International Journal of GEOMATE, Dec., 2020, Vol.19, Issue 76, pp. 25–32
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2020.76.9134
Geotechnique, Construction Materials and Environment

THE CONTACT PATCH CHARACTERIZATION OF VARIOUS SOLID TIRE TESING METHODS BY FINITE ELEMENT ANALYSIS AND EXPERIMENT

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*Corresponding Author, Received: 14 June 2019, Revised: 05 Sep. 2019, Accepted: 28 Nov. 2019

ABSTRACT: The solid tire performance can be characterized by the contact patch. The footprint is the particular method to achieve the contact patch between a tire and pavement. The flat surface is often equipped to support a pressure measurement film which is pressed by the tire tread. This derivative patch illustrates characteristic seems the probable result to predict tire performance. Practically, the contact patch happens by the rolling tire. To understand the patch characteristic, the contact patch between the rolling tire and pavement was studied. The 3D finite element model of solid tire which pressed on three different surfaces was developed. The experimental footprint on the flat surface was carried out to validate the finite element model. The contact patch of solid tire tread on the drum surface was investigated to discuss the effect of supporting floor under various testing method. The stress distribution in the solid tire model is the exceptional criteria to clarify the contact patch on the road. The developed models will be used to design the tire tread and pavement in the future work.

Keywords: Solid tire, Finite element method, Ride Contact patch, Pavement, Tread

1. INTRODUCTION

The solid tire has an excellent performance for supporting the heavy load. To develop solid tire performance, the tire testing is carried out to provide the physical behavior of tire. The tire stiffness testing is used to study the tire characteristic under the compression load which compose of the vertical stiffness and contact patch. Liang et al., [1] had been used the tire static loaded machine and Tekscan (tire pressure measurement system) to studied the footprint geometry. The footprint shape was described in order to build the relationship between the footprints and tread wear. Nowadays, the engineering design technology has been employed popularly to develop the tire performance. The Computer Aided Design (CAD) and Computer Aided Engineering (CAE) can be used to develop the solid tire. The performance testing by the stiffness tester is the compressing on flat surface which performed on solid tires to create benchmark for validation of the solid tire deformation models [2]. Alkan V. et al. [3, 4] had been investigated the static tire enveloping characteristic by experimental setting and 3D finite element model. The finite element method had been used to design tires popularly. The vertical stiffness of the rolling pneumatic tire was studied on a flat surface. To develop the tire safety and effective driving action, the carcass stiffness was studied [5]. The pneumatic tire was compressed on flat surface in laboratory. The carcass stiffness was carried out from experiment to validate the finite element model. Subsequently, the finite element model which can provide the gradient of contact stress was used to study the effect of carcass stiffness. Practically, the tire is used in the rolling state. The drum testing method is ideal for rolling tire testing in laboratory [6]. Then, the drum testing method which mimics the tire rolling on flat road was widely used to investigate the mechanical behavior of rolling tire. Phromjan J. and Suvanjumrat C. [7] had been carried out the drum testing method with a drum diameter of 1.7 m to study the vibration behavior of solid tire and pneumatic tire. The rolling velocity and compression load on tire was controlled. They found that the contact force on the solid tire was more than on the pneumatic tire of 2.6 times. Wei C. and Olatunsun O.A. [8] were studied the effect of different height obstacle on the pneumatic tire traversing behavior by the finite element method. The drum testing method with a drum diameter of 2.44 m was performed in order to examine the transient dynamic responses of a pneumatic tire rolling over road obstacles and to validate the finite element model of pneumatic tire. Moreover, the drum testing method was modeled in 3D finite element model to develop the accurate simulation of pneumatic tire rolling over cleat by the transient dynamic model [9]. The transient dynamic response was studied in time and frequency domain. The tire rolling speed gave the remarkable influence while the change of the tire inflation pressure only produced the remarkable variation in vertical dynamic force. Both flat and curvature surfaces were used to support tires under the performance testing without proofing its effect. Consequently, the effect of curvature of drum on tire/road contact is interesting.

In this research, the 3D finite element model of solid tire was developed to study the contact patch characteristic by the compression on three tendentious difference pavements.

2. THE TIRE TESTING METHOD

The 6.00-9 inch solid tire was interesting to study in this research. The characteristics of solid tire are described in Table 1. According to the tire standards, the tire testing was set to characterize the tire performance. For example, the tire stiffness testing was performed in order to achieve the tire deformation, tire stiffness and tire-pavement contact patch by steel flat surface. On the other hand, the drum testing method which was performed by cylindrical steel surface provided the tire rolling characteristic. The curvature of steel drum surface might be effects to the rolling solid tire which was provided the deformable behavior as like as the tire testing on flat surface.

Table 1 The characteristic of solid tire

Size (inch)	Rim Size (inch)	Tire Dimension (mm)		Weight (kg)
		Width	Outside Diameter	
6.00-9	4.00E-9	145	523	27

2.1 The Tire Stiffness Testing

The tire stiffness testing has been performed by mounting an interested solid tire on axle of the tire stiffness tester EKTRON TEK model: PL-2003 of Research and Development Center for Thai Rubber Industry (RDCTRI) as shown in Fig.1. The stiffness characteristic of solid tire was measured by loading the solid tire on measurement table which had a pressure measurement film. In order to investigate the contact patch, the solid tire was pressed by three different loads which were comprised of 400, 800 and 1200 kg, respectively. Fig. 2 shows the contact patch on pressure measurement film which illustrates Contact Area (CA) and Footprint Area (FA). The FA was calculated by a×b while the contact area was presented in red color. Moreover, the contact

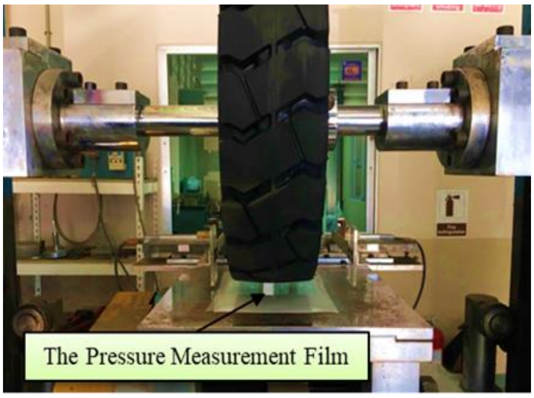


Fig.1 The tire stiffness testing.

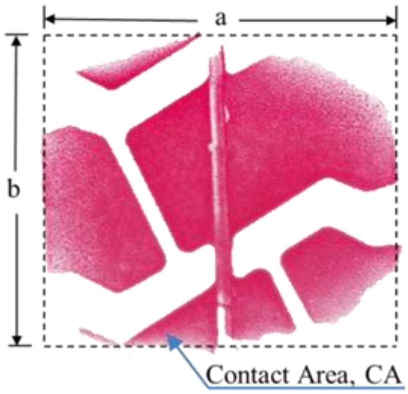


Fig.2 The contact patch on pressure measurement film.

pressure distribution on pressure measurement film was presented by color intensity of the CA. The vertical force and deformation were measured by a load cell and position transducer while the measurement table was driven by hydraulic motor to lift and press the stationary solid tire.

2.2 The Drum Testing Method

The mechanical behavior of rolling tire was investigated by mimicking rotation state of the solid tire. The drum testing method is an ideal testing in the laboratory. It is exclude the various factors such as road surface and vehicle system which are not the effect of the rolling tire. The drum testing method has been performed by mounting an interested solid tire on a mounting arm as shown in Fig.3. The steel drum was driven by hydraulic motor and then the solid tire was move to press on the rolling steel drum. The solid tire would be pulled to roll at the same velocity with the rolling steel drum by using the friction which happened between the contact areas of drum and solid tire. This testing method could obtain the rolling resistant result but could not achieve the FA and CA as same as the previous testing method.

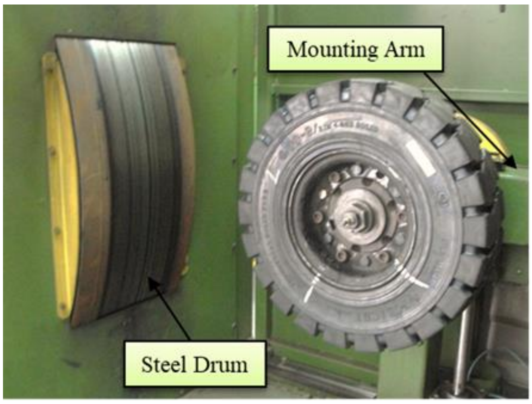


Fig.3 The drum testing method.

3. FINITE ELEMENT METHOD

The finite element analysis (FEA) of the solid tire testing was governed by Eq. 1.

$$m\ddot{u}_i + c\dot{u}_i + ku_i = F_i \quad (1)$$

where u_i is the time-dependent displacement field, c is the damping coefficient, m is mass, F_i is the total force.

The Eq. (1) can be transformed into the form of system total work which balanced the work per unit element as shown in Eq. (2) [10]. Hence, V and s is the element's volume and element's surface, respectively.

$$\begin{aligned}&\int \{\delta u\}^T \{f_i\} dV + \int \{\delta u\}^T \{\Phi\} ds + \sum_{i=1}^{n} \{\delta u\}_i^T \{p\}_i \\ &= \int \left(\{\delta u\}^T \rho \{\ddot{u}\} + \{\delta u\}^T c \{\dot{u}\} + \{\delta \varepsilon\}^T \{\sigma\} \right) dV\end{aligned} \quad (2)$$

where f_i is body force, Φ is surface force, p is determined force, ρ is mass density, ε is strain, σ is stress and n is the number of nodes.

The solution of transient FEA can obtain by the Housbolt method. The general form of the single-step Housbolt is written in Eq. (3) and Eq. (4) [11].

$$\dot{u}_{n+1} = \dot{u}_n + \gamma \Delta t \ddot{u}_n + \gamma_1 \Delta t \ddot{u}_{n+1} \quad (3)$$

$$u_{n+1} = u_n + \Delta t \dot{u}_n + \beta \Delta t^2 \ddot{u}_n + \beta_1 \Delta t^2 \ddot{u}_{n+1} \quad (4)$$

where β_i is the constant and γ_i is the defined parameter.

In case of large strain, the hybrid formulation is effective for the analysis of rubberlike material [12]. The FEA of the solid tire testing was governed by the following equations which the strain energy density per unit volume, ${}_0^t\bar{U}$ is defined in Eq. (5).

$$d\,{}_0^t\bar{U} = {}_0^t\bar{S} d\,{}_0^t\varepsilon_{ij} \quad (5)$$

where $d\,{}_0^t\bar{U}$ and ${}_0^t\bar{S}$ are incremental potential energy and Piola-Kirchhoff stress which computed only from the displace field.

The integral form of total Lagrangian formulation is shown in Eq. (6).

$$\int_{V_0} {}_0^t S_{ij} \delta\, {}_0\varepsilon_{ij} dV_0 = R \quad (6)$$

The general form of principle of virtual work which written in the total Lagrangian formulation is given in Eq. (7)

$$\delta \left(\int_{V_0} {}_0^t U dV_0 \right) = R \quad (7)$$

where ${}_0^t U$ is the incremental potential which can be modified to include the effect of interpolated pressure by adding to the term of the displacement based total element pressure.

3.1 Material Properties

The solid tire which is studied in this research is comprised of the three rubber layers and 4 steel wires (Fig.4). The rubber layers were built by different formula of rubber compounds. The internal layer (M058) was hardest, the middle (M047) and the tread layer were softer, respectively. The material property of each rubber layer of solid tire was obtained by the tensile testing according to ASTM D412 standard. The stress-strain curve from the tensile testing was fitted by linear regression method. The Ogden hyperelastic constitutive model (Eq.8) which is the strain-energy density function was the most suitable to represent the solid tire deformation behavior in all rubber layers [13]. The values in Table 2 are the constant of Ogden constitutive model of three rubber layers. The steel wire model was specified with elastic modulus and Poisson's ratio of 200 GPa and 0.3, respectively.

$$U = \sum_{i=1}^{n} \frac{\mu_i}{\alpha_i} (\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3) + 4.5K(J^{1/3} - 1)^2 \quad (8)$$

and $\bar{\lambda}_i = J^{-1/3} \lambda_i$, $J = \lambda_1 \lambda_2 \lambda_3$

where λ_i is the deviatoric principle stretches, J is the Jacobean determinant, K is the initial bulk modulus, and μ_i, α_i is constant.

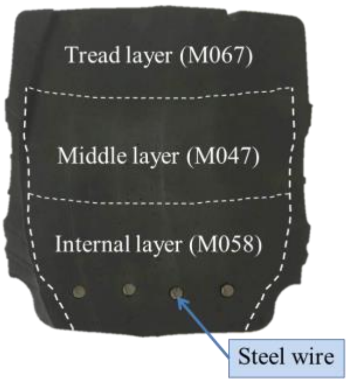


Fig.4 The cross section of solid tire.

Table 2 The constant of Ogden constitutive model.

Rubber layer	μ_1	μ_2	α_1	α_2	K
M067	1.075	154.616	2.927	1.14e-7	7,866.61
M047	0.362	510.855	3.233	0.0056	10,078
M058	3,615.31	2,915.36	0.0028	0.0024	42,449

3.2 Solid Tire Finite Element Model

The solid tire model was created in three dimensions using data from the 3D scanner (Artec 3D, Eva) and Computer-Aided Design (CAD) software. The solid tire model was meshed by hexahedral elements. Consequently, the internal, middle, tread layer and steel wires are created using 16,623, 8,448, 14,366 and 7,040 elements, respectively (Fig.5). The element of steel wire, internal, middle and inner tread layer are connected together with conjunct node while the outer tread layer is connected with the inner tread by glue contact condition as presented in different color as shown in Fig. 6.

3.2.1 The finite element model of tire stiffness testing

The finite element model of solid tire which was described in above section was compressed on a rigid flat plate according to the physical tire stiffness testing. Fig.7 shows the boundary conditions of FE solid tire testing model which the RBE2 elements were defined to link the axis of solid tire model as the steel wheel. The fixed boundary condition was assigned on wheel fixed point as same as the solid tire mounting on the axis of the stiffness tester. The contact boundary condition between the solid tire model and rigid flat plate was specified with 0.8 of static friction coefficient. The vertical loads were assigned on a rigid flat plate to lift and press the solid tire model. Subsequently, the solid tire model was compressed by three different loads which were 400, 800 and 1,200 kg, respectively.

3.2.2 The finite element model of drum testing method

The cylindrical steel drum was created using the curvature rigid element with a diameter of 1.7 m according to the size of the drum testing machine, KAYTON; model: DTM-350PC of RDCTRI. It provided the diameter ratio of 3.25 between the diameter of drum and tire. First, the vertical load was assigned on a rigid drum to move and press the solid tire model by three different loads, 400, 800 and 1,200 kg. Next, the rigid drum was rotated with a constant velocity of 20 km/h. After that, the solid model was pulled by the rolling drum with the dynamic friction coefficient of 0.5 which referred to the principle of drum testing machine. The implicit dynamic transient with single-step Houbolt was used to operate the rolling solid tire finite element model. The constants for analysis were 1.5 and -0.5 for γ_1 and γ , respectively. Fig.8 presents the boundary condition of rolling solid tire on steel drum to study the effect of curvature surface on contact patch by finite element method (FEM). MSC. Marc software which was installed in a personal computer with a Core-i7 processor and 8 GB RAM memory had been used to process finite element method of solid tire testing.

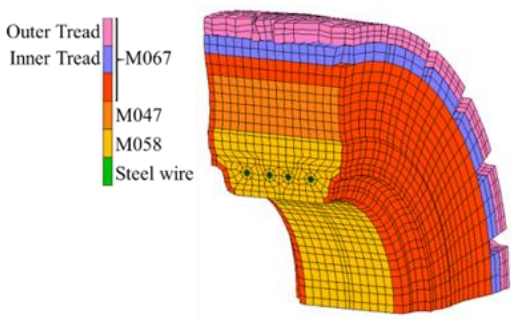


Fig.5 The finite element model of solid tire.

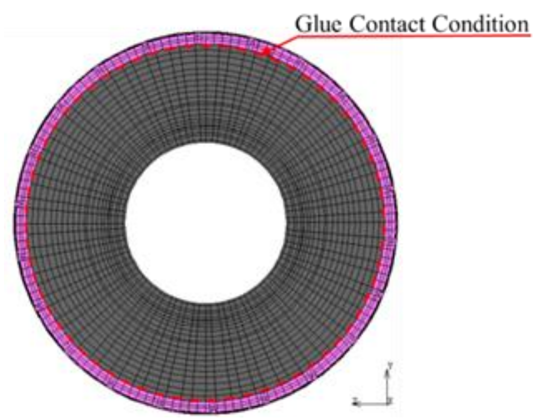


Fig.6 The contact condition of solid tire model.

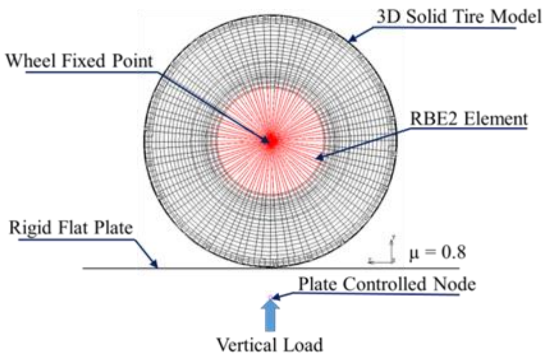


Fig.7 The boundary condition of compressed solid tire finite element model.

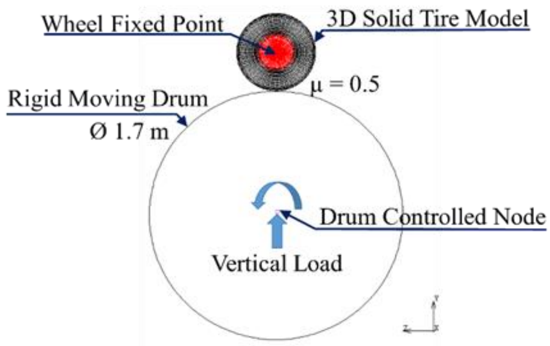


Fig.8 The boundary condition of rolling solid tire finite element model.

4. RESULTS AND DISCUSSIONS

The simulation results of the compression on solid tire (size 6.00-9 inch) by the rigid flat plate were compared with the stiffness testing experiment for the validation. The contact patch of compressed solid tire on the rigid flat plate model found to be in good agreement with the experimental results under the compression loads of 400, 800 and 1,200 kg. It is shown in Table 3. The contact patches of all studying conditions were observed at the same tread pattern position with experiment.

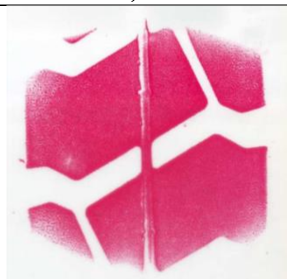
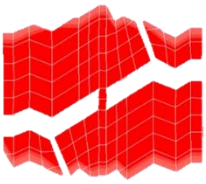
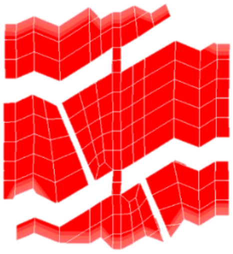
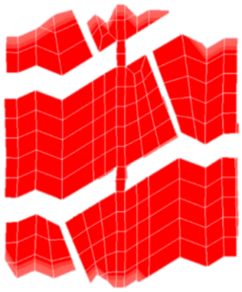
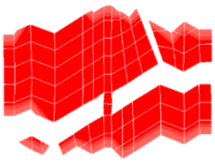
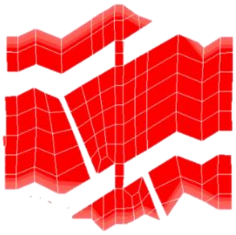
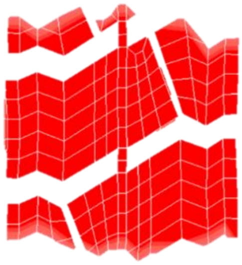
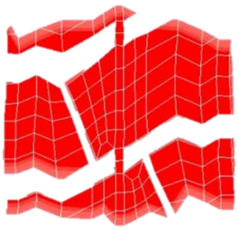
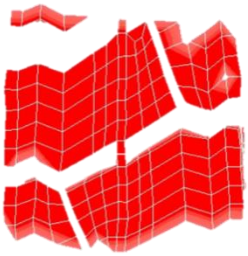
The solid tire deformations of simulation and experiment were compared. The vertical deformations increase by the increase of compression loads as shown by the vertical deformation vs. load graphs in Fig.9. The stationary drum testing model yielded the vertical deformation in good agreement with the flat plate testing. The rolling drum testing model was under estimate when compared with the experimental flat plate testing.

The CA of experiment and simulation was investigated. The comparison graphs in Fig. 10 also indicated that the footprint area of solid tire on measurement table under various compression loads by experiment is smaller than footprint area of compressed solid tire model on rigid flat plate and drum. It was the color contour of the simulation results could not distributed as same as the experimental results.

The maximum stress which happens on the tire tread can illustrate by FEM as shown in Fig. 11. The maximum normal stress happened at the contact area of the solid tire model to the pavements. At the same time, the concentrate stress also happened between glue contact area of inner and outer tread. This phenomenon affected to the poor distribution of contact patch. The better stress distribution of compressed solid tire model on rigid flat plate provided the lower vertical deformation and maximum normal stress than stationary drum because of the smooth curvature of cylindrical drum. The maximum normal stress which happened on solid tire under rolling drum was higher than the rigid flat plate. It was explained that the acting forces caused the maximum stress happening in solid tire came from other direction. The tangent force happened on the solid tire by the rolling drum caused of the additional stress. Fig. 12 shows the comparison graphs of maximum stress between the flat plate and the curvature rolling drum. There was good illustration of the rolling effect of contact surface on tire tread.

The contact patch was affected by drum pulling and then some of solid tire elements were deformed extremely. However, the contact coefficients (CA/FA) which represent the adhesion and wear behavior of solid tire were similar. Fig. 13 shows the comparison graphs of the contact coefficients by various testing methods. The average contact coefficient of experiment of solid tire stiffness testing, finite element model of solid tire stiffness testing, finite element model of loaded drum and finite element model of rotated drum were 0.70, 0.70, 0.67 and 0.68, respectively. The error of contact coefficient of solid tire models on the rolling drum surface from the flat plate was less than 2.71%. This results shown that the curvature of drum surface was not affected to the contact patch analysis. It means that the compression on solid tire by flat plate can used to investigate the contact patch characteristics instead the drum testing.

Table 3 The contact patch characteristic of solid tire (size 6.00-9 inch).

Type of Testing		Vertical Load (kg) 400	800	1,200
Stiffness testing	Loaded (EXP)			
	Loaded (FEM)			
Drum testing method	Loaded (FEM)			
	Rotated (FEM)			

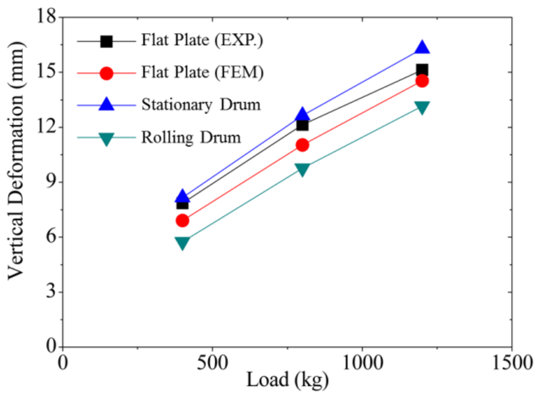


Fig.9 The vertical deformation of solid tire by three different compression loads on three different pavements.

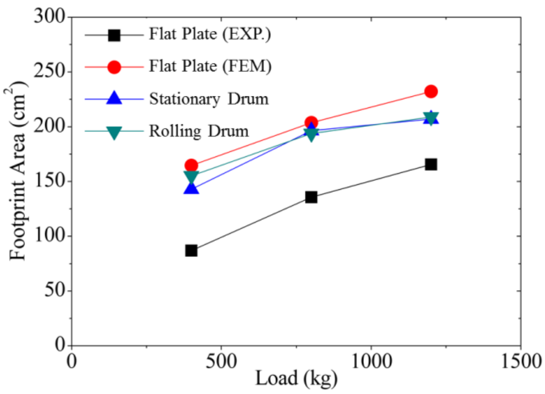


Fig.10 The footprint area of solid tires by three different loads and pavements.

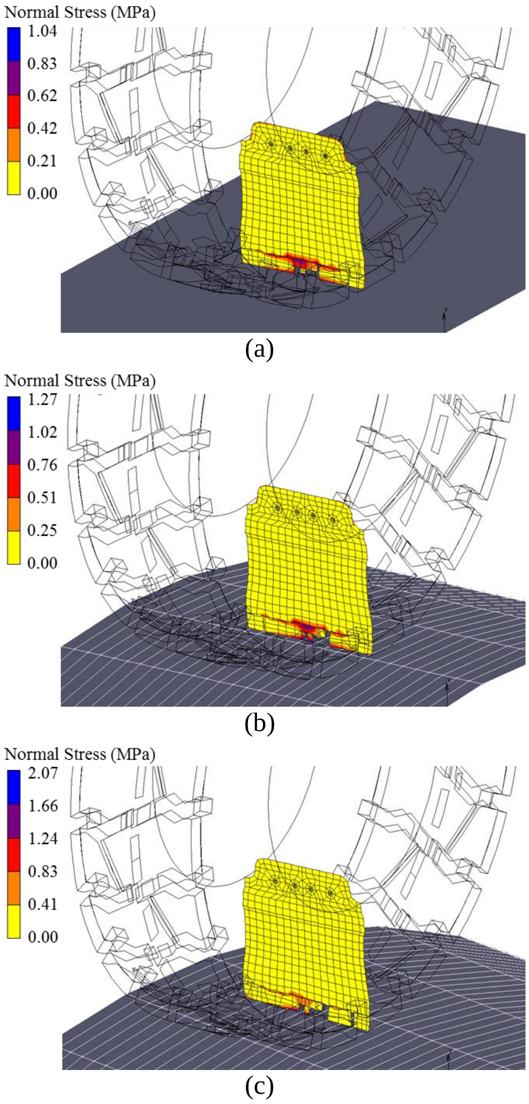


Fig.11 The normal stress on the cross section of solid tire under the compression load of 3,924 N on (a) flat plate, (b) stationary drum and (c) rolling drum.

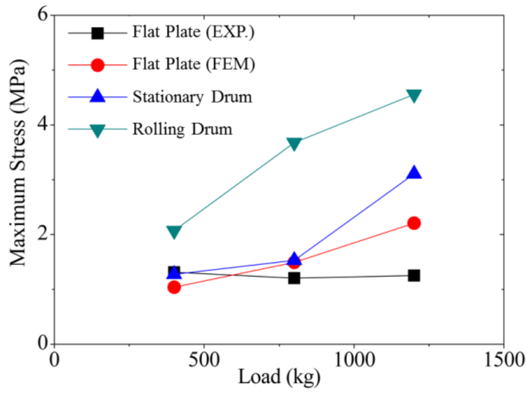


Fig.12 The maximum stress of solid tires by three different loads and pavements.

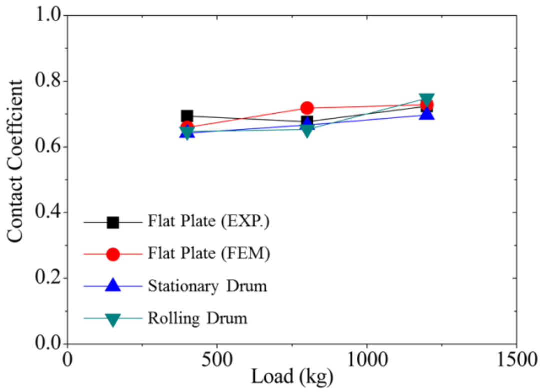


Fig.13 The contact coefficient of solid tires by three different loads and pavements.

5. CONCLUSSION

The contact patch which was used to characterize the solid tire performance was studied by finite element method and experiment. The solid tire model was compressed on three different pavements with various loads which composed of 400, 800 and 1,200 kg, respectively. The contact patch characteristics, vertical deformations and maximum normal stresses were obtained by FEA. The results of FEA on rigid flat plate had a good agreement with the experimental results under the average error was less than 0.52%. The footprint area of solid tire model on drum was less than on rigid flat plate because of the curvature of cylindrical drum. Consequently, the stress distribution of solid tire by the flat plate was more than the drum surface. On the other hand, the contact coefficient of solid tire which was compressed on flat surface and drum were similar. It was indicated that the contact patch characteristic on flat surface by stiffness testing can represent the adhesion and wear behavior of rolling solid tire. The developed models will be used to design the tire tread and pavement in the future work.

6. ACKNOWLEDGMENTS

This research was supported by the Thailand Research Fund (TRF) and V. S. Industry tyres Co., Ltd. Under Research and Researchers for Industries (RRI) Master Scholarship (MSD59I0010).

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