Friction of Short-Fiber–Reinforced Rubber on Wet Surfaces

Yoshitaka Uchiyama,[1] Noriaki Wada,[2] Tomoaki Iwai,[1] Seiichi Ueda,[1] Shinji Sado[1]

[1]*Faculty of Engineering, Kanazawa University, 40-20, Kodatsuno 2-chome, Kanazawa 920-8667, Japan*
[2]*Central Research Laboratory, Bando Chemical Industries Ltd., 1-6, Ashiharadori 3-chome, Hyogo-ku, Kobe 652-0882, Japan*

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ABSTRACT: The friction coefficient of short-fiber–reinforced rubber (SFRR) was examined under dry and wet conditions. When the unfilled rubber is rubbed against a dry glass disk, the friction coefficient is higher than that of the SFRR and decreases as contact pressure increases. On the other hand, the friction coefficient for the SFRR is relatively low, and decreases slightly with the increase of contact pressure. When the unfilled rubber is rubbed against a silicone oil–lubricated glass disk, the friction coefficient is lower than that in a dry condition, and decreases with increasing sliding speed to reach a minimum value. After that, it increases slightly with the increment of the sliding speed at the sliding speed range examined. The friction coefficient of the SFRR on the wet surfaces is lower than that of the unfilled rubber at low sliding speeds. With an increase in speed, the friction coefficient initially decreases, and then reaches a minimum value. After that, it increases with the increment of sliding speed. The minimum for the unfilled rubber and the SFRRs shifts toward lower sliding speeds when the contact pressure is increased. Therefore, under the condition of mixed lubrication at low speeds, the friction coefficient at low contact pressure is higher than that at high contact pressure. This trend is distinguishable as the fiber content of the SFRR is increased. The phenomena at high contact pressures arise from the reduction of effective surface roughness, as the unfilled rubber deforms and the SFRRs deflect because of the applied load. J Appl Polym Sci 95: 82–89, 2005

Key words: short-fiber–reinforced rubber (SFRR); friction coefficient; fibers; adhesion; mechanical properties

INTRODUCTION

Short-fiber–reinforced rubber (SFRR) has been widely used for V-belts, hoses,[1] rollers, and tire treads, to cite but a few examples. Reports have examined the effect of adhesion between fibers and rubber on the mechanical properties of the SFRRs.[2–5] In a previous work, we reported on the effect of the dispersion and orientation of short fibers in SFRR.[6] The friction and wear properties of SFRRs were also studied when they were rubbed against abrasive cloth.[7] The friction coefficients of SFRRs were less than those of the unfilled rubber, and scarcely dependent on the orientation of the fiber during the abrasive wear. However, the wear rates of the SFRRs depend on the sliding direction. Minimum wear rates were found when the short fiber orients normal to the mating surface. The friction and wear properties of the SFRRs were also examined under various sliding speeds against abrasive papers.[8] The previous reports on the friction and wear properties involved dry conditions. However, SFRRs are also used under wet conditions, for example, in the case of V-belts, tires, rollers, and shoes. In a previous work, we studied the frictional properties of the SFRRs under water-lubricated conditions.[9] The friction coefficient for the unfilled rubber is lower than that in dry conditions, and decreases with an increasing sliding speed. The friction coefficient of SFRRs on wet surfaces is lower than that of unfilled rubber at low sliding speeds. However, with an increase in speed the friction coefficient on wet surfaces increases, and shows a peak. The peak is much higher at lower contact pressures. Thus the sliding speed at the peak tends to increase by minimizing the contact pressure.

This report describes experiments made under silicone oil–lubricated conditions to investigate the friction of short-fiber–reinforced chloroprene rubber, which was filled with various contents of *m*-aramid fiber. The SFRRs were rubbed against a silicone oil–lubricated glass and their frictional properties were examined under various contact pressures and sliding speeds. They were then compared with those of an unfilled matrix rubber.

Correspondence to: Y. Uchiyama (uchiyama@kenroku.kanazawa-u.ac.jp).

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EXPERIMENTAL

Rubbing experiments were made using a pin-on-disk type apparatus, and a square cross section of rubber (3

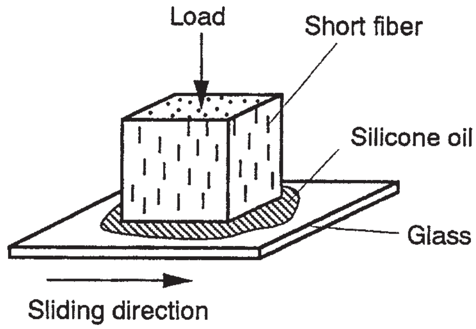

Figure 1 Configuration of the sliding pair.

× 3 mm), such as unfilled matrix rubber and SFRRs, was rubbed against a glass disk. Figure 1 shows the configuration of the sliding pair when the SFRR pin is rubbed. The SFRR pin was rubbed in the configuration such that the fiber orients normal to the mating disk. The matrix rubber (specimen No. U-0) was chloroprene rubber filled with FEF (N550) carbon black 40 parts for hundred parts of rubber. Two SFRRs (specimen Nos. CM-10 and CM-20) contained poly-*m*-phenylene-isophthalamide fiber (average diameter 14 μm; length 3 mm) at 10 and 20 vol %, respectively. Under a wet condition, silicone oil was dropped in front of the rubber pin specimen, and received in a vessel. Before the friction measurements, the rubber specimens were abraded by abrasive paper (cc#100) on the glass disk under a contact pressure of 0.108 MPa and a sliding speed of 11.8 cm/s. Under either a dry condition or a wet condition involving silicone oil (kinematic viscosities 0.1, 1.0, and 10.0 cm^2/s), the experiments were performed at sliding speeds from 3 to 300 mm/s, and contact pressures from 0.054 to 0.544 MPa.

RESULTS AND DISCUSSION

Variations in the coefficient of friction with sliding speed under a dry condition

Under a dry condition the friction coefficients for the matrix rubber and the SFRRs were examined under various sliding speeds and contact pressures. As shown in Figure 2(a), the friction coefficients for the matrix rubber (U-0) were plotted against sliding speed. For the matrix rubber, the friction coefficient, which depends on contact pressure, was lower at the higher contact pressure and increased with the increment of sliding speed, as shown in Figure 2(a). In Figure 2(b), a typical result for the SFRR CM-20 is shown. The friction coefficient for the CM-20 is lower than that for the matrix rubber examined, and also increased with the increment of sliding speed. The value was around one-fourth compared with that of the matrix rubber, and the difference in the coefficients among the contact pressures examined was small compared with that of the matrix rubber. As previously reported,[9] the friction coefficients for the SFRRs tended to decrease substantially as the fiber content increased from 0 to 10 vol %, and the difference in the coefficients among the SFRRs containing fiber from 10 to 20 vol % were small. In this experiment, the difference in the friction coefficients between the SFRRs CM-10 and CM-20 was also small.

Variations in the friction coefficient with sliding speed and contact pressure under a wet condition

The friction coefficients were examined when lubricated with silicone oil (kinematic viscosity 1.0 cm^2/s). As

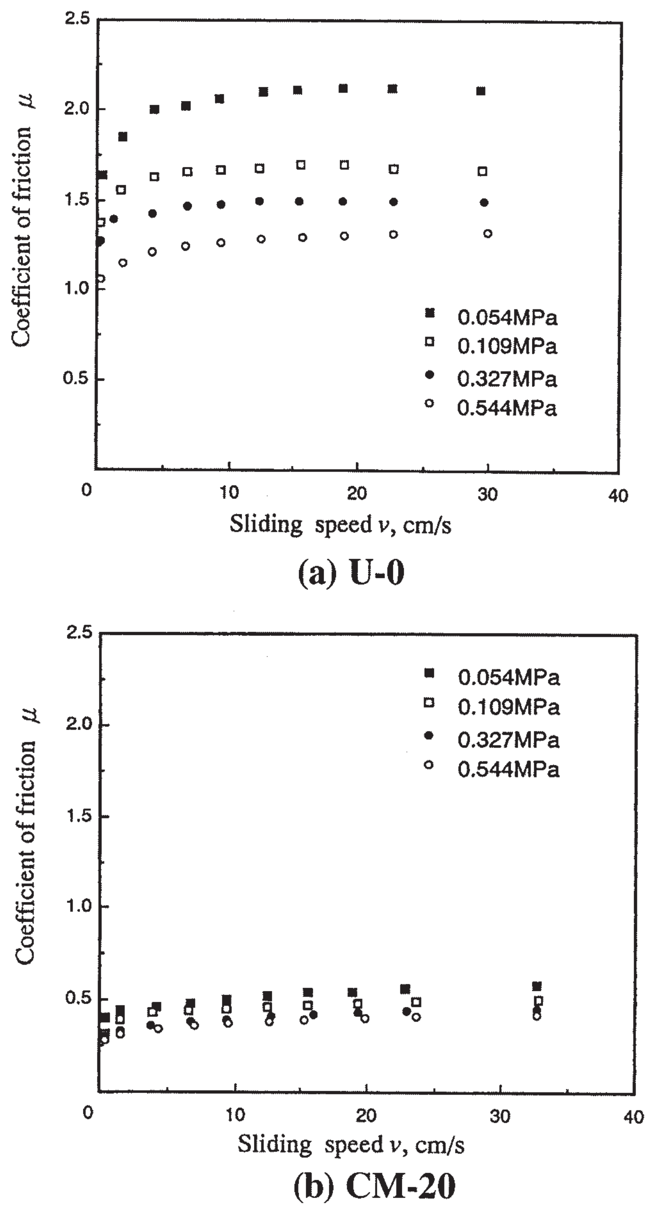

Figure 2 Variations in the dry friction coefficients with sliding speed under various contact pressures: (a) unfilled matrix rubber U-0; and (b) SFRR CM-20.

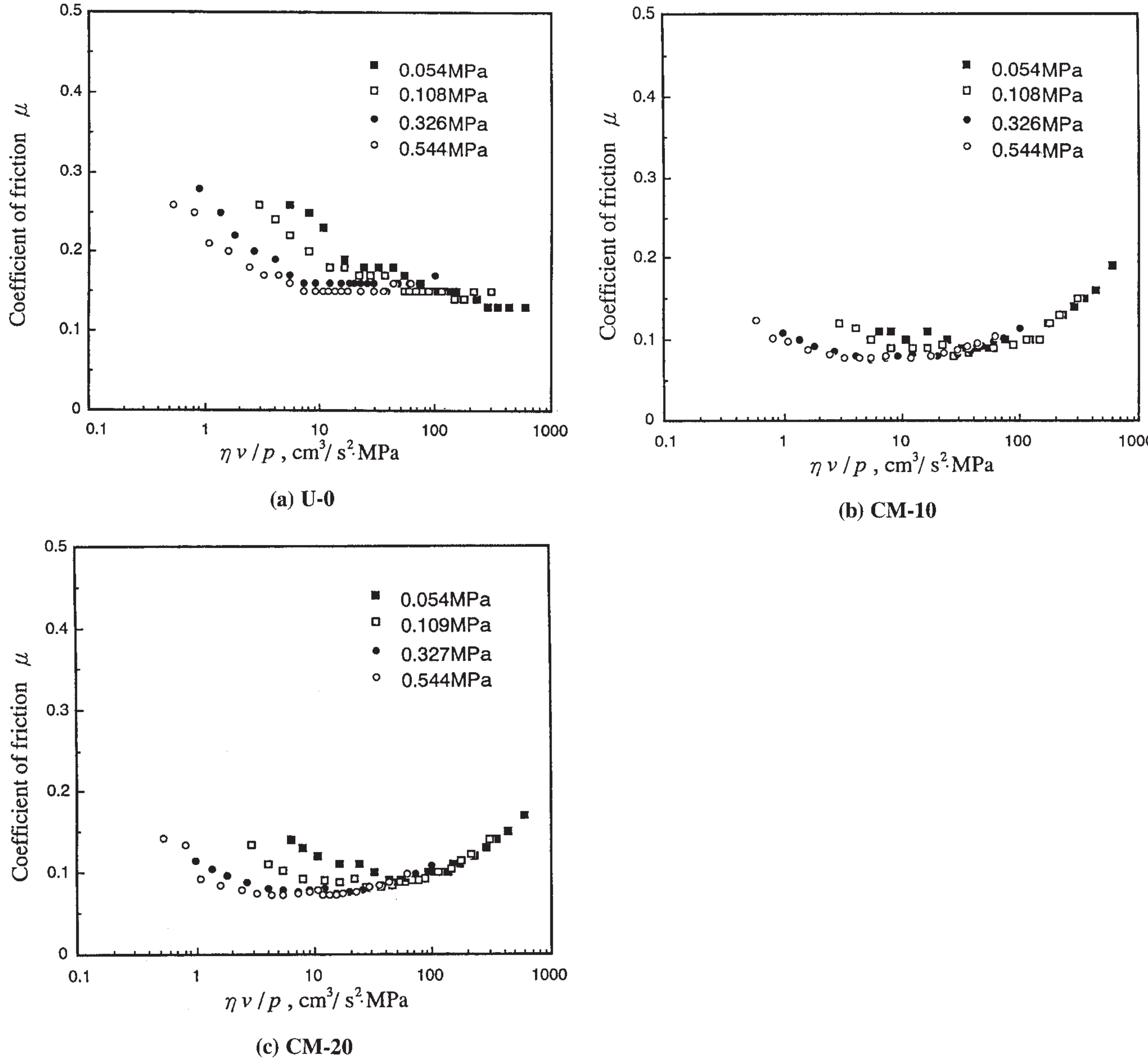

Figure 3 Variations in the friction coefficients for (a) the unfilled matrix rubber U-0, (b) SFRR CM-10, and (c) SFRR CM-20 in a wet condition, lubricated by silicone oil (kinematic viscosity 1.0 cm^2/s), with the bearing characteristic number $\eta\nu/p$ under various contact pressures.

shown in Figure 3(a), (b), and (c), the friction coefficients for the matrix rubber and the two SFRRs were plotted against bearing characteristic number $\eta\nu/p$ (kinematic viscosity $\eta \times$ sliding speed ν/contact pressure p), respectively. For the matrix rubber (U-0), the friction coefficient, which depends on contact pressure, was lower at the higher contact pressure and decreased to attain a minimum value of around 0.15 with the increment of $\eta\nu/p$ [Fig. 3(a)]. However, the friction coefficients for the SFRRs CM-10 and CM-20 initially decreased with the increment of $\eta\nu/p$, and showed minimum value at individual pressures, as shown in Figure 3(b) and (c). After that, at higher $\eta\nu/p$ values the friction coefficient increased with the increment of $\eta\nu/p$. For the SFRRs CM-10 and CM-20, the minimum friction coefficients tended to decrease slightly with increasing contact pressure, and the minimum point also shifts toward a lower $\eta\nu/p$ value. From these results, the state of elastohydrodynamic lubrication for the matrix rubber and the SFRRs is markedly observed at lower sliding speeds.

Effect of silicone oil viscosity on the friction coefficient for the matrix rubber and the SFRRs

Similar experiments for U-0, CM-10, and CM-20 were made using silicone oil with a viscosity of 0.1 cm^2/s

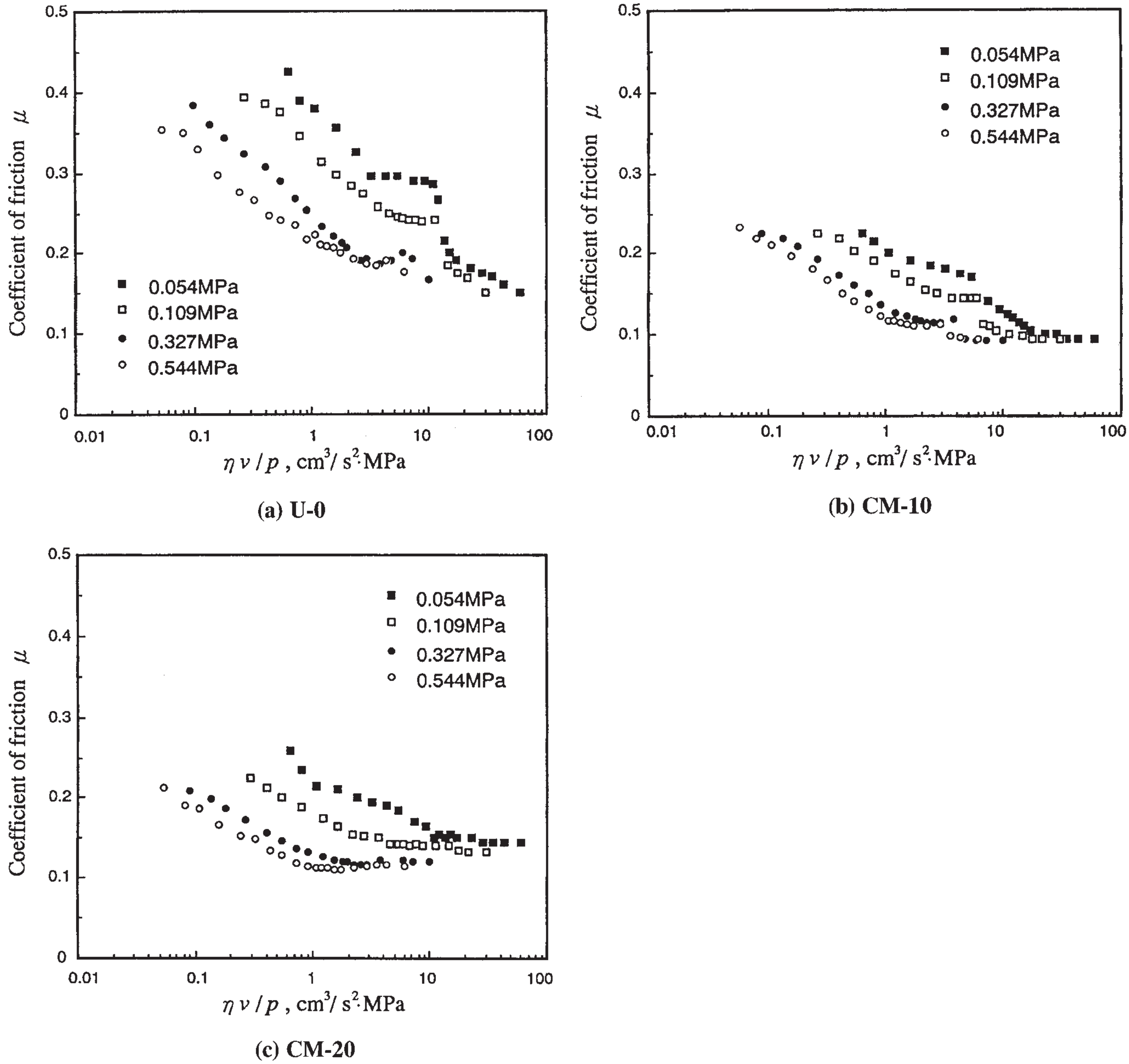

Figure 4 Variations in the friction coefficients for (a) the unfilled matrix rubber U-0, (b) SFRR CM-10, and (c) SFRR CM-20 in a wet condition, lubricated by silicone oil (kinematic viscosity 0.1 cm^2/s), with the bearing characteristic number $\eta\nu/p$ under various contact pressures.

[Fig. 4(a), (b), and (c)]. The friction coefficient μ versus $\eta\nu/p$ curves (μ–$\eta\nu/p$ curves) for the three specimens examined showed negative slopes at lower speeds. At that time, phenomena regarding mixed lubrication were observed, whereas stick-slip phenomena occurred especially at lower sliding speeds.

At a higher silicone oil viscosity of 10.0 cm^2/s, the friction coefficients of the U-0 showed minimum values and they shifted to lower sliding speeds with increasing contact pressure, as shown in Figure 5(a). The friction coefficients for the CM-10 and CM-20 also showed minimum values at lower speeds, as shown in Figure 5(b) and (c). With increasing contact pressure, the minimum values tended to shift toward lower sliding speed and the values also tended to decrease. When the friction coefficients varied from the minimum values to higher values, elastohydrodynamic lubrication was observed.

From Figures 3, 4, and 5, the unified figures were obtained as shown in Figure 6(a), (b), and (c). In Figure 6(a), (b), and (c), the variations of the friction coefficient for the unfilled matrix rubber U-0, the SFRR CM-10, and the SFRR CM-20, with $\eta\nu/p$ were shown when lubricated by three kinds of silicone oils with

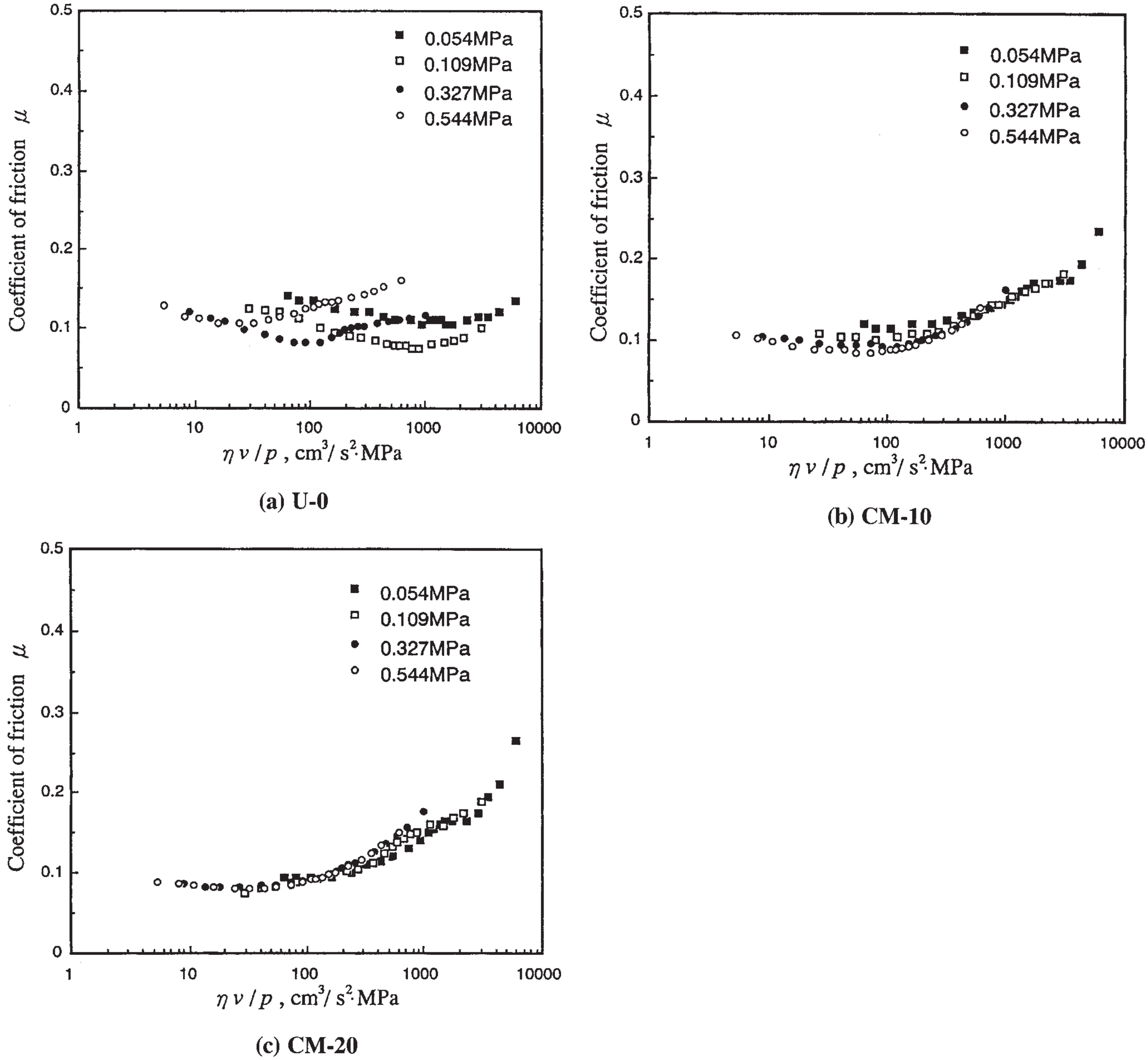

Figure 5 Variations in the friction coefficients for (a) the unfilled matrix rubber U-0, (b) SFRR CM-10, and (c) SFRR CM-20 in a wet condition, lubricated by silicone oil (kinematic viscosity 10.0 cm^2/s) with the bearing characteristic number $\eta\nu/p$ under various contact pressures.

kinematic viscosities of 0.1, 1.0, and 10.0 cm^2/s under various contact pressures. As shown in Figure 6(a) the friction coefficients of the unfilled matrix rubber decreased with the increment of $\eta\nu/p$. Minimum friction coefficients were also observed at $\eta\nu/p$ values from 20 to 2000 $cm^3/s^2 \cdot MPa$. For the SFRRs CM-10 and CM-20, the minimum values are observed at $\eta\nu/p$ values approximately from 10 to 100 and approximately from 5 to 70 $cm^3/s^2 \cdot MPa$, respectively. As shown in Figure 6(a), (b), and (c), the friction coefficients at lower $\eta\nu/p$ values are affected by contact pressure. The friction coefficient for the CM-20 is more significantly affected by contact pressure at a low $\eta\nu/p$ value compared with that for the CM-10.

There is a report on the deformation of rubber.[10] When a high load (or high contact pressure) is applied, the surface of the matrix rubber deforms to reduce the surface roughness, as shown in Figure 7. The fibers of the SFRR also minimize the surface roughness, as shown in Figure 8.

As the film thickness of the silicone oil increases with increasing sliding speed, the state changes from mixed lubrication to elastohydrodynamic lu-

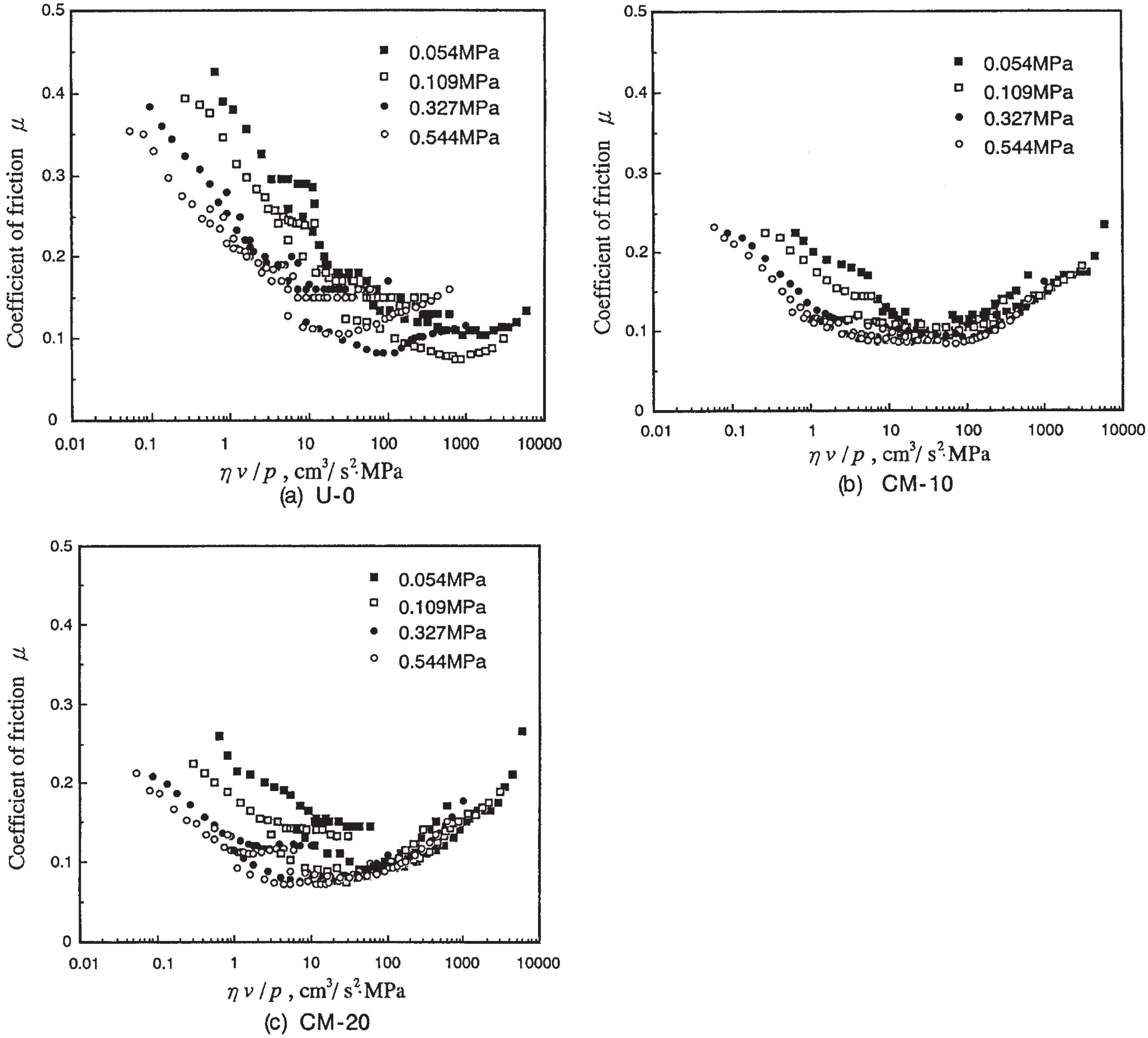

Figure 6 Variations in the friction coefficients for (a) the unfilled matrix rubber U-0, (b) SFRR CM-10, and (c) SFRR CM-20, during lubrication by three kinds of silicone oil (kinematic viscosities: 0.1, 1.0, and 10.0 cm^2/s), with the bearing characteristic number $\eta\nu/p$ under various contact pressures.

brication.[11,12] Minimum points exist when the film thickness exceeds the roughness of the slider,[13,14] and the lowest values of the friction coefficients for the rubber specimens are observed under various contact pressures. At that time, the minimum point moves to the lower sliding speed when the contact pressure increases, as depicted in Figure 9. After that, the friction coefficients increase with the increment of sliding speed. Then the μ–$\eta\nu/p$ curves tend to move toward a lower $\eta\nu/p$ value with increasing contact pressure, attributed to the reduction of the effective surface roughness, as shown in Figures 7 and 8.

CONCLUSIONS

The friction coefficients of chloroprene rubber (CR) and the short-fiber–reinforced rubbers (SFRRs) (whose matrix rubber is CR) were examined under dry and silicone oil–lubricated conditions. Under the dry condition, the friction coefficients for the matrix rubber and the SFRRs tend to increase with increasing sliding speed, and also decrease with the increment of contact pressure. However the friction coefficients for the SFRRs are lower than those for the matrix rubber. Under a wet condition lubricated by silicone oil, the friction coefficients for the matrix rubber are lower at

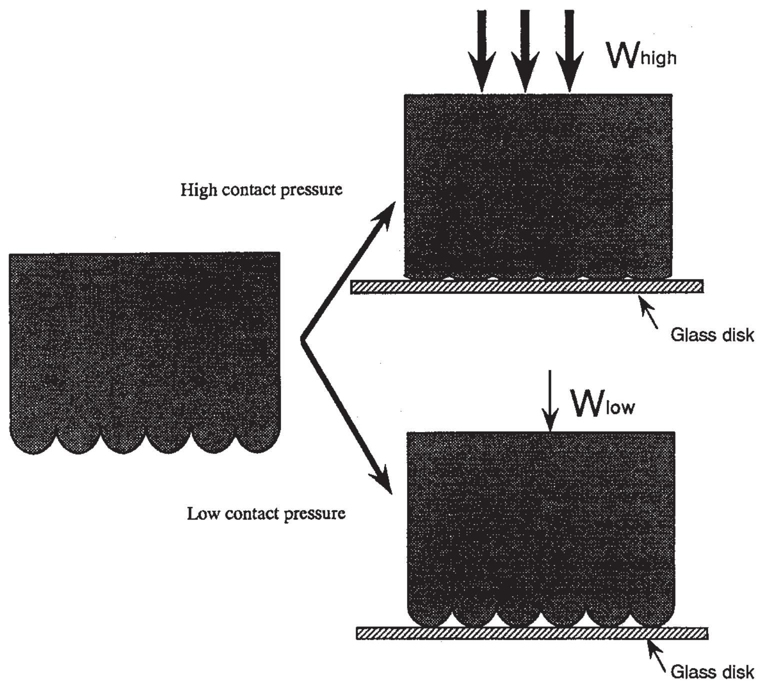

Figure 7 Deformation of the unfilled matrix rubber under low and high contact pressures.

higher contact pressures and decrease with the increment of characteristic bearing number $\eta\nu/p$ (kinematic viscosity $\eta \times$ sliding speed ν/contact pressure p) to reach minimum points. On the other hand, the friction coefficients of the SFRRs decrease initially with the increment of $\eta\nu/p$, and show minimum val-

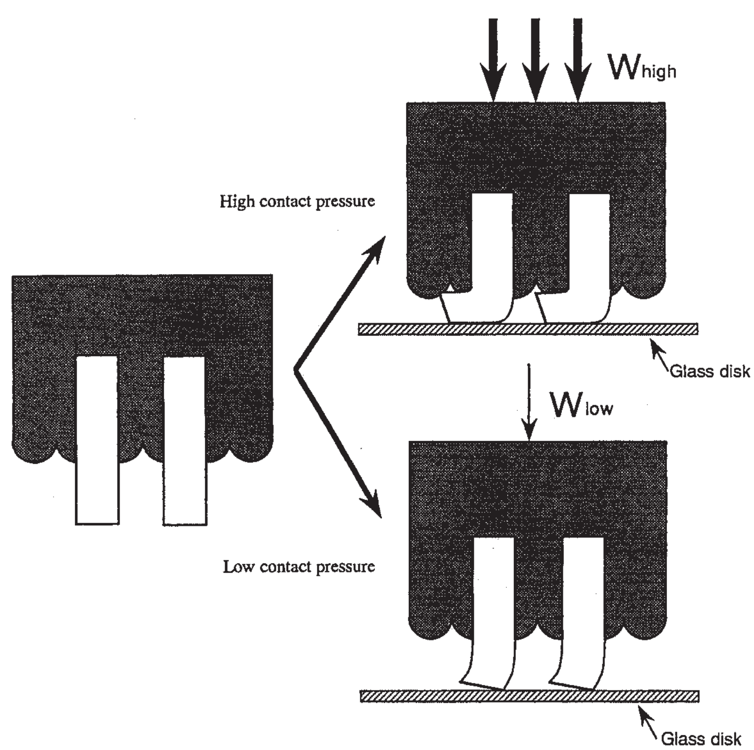

Figure 8 Deflection of the SFRR fibers under low and high contact pressures.

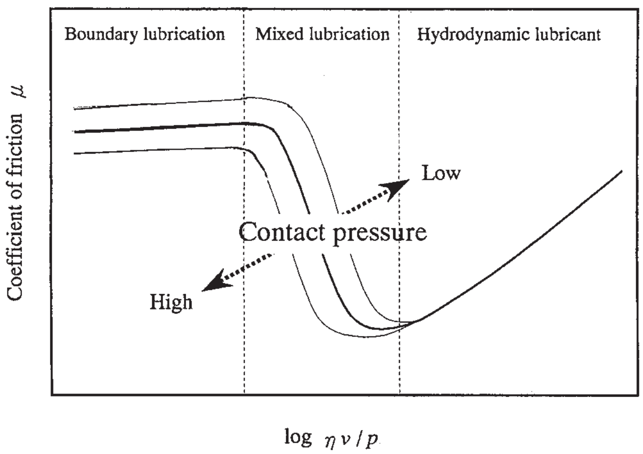

Figure 9 Influence of contact pressure on the μ–$\eta\nu/p$ curve.

ues at individual contact pressures. After that the friction coefficients increase with the increment of $\eta\nu/p$. The effects of elastohydrodymamic lubrication are markedly observed at the minimum values for each rubber specimen. At lower speeds, the minimum friction coefficients for the SFRRs are lower than those for the matrix rubber. The μ–$\eta\nu/p$ curves shift toward a lower $\eta\nu/p$ with increasing contact pressures. These phenomena arise from the reduction of the effective roughness of the matrix rubber and the SFRRs with the increment of contact pressure.

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