

# Comparative behavior of local hyperelastic low-grade rubbers for low-cost base isolation

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**Abstract.** As the second largest rubber producer in the world, Indonesia has a very potential opportunity to support the development of rubber base isolation. Various grades of rubber are produced by the local rubber manufacturers starting from the low to high grade rubbers. In the study, the local rubbers were also compared to the rubbers from another developing country, e.g. India. The laboratory test results used to develop the suitable constitutive model for hyperelastic material and then compared to the hyperelastic model of Shahzad et al. Several tests on the local low-grade rubbers have been conducted, namely the uniaxial tensile, planar shear, and equibiaxial tensile tests. From the tests, it can be concluded the behavior of the local low-grade rubber can be fitted with the Ogden model different from the characteristic of rubber tested by Shahzad et al. which was fitted with the Yeoh model.

## 1 Introduction

Base isolation is claimed to be the most effective device in reducing earthquake loads on buildings and other structures [1,2]. The basic principle of base isolation is to extend the period of the building so that the earthquake force entering the structural members can be reduced significantly. The use of base isolation in the world of civil engineering is not new [3,4]. Since the 1980s, base isolation has been widely used as a seismic device for buildings in high earthquake areas in many developed countries [5]. Lately, the development of base isolation in developing countries is also quite rapid [6,7]. For this reason, it is necessary to study the grade of rubbers available in the developing countries. As it describes above that rubber is a hyperelastic material that can extend the period of building where this material can experience a large strain and has very high nonlinear properties in the stress-strain relationship curve [8].

However, the application of base isolation for public housing has not been extensively explored and developed due to the economic consideration, particularly for low-cost public housing. This is because most people in Indonesia live in the public houses and not in the public multi-story apartments. Thus, it is deemed urgent to come up with low-cost base isolation with various low-grade local rubbers. As the second largest rubber producer in the world, Indonesia has a very potential opportunity to support the development of rubber base

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isolation. Various grades of rubber are produced by the local rubber manufacturers starting from the low to high grade rubbers. The low-grade rubbers also sometimes involve the use of recycled rubber and mixed with the natural one. The lower the grade, the higher portion of the recycled rubber used in combination with the natural one.

Most rubber materials have a variety of behaviors according to their basic rubber-forming materials. The common behavior in rubber is that rubber which has relatively low stiffness will experience a small strain, and a relatively high rubber stiffness will have a strain value that reaches a certain value [9]. For this reason, it is necessary to study the properties of various low-grade rubbers available in the developing countries such as Indonesia. In the study, the rubbers were selected from the low-grade rubbers available in Indonesia. These local rubbers were also compared with those from another developing country, e.g. India. There are several constitutive models applicable for hyperelastic material to evaluate the selected local low-grade rubbers such as Yeoh, Ogden, Mooney-Rivlin, Arruda-Boyce, and Neo-Hookean models.

The laboratory test results from the selected local low-grade rubber samples were used to develop the suitable constitutive model of hyperelastic material and then compared to the hyperelastic model recommended by Shahzad et al. [10]. Uniaxial tests were carried out to estimate the behavior of selected local low-grade rubbers. From the tests, it can be concluded the stress-strain curves of local low-grade rubbers can be fitted by curves generated from the Ogden model different from the characteristics of the rubber tested by Shahzad et al. which was fitted with the Yeoh model.

## **2 Hyperelastic material tests of local low-grade rubbers**

Prior to testing, the rubber samples were prepared by the rubber manufacturer. The raw materials of rubbers called compounds were designed and composed by the rubber manufacturer to provide certain target hardness when they become ready-to-use rubber, i.e. 35–40 durometer scale. The compounds were then vulcanized under high temperature and pressure to obtain specific design hardness of rubber. The mechanical properties of various types of rubbers are very unique particularly for local low-grade rubbers. The local low-grade rubbers in Indonesia also has particularly different properties. To obtain these properties, several laboratory tests needs to be carried out before they can be used as the basic rubber material for base isolation.

Three sets of rubber samples were fabricated to accommodate the deviation of the manufacturing production process of the rubber samples. Each set of rubber samples were labeled as INA-A, INA-B, and INA-C. Uniaxial tests were then carried out to investigate the characteristics of the local low-grade rubbers.

## **3 Hyperelastic models for local low-grade rubbers**

Hyperelastic models of elastomeric rubber can be determined by several deformation models available, such as Yeoh, Mooney-Rivlin, Neo-Hookean, Ogden, and Arruda-Boyce models [10].

### **1.1 Yeoh model**

Yeoh suggested the reduced polynomial model. The strain energy density of Yeoh model is the second order of Neo Hookean model. The Yeoh model is given by the following equation [11, 12]:

$$W = \sum_{i=1}^3 C_{10} (\bar{I}_1 - 3)^i + \sum_{i=1}^3 \frac{1}{D_i} (J_{el} - 1)^{2i} \quad (1)$$

## 1.2 Mooney-Rivlin model

Mooney-Rivlin model is a complete polynomial model for expansive strain in elongation and shear deformation. The strain energy function of the Mooney-Rivlin model can be resolved as follows [13, 14]:

$$W = C_{10} (\bar{I}_1 - 3) + C_{01} (\bar{I}_2 - 3) + \frac{1}{D_1} (J_{el} - 1)^2 \quad (2)$$

where  $C_{10} = \frac{\mu_0}{2}$  is an initial shear modulus, and  $D$  is a constant.

## 1.3 Neo-Hookean model

Neo Hookean model can be simply derived from Mooney-Rivlin model formula. In Neo Hookean model,  $C_{01} = 0$ , thus, the formula becomes [15]:

$$W = C_{10} (\bar{I}_1 - 3) \quad (3)$$

## 1.4 Ogden model

Ogden proposed some extent different with others. Stress-strain curve of Ogden model is computed based on the strain energy function of stretch ratio and derived form of two strain invariants  $I_1$  and  $I_2$ . The model formula can be commonly given below [16]:

$$W = \sum_{i=1}^N \frac{2\mu_i}{\alpha_i^2} (\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3) + \sum_{i=1}^N \frac{1}{D_i} (J_{el} - 1)^{2i} \quad (4)$$

where:  $\lambda_1^2 + \lambda_2^2 + \lambda_3^2 = 1$ ;  $I_1$  and  $I_2$  are the strain energy functions of Ogden model.

## 1.5 Arruda-Boyce model

Strain energy function of Arruda-Boyce model represents the hyperelastic rubber material as follows [17]:

$$W = \mu_0 \sum_{i=1}^5 \frac{C_i}{\lambda_m^{2i-2}} (I_i - 3) + \frac{1}{D} \left[ \frac{J_{el}^2 - 1}{2} - \ln(J_{el}) \right] \quad (5)$$

where  $C$  is a constant, and  $\lambda_m$  is the locking stretch ratio.

## 4 Curve fitting and results

The hyperelastic rubber constitutive model constants of nonlinear elastic properties were fitted to experimental characterization data. The experimental characterization data was a precondition to several constitutive stress-strain behaviors of hyperelastic material such as rubbers particularly local low-grade rubbers selected in the study and then compared with those studied by Shahzad et al. [10]. By curve fitting the experimental data with the

available constitutive models for hyperelastic materials (local low-grade rubbers), the predicted constants for each constitutive model can be obtained. The values of constants obtained are listed in Table 1.

The rubber tested by Shahzad et al. [10] can be accurately fitted using all of the model which can be concluded that the characteristics and properties is different with those of the local low-grade rubber in Indonesia.

**Table 1.** Comparison of coefficients of various hyperelastic models for local low-grade and Shahzad's rubbers (IND).

Model		INA-A	INA-B	INA-C	IND	Unit
		Constant	Constant	Constant	Constant	
Arruda-Boyce	$\mu$	0.383854	0.29621	0.09395	0.4283	MPa
	$\mu_0$	0.383854	0.30668	0.14088	0.4462	MPa
	$\lambda_m$	2369.145	4.23256	1.45762	3.9142	MPa
	$D$	-	-	-	1.71E-03	MPa
Yeoh	$C_{10}$	0.2019470	0.15226	0.05334	0.2019	MPa
	$C_{20}$	-4.07E-03	1.219E-03	0.01999	4.43E-05	MPa
	$C_{30}$	3.33E-04	-	-	1.29E-04	MPa
	$D_1$	-	-	-	2.18E-03	MPa
	$D_2$	-	-	-	8.68E-05	MPa
	$D_3$	-	-	-	-1.79E-05	MPa
Ogden	$\mu_1$	3.823290	0.287341	0.14936	0.4451	MPa
	$\alpha_1$	4.25347	2.39603	3.98308	-0.2241	MPa
	$D_1$	-	-	-	1.824E-03	MPa
Mooney-Rivlin	$C_{10}$	0.15877	0.1671	-	0.339	MPa
	$C_{01}$	0.02944	-3.88E-04	-	-3.37E-04	MPa
	$D_1$	-	-	-	1.58E-03	MPa
Neo-Hookean	$C_{10}$	0.19192	0.16011	0.09643	0.2587	MPa
	$D_1$	-	-	-	1.58E-03	MPa

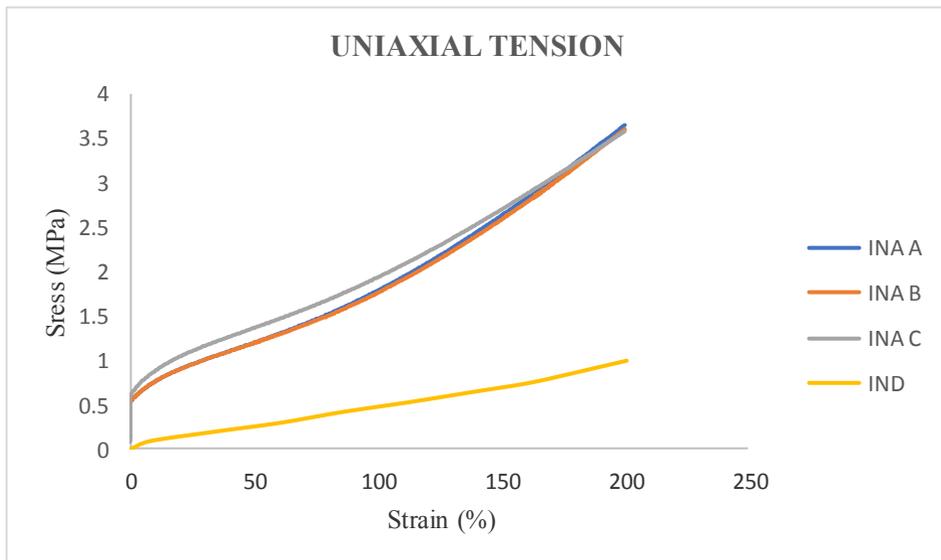
#### 4.1 Limitation of hyperelastic material models

From the study, it can be concluded that the advantages and disadvantages of several hyperelastic material models used in curve fitting or predicting the local low-grade and Shahzad's rubber characteristics and properties are given in Table 2. Even Indonesian rubber cannot be fitted all of the models, the behavior tested from simple tension were better than Shahzad et al. [10] rubber.

**Table 2.** Advantages and disadvantages of several hyperelastic material models.

Constitutive model	Advantages	Disadvantages
<b>Arruda-Boyce</b>	Elongation limited to the numerical cases	Instabilities limited stiffness
<b>Yeoh</b>	- Higher order ( $N > 2$ ) to capture other models, easy fitted with other behavior. Easy to match experimental data points at small and large strain values under 200% strain.	-
<b>Ogden</b>	Good fit and more accurate when it performs to planar shear test.	Big data perform (it needs much more Eigen values to perform this test.
<b>Mooney-Rivlin</b>	Good fit to a single state of biaxial extension.	Caution when fitting possibility of losing physical meaning in other states of stresses.
<b>Neo-Hookean</b>	Acceptable at low strain	Higher order model is required.

#### 4.2 Behavior of hyperelastic material models for local low-grade rubbers



**Fig. 1.** Comparison of curve-fitting results of hyperelastic material models for local low-grade and Shahzad's rubbers

The most fitted hyperelastic model (Ogden model) for the three sets of local low-grade rubber samples (INA-A, INA-B, and INA-C) under uniaxial tests shown in Figure 1 are compared to those studied by Shahzad et al. (IND). The comparisons describe that for all the laboratory tests carried out (uniaxial tensile tests) the local low-grade rubbers (INA-A, INA-B, and INA-C) have higher grade than those tested by Shahzad et al. (IND). Thus, it

can be concluded that the local low-grade rubbers have a very promising future to be used as an alternative for the development of low-cost base isolation system for public housing in Indonesia, particularly those located in the high-risk seismic regions.

## 5 Conclusions

In the paper, the experimental data obtained from laboratory tests, were used to find the most fitted available hyperelastic models and the corresponding coefficients of strain energy functions for local low-grade rubbers. The behavior of the local low-grade rubber can be well predicted by the Ogden hyperelastic model, whereas the Shahzad's rubber is better fitted with the Yeoh model. The comparisons describe that for all the laboratory tests carried out (uniaxial tensile tests) the local low-grade rubbers (INA-A, INA-B, and INA-C) have higher grade than those tested by Shahzad et al. (IND). Thus, it can be concluded that the local low-grade rubbers have a very promising future to be used as an alternative for the development of low-cost base isolation system for public housing in Indonesia, particularly those located in the high-risk seismic regions.

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