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Tensile Properties of Silicone Rubber via. Experimental and Analytical Method Adapting Hyperelastic Constitutive Models

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Abstract: Generally, silicone rubber has the ability to stretch and elongate at a very large deformation. Due to its behaviour, silicone rubber can be classified as hyperelastic material or rubber-like material. However, there is little research done to study the mechanical characteristic of this rubber-like material. Thus, this study aims to investigate the mechanical properties of the silicone rubber via experimental and analytical methods by adapting hyperelastic constitutive models which are Neo-Hookean and Mooney-Rivlin Models. Moreover, in order to determine its mechanical properties, uniaxial tensile test was performed to obtain stress, σ-stretch, λ relations. The specimens were prepared according to ASTM D412 standard. The experimental data were then employed in the hyperelastic constitutive models to obtain the silicone rubber's material constants, C; the hyperelastic constitutive models were then analysed using analytical methods to be compared with the experimental method. It was found that Neo-Hookean and Mooney-Rivlin Models were incapable to best fit the tensile properties (stress, σ-stretch, λ curve) from the experimental method. Therefore, it can be concluded that both hyperelastic models which are Neo-Hookean and Mooney-Rivlin Models are unable to describe the tensile of the silicone rubber whereas another hyperelastic constitutive models can be employed to successfully describe the tensile properties of the silicone rubber and to obtain accurately its material constants.

Key words: Silicone rubber, Neo-Hookean, Mooney-Rivlin, hyperelastic material, tensile properties, deformation

INTRODUCTION

Hyperelastic is a term for a material that has the ability to stretch and elongate at a very large deformation. The hyperelastic materials are also known as rubber-like materials. Skin is also categorized as hyperelastic material as its behaviour is still not well understood (Manan *et al*., 2012, 2013) and one of the most common rubber-like material known is silicone rubber. Silicone elastomers can also be categorized as thermoset as some of their properties are quite similar as it can degrade at a very high temperature (depending on the type of the material), requires hardener in order to achieve complete curing process and they are unable to return to their original state once curing process had completed.

In recent years, silicone rubber has gain attention in mechanical sensors (Nunes, 2011), bio-medical applications (Nunes, 2011; Meunier *et al*., 2008; Sadrnezhaad *et al*., 2009; Iacob *et al*., 2014) and also in pad printing process due to its high elongation and flexibility, high mechanical strength, long term service life and good temperature and humidity tolerance (Iacob *et al*., 2014; Korochkina *et al*., 2008). Silicone rubber too exhibits excellent dielectric properties as it is also being used for electrical applications (Nunes, 2011; Namitha *et al*., 2013). With a molecular backbone of silicon-oxygen atoms, the main contributor to give the silicone rubber its unique properties is due to the organic groups attached to the silicon atoms. Due to these excellent properties in silicone rubber, it is mostly employed in medical applications for its excellent water repellence properties and good bio-compatibility (Meunier *et al*., 2008).

Furthermore, due to its high deformation and elongation rate, its behaviour has been discovered using hyperelastic constitutive models in obtaining its material constants. Using Ogden Model, a study by Zhou *et al*. (2010) has conducted tensile loading on pig skin under different temperatures and loading rates to model the hyperelastic properties of the skin. Yeoh and Lopez-Pamies Models were also being applied by Benevides and Nunes (2015) to obtain the material constant of the neat silicone rubber. Silicone rubber has also been investigated using simple shear test and the material constants are obtained through Mooney-Rivlin hyperelastic constitutive model (Nunes, 2011).

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Therefore, this study aims to investigates the tensile properties of the silicone rubber using hyperelastic constitutive models to demonstrate the non-linear behaviour of this rubber-like material. This study emphasizes in obtaining and demonstrating the tensile properties of silicone rubber using Neo-Hookean and Mooney-Rivlin Models while introducing new findings through different types of silicone rubber which has not yet been studied by others.

The Neo-Hookean Model is known to be the simplest model which is extended from the Hooke's Law (Noor and Mahmud, 2015). Its strain energy density function, W is modelled as (Eq. 1):

$$W = C_1\,(\bar{I}_1 - 3) \tag{1}$$

While Mooney-Rivlin's strain energy density function is described as (Eq. 2):

$$W = C_1\,(\bar{I}_1 - 3) + C_2(\bar{I}_2 - 3) \tag{2}$$

Where:

C_1 and C_2 = The material constants

$\bar{I}_1$ = The first invariant of the Cauchy-Green deformation tensor

$\bar{I}_2$ = The second invariant of the Cauchy-Green deformation tensor

MATERIALS AND METHODS

Material preparation: In this study, the selected silicone rubber is Silicone Ecoflex 00-30 platinum cure which is supplied by Castmech Technologies Sdn Bhd, Malaysia. The product consists of two parts; Part A and B which are to be mixed together by 1:1 ratio in order to cure.

Specimen fabrication: Using ASTM D412 standard for rubber, a mould (Fig. 1) made of aluminium was used to obtain a dumb bell shape specimen for tensile test. The silicone mixture was mixed thoroughly and poured into the dumb bell cavity and let cure for about 4 h.

Tensile testing: In order to determine the tensile properties of the pure silicone rubber, destructive tensile test based on ASTM D412 was conducted. An Instron Universal Testing Machine 100 kN was used with speed rate of 500 mm/min, gauge length of 33 mm, gauge thickness of 3 mm and gauge width of 6 mm (Fig. 2), the test was conducted until reaching its failure state.

Ten specimens were prepared and the test was performed in Strength of Materials Laboratory, Faculty of Mechanical Engineering, Universiti Teknologi MARA. Figure 3 shows the tensile test of the pure silicone rubber was carried out and its schematic behaviour when tensile load has been exerted on it (Fig. 4).

Fig. 1: Aluminum mould

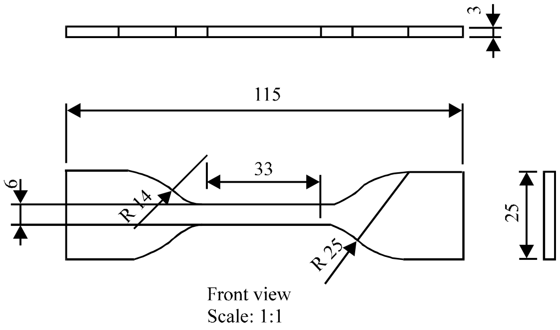

Fig. 2: Actual dimension based on ASTM D412 testing standard

Fig. 3: Tensile test while in progress

As stress, σ-strain, ε data was acquired from the tensile test, the stretch, λ can be computed through Eq. 3. Thus, stress, σ-stretch, λ relations obtained is denoted as experimental results:

$$\lambda = 1+\varepsilon \tag{3}$$

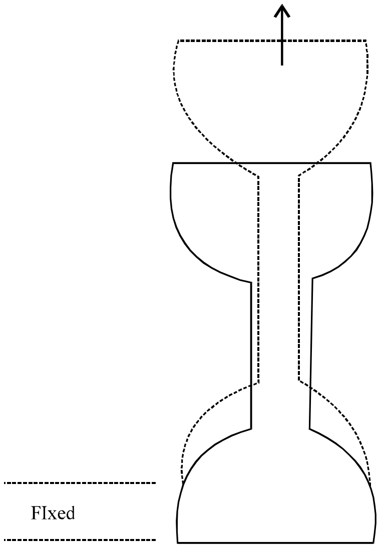

Fig. 4: Schematic diagram of dumb bell specimen when exposed to uniaxial tensile test

Quantifying material constants through hyperelastic constitutive models: The material constants are required to study the material's behaviour and it can be obtained through employing hyperelastic constitutive model. Considering silicone rubber as isotropic, hyperelastic and incompressible material, two equations based on Neo-Hookean Models (Eq. 4) and Mooney-Rivlin Models (Eq. 5) are employed:

$$\sigma_E = 2C_1\left(\lambda - \frac{1}{\lambda^2}\right) \tag{4}$$

$$\sigma_E = \frac{1}{\lambda}\left[\left(2C_1 + \frac{2C_2}{\lambda}\right)\left(\lambda^2 - \frac{1}{\lambda}\right)\right] \tag{5}$$

Both equations are expressed in terms of engineering stress, σ_E and stretch, λ. Thus, to obtain the material constants, C for each model, stress-stretch values obtained from conducted tensile test previously were used.

Analytical method employed in this study was executed in two techniques (Prediction method 1 and 2) and they were executed by reversing the equation of hyperelastic constitutive models to compute new predicted stress:

- Prediction method 1 by obtaining the average value of material constant, C from the experimental data
- Prediction method 2 curve fit technique using regression method by minimizing errors in each data point

RESULTS AND DISCUSSION

Figure 5a shows the ready tensile test specimens according to ASTM D412 testing standard while Fig. 5b shows the state of the specimens when it has already failed.

Figure 6 illustrates stress-stretch relationship of pure silicone rubber where x-axis represents stretch, λ while y-axis represents engineering stress, σ_E. From the graph, it is clearly shown that the silicone rubber specimens exhibit hyperelastic properties as it presents non-linear elastic curves. All specimens show similar behaviour at initial stage where the silicone rubber shows constant stretch value up to 0.15 MPa and continues to behave non-linearly.

By applying Neo-Hookean Model, the behaviour of the curves can be seen as in Fig. 7. In short, Neo-Hookean model shows increasing values of stretch as stress is becoming higher. The model too displays a concave downward curve for both prediction methods which clearly unable to demonstrate the silicone rubber's tensile behaviour. This is proven in other studies by Meunier *et al.* (2008) and Martins *et al.* (2006) which state that Neo-Hookean constitutive model shows poor performance compared to other type hyperelastic constitutive models. Best judgment for Neo-Hookean Model is that the model itself is suitable for materials with less hyperelastic properties as it still present non-linear curve but still unable to demonstrate certain types of hyperelastic material's behaviour.

As for Mooney-Rivlin Model, the results as shown in Fig. 8 shows a very distinct behaviour compared to Neo-Hookean Model. It can be observed that prediction method 1 is obviously incapable to capture the silicone rubber's mechanical tensile properties. Based from the graph, the stresses indicated negative values up to stretch value of 5. This behaviour acknowledges that compressive force has exerted on the silicone rubber while tensile test is in progress. It is an illogical phenomenon when comparing to experimental results, there are no signs of compressive force as there are no negative stress values. Same goes to prediction method 2 where the line mimics prediction method 1's result. However, it can be seen that the line is closely attached to experimental curve as errors between each point has been reduced.

Table 1 shows the material constants obtained through analytical method. It can be observed that prediction method 2 shows lower material constant values compared to prediction method 1 for both Neo-Hookean and Mooney-Rivlin Models. This is because prediction method 2 was employed to reduce percentage errors in each data point to obtain the best fit line that can almost

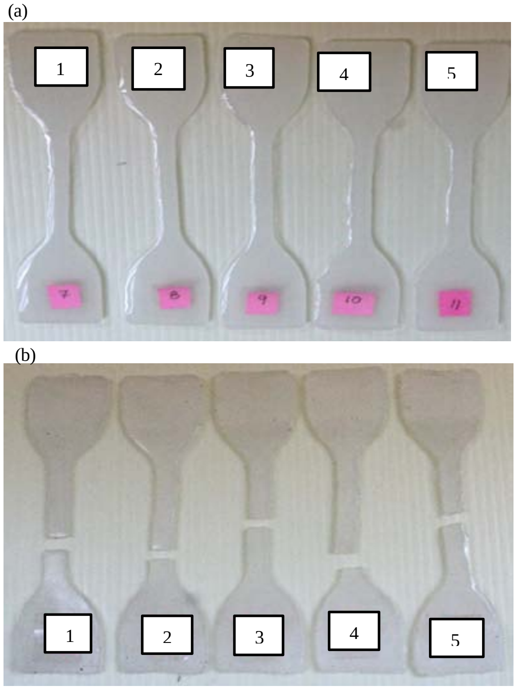

Fig. 5: Pure silicone specimens; a) Before tensile testing and b) After tensile testing

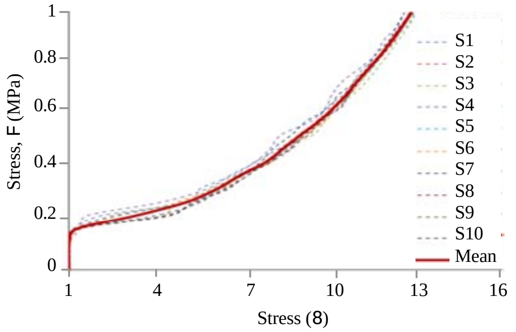

Fig. 6: Graph of stress, σ (MPa) vs. stretch, λ

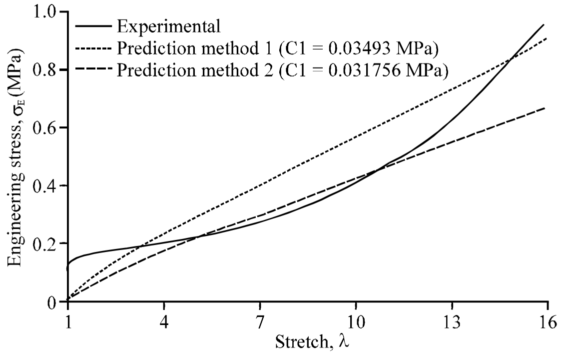

Fig. 7: Comparison of engineering stress, σ (MPa) vs. λ stretch, λ of pure silicone specimen's using Neo-Hookean Model

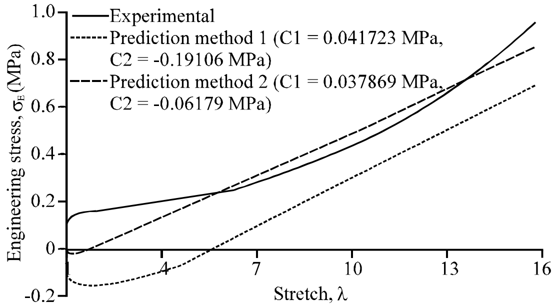

Fig. 8: Comparison of engineering stress, σ(MPa) vs. stretch, λ curves of pure silicone specimens using Mooney-Rivlin Model

Table 1: Material constants for each hyperelastic constitutive models

Models	Prediction method 1 (MPa)	Prediction method 2 (MPa)
Neo-Hookean	$C_1 = 0.0349$	$C_1 = 0.0318$
Mooney-Rivlin	$C_1 = 0.0417$	$C_2 = -0.1911$
	$C_1 = 0.0379$	$C_2 = -0.0618$

imitate the experimental curve. Thus, it can be said that prediction method 2 is much accurate in demonstrating best fit line compared to prediction method 1.

While other study by Shergold *et al*. (2006) reported that the values of material constants obtained for silicone rubber (Sil8800) were C_1 = 1.0 MPa and C_2 = 0.9 MPa which is obviously indicates that this type of silicone rubber is much stiffer than silicone Ecoflex 00-30. His study also states that Mooney-Rivlin Model is unable to capture strain hardening response at high stretch ratio.

As for this study, both models are unable to capture the experimental curve of the silicone rubber, especially, at constant stretch of 1 and the non-linear behaviour graph pattern. Thus, more studies are required to seek a better approach to model this rubber-like material so that, its real behaviour can be well understood and described using hyperelastic constitutive models.

CONCLUSION

Through this study, the tensile properties of silicone rubber Ecoflex 00-30 via. tensile test and hyperelastic constitutive models have been described. It is clearly shown that silicone rubber exhibit hyperelastic properties as it demonstrates non-linear stress, σ-stretch, λ curve. However, to demonstrate this hyperelastic behaviour, Neo-Hookean and Mooney-Rivlin Models which have been adapted in were unable to capture the silicone rubber's tensile properties.

RECOMMENDATIONS

Therefore, this study could contribute to further investigate in depth the silicone rubber's behaviour using other types of hyperelastic constitutive models or best to develop new mathematical modelling in describing the mechanical behaviour of the silicone rubber.

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