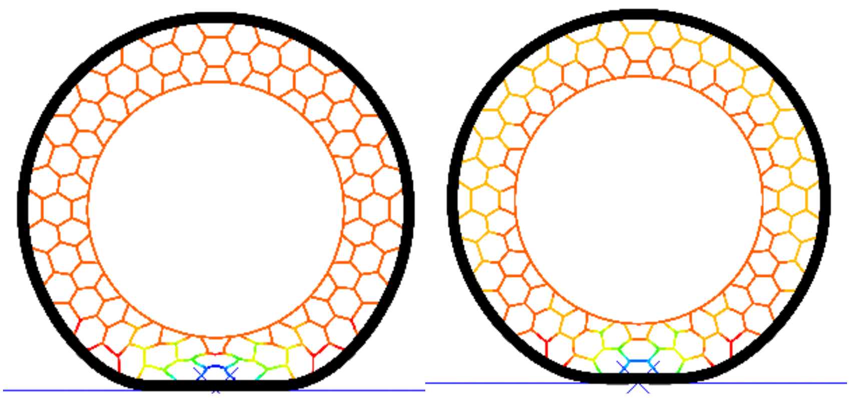


Figure11. Variation in vertical stiffness for PU and PU/CNT.

Based on equation (1), the tyre with PU/CNT is stiffer more than PU, as shown in Figure 12.



a) Neat PU b) PU/CNT

Figure12.NPT deflection (a) with PU, and (b) with PU/CNT.

The maximum stresses vary with the roll of NPT. Figure 13 illustrates the values of the maximum Von Mises stress at various loads, and it is observed thatthe stresses are reduced when added carbon nanotube to the polyurethane.

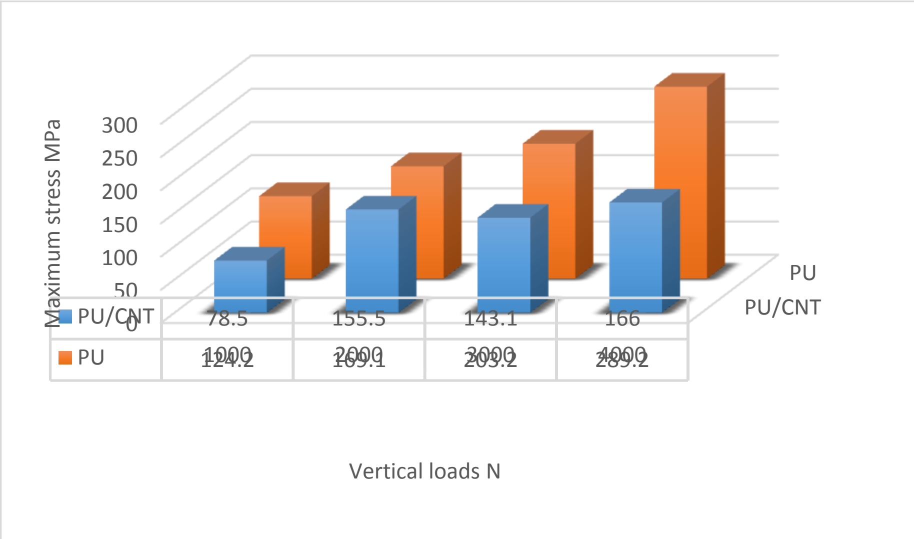


Figure13. Variation in maximumVon Misesstresses for PU and PU/CNT.

Rolling resistance (R_r) calculated bythe viscoelastic energy dissipation (W_d) of an NPT per unit rolling distance (D) as illustrated in the following equation with a friction coefficient μ= 0.65. The results is numerically obtained in ABAQUS by the history output(ALLCD)[34,35].

$$R_r = \frac{W_d}{D} \qquad (3)$$

Therolling resistance responseusing PU and PU/CNT is compared, as shown in Figure 14.Rolling resistanceresult using PU/CNT is 112.2*N*, while the result using pure PU is 89.3 *N* at the vertical load 4000*N*.Figure 15 shows the rolling resistance values at 1000, 2000, and 3000 *N* vertical loads at various speeds for Neat PU and PU/CNT. The rolling resistancedecreased with the speed increase at the same vertical load. The increase in rolling resistance in PU/CNT from speed 20 to 60 *km/h* at 3000 *N* is 18.4%, while the rolling resistance increasewith the load increase, the risefrom load 1000 to 3000 at speed 60 *km/h* is 85.2%.

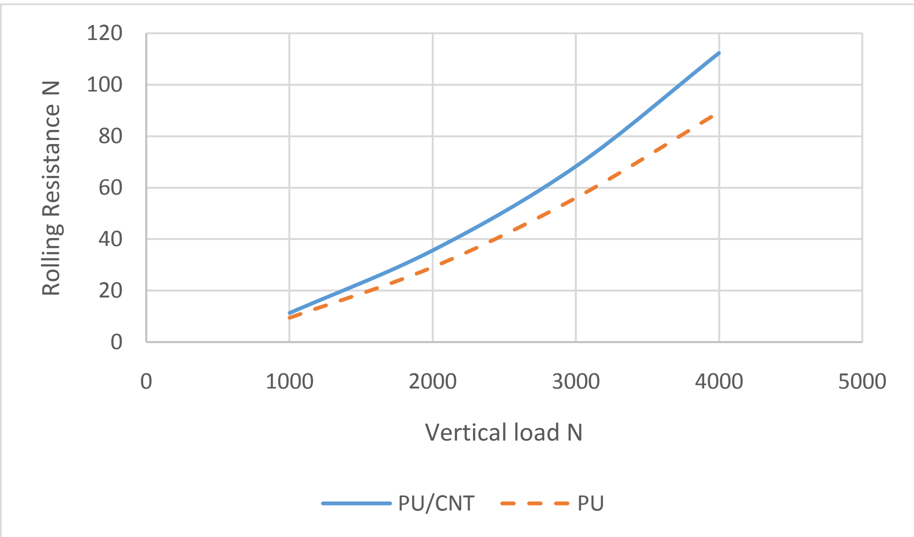


Figure14. Variation in rolling resistance for PU and PU/CNT at speed 20km/h.

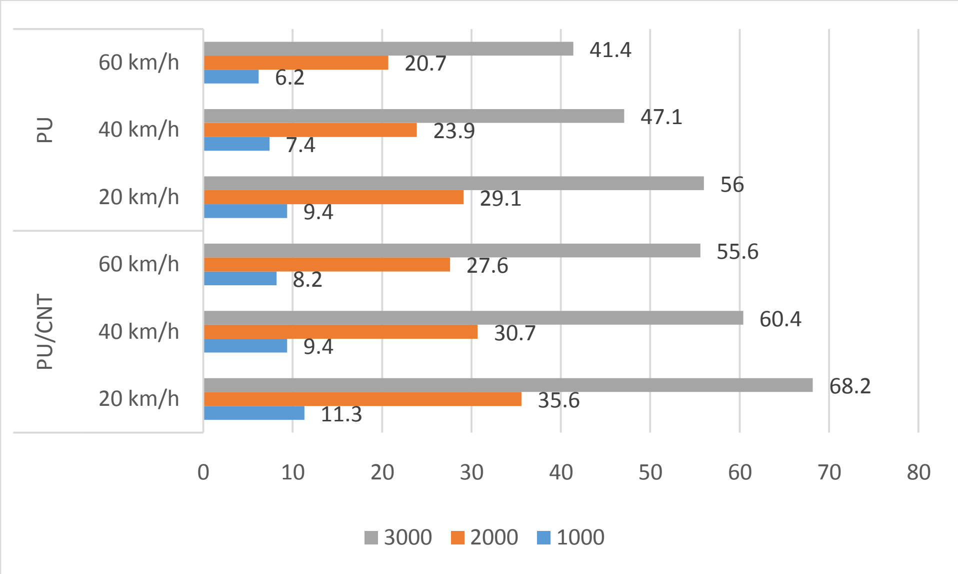


Figure15. Rolling resistance at various loads/speedsfor PUand PU/CNT.

IV. CONCLUSION

A PU/CNT was suggested, and its structural performance on the rolling resistance was investigated when used on an NPT. The significant findings in this study are as follows:

- The parametric study shows that PU/CNT makes the NPT stiff, resulting in a reduction in vertical deflection and an increase in the peak contact pressure value.
- Reduce the von mises and shear stresses.
- Increase rolling resistance of NPT by 18.4% at 4,000*N* in the unpaved soil, which make it more suitable for a paved road.

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