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The Effect of Load and Moving-Speed on Free Rotating Rubber Contact Through Fluorescence Microscopy Observation Technique.

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Abstract. An experimental study was conducted to identify the effect of applied load and moving speed of free rotating rubber specimen contact area on smooth surfaced glass plate. The contact area of rubber specimen and flat surface was observed using fluorescence microscopy by utilizing ultraviolet as an excitation light source and pyranine as a dye substance. The amount of apparent contact area between rubber specimen and flat surface was measured using an image processing software based on Otsu thresholding method. The result illustrates an increasing pattern of trendline due to applied normal load dependency which agreed with Hertz theory. On moving speed influence, the trendline of rubber contact increased at lower speed reaching the highest value at 8 mm/s moving speed and decreased as moving speed increased further.

Keywords: Fluorescence; apparent contact area; rubber; free rotating

1. Introduction

Since decades ago, many scientists have been conducting a number of experiments related to contact mechanics of soft materials due to its significant utilities in many industries [Fowell, et al., 2014] [Fujii, 2008] [Bódai & Goda, 2012] [Nakajima & Takahashi, 2002]. One of them is the research about rubber tire of vehicles. The important role of a tire in the vehicle system can be comprehended as its function in transmitting forces on the vehicle through tire rubber to the road surface in a safe and comfortable manner. Therefore, traction force or grip between tire and road surface becomes one of the most important performance characteristics needed to understand in automotive industry [Liang, et al., 2020]. For example, it helps to understand what range of friction is needed to keep the vehicles safe when breaking or cornering, or how fast the vehicle can be utilized to maintain the vehicle under control. If the frictional characteristics fail to satisfy the required tractional force, then the entire system of the vehicle will be out of control leading to car accident.

In general, the grip performance of rubber tire is affected by both internal factors and external factors. One internal factor is the filler inside the tire, which affects its performance greatly. Thus, enhancing the quality of filler enables the tire to increase its grip performance. This result was reported by Hasan, et al. through their study about the properties of tire rubber by modifying the clay filler of tire [Hasan, et al., 2020].

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Similarly, external factors such as moving speed and loads on the vehicles also have great impact on the vehicle performance. The more weight is loaded on the vehicle, the faster the tire wears down. Faster vehicle run causes the driver loses control easily. Therefore, studying about these two factors is very important in order to maintain the tire lifetime and also for driving safety. Although the importance of tire grip performance is applied on both dry and wet surface conditions, its influence is much more reduced on the wet surfaces. This phenomenon was shown in the report from Micheline corporation (Michelin, 2001). Binshuang et. al. also reported similar result as the adhesion coefficient reduced when the tire run on wet surface, and it reduced further as the water thickness increases (Zheng et. al., 2018). Due to its significant impact on the grip performance of tire, we decided to observe and measure the contact condition of tire rubber in wet surfaces.

Tire grip performance or coefficient of friction is generally calculated based on frictional force as stated in "laws of friction". It was reported that the friction force (F_μ) of elastomer contact is generally produced by two types of forces, adhesion force (F_a) and hysteresis force (F_h), respectively (Tabor, 1960). Thus, frictional force can be expressed as,

$$F_\mu = F_a + F_h \tag{1}$$

However, in rough surface contact like between tire and road surface, the most dominant factor on the friction force is hysteresis force, while the effect of adhesion force is very minimum (Persson, 2001). On the other hand, when the surface of rubber contact is very smooth, then the adhesion force has the biggest contribution on the friction force (Persson & Volokitin, 2006). As current study utilized smooth surface of both rubber-wheel and glass plate, the frictional solely depends on adhesion force. Thus, the coefficient of friction can be expressed as,

$$F_\mu = F_a \tag{2}$$

Maegawa et.al. mentioned in their article that the correlation between kinetic friction force and the contact area of elastomer was linear (Maegawa et al., 2015). Therefore, the frictional force of elastomer can also be measured based on the contact area between rubber tire and mating surface. The coefficient of friction of adhesion force can be expressed as,

$$F_\mu = F_a = \tau A \tag{3}$$

where τ is the shear strength and A is the contact area between elastomer and mating surface. As the shear strength does not change, the only factor affecting the adhesion force is elastomer contact area. It means that the contact area of tire rubber determines the amount of frictional force of the vehicles in a certain manner.

The only way to directly observe the contact condition in situ was by utilizing the visualization method like fluorescence microscopy. Fluorescence microscopy is the best in observing and measuring the contact area of elastomer material. Fluorescence microscopy manages to provide detail information based on the amount of fluorescence dye that exists within the contacting parts. Therefore, the intensity produced in the fluorescence microscopy represents the gap within mating contact. Moreover, differentiating the contact region and non-contact region is becoming easier and more accurate. There are several samples of fluorescence microscopy applications in the field of tribology. For example, Fowell et al. used fluorescence microscopy on elastomeric seal material to measure lubricant film thickness of contact area at several entrainment speed (Fowell et al., 2014). Petrova et al. utilized fluorescence microscopy to visualize solid-to-solid contacts regimes (Petrova et al., 2019). As it is a very sensitive observation method, fluorescence technique is also used more frequently in other fields of studies such as chemical [Ali, et al., 2012], biology (Hötzer, et al., 2012) and medical (Marcu, 2012).

As the contact condition of tire is closely related to the coefficient of friction and the grid performance of tire, a lot of data is required to design and produce better performance of tire. The information about contact condition of tire also can be used to analyze condition of tire wear, to predict the lifetime of tire and for some other purposes. However, the currently existing reports and data are still far from enough to satisfy the needs of data on many circumstances of tire contact conditions. One of them is the contact condition of rubber tire due to the influence of moving speed and applied load in wet surfaces.

Therefore, in order to contribute to providing data for these purposes, this study conducted experiment to investigate how the applied loads and moving speeds affect the contact condition of rubber tire. As a fundamental study, the experiment was carried out as a rubber tire wheel running on the top of flat surface of glass plate under several applied loads and moving speeds. The contact condition of tire and mating surface was observed using ultraviolet-induced fluorescence technique. The moving speed in this study indicates free rotation which is mixed movement of rolling and sliding. The rubber-wheel has the same material as tire rubber of regular vehicles, and the mating surface was smooth glass plate (BK7). During the experiment, the fluorescence liquid made of pyranine-dyed solution was covered on the top of mating surface simulating the condition of wet surfaces.

2. Methods

2.1. Experimental setup

The experiment of measuring the contact area was operated using a smooth surface of cylindrical rubber specimen and smooth surface glass plate. During the test, the glass plate surface was covered by pyranine solution representing wet condition in rainy season. As shown in Figure 1, the rubber specimen was shaped in the form of cylinder with outer diameter, inner diameter and width of 80 mm, 42 mm, and 32 mm, respectively. A gear-patterned aluminum was added to the inner side of rubber specimen with a hole diameter of 16 mm. It helped the rubber specimen to connect to the linear guide for dynamic contact experiment. This dimension is a commonly used rubber size for laboratory scale experiment, which refers to ISO 23233 in LAT 100 (Laboratory Abrasion Tester 100). The diameter of rubber specimen was similar; however, the thickness was twice larger due to supplier's (TOYO TIRE corporation, a tire manufacturer company in Japan) reason. The mating contact was a glass plate branded as BK7 in a rectangular shape with 100 mm width and 5 mm thickness. The rubber specimen was connected to a linear guide device through a shaft with a possibility of normal loading adjustment. The details on flat surface of glass plate and rubber specimen materials are shown in Table 1 and 2.

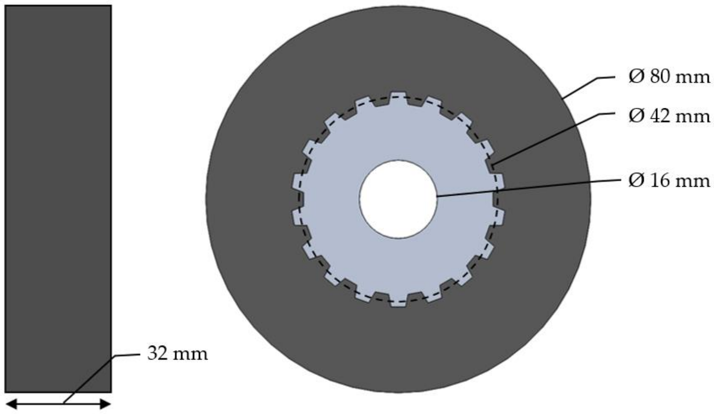

Figure 1. Rubber-wheel dimensions

Table 1. Specification of glass plate

Specimen	BK7
Dimensions, mm	100 x 100 x 5
Density, g/cm^3	2.51
Poisson`s ratio	0.206
Young modulus, MPa	82 x 10^3
Refractive index	1.53627 (365 nm)
Internal transmittance	0.988 (365nm)

Table 2. Specification of rubber-wheel material

Specimen	Tire rubber
Diameter, mm	80
Width, mm	32
Poisson`s ratio	0.49
Young modulus, MPa	2

The observation of rubber specimen contact area was provided by fluorescence microcopy using ultraviolet light as an excitation light source and pyranine compound as a fluorescence dye. The ultraviolet light source was generated by ring-shaped ultraviolet device with 365 nm peak of wavelength. It was situated below the mating surface and above a high-speed camera. Also, a piece of dichroic filter with passing wavelength between 505 nm and 575 nm was placed on the top of camera in order to avoid other lights than the green color fluorescence light for more accurate analysis. This arrangement allowed us to directly observe the contact condition of rubber specimen on flat surface. Finally, the image of rubber-wheel contact area was captured and recorded using a high-speed digital camera HAS-U2 (manufactured by DITECT Ltd. of Japan). The outline of fluorescence microscopy used in the current study is shown in Figure 2.

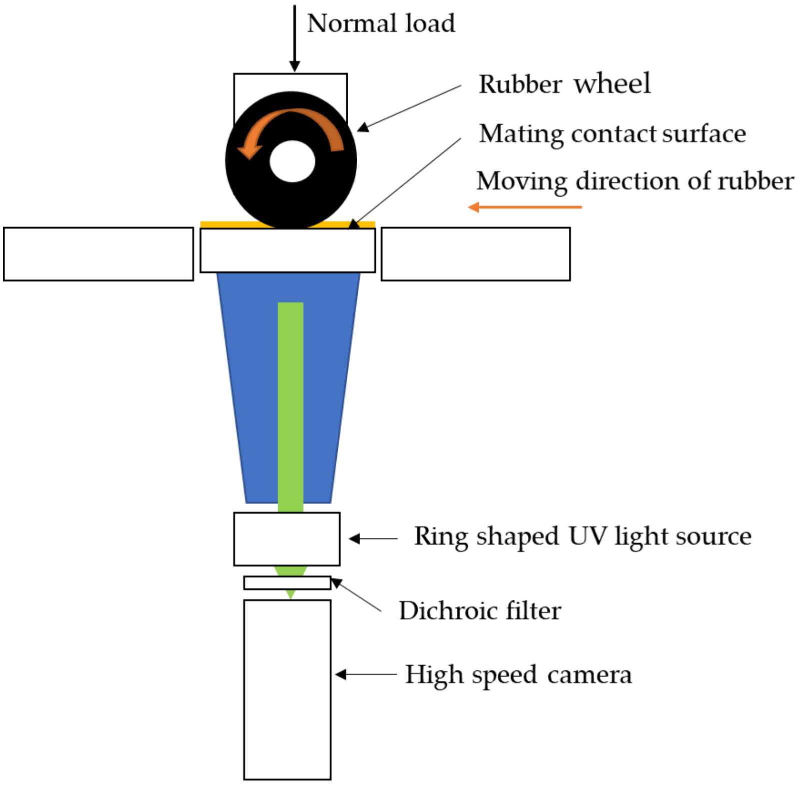

Figure 2. The schematic figure of fluorescence microscopy set-up

The pyranine substance that was used as a fluorescence dye in the microscopy has a chemical composition of $C_{16}H_7Na_3O_{10}S_3$ with 524.39 g/mol molecular weight. Pyranine dye was adopted in this study owing to its advantage of having a wide range stock-shift. It enables the researchers to distinguish the contact and non-contact regions without the interference of excitation light source. The pyranine solution was made by mixing pyranine substance with distilled water according to the desired density (3200 mg/L). In the process of fluorescence, the pyranine solution will absorb the excitation light and then it instantly emits green fluorescence light with a peak wavelength of 513 nm. Additionally, to avoid external factor influences on the fluorescence intensity such as temperature and humidity, the experiment was conducted in a room with identical temperature and humidity of 22.1^{o}C and 54 %, respectively.

2.2. Condition and procedure

The experiment was carried out in stationary (applied load dependency) and dynamic (moving speed dependency) conditions. In the stationary state, the weight was placed on the experiment apparatus ranged from 40.2 N to 157.7 N, in nine selected variations of applied loads. In order to solve the problems of creep deformation that makes the rubber material keep deforming over the pressing time, creep deformation test was conducted. The result shows that the pressing time was similar with the rubber contact on rough surface conducted in the previous experiment which was 300 seconds (Rahman et al., 2020). Consequently, the rubber specimen contact area due to applied load dependency was captured 300 seconds after the rubber specimen bumped to the flat surface. And to ensure that the rubber specimen return to its initial state after the test, the rubber specimen had to wait for about 300 seconds before conducting the next applied load test. As for moving rubber contact, the experiment was carried out with several moving-speeds and applied loads. The moving-speed ranged from 4 mm/s up to 160 mm/s in six variation moving-speed, and three different applied loads of 60.8 N, 80.4 N, and 99 N, respectively. The detailed information about the experimental condition in static and dynamic conditions is shown in Table 3. The moving rubber specimen in the current study was performing free rotation with mixed movement of rolling and sliding. The ratio of rolling and sliding in moving rubber specimen was generated naturally based on the moving speed.

Table 3. Experimental conditions on moving rubber specimen contact

Contact condition	Applied load (N)	Moving speed (mm/s)
Static contact	40.2 – 157.7	0
Dynamic contact	60.8, 80.4, 99	4 - 160

The contact area of rubber specimen was then captured utilizing a high-speed camera. Following that, the image of rubber specimen contact was processed using an image processing software known as Image-J to measure the contact area between rubber specimen and flat surface. In this study, the measured contact area was apparent contact area. And the boundary between apparent contact area and non-contact region was determined based on a series formula developed by Nobuyuki Otsu in 1979, a well-known expert in image segmentation analysis [Otsu, 1979]. This method is known as Otsu thresholding method. The boundary of apparent contact area calculated using Otsu thresholding method was at the intensity of 36. Thus, the intensity of 36 and below was recognized as the apparent contact area, and the intensity above 36 was categorized as non-contact region. Figure 3 shows the flow chart of experimental procedure using fluorescence microscopy to measure the rubber specimen contact area.

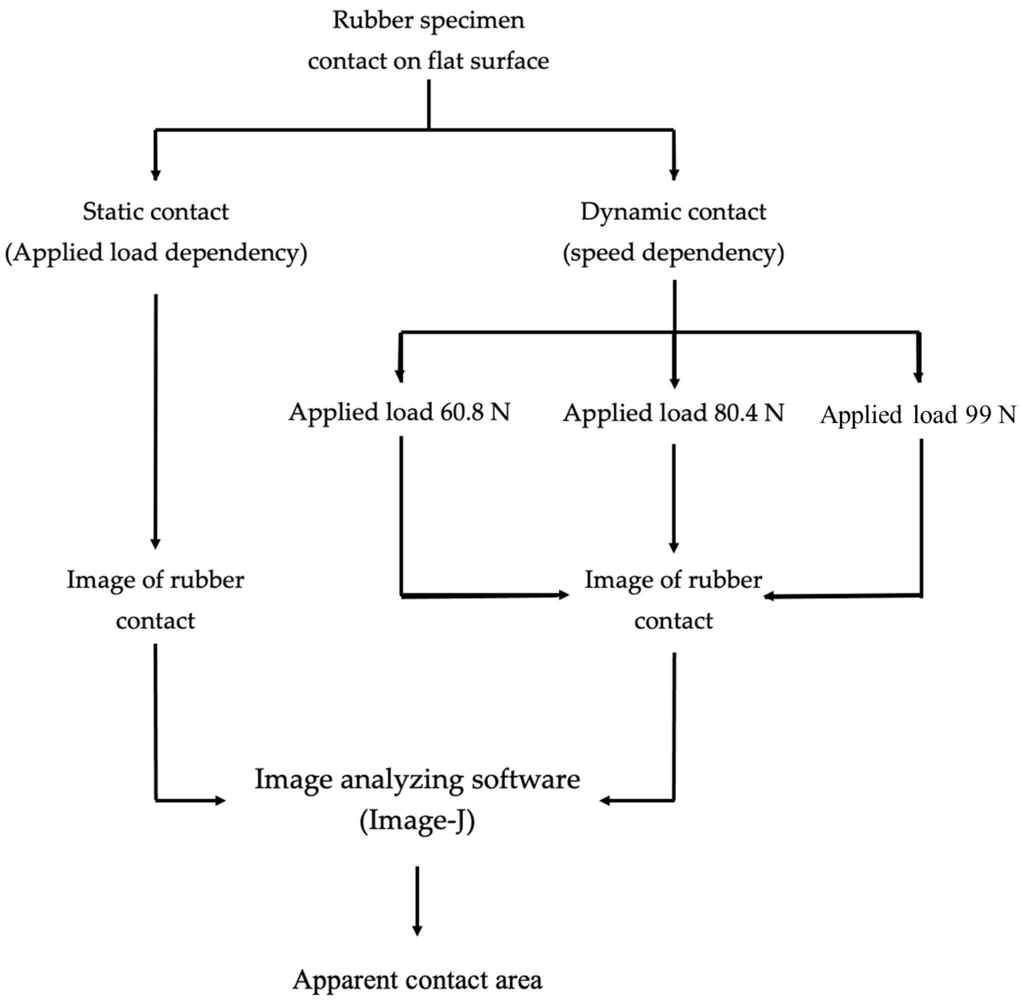

Figure 3. The flow chart of the experiment

3. Results and Discussion

3.1. Applied Load Dependency

As rubber specimen was in contact with flat surface, the main cause of coefficient of friction was the adhesion force between rubber specimen and glass plate. At the same time, the applied load on rubber-wheel widened the range of contact area due to its viscoelasticity. Figure 4 shows the binary image of apparent contact area between rubber-wheel and flat surface for nine selected applied loads. The experiment was executed three times to obtain more accurate data in applied load dependency.

As shown in Figure 4 the apparent contact area between rubber wheel specimen and flat glass plate was wider as the applied load increased, which indicating load influences on rubber wheel specimen contact. The higher load applied on the rubber wheel specimen, the more it deformed and then formed wider contact area. Previously, we had reported load dependency of rubber specimen contact in a conference [Rahman et al., 2018]. However, we could not identify the increasing pattern of the contact area because the number of data was insufficient. Therefore, in the current study we conducted experiment with enough variation of applied loads to obtain more precise information. Figure 5 shows the graph of plotted apparent contact area of rubber wheel specimen based on applied load dependency in log-log axis. The plotted measured apparent contact areas of rubber wheel specimen for every applied load from three times tests was distributed within the range approximately 20 mm^2 on each applied load. Also, the apparent contact area of rubber specimen in graph with log-log axis increased linearly as applied load increased. The log-log axis is usually used by researchers who studies about contact mechanics to describe whether the obtained data is following the theoretical formula in contact mechanic or not. As shown in figure 5, a straight line of trendline was formed. It means that the obtained results agreed with the predicted contact theory of Hertz as the half-width of contact area is proportional to applied load $W^{1/2}$ (Johnson, 1987).

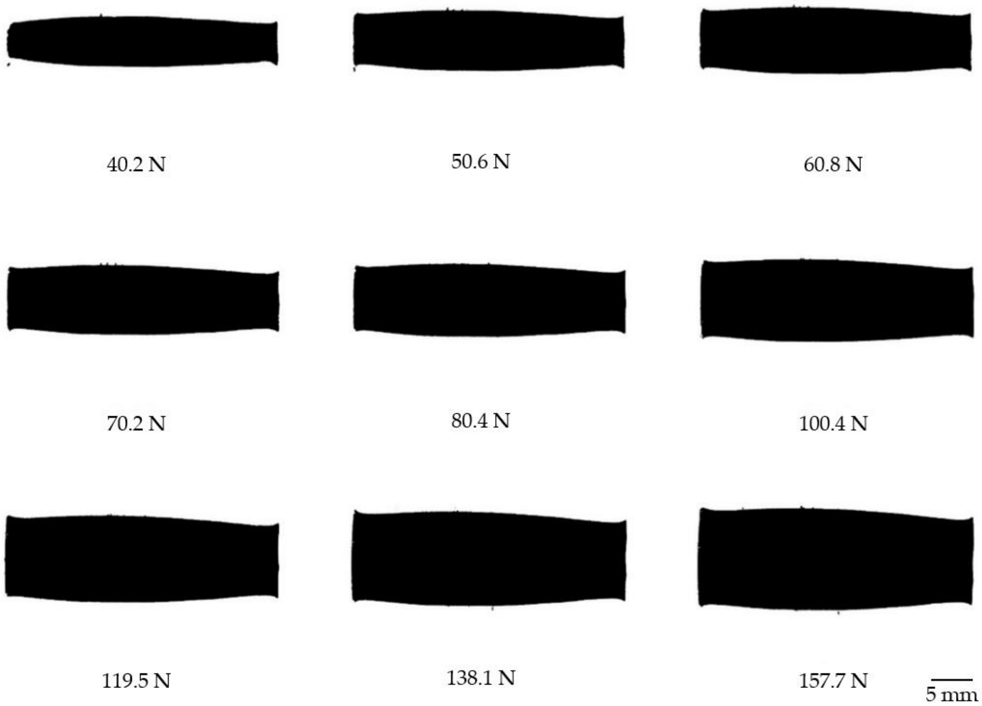

Figure 4. Images of rubber specimen apparent contact area due to applied load (the images belong to trial 2)

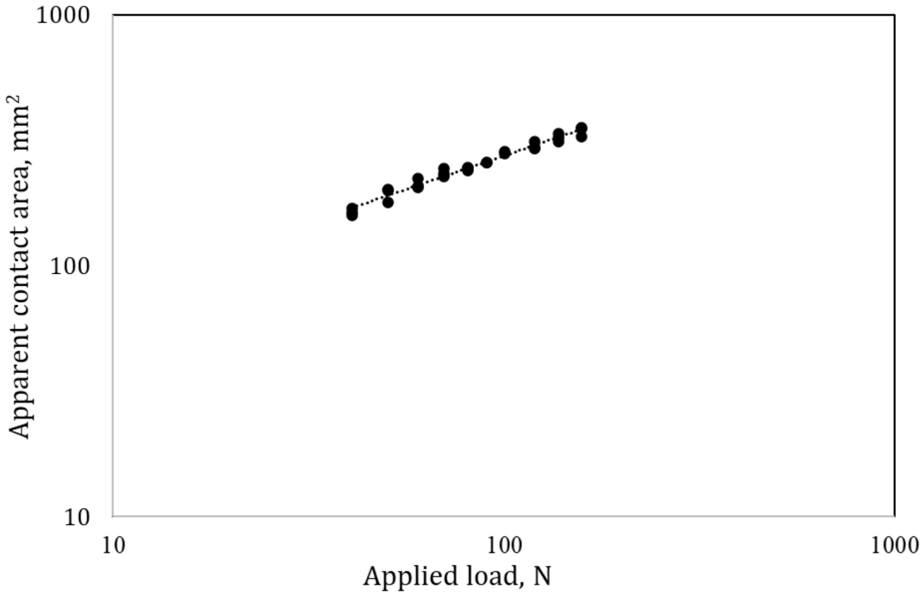

Figure 5. Rubber specimen contact area vs applied load in log-log axis

3.2. Moving-Speed Influence

Figure 6 displays the binary images of rubber specimen contact due to variant moving speeds ranging from 4 mm/s up to 160 mm/s. Something that is popped out in the images of rubber wheel specimen contact was air bubbles which sometimes attached on the surface of glass plate and moved along with rubber wheel specimen forming air pillars. The interference of air pillars was omitted from the calculation of contact area of rubber wheel specimen. Figure 7 shows the graph of rubber wheel specimen apparent contact area due to the influence of six selected moving speeds under three chosen applied loads. Overall, the apparent contact area of rubber specimen was fluctuated as it increased reaching the highest at moving speed of 8 mm/s, and then decreased gradually as moving speed increased. The graph also shows the effect of applied load on moving rubber specimen, as the apparent contact area increased along with applied loads.

As reported by Michelin (Michelin, 2001), rubber material is divided into three states based on the influence of stress frequency. First is rubbery state that occurs at low frequency. Next, as the frequency increases the rubber material appears to be visco-elastic, which is the most ideal condition for grip performance. Lastly, it becomes glassy state as the frequency increases further. Moreover, the adhesion bond between rubber specimen and flat glass surface is formed and separated repeatedly as the rubber specimen moving along the path. Based on these conditions, at lower speed where the stress frequency of rubber is low, the apparent contact area of rubber specimen increased as speed increased. The possible reason is likely due to similar phenomena of junction growth theory developed by Tabor. When rubber specimen was moving at lower speed, due to strong adhesion force, the separation speed between rubber and flat surface was lower than that of the formation speed, making it look like the junction between rubber-wheel and flat surface growth. As a result, the apparent contact area increased as moving speed increased up to 8 mm/s. This result has similar tendency with experiment result (in form of coefficient of friction vs speed) and theoretical approach developed by M. Klupper et.al. (Kluppel et al., 2003). However, as the moving speed increased to more than 8 mm/s, the viscous characteristic of rubber became dominant, which led to a glassy state.

Therefore, the apparent contact area of rubber specimen decreased as moving speed increased.

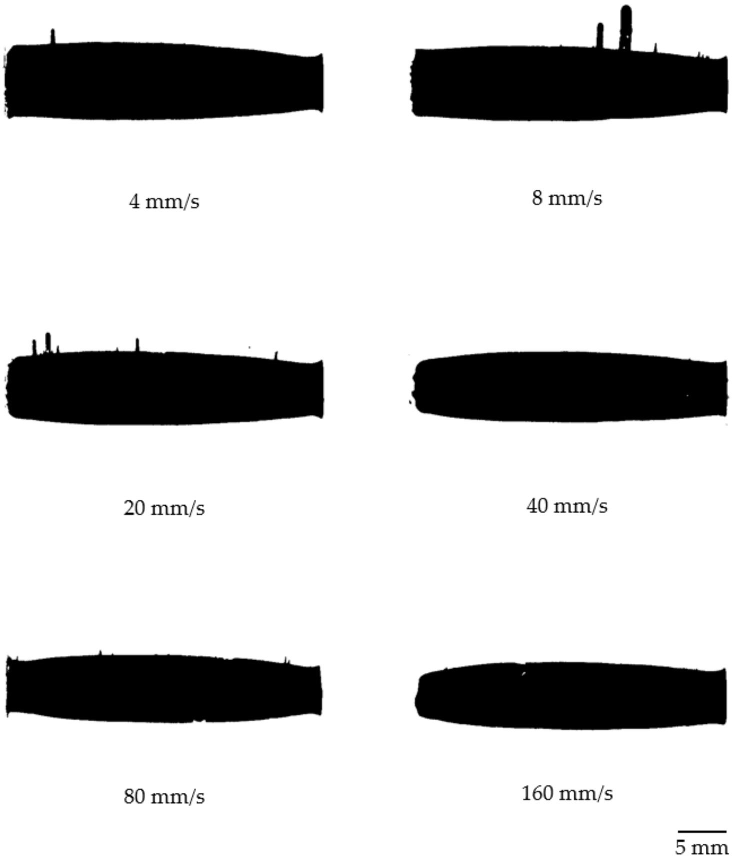

Figure 6. Rubber specimen contact area as the influence of moving speed (images belong to applied load 80.4 N)

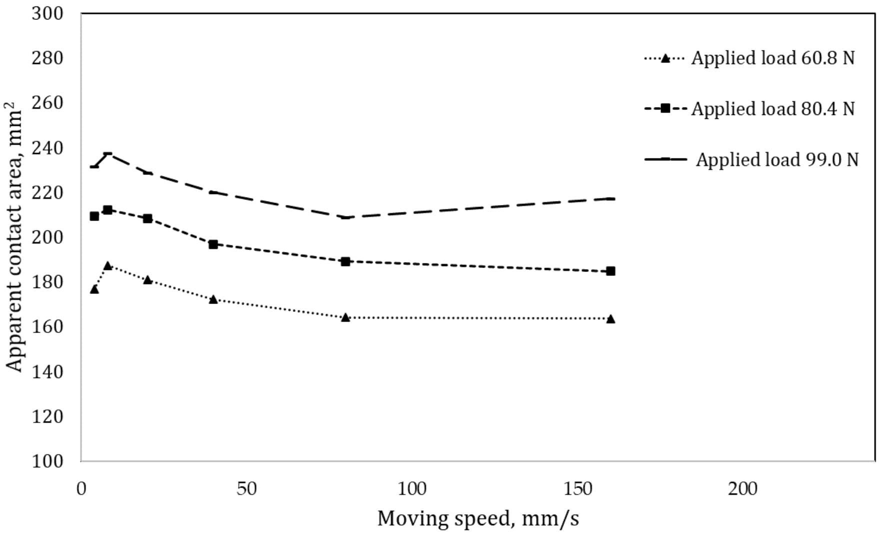

Figure 7. Rubber specimen apparent contact area on dynamic condition with three variants applied load 60.8 N, 80.4 N and 99 N, respectively.

4. Conclusions

The study of rubber wheel specimen contact on flat glass surface under applied loads and moving-speed effect was conducted. The results indicate different tendency between applied load and moving-speed dependencies. In applied load dependency, the plot distribution of rubber specimen apparent contact area was situated within 20 mm^2 range for each applied load from three tests. In overall, the apparent contact area increased linearly as applied load increased in the graph with log-log axis. This result fits the function of Hertz theory as the half-width of contact area is proportional to applied load in the power of ½. Regarding moving-speed influences, some information can be obtained from the result. First, the applied load also increased the apparent contact area of rubber specimen. Second, moving speed of rubber specimen increased the rubber apparent contact area at lower speed up to 8 mm/s and then it decreased as moving speed increased further.

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