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Transient Response Monitoring of a Loaded Rubber Using a Circular-Shaped Optical Fibre Bend Sensor

Ahmad Marzuki[1*], Halimah Primeria Yanuar[1] and Gesit Tali Singgih[1]

[1]*Department of Physics, Sebelas Maret University, Surakarta 57126 Indonesia.*

ABSTRACT

When rubber is subjected to a load, deformation will occur in the form of transverse compression. At a microscopic level, the bond structure in the rubber is transformed from one equilibrium state, corresponding to the unloaded rubber, to another, corresponding to the loaded rubber. As in any transformation process, this takes a certain amount of time called transient response time. This paper presents a simple fibre sensor configuration to experimentally monitor transient response of the loaded rubber bar at a desired point in the rubber at a constant temperature is presented. For this purpose, a coil of polymer optical fibre (POF) with cross-section diameter 10 mm was inserted into a cylindrical rubber rod with cross-section diameter of 3 mm and thickness of 2 cm. Five different loads (2 kg, 2.5 kg, 3 kg, 4 kg and 7 kg) were carefully placed on the cylindrical rubber rod and the resulted change in transmitted light intensity through the fibre sensor was recorded. It was shown that transient response time is load mass dependent which increases with increasing load. Transient response time was also measured as function of depth, it decreases with the increase of the depth, i.e., vertical distance from rubber rod surface. In addition to static loading, transmission curve resulted from dynamic loading was also demonstrated. Based on these results we suggest that smart rubber might be simply formed by sandwiching optical fibre coil into one or more desired points in the rubber bar.

Keywords: Compression Time, Transient Response, Optical Fibre Sensor, Compressive Stress, Silicon Rubber.

1. INTRODUCTION

Rubber is a well-known class of material due to its excellent properties: it is elastic, flexible, strong, waterproof and durable. In view of these properties, rubber has been used in a wide variety of applications, such as home appliances, laboratory, military, automotive, nuclear and aeronautical applications and sensor packaging.

The use of rubber in sensor packaging not only provides protection for the main sensing element but can also adjust the function of the main sensing element. Examples of the use of rubber to adjust the function of the main sensing element are mechanical fibre sensors such as rail pad sensors [1], structural health monitoring [2], pressure mapping [3, 4] and weigh-in-motion (WIM) fibre sensors [5,6,7]. In weigh-in-motion (WIM) fibre sensors, an fibre sensor is embedded or sandwiched within a rubber component. The change in light intensity coming out of the fibre is controlled by the pressure given by the vehicle load, which is in the same principle as that of pressure mapping pad [3, 4]. In this type of sensor, rubber is squeezed to the depths which depends on the magnitude of load. The measuring principle is then similar to that of a spring-based weight measuring system based on Hooke's law. In addition to that, Yu et al. [8] proposed a new sensor for measuring the strength and intensity of respiration by employing the wrinkled pattern of nitride rubber films attached to the different states of pre-stretched elastomer films. This sensor performance is determined by the 3-D structure of the wrinkle and it is controlled by

*Corresponding Author: *amarzuki@mipa.uns.ac.id*

their elastic properties. For such a reason, deep understanding of the mechanical properties of a chosen rubber is very important.

In addition to the existing Dynamical Mechanical Thermal Analyser (DTMA), several suitable methods for characterising the dynamic properties of rubbers have been developed. Romarino et al. [9] proposed a new method for characterizing the dynamic behaviour of rubber compounds within the frequency range of 10 to 1000 Hz using electrodynamic shaker. In their experiment, a cylindrical rubber specimen was positioned between two steel rings in which the upper ring acted as a suspended mass while the lower ring is fixed to the vibrating table. Shoyama and Fujimoto [12] developed a new method to measure viscoelastic properties of rubber at high frequency by applying simple static shear pre-strain and hydrostatic pressure independently. In these two new methods [9, 10] and that used in other literatures [11, 12] data were collected as energy transmissivity, i.e., energy flowing from one end of the sample to the other end. For this purpose, samples are prepared in certain dimension and characterized to picture a property of a sample as a whole system.

There are many conditions under which there may be a need to monitor the dynamic behaviour of a fixed point in the rubber specimen, and for this purpose, the sensor must be integrated into the rubber. Knowing the dynamic behaviour at a particular point inside a rubber is very important since it can help to locate the sensor at the right position inside the rubber. In this paper, we introduce a method to measure the relaxation time of a rubber (silicon) subjected to a static force. Two examples were given: rubber inserted with one fibre coil and that with four coils. Measurements were carried out by detecting light from the fibre sensor inserted into the rubber rod. The goal was to determine the deformation $x(t)$ at the point where the sensor is located at time t, measured with reference to its equilibrium position. This method is very important since it allows us to study the transient respond of the rubber subjected to either static or dynamic loading measured at different point along the vertical axis of the rubber.

2. EXPERIMENTAL

In this experiment, a rod of silicon rubber (RTV 588) with cross section diameter of 3 cm and thickness of 2 cm was used. An optical fibre sensor made of polymer optical fibre (POF) was sandwiched into the rod (Fig. 1). The experiment was carried out by placing five different loads (2 kg, 2.5 kg, 3 kg, 4 kg and 7 kg) onto the rod, causing a decrease in its height. The purpose of this experiment was to record the time required by the rubber to achieve its new equilibrium dimensions as a function of the mass of the load. Fig. 2 is a schematic diagram illustrating the basic principle of the sensor, which was made by forming POF into a coil with a diameter of 10 mm. Light was input at one end and its intensity detected at the other end. As the coil undergoes loading by a force F (Fig. 2), some of the light will be radiated out of the core at the far left- and right-hand sides of the optical fibre (marked in Fig. 2 as X). A larger force (load) will result in a smaller radius for the curvature of the coil at the positions marked X. By applying Snell's law to trace the incident angle of the light reflected back and forth along the core of the fibre, it can be seen that more light will be radiated out of the core as the load increases. As shown in Fig. 2, the incident angles at the far left- and right-hand sides of the fibre decrease as the load (force F) is increased. Since the radius of the coil is already chosen to be less than the critical radius, this decrease in the incident angle results in part of the propagated light being transmitted across the cladding.

Since this component was designed as an intensity-modulated fibre sensor, we must ensure that the change in the intensity of the light emerging from the fibre (I_t) is only caused by the applied force F; any possible variation in I_t due to power instability of the light source and resulting in a variation of light intensity entering the optical fibre sensor (I_0) must be resolved. Fig. 3 is a schematic diagram of the experiment, which was designed with this consideration in mind. Light was shone into one end of the fibre, and was then divided by the optical splitter into two paths: a reference fibre and a modulated fibre. The modulated fibre was connected to the fibre sensor located inside the silicon rubber, and the reference fibre was connected to a fibre attenuator. Before loading, the fibre attenuator was adjusted so that the light intensity detected by photo-detector #1 (I_m) was equal to that detected by photo-detector #2 (I_r). In other words, the transmittance T defined by $T = I_m/I_r$ was set to one. As the rubber rod is loaded, I_m decreases. Since I_r is kept constant (and is taken as a reference), a decrease in I_m means that T will decrease. The transmittance before loading (T_0) and that after loading (T_t) can be related by equation:

$$T_t = T_0 e^{-(\alpha_i + \alpha_b)x} \quad (1)$$

where α_i is the intrinsic loss, α_b is the bending loss and x is the length of the fibre shaped to form a coil. Once the decrease in the light intensity (represented by T) over time is obtained, the compression time, which indicates the time required by a process to undertake a new structural arrangement, can be derived.

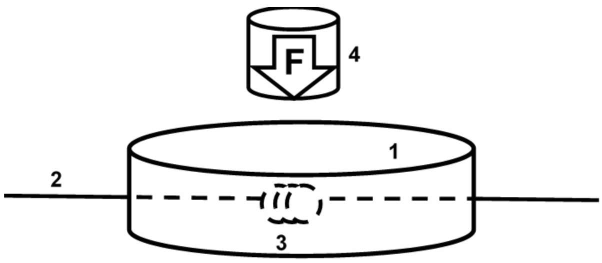

Figure 1. Fibre coil sandwiched rubber subjected to a load F: (1) rubber rod; (2) optical fibre; (3) fibre coil; and (4) load F.

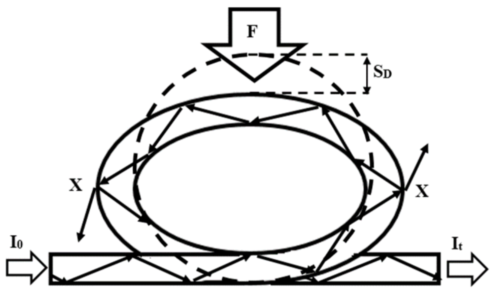

Figure 2. Change in fibre coil cross-section from circular shape (dashed line) to elliptical shape (solid line) as a force F applied vertically from the above such that the vertical diameter of the coil is squeezed to a distance S_D.

Similar arrangement as given in Figure 1 applies if the number of fibre coil inserted into the rubber is more than one. Four two-turns coils of POF, each has a diameter of 5 mm, were vertically stacked with arrangement as given in Fig. 4. Light transmitted through each fibre sensors were simultaneously measured as function of time such that transient response at each desired point can be obtained.

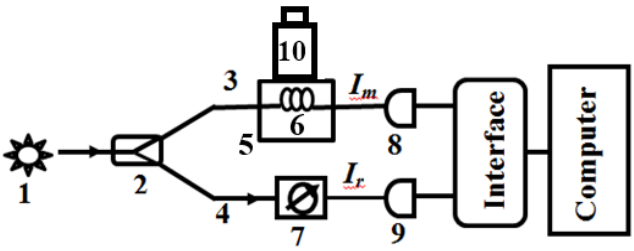

Figure 3. Experimental setup used to measure transient response time. (1) light source, (2) splitter, (3) modulated optical fiber, (4) reference fiber, (5) silicone rubber, (6) fiber sensor, (7) attenuator, (8) photo-detector #1 and (9) photo-detector #2 and (10) load

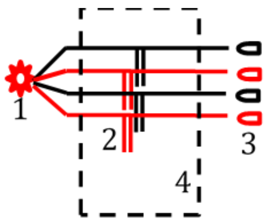

Figure 4. Basic experimental setup for measuring transient response time at four different points inside the rubber: (1) light source, (2) closely arranged fibre coils, (3) light detectors, (4) rubber bar.

3. RESULTS AND DISCUSSION

A sensing mechanism to record the history of deformation of the rubber due to the normal force was made by sandwiching a optical fibre sensor into a silicon rubber component. The optical fibre sensor was designed to work based on bending loss. In the experiment reported in this work, a POF was coiled such that its cross-sectional shape was circular (Fig 3). As the fibre coil is loaded with a weight F (Fig. 3), the cross-section of the fibre changes in shape, from circular (dash line) to elliptical (solid line). The vertical diameter of the circular coil is compressed into a minor axis of the ellipse by a distance S_D. Fig. 5 shows the change in transmittance as the vertical diameter of the coil is compressed by S_D; this corresponds to a weight or force $F = m_i g$, where F is the force, m_i is the load mass, and g is gravitational acceleration. We derive an equation that relates the percentage of light radiated out of the fibre due to bending loss (α_b) as function of the reduction in the diameter S_D [13]:

$$\alpha_b = C_1 \exp\left(-C_2 \frac{r^2 - rS_D + \frac{S_D 2}{4}}{\sqrt{r^2 + rS_D - \frac{S_D{}^2}{4}}}\right) \tag{2}$$

where r is the circular radius and C_1 and C_2 are constants. It can clearly be seen from Eq. 2 that bending loss (α) increases as S_D is increased. Inserting Eq. 2 into Eq. 2 we have:

$$T_t = T_0 \exp\left[-\alpha_i - C_1 \exp\left(-C_2 \frac{r^2 - rS_D + \frac{S_D{}^2}{4}}{\sqrt{r^2 + rS_D - \frac{S_D{}^2}{4}}}\right)\right] \tag{3}$$

From Eq. 3 it can be seen that light transmitted through the fibre sensor decreases as S_D increases. Moreover, since the fibre sensor is embedded in the rubber, and S_D is controlled by the variation in the compression of the rubber, the change in the transmittance of the optical fibre sensor can be related to the change in the rubber's molecular structure. In this regard, the compression of the rubber can be associated with a reduction in intermolecular distance in the same direction as the compressive force.

Fig. 5 shows a comparison of the change in transmittance as different values of mass are loaded onto the rubber rod. All the transmittance curves are similar in shape, showing step decay curves. Before loading, the light transmitted through the optical fibre sensor is set to a value of 100%. As the load is applied, the light transmitted through the fibre drops (decays) nonlinearly, until a constant minimum transmittance is achieved. The magnitude of the drop in transmittance is controlled by the mass of the load, in accordance with Hook's law; the larger the mass of the load, the less light emerges from the optical fibre sensor.

From Fig. 5 it is also clearly seen that the transmitted light (T) falls quickly to a minimum value of transmittance for a given load mass, corresponding to a new equilibrium. The curves connecting the initial equilibrium (point A), corresponding to the unloaded rubber, to the new equilibrium (points $B_{fo\text{-}n}$), corresponding to the loaded rubber, are well fitted using a polynomial of order three with a degree of confidence (R^2) larger than 0.99 (Table 1).

The shape of all the transmittance curves in Fig. 6 is similar to that obtained by Luo et al. [14], showing a sigmoid curve, a typical S-shaped load-deflection curve for loaded rubber. The force used by Luo et al. [14] to create this deformation is represented in Fig. 6 as transmittance. In this respect, a small force corresponds to high value of transmittance. Since the optical fibre sensor inserted into the rubber is in the form of a coil, both tensile and compressive stresses applied to the rubber will result in a change in the shape of the coil, i.e. a change in cross-section from a circular to an elliptical form. Loading the rubber by either elongating or squeezing it will give the same shape for the change in transmittance. These findings can be explained with help of Fig. 2. Since a decrease in transmittance (increase in bending loss) means a reduction in the vertical diameter of the optical fibre coil and therefore a squeezing of the rubber rod in the y-direction, the way in which the transmittance changes over time (t) can illustrate the dynamics of structural compression within the rubber [15,16]. To prevent fibre damage due to excessive pressure, the circular shape of the fibre coil should not be squeezed to a distance S_D which is greater than its radius (see Fig. 2).

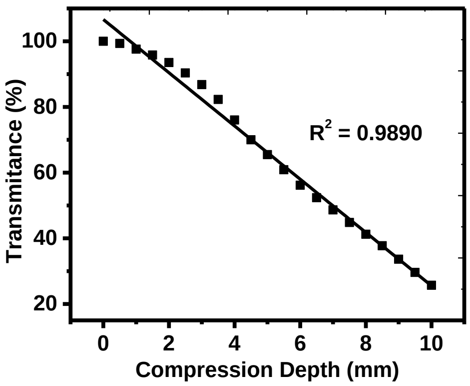

Figure 5. Reduction in the intensity of light emerging from the optical fibre sensor as the rubber rod is compressed by S_D, which is related to the load mass *m.*

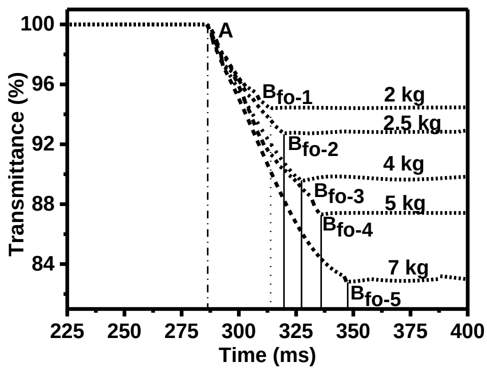

Figure 6. Light transmitted through the fibre sensor inserted into silicon rubber, loaded with different masses (curves were shifted to give the same starting point). Transient response times were measured from point A to $B_{fo\text{-}n}$.

Table 1 Transient response time and regression model describing the transient response of silicon rubber subjected to a load of mass *m*, as shown in Figure 6

Mass of load (kg)	Transient response time (ms)	Line equations (transmittance as a function of time)	R^2
2.0	314.4	$T = -851.6271 + 10.3516t - 0.0362t^2 + 0.00004t^3$	*0.9995*
2.5	319.5	$T = -379.1641 + 5.8885t - 0.0224t^2 + 0.00003t^3$	*0.9953*
4.0	327.9	$T = 769.0403 - 5.4662t + 0.0149t^2 - 0.00001t^3$	*0.9988*
5.0	335.8	$T = 3723.9786 - 34.8512t + 0.1121t^2 - 0.00001t^3$	*0.9952*
7.0	347.6	$T = 2273.2459 - 20.3583t + 0.0638t^2 - 0.00007t^3$	*0.9980*

By representing this molecular structure as an arrangement of balls and springs, and taking the resultant binding force along the y-axis as a single spring force, this result can be well understood using Hooke's law, which can be expressed as:

$$F = -kS_D \tag{4}$$

The change in S_D, and thus the light transmittance, is linearly controlled by the applied normal external force F multiplied by a spring constant k that characterises the unique properties of the rubber. As this normal external force is applied to the silicon rubber rod, an internal intermolecular force arises that opposes the external force. If the external force is small, the internal force may be sufficient to resist the external force, allowing the rubber to assume a new equilibrium. Assuming that the rubber can be represented as a collection of springs, this internal force can be regarded as a strong damping force, and loading a mass onto the rubber can lead to over-damped oscillation. This means that there is no periodic motion, and the amplitude dies away as a modified exponential. In the transmittance curves shown in Fig. 5, this state is shown as a minimum constant transmittance. As can be seen, the deformation of the rubber and the time required to reach its corresponding new equilibrium increase with an increase in the loaded mass (Fig. 7). This finding suggests that the experimental method used in this work can be used to study the dynamical properties of rubber, and is not limited to a determination of the compression time resulting from compression due to loading.

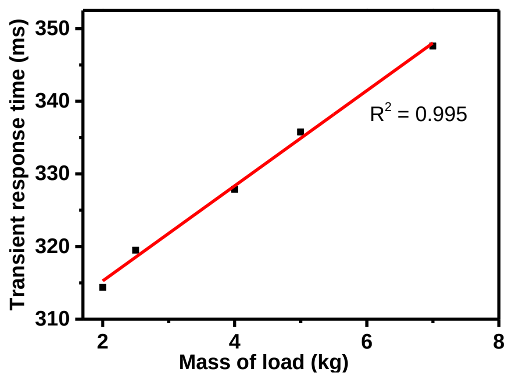

Figure 7. Time required by silicon rubber under loading to relax to a new equilibrium position

Figure 8. Example of a rubber inserted with 4 fibre sensors

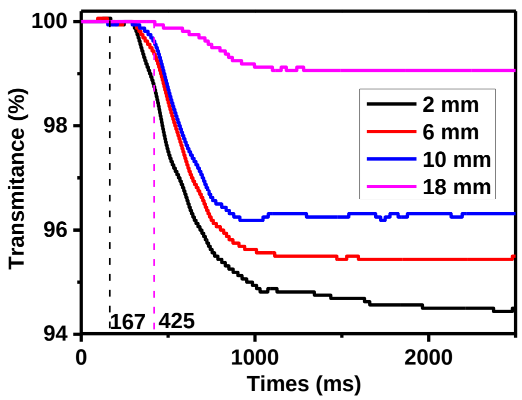

Figure 9. Transient response at different depth (2 mm, 6 mm, 10 mm and 18 mm) as a load of 4 kg was slowly put on the rubber.

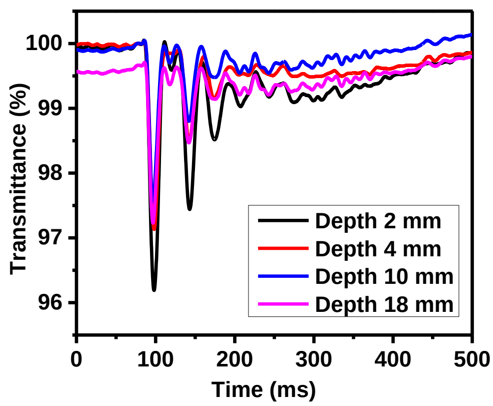

Figure 10. The change in light coming out of the fibre describing stress history as the rubber was subjected to the impact loading of 4 kg.

Similar analysis applies if the number of fibre coil inserted into the rubber bar is more than one (Fig. 8). The different in transmittance and transient response time observed for each fibre as shown in Fig. 9 can describe the dynamic behaviour of the loaded rubber at the fibre coil positions (depth y = 2 mm, 6 mm, 10 mm and 18 mm). Fibre sensor positioned at a shallower point responds the disturbance wave resulted from loading earlier than those at deeper points. As shown, fibre sensor buried at 2 mm starts to respond the propagating disturbance at time t = 167 ms while other three fibre sensors positioned at 4 mm, 10 mm and 18 mm respond that disturbance at time t = 300 mm, 335 mm and 425 mm, respectively.

From the two fibre sensor configurations and results presented above we suggest that the experimental method used in this work can be used to study the dynamical properties of rubber (Fig. 10), and is not limited to a determination of the compression time resulting from compression due to loading. Figure 10 is typical transient response as rubber rod with four fibre sensors was subjected to the impact loading of 4 kg. Referring to Figure 5, result as presented in Figure 10 indicates that more deformation (strong response) occurs at a sallower point than at a deeper point.

4. CONCLUSIONS

We have demonstrated a method for experimentally monitoring the time compression in a rubber rod subjected to various normal loads. In the proposed method, sensing was carried out by inserting a optical fibre sensor into silicon rubber, and measurements were based on the change in intensity of light transmitted through this optical fibre sensor, from a state in which rubber is not loaded to a loaded state. In this method, the light transmitted through the optical fibre sensor can be associated with the deformation in the rubber resulting from loading. Light transmitted through the fibre sensor decrease linearly with the increase of depth compression. Lower transmittance was observed for heavier loading. In addition, transient response time experiment with four fibres sensor were carried out. The result shows that the transient response time decreases with increasing depth. Based on this finding, we suggest that an optical fibre sensor inserted into a rubber, as used in this method, may be used in future work to study the dynamic behaviour of rubber.

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