The study of compression relaxation time of silicon rubber using optical method

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Abstract. When rubber is subjected to a load, deformation will occur. Microscopically, the rubber bond structure is transformed from one equilibrium corresponds to the unloaded rubber to that corresponds to the loaded rubber. As with any other transformation process, this process will take time. This paper experimentally demonstrates the relaxation time dependence on the mass of load observed at a constant temperature. The experiment was carried out by inserting the fiber sensor was into a silicon rubber bar. As the rubber bar was loaded, the intensity of light coming out of the fiber decreases exponentially with time. It is shown that the relaxation time increases with the increase of mass loaded on the fiber. By knowing this, the results of the fiber sensor can be adjusted according to the time-based review of rubber deformation.

1. Introduction
Rubber is a class of material that everybody knows because of its excellent properties: elastic, stretchy, strong, waterproof, and durable. With these properties in mind, rubber has been used for a wide variety of applications such as the use of home appliances, laboratory, military, automotive, nuclear, aerospace, and sensor packaging.

The use of rubber for sensor packaging will provide not only protection to the main sensing element, but also to adjust the function of the main sensing element. The example of the rubber that used to adjust the function of the main sensing element is mechanical fiber sensors such as rail pad sensors [1], structural health monitoring [2], weight measuring system [3,4], and weigh in motion (WIM). In this study, we applied a rubber for weight in motion sensor. In weigh in motion (WIM) fiber sensor, an optical fiber sensor is embedded or sandwiched in a rubber. The measuring principle is then similar to that of spring based weight measuring systems that work based on Hooke’s law. WIM technology is a technology for detecting the weight of a vehicle moving at a certain speed on the road by measuring the wheel axle load of the vehicle while it is running. When there is an emphasis on the WIM sensor, there will be a change in the intensity of the optical signal that is transmitted in the optical fiber. This change in optical signal corresponds to the weight of the load on it. This can be used to detect the weight of a load. Since this object is measured in motion, the relaxation time of the rubber should be as short as possible. This occurrence cause a differences optical signal measurement between movement and un-movement conditions.

In this paper, we present how the relaxation time of the rubber (silicon rubber) depends on the mass of the load. Measurement was carried out by detecting light coming out of the fiber sensor inserting into the rubber bar.
2. Experimental method and working principle
This experiment was carried out using silicon rubber (RTV 588) inserted with the optical fiber sensor made of polymer optical fiber (POF). The optical fiber sensor was designed to work based on bending loss. Figure 1 is a schematic diagram explaining the basic principle of the sensor. POF was coiled onto a cylindrical tube with a diameter of 1.0 cm. The light was launched from one end and detected its intensity from the other end. As the coil is loaded (figure 1), part of the light at the far left and right sides of the fiber will be radiated out of the fiber core. Larger force (load) will result in a smaller radius of coil curvature at X position. Applying Snell’s law to trace the incident angle of light reflected back and forth along with the fiber, it can be seen that more light will be radiated out of the core as the load increases. As shown, the incident angle at the far left and right of the fiber decreases as the load (Force $F$) is increased. Since the radius of the coil is already chosen less than a critical radius, this decrease of the incident angle results in part of the propagated light is transmitted across the fiber clad.

![Figure 1](image1.png)

Figure 1. Working principle of the sensing element used in the experiment.

Figure 2 is a schematic diagram of the experiment. Light is launched from one end of the fiber. Light is then split by the optical splitter into two paths: reference fiber and modulated fiber. Reference fiber is connected to the fiber sensor which is inserted into silicon rubber and the modulated fiber is connected to the fiber attenuator. Before loading, fiber attenuator is adjusted so that light intensity detected by photo-detector 1 ($I_m$) equals to that detected by photo-detector 2 ($I_r$) or the transmittance $T$ defined by $T = I_m/I_r$ is equal to one. As the rubber bar is loaded, $I_m$ decreases. Since $I_r$ is kept constant (taken as a reference), decreasing $I_m$ means $T$ will decrease. Once the decreasing light intensity (represented by $T$) over time is obtained, relaxation or decaying time relating to a process of rubber deformation can be constructed.

![Figure 2](image2.png)

Figure 2. An experimental setup used to measure rubber relaxation time, (1) light source, (2) splitter, (3) modulated fiber, (4) reference fiber, (5) silicone rubber, (6) fiber sensor, (7) attenuator, (8) photo-detector 1 and (9) photo-detector 2.
3. Results and discussion
The sensing mechanism to record the history of rubber deformation due to normal force was made by sandwiching a fiber sensor into silicon rubber. The fiber sensor was designed to work based on bending loss. In an experiment reported in this paper (figure 1), polymer optical fiber (POF) was coiled such that its cross-section shape was circular. As the fiber coil is loaded with a weight $F$ (figure 1), the fiber cross-section changes its shape from circular to elliptical. The vertical diameter of the circular coil is compressed into a minor axis (of the ellipse) by $S_D$. Figure 3 shows the transmittance change as the vertical diameter of the coil is compressed by $S_D$ which corresponds to the weight or force $F = m_i g$ where $F$ is force, $m_i$ is load mass, and $g$ is the gravitational acceleration. We have derived the equation that relates the percentage of light radiated out of the fiber due to bending loss ($\alpha$) as a function of the amount of the diameter reduction $S_D$ [5]:

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

(1)

where $r$ is circular radius and $C_1$ and $C_2$ are constants. It is seen from equation (1) that bending loss ($\alpha$) increases as $S_D$ is increased. In another word, light transmitted through the fiber sensor decreases as $S_D$ increases.

![Figure 3](image1.png)

**Figure 3.** Reduction of light intensity coming out of the fiber sensor as the rubber bar is compressed by $S_D$ which corresponds to the load mass $m$.

![Figure 4](image2.png)

**Figure 4.** Light transmitted through fiber sensor inserted into silicon rubber loaded with different load mass.
Figure 4 shows the comparison of transmittance change as the different values of mass is loaded on the rubber bar. Before loading, light transmitted through a fiber sensor is in a constant maximum value over time. As load is given, light transmitted through the fiber drops exponentially until a constant transmittance is achieved. As schematically explained in figure 1, since a decreasing transmittance (increasing bending loss) means shortening the vertical diameter of the fiber coil, the way the transmittance changes over time can then describes the dynamics of structural relaxation in rubber [6,7].

As a normal external force is applied to the silicon rubber bar, an internal intermolecular force arises that oppose the external force. If the external force is not too great, the internal force may be sufficient to resist the external force and allow the rubber to assume a new equilibrium. Assuming the rubber as a collection of springs, this internal force can be regarded as a strong damping force, loading a mass on 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. The maximum amplitude at which the rubber does not move any more concludes that the rubber is in a new equilibrium. In transmittance curves, as shown in figure 4, this state is shown as a lower constant transmittance. As shown, rubber deformation as well as the time required for the rubber to go to its corresponding new equilibrium increases with the increase of the loaded mass (figure 5). This is easily explained using Hooke’s law that heavier load will result in a larger value of deformation and therefore longer decay time. This finding suggests that the experimental method used to determine the relaxation time as described herein can be used as a tool to select an appropriate rubber used to a base for weight sensor as well as a tool for studying time relaxation in a rubber.

![Figure 5](image.png)

**Figure 5.** Time required by silicon rubber subjected to a load to relax to a new equilibrium position.

4. **Conclusion**

We have demonstrated a method to experimentally monitor time relaxation in rubber subjected to different normal loads. In the proposed method, sensing was carried out by inserting a fiber sensor into a silicon rubber. We have shown the history of light transmitted through this fiber sensor from a state at which rubber is not loaded to that is loaded. In this method, light transmitted through a fiber sensor can be associated with the rubber deformation resulted from loading. From this finding, we have suggested that fiber sensor inserted rubber made in this method might be used for weight sensing as well as the history of rubber deformation.

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