Numerical investigation of the hardness of tire rubber material by indentation method

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Abstract. Hardness is an important mechanical property to express the rubber material's properties. The hardness is closely related to elastic modulus value that is usually obtained by indentation technique. In elastic modulus investigation, the indentation method is more practical to be applied than tensile test method. Analytically, due to the hyper-elastic and non-linear nature of rubber material, theoretical discussion about the rubber properties is difficult to be performed therefore a numerical method is applied. This paper discusses the investigation of the elastic modulus of tire rubber specimens by indentation method numerically and compares to the tensile test method experimentally. Analysis was carried out by Finite Element Analysis (FEA) and two types of vulcanized rubber were analysed. The rubber analysed are often called as a hard compound (vulcanized 1) and soft compound (vulcanized 2) that is commonly used for tires. Indentation modelling was carried out to follow ASTM D 1415-88. Mooney-Rivlin model for Strain Energy Function (SEF) was applied to describe the material’s behaviour. The analysis shows that the results of the indentation method are close to the results of the tensile test method.

1. Introduction

Hardness and modulus of elasticity are very important mechanical properties for technical materials, including rubber [1,2]. The value of hardness is closely related to the modulus of elasticity and can be searched by several methods. Tensile testing is a method commonly used to find the modulus of elasticity, but this method is less practical when compared to the indentation method. The tensile test method requires the preparation of more complicated specimens compared to the indentation test. One of the indentation test standards used for rubber materials is that issued by ASTM D-1415 [3-6].

American Society for Testing and Materials (ASTM) issued the method to estimate the hardness of rubber by using indentation technique. According to this method, formulation to obtain the rubber hardness and the elastic modulus are presented. It depends on the depth of indentation (penetration), ball indenter dimension and indenter force. The elastic modulus of rubber can be directly determined by a tensile test method but it is not simple to conduct such test compared to the indentation test. However, tensile test method is often conducted because of obtaining the mechanical strength in addition to the elastic modulus. On the other side, it is difficult to find accurately the elastic modulus of the elastomer by theoretical formulation due to its complex material behaviour [2,7].
Apart from experimental tests, rubber is very difficult to analyze theoretically, due to the hyperelastic and nonlinear nature of rubber [2]. Therefore, analyzes of rubber behavior are generally carried out numerically using Finite Element Analysis (FEA). But in numerical analysis, it still requires testing data in the form of a tensile test. This is due to the fact that rubber manufacturing technology is still developing with various mechanical properties, especially in compound rubber products. So that in numerical analysis it is still necessary the rubber properties of test results as input data for analysis. The rubber properties for rubber are in the form of several constants known as the Strain Energy Function (SEF). There were some experts who developed methods to determine the value of the SEF, including Mooney-Rivlin, Yeoh, Odgen and others [7,8].

This paper discusses the method of investigating the hardness or elastic modulus of compound rubber commonly used for vehicle tires in the form of hard compounds (vulcanized 1) and soft compounds (vulcanized 2) with numerical methods using ABAQUS software [9]. By using FEA, the elastic modulus investigation is numerically carried out by the indentation method based on ASTM D-1415. The elastic modulus of the numerical method is then compared to the elastic modulus from the tensile test results. By obtaining the elastic modulus value, the rubber hardness can be determined.

2. Material and Method

This study, the elastic modulus investigation is carried out by two methods, the tensile test (experiment) and the indentation (numeric). The rubber material analyzed are vulcanized 1 (hard rubber compound) and vulcanized 2 (soft rubber compound) which are commonly used as tire. The tensile test method was carried out and obtained the stress-strain relationship, tensile strength and elongation at break. From the stress-strain relationship resulted, the elastic modulus value can be obtained directly. The indentation method uses numerical simulation that requires input data in the form of rubber material properties, namely Strain Energy Function (SEF). The SEF data is constructed from the stress-strain relationship that was obtained from the tensile test results. This research uses Mooney-Rivlin method for finding the SEF from stress-strain data.

![Indentation model schematically (a) Original model (b) 2D axisymmetric section for finite element model](image)

Figure 1. Indentation model schematically (a) Original model (b) 2D axisymmetric section for finite element model

Figure 1(a) shows the original model of a schematic indentation based on ASTM D-1415. In numerical simulations, specimens are modeled with cylinders of 20 mm diameter and 10 mm height. A rigid ball with 2.5 mm diameter applies at the center of the top rubber surface. However, for simplifying analysis, two dimensions axisymmetric section is used for FE Model as depicted in Fig. 1(b). Boundary conditions of the indentation system are depicted schematically in this figure as well. It can be seen that the base of cylinder specimen is in fixed condition, meanwhile, the cylinder wall can freely move in vertical direction. The finite element analysis of the present work was performed using a commercial
finite element software package, ABAQUS 6.11 [9]. The FE results presented are deformation (including depth of indentation) and von Mises stress.

The FE simulation for indentation method based on the ASTM D-1415 standard, term and procedure for finding the elastic modulus and hardness are given as follows [6]:

1. The indenter is a rigid ball with a standard diameter of 2.5 mm
2. The minor and major forces in testing use values of 0.3 N and 5.7 N
3. Apply the minor force on the indenter ball down vertically to the specimen for 5 seconds
4. Add the major force to the indenter and hold for 30 seconds.
5. At the end of the indentation process (after 35 seconds), note the final depth of indentation.
6. With the final depth (displacement) data, it can find the elastic modulus.

Using given formulation issued by ASTM, the elastic modulus of the rubber can be obtained that involve the final depth of indentation and force applied. For validation, the elastic modulus obtained from indentation is compared to the elastic modulus from the tensile test results. Based on ASTM converter, the elastic modulus resulted can be converted to the hardness term in IRHD (International Rubber Hardness Degree).

3. Result and Discussion

Figure 2 and Fig. 3 depict the von Mises stress distribution and deformation for vulcanized 1 and vulcanized 2 respectively. The von Mises stress and deformation are presented in three dimensions section due to total applied force (minor and major indenter force) at the end of indentation process. The stress legend and isobaric line are presented as well in these figures. It shows that the maximum stress of vulcanized 1 (3.540 MPa) is higher than vulcanized 2 (3.416 MPa). The stress distribution is seen as a symmetric pattern and the maximum stress is located below the ball indenter tip.

![Figure 2](image1.png)

(a) Stress legend (b) 3D section stress (c) Isobaric line of stress

![Figure 3](image2.png)

(a) Stress legend (b) 3D section stress (c) Isobaric line of stress
From indentation processes, it can be obtained the relationship between indenter force and depth of indentation (displacement) as depicted in Fig. 4(a). In the same displacement, it can be seen that vulcanized 1 requires higher indenter force than vulcanized 2, therefore the vulcanized 1 is stiffer than vulcanized 2. In general, material that have high stiffness also have high hardness and elastic modulus. Referring to ASTM D-1415, the elastic modulus due to indentation is obtained with Eq. (1) as following:

\[
E = \frac{F}{1.9R^2(\delta/R)^{1.35}}
\]

Where \( E \) is the elastic modulus (MPa), \( F \) is indenter force (N), \( R \) is indenter tip radius (mm) and \( \delta \) is the depth of penetration or displacement (mm). The force \( F \) is the minor and major indenter force that apply during 35 second, meanwhile the depth of penetration \( \delta \) is obtained after the indentation process is finish. From the simulation, the final depth of indentation for both rubber material are around 0.36 mm as seen at Fig. 5(b). It can be taken, that the elastic modulus from indentation method for vulcanized 1 and vulcanized 2 are 10.59 MPa and 10.41 MPa respectively.

![Figure 4. Indentation result (a) Indenter force vs displacement (b) Elastic modulus vs displacement](image)

The elastic modulus can be directly obtained from the tensile test data. The tensile test data is presented at Table 1. It can be seen that the vulcanized 1 has lower tensile strength and extension ratio at break than vulcanized 2. It is defined that the extension ratio is final length divided by initial length of the test specimen.

| Rubber Material | Tensile Strength (MPa) | Extension ratio at break (%) | Testing Method |
|-----------------|------------------------|-----------------------------|----------------|
| Vulcanized 1    | 16.1                   | 480.1                       | SNI ISO 37: 2015 (IDT - 2011) |
| Vulcanized 2    | 18.0                   | 507.1                       | SNI ISO 37: 2015 (IDT - 2011) |
From the stress-strain relationship from the tensile test result, the elastic modulus is given as:

$$E = \frac{\sigma}{\varepsilon} = \frac{\sigma}{\lambda - 1}$$  \hspace{1cm} (2)

Where $\sigma$ is true stress, $\varepsilon$ is strain and $\lambda$ is extension ratio of the test specimen. It has been noted that in rubber tensile test, the extension ratio is $\lambda = 1 + \varepsilon$ and true stress is defined as $\sigma = \sigma_e \lambda$ which $\sigma_e$ is the engineering stress. From the tensile test, the relationship between engineering stress versus extension ratio is given at Fig. 5(a). Therefore, by using the above equation, the elastic modulus versus extension ratio can be plotted at Fig. 5(b). The graphic is started from extension ratio of 1.25. However, ISO 7743:2011 recommended that the really elastic modulus is at extension ratio around 1.3. It can be obtained that the elastic modulus for vulcanized 1 and vulcanized 2 are 10.63 MPa and 10.46 MPa respectively.

**Figure 5.** Tensile test result (a) engineering stress vs extensio ratio (b) Elastic modulus vs extensio ratio

From the above results, the hardness of the rubber can be obtained using ASTM D-1415 data. The relationship between hardness and elastic modulus of the rubber is presented in Fig. 6. The hardness rubber is stated as IRHD (International Rubber Hardness Degree). It can be seen that the hardness of both of vulcanized rubber is around 79.7.

**Figure 6.** The diagram between hardness and elastic modulus of the rubber

| Rubber Material | Methods to obtain elastic modulus | Error (%) |
|-----------------|-----------------------------------|-----------|
|                 | Indentation | Tensile Test |
| Vulcanized 1    | 10.59       | 10.63 | 0.35 |
| Vulcanized 2    | 10.41       | 10.46 | 0.45 |
Summary of the above results are presented in Table 2. It can be seen that the indentation method results are close to the tensile test with small error, around 0.4%. It can be concluded that both methods are validly applied for obtaining the elastic modulus with vulcanized 1 is slightly higher than vulcanized 2. Meanwhile, the rubber hardness of both rubber type is around 79.7 IRHD.

4. Conclusion
This paper discusses the investigation of the elastic modulus of tire rubber specimens by indentation method numerically and compares to the tensile test method experimentally. Analysis was carried out by Finite Element Analysis (FEA) and two types vulcanized analysed are often called as hard compound and soft compound that are commonly used for tires. Indentation modelling was carried out to follow the standards determined by ASTM D 1415-88. The analysis shows that the results of the indentation method are close to the tensile test method with small error, around 0.4%. The elastic modulus with vulcanized 1 (hard compound) is slightly higher than vulcanized 2. Meanwhile, the rubber hardness of both rubber type is around 79.7 IRHD.

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