Friction reduction behavior of oil-infused natural wood

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Abstract: Natural materials tend to exhibit excellent performance in the engineering field because of their structure and special functions. A natural red willow, called natural porous wood material (NPWM), was found, and wear tests were conducted to determine its potential as an oil-impregnated material by utilizing its special porous structure. Fluorination treatment was adopted to improve the NPWM properties for absorbing and storing lubricating oil. The different contributions of soaking and fluorination-soaking treatments on the tribological properties of NPWMs and their respective mechanism of effect were revealed. The results showed that the fluorination-soaking treatment helped absorb and store sufficient lubricating oil in the NPWM porous structure; therefore, more lubricating oil would be squeezed out and function as a tribol-film between contacting surfaces during the friction process, thus ultimately contributing to stable and smooth wear responses even under prolong friction. However, the formation of an oil-in-water emulsion, caused by the buoyancy effect, destroyed the oil films on the worn NPWM surface in a water environment, resulting in higher coefficients of friction (COFs) under water conditions than under dry friction, even after the fluorination-soaking treatment. The knowledge gained herein could not only verify the potential of NPWM as an excellent oil-impregnated material in the engineering field but also provide a new methodology for the design of artificial porous materials with stable and smooth friction processes.

Keywords: natural porous material; oil infusion treatment; fluorination; frictional behaviors

1 Introduction

The friction and wear behaviors of materials have received much attention because they directly influence the reliability and stability of machinery in various engineering fields such as aerospace, automotive, medical, and marine machinery [1–4]. However, widely used materials, such as polymer-based and metal-based composites, are more likely to exhibit surface deformation behaviors under the coupling effects of poor working conditions, unsatisfactory lubrication conditions, and uneven impact forces, thus leading to fluctuations in the entire frictional system [5–9]. For example, polymer-based water-lubricated stern bearings and bearings in helicopter propellers, because of severe surface deformation behavior and poor lubrication conditions, are more likely to exhibit poor operational performance, such as notable vibration and noise problems [10, 11]. Therefore, to improve the lubricating conditions of engineering materials, some functional fillers, such as molybdenum disulfide (MoS\textsubscript{2}), black phosphorus (BP), and carbon nanotubes, as well as optimizing structures such as sandwich and porous structures, have been used as typical modification methods [12–17]. Currently, attention has been focused on exploiting the potential of some natural materials to be used as novel materials because of their reasonable structures and special functions.

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Natural, renewable, and biodegradable frictional materials, such as wood, have been used in engineering practices for a long time with outstanding performance. *Lignum vitae*, owing to its ability to create complex compounds with lubricating effects in water environments, has been used as a marine water-lubricated stern bearing for many decades [18–21]. In addition, because of its native form, wood is an inhomogeneous, porous, and anisotropic material consisting of ducts, fibers, and parenchymal cells; thus, impregnation is used to improve its inherent drawbacks of unsatisfactory mechanical properties and bad wear behaviors in long friction time [22–25]. Therefore, some curing agents, such as waxes and epoxy, have been used to fill wood to enhance mechanical properties such as surface hardness [26, 27]. In addition, some lubricants such as waxes and fats have been adopted to immerse wood to improve their lubricating behaviors [28, 29]. Impregnated wood has been widely applied to engineering practices, such as hydro-turbine bearings made from oil-impregnated maple wood, and beeswax-impregnated wood (*Fagus sylvatica*) has been used to manufacture bike bearings [30, 31].

However, many beneficial structures of natural woods have been attempted to be applied to polymer- and metal-based composites because of the decreasing wood resources in nature [32, 33]. The typical porous structure, with outstanding performance in storing and transferring lubricants, exhibits excellent application as a friction material to improve the lubricating conditions during friction [34–37]. However, compared to the naturally porous structure of wood, problems such as low manufacturing accuracy, incomplete structure, and unreasonable size of the artificial porous structure have negative effects on the storage and lubricating performance of wood. In this study, a natural porous wood material (NPWM) with a natural porous structure was tested to determine its potential as a new oil-impregnated material. Therefore, chemical treatment of the NPWM surface was carried out to improve the pore efficiency in storing lubricating oil, and the frictional responses were tested to reveal the tribological mechanism of NPWM under different friction conditions. The results obtained herein could not only have positive effects on the discovery of a new oil-impregnated material, but also on the creation of a new surface chemical treatment to improve the oil storage property of porous structures.

2 Methods and experiments

2.1 Experimental materials

Red willow, with an excellent and typical porous structure, was used as the testing specimen and is referred to as the natural porous wood material (NPWM) in this paper (shown in Fig. 1(a)). Scanning electron microscopy (SEM) was used to observe the typical porous structures on the NPWM surface; the results are displayed in Figs. 1(b) and 1(c). Numerous ducts with an average diameter of approximately 100 μm can be observed evenly distributed along the wood lines on the surface (Figs. 1(b), 1(b-1), and 1(b-2)) and the cross-section is shown in Fig. 1(c), which shows that the ducts penetrate through the entire wood sample, which could contribute to the excellent integrity of the depth structure. Therefore, evenly distributed ducts with a natural satisfactory diameter, depth, and numbers formed a typical porous structure.

![Fig. 1](image-url)  
**Fig. 1** Natural porous wood material (red willow) (NPWM): (a) NPWM; (b) micro-surface of NPWM: (b-1) and (b-2) show the micro-ducts; (c) cross-section of the duct.
on the NPWM surface, which could contribute to outstanding properties for storing lubricants.

2.2 Fluorination treatment on the NPWM

Fluorination treatment has been widely adopted as a material surface treatment method to improve the interface bonding ability effectively by forming a fluorinated layer [38–40]. Therefore, a fluorination treatment was conducted on the NPWM surface to improve its oil-absorbing properties, and the process is shown in Fig. 2. The NPWM specimen was first polished in a water environment to obtain a mean surface roughness ($S_a$) of approximately 50 ± 10 nm (white light interferometer, Micro Xam, ADEP Hase Shift, Inc., Tucson, AZ, USA) before being inactivated with ultraviolet light for 24 h (Figs. 2(a) and 2(b)). The functional groups present on the NPWM surface would be inactivated in the pure ultraviolet environment, thus ensuring that no additional chemical reactions and products other than a single fluorination reaction would occur on the NPWM. The mixed fluorination solution, composed of 99 wt% ethanol (95%) and 1 wt% PFTEOS ((1H, 1H, 2H, 2H-perfluorooctyl)-triethoxysilane, 97%) (all provided by Aladdin Co. Ltd., Shanghai, China), was used to soak the NPWM specimen for 24 h as a fluorination treatment (Fig. 2(c)). Stepwise, the fluorinated NPWM specimen was obtained after the treated NPWM specimen was dried naturally for 24 h (shown in Fig. 2(d)). The energy dispersive spectrometry (EDS) results (Figs. 2(e) and 2(f)) show that element F was distributed on the fluorinated NPWM surface as well as the duct wall in the cross-section. The Fourier transform infrared spectrometry (FTIR) results (Fig. 2(g)) also show the success of fluorination, as new C–F bonds at 1,203 cm$^{-1}$ and Si–O bonds at 1,080 cm$^{-1}$ were found on the fluorinated NPWM surface compared to non-fluorinated NPWM. Therefore, the EDS and FTIR results confirmed the successful creation of new chemical bonds caused by the fluorination treatment that occurred not only on the NPWM surface but also on the inside of the ducts.

2.3 Vacuum soaking treatment on the NPWM

The soaking treatment was conducted to fill the NPWM’s porous structure with lubricating oil (PAO10 or PAO40), and the process is shown in Fig. 3. Fluorinated NPWM (shown in Fig. 3(a)) was thoroughly soaked in lubricating oil in a special container for 48 h, while a vacuum pump was operated to generate a negative pressure environment in the container by means of connecting pipes (Fig. 3(b)). In this case, more lubricating oil would be filled into the ducts because the remaining air in the NPWM would be squeezed out under the effects of the internal and external differential pressure. The soaking-treated NPWM specimens were obtained after a 24 h natural drying process (Fig. 3(c)).

![Fig. 2](https://mc03.manuscriptcentral.com/friction)

Fig. 2 Fluorination treatment of NPWM: (a) natural porous wood material (NPWM); (b) ultraviolet treatment; (c) fluorination treatment; (d) fluorinated NPWM and its cross-section; (e) EDS curve and elements distribution of cross-section of fluorinated NPWM; (f) EDS and element distribution of the surface of fluorinated NPWM; (g) surface FTIR result.
2.4 Sliding wear tests under different testing conditions

The sliding wear tests for discovering the wear and friction behaviors of the treated NPWMs are displayed in Figs. 4(a)–4(e). A 10 mm diameter ceramic ball was chosen as the frictional pair because of its good wear resistance and stable properties (Fig. 4(b)) [41, 42]. Its surface roughness was 15 ± 5 nm, which was examined using a laser scanning microscope (VX-X1000, KEYENCE, Japan). NPWM specimens (Fig. 4(a)) were polished in a water environment to obtain a $S_a$ result of 30 ± 5 nm (White Light Interferometer, Micro Xam, ADEP Hase Shift, Inc., Tucson, AZ, USA). In addition, all the friction tests were conducted using a commercial ball-on-pin friction testing machine (R-tec tribo-tester, Rtec Instruments Inc., USA), as shown in Fig. 4(e).

Two different treatments were conducted on the NPWMs. The first consisted of soaking them only in lubricating oil (PAO10 and PAO40) (soaking treatment), and the other consisted of fluorinating the NPWMs before the soaking treatment with lubricating oil (PAO10 and PAO40) (fluorination-soaking treatment). In addition, various friction tests were designed by setting different experimental conditions, of which the different contributions of the soaking and fluorination-soaking treatments on the friction responses of NPWM were studied by conducting regular (1,800 s) and long-term (7,200 s) single wear tests at low speed (2 Hz, 0.09 m/s) and light load (10 N) under dry and water conditions. During these tests, the ceramic ball was maintained stationary at the top, while the lower pin specimens were moved in a reciprocating motion (shown in Fig. 4(c)) with 4.5 mm sliding distances. In addition, various loads (10, 20, 30, and 40 N) were set to test its reliance on the wear behaviors of the NPWM with fluorination-soaking treatment at a constant speed of 2 Hz (0.09 m/s). The friction test in the water condition was realized by dropping pure water to the friction interfaces, and
sufficient water content was ensured by constantly adding water (shown in Fig. 4(d)). Moreover, the test data were recorded at 0.002 s intervals during all tests, and all experiments were repeated three times to ensure repeatability, and a new NPWM specimen and ceramic ball were used for each test.

2.5 Measurement techniques and equipment

The worn surface topographies and the solution after friction were examined using a confocal laser scanning microscope (CLSM) (VX-X1000, Keyence, Japan), and the micromorphology of the wood plate was observed using a scanning electron microscope (SEM) (VEGA3, TESCAN, Czech Republic). An energy dispersive spectrometer (EDS) (X-act one, Oxford, UK) and Fourier transform infrared spectrometer (FTIR Spectrometer) (Nexus, Thermo Nicolet, USA) were used to determine the surface chemical elements and functional groups of the NPWMs after fluorination. Moreover, the surface hydrophilicity with lubricating oil (PAO10 and PAO40) of the NPWMs was characterized by contact angle measurements (DSA 100, KRUSS GmbH, Germany) at 23 °C.

3 Results

3.1 Results of contact angles with PAO10 and PAO40

Figure 5 displays the lipophilicity properties of the NPWMs with PAO10 and PAO40 individually based on the contact angle results. Figures 5(a) and 5(c) show that the NPWMs, without fluorination treatment, had 84° and 87° results in contact with PAO10 and PAO40, respectively, indicating neutral properties in these two lubricating oils. However, this behavior reduced sharply to 13° and 19°, as shown in Figs. 5(b) and 5(d) with the same lubricating oil after the NPWMs were fluorinated. Therefore, the contact angle results demonstrated the neutral absorption behaviors of PAO10 and PAO40 on the pure NPWMs, but the fluorination treatment contributed to their excellent oil-absorbing properties, thus storing more lubricating oil in the porous structure and ducts during the oil-soaking treatment.

3.2 COF results in dry and water wear conditions

The COF properties of the NPWMs in dry and water friction conditions were investigated in separated PAO10 and PAO40 infusion environments at 2 Hz (0.09 m/s), 10 N, and for 1,800 s to investigate the different contributions of soaking and fluorination-soaking treatments (Fig. 6). In dry friction, four different treatments were conducted on the untreated, untreated but lubricating (oil-lubricated), soaking-treated, and fluorination-soaking-treated NPWMs. Therefore, the COFs of NPWMs reached a maximum of 0.22, with an evidently increasing trend in direct contact wear, but these behaviors were sharply reduced and stabilized the COFs to 0.121 and 0.102, respectively, because PAO10 and PAO40 were used as lubricating treatments. Moreover, the soaking treatment continued to reduce the COFs to 0.103 in PAO10 and 0.086 in PAO40 individually, and the fluorination-soaking treatment contributed to the lowest COFs with outstanding stable frictions in both PAO10 and PAO40 conditions. The different COF behaviors contributed by the four NPWM treatments were averaged to obtain the average COF results and are shown in Fig. 6(a-2). The untreated NPWM presented the highest average COF (0.21) in dry friction, but 43.8% and 54.4% COF reductions occurred because PAO10 and PAO40 were used as lubricating treatments. Moreover, the soaking treatment continued to reduce the COFs to 0.103 in PAO10 and 0.086 in PAO40 individually, and the fluorination-soaking treatment contributed to the lowest COFs with outstanding stable frictions in both PAO10 and PAO40 conditions. The different COF behaviors contributed by the four NPWM treatments were averaged to obtain the average COF results and are shown in Fig. 6(a-2). The untreated NPWM presented the highest average COF (0.21) in dry friction, but 43.8% and 54.4% COF reductions occurred because the lubricating treatment was conducted in PAO10 and PAO40, respectively. Moreover, soaking treatment increased these reductions to more than 50%, and the soaking-fluorination treatment led to the maximum reductions in COFs of approximately 62.5% in PAO10 and 66.1% in PAO40.
The COF responses demonstrated that oil-soaking treatments on NPWM led to better COF reductions than the original oil-lubricating treatment, and fluorination enhanced the efficiency of the oil-soaking treatment.

In addition, the untreated, soaking-treated, and fluorination-soaking-treated NPWMs were tested for water friction under PAO10 infusion (Fig. 6(b)), and PAO40 infusion (Fig. 6(b-1)). Among them, the NPWM similarly appeared to increase in the COF curve, with a maximum of 0.191, and averaged in 0.171 throughout the testing period, but 25.1% (PAO10) and 29.8% (PAO40) reductions occurred on the average COFs since the NPWM had been treated by soaking treatment. Moreover, the fluorination-soaking treatment not only contributed to the maximum reductions of 55.6% in PAO10 and 56.7% in PAO40 but also led to a smooth and stable friction process. Undoubtedly, the oil-soaking and fluorination-soaking treatments were effective in improving the friction and wear process of NPWMs in water friction by stabilizing and decreasing the COF responses, and the latter exhibited the best performance, even though it was not as satisfactory as that in dry friction.

Figures 6(c) and 6(c-1) show the differences in NPWMs in dry friction and water friction under the same soaking treatment and fluorination-soaking treatment. Among them, the NPWMs with the same treatments exhibited higher COF values and curves in water friction than in dry friction in both PAO10 and PAO40. This interesting phenomenon could be attributed to the fact that too much water would replace the oil and exist on the contacting surface, thus weakening the lubricating condition for the oil-soaked NPWMs [43, 44].

3.3 Coefficient frictional results after long-time friction

The different contributions of soaking and fluorination-soaking treatments on the frictional responses of NPWMs in long-time friction with PAO10 infusion at 2 Hz and 10 N were studied, and different COF
curves in dry friction and water friction are shown in Figs. 7(a) and 7(b), respectively. For the dry friction (Fig. 7(a)), the NPWM with the fluorination-soaking treatment displayed a very stable and smooth friction process, and the COF remained close to 0.86 without clearly fluctuations. However, after presenting a stable COF period within the initial 1,800 s at 0.10, the NPWM with only the soaking treatment presented an evident growing trend with severe fluctuations (0.108–0.148) and upped to 0.161 at the end. A similar phenomenon also occurred in water friction; the fluorination-soaking treatment also led to a low COF value and remained stable at 0.94 throughout the entire testing period (Fig. 7(b)), and the soaking treatment led to a sharp increase in the COF curve, reaching a maximum of 0.162 in the rest of the testing period, even though it remained stable at 0.113 for the first 3,600 s. The results obtained herein proved that the fluorination-soaking treatment contributed to the low and stable wear process of the NPWM in long-time friction on both dry and water frictions, which can be attributed to its excellent improvement in oil absorption and storage properties.

3.4 COF responses of fluorination-soaking NPWM in various friction conditions

The test results showed that the fluorination-soaking treatment could contribute to the excellent COF responses of NPWMs in regular and long-time frictions under both dry and water frictions, and the influence of different frictional conditions on the COF responses was tested (Fig. 8) at a constant velocity of 2 Hz (0.09 m/s) in dry friction with PAO10 infusion. The effects of various loads, set at 10, 20, 30, and 40 N, on the fluorination-soaking-treated NPWM are shown in Fig. 8(a). Therefore, the COF curve at 10 N remained stable and smooth close to 0.09 (average COF = 0.083) after a significant decrease in the initial friction, and the average continued to decrease to 0.078 at 20 N. Additionally, more reductions were observed at 30 N at 0.075 and 40 N, which contributed to the lowest value of 0.073, with all presented stable and smooth COF processes. In this case, it directly demonstrated that the increasing loads led to the rising reductions in COFs because more lubricating oil might be squeezed out in the high-load effect on the NPWM.
with fluorination-soaking treatment. Figure 8(b) shows various COF responses of the NPWMs under different lubricating conditions after fluorination-soaking treatment. The COFs of two tested NPWMs were stable and remained around 0.08, but they increased significantly to approximately 0.12 after water was added at the 2,400 s mark, and the other one declined to approximately 0.07 after PAO10 was added at the same time, which was close to the COF value of the fluorination-soaking-treated NPWM with PAO10 lubrication throughout the entire test period. Therefore, the fluorination-soaking treatment, in combination with other lubricating oils, was more effective in improving the lubricating condition of the NPWM and contributed to the lowest COF responses because more lubricating oil would exist on the contacting surfaces; in addition, the COF would be increased because water was added and weakened the lubricating effect.

3.5 Wear profiles of the NPWMs

Figure 9 shows the wear profiles of the NPWMs at
2 Hz (0.09 m/s), 10 N, and 1,800 s with two different lubricating oil infusion treatments (PAO10 and PAO40) to analyze the different contributions from soaking treatment and fluorination-soaking treatment on the NPWMs’ wear-resistant responses in the dry frictional condition. Figures 9(a) and 9(b) display the wear morphology and its 3D topographies of pure NPWM after being tested in dry friction, and it shows noticeable wear scratches on the wear surface. The cross-sectional profiles of the wear scratches of the pure, soaking-treated, and fluorination-soaking-treated NPWMs are displayed in Fig. 9(c) (PAO10 infusion treatment) and Fig. 9(d) (PAO40 infusion treatment). Generally, the pure NPWM showed more significant wear scratches, with maximum values of 124 and 120 μm under two different infusion conditions. However, the maximum depths notably declined to 86 μm (in PAO10) and 83 μm (in PAO40) after soaking under the same infusion conditions. Moreover, the fluorination-soaking treatment was capable of reducing the maximum wear depths to 59 μm (in PAO10) and 56 μm (in PAO40), which were nearly twice as small as the pure NPWMs. Specifically, the soaking treatment led to a more than 30% reduction in the maximum NPWM wear depth, and the fluorination-soaking treatment continued to increase these reductions to more than 50% under the same oil infusion conditions (presented in Figs. 9(e) and 9(f)).

In addition, notable reductions occurred in the NPWM wear widths, which declined from 2,399 μm (pure) to 2,122 μm (soaking) and then decreased to 1,959 μm (fluorination-soaking) in PAO10 infusion. Similarly, 256 μm (soaking treatment), and 391 μm (fluorination-soaking treatment) reductions occurred on the wear depths in PAO40 infusion, compared to the pure NPWM with 2,313 μm.

In addition, based on the measured profile curves, we can calculate the cross-sectional area of the wear scar and wear volume using the integral principle. Representing the wear volume of the NPWM by \( V \), it might be determined by using other quantities, such as wear distance \( (L) \), wear scratch width \( (W) \), unit increment length (unit testing interval) \( \Delta x \), and the wear depth of the \( i \)th rectangle \( (f(x_i)) \). With \( \Delta x \) having a testing interval of 0.001 mm, any area \( (S_a) \) of the unit rectangle can be calculated by

\[
S_{ai} = f(x_i) \Delta x
\]

The full cross-section of the wear scratch thus had an area denoted by

\[
S_{all} = \sum_{i=1}^{W/\Delta x} S_{ai}
\]

Therefore, the whole wear volume could be calculated as

\[
V = S_{all} \times L = L \times \sum_{i=1}^{W/\Delta x} f(x_i) \Delta x
\]

The wear volumes of the different treated NPWMs were calculated; these are presented in Figs. 9(g) and 9(h). The wear rates of the pure NPWM reached 0.23 mm³ in the PAO10 infusion environment and 0.22 mm³ in the PAO40 infusion environment, and these two values experienced 31.6% and 30.9% reductions in the same lubricating oil conditions after the soaking treatment. Moreover, the fluorination-soaking treatment resulted in the lowest wear rate. Therefore, it proved that the fluorination-soaking treatment notably enhanced the wear resistance of the NPWM, which might be due to the increasing oil-absorbing and storing behaviors.

3.6 Micro-wear profiles of the NPWMs

To further investigate the wear process of NPWMs under different treatments, the wear topographies of different treated NPWMs, after conducting dry friction at 2 Hz, 10 N, and 1,800 s, were examined by scanning electron microscopy (SEM), and the results are shown in Fig. 10. The complete ducts and flat wood surface of the NPWMs are shown in Figs. 10(a), 10(a-1), and 10(a-2) before the wear tests. However, these ducts were completely out of shape and covered by debris (Fig. 10(b-1)). In addition to significant waving cracks along the friction direction on the wood surface (Fig. 10(b-2)), these critical deformation behaviors caused severe worn surfaces as well as frictional processes on the pure NPWM in dry friction. Although lubrication with PAO10 could reduce the surface deformation behaviors of pure NPWM, some significant deformations, such as almost covered ducts (Fig. 10(c-1)), and evident cracks (Fig. 10(c-2)) were
also observed. However, more slight deformations occurred on the NPWM surface after soaking treatment, therefore, the duct was not blocked and the surface was not affected by fringing deformations, even though they were clearly shaped (as shown in Figs. 10(d)–(d-2)). Moreover, the slightest deformation behaviors resembled almost complete duct structures (Fig. 10(e-1)), and slight cracks on the wood surface (Fig. 10(e-2)) occurred in the NPWM after fluorination-soaking treatment (Fig. 10(e)), which contributed to intact porous structures. The lubricating oil stored on the ducts after soaking could lead to supporting effects; thus, slight deformations occurred on the NPWM [31, 45]. Therefore, more stored lubricating oil was delivered from the inside to the contacting surfaces to improve the lubricating condition and consequently led to lower COF values compared to the pure and lubricated NPWMs.

4 Discussion

According to the different COFs, wear resistances, and micro-wear topographies shown above on the pure, soaking-treated, and fluorination-soaking-treated NPWMs, both soaking and fluorination-soaking treatment could significantly improve the NPWM wear behaviors, but the best performance was attributed to the fluorination-soaking treatment in all short-time (1,800 s) and long-time (7,200 s) frictions, and the mechanisms are schematically illustrated in Fig. 11. For the NPWMs with only soaking treatment, because of the neutral properties of PAO10 (84°) and PAO40 (87°) absorption observed in contact angle experiments (shown in Fig. 5), limited lubricating oil was absorbed and stored in the ducts after lubricating oil soaking treatments. Therefore, when the frictional ball (ceramic ball) contacted the NPWMs (Fig. 11(a)), the duct wall began to deform under the effects of frictional force and vertical load; therefore, due to the mixed external action, a part of the stored lubricating oil expelled towards the contact surface, while the other part fell vertically along the wall (Fig. 11(a-1)). With the existence of squeezed lubricating oil on the contacting surfaces, the lubricating condition was improved and led to a reduction in COFs. However, because of the limited amount of stored lubricating oil, the lubricating condition was weakened even without continuous replenishment of lubrication in long-time friction, thus causing an increase in the COF process (Figs. 11(a-2) and 7).

However, the oil absorption properties of NPWMs were significantly strengthened after the fluorination modification, which contributed to 13° in PAO10 and 19° in contact angle experiments (Fig. 5). In this case, sufficient lubricating oil would be stored in the ducts of the porous structure, and an increasing amount of stored lubricating oil would also be squeezed out under the external force and duct deformation (Figs. 11(b) and 11(b-1)); therefore, a satisfactory lubricating condition was formed, and the COF was reduced to a greater extent (Figs. 6 and 8). Moreover, sufficient storage of lubricating oil ensured continuous
replenishment of the lubricating condition, in which a low COF value was maintained for a long time (Figs. 7 and 11(b-2)).

Figures 6 and 8(b) show that the NPWMs exhibited higher COF values in the water condition than in the dry condition, even after fluorination-soaking treatment; the mechanism of this phenomenon is illustrated in Fig. 12. Under the dry condition (Fig. 12(a)), the stored lubricating oil in the ducts was squeezed from the inside and created a satisfactory oil film on the contacting surfaces, thus minimizing the COFs (Fig. 12(a-1)). However, under the water conditions (Fig. 12(b)), because of the existence of water between the contacting surfaces of the frictional ball and NPWM, the squeezed lubricating oil from the duct first enters the water and forms droplets or an oil-in-water emulsion during the reciprocating friction process (Figs. 12(b-1) and 12(c)) [46, 47]. Moreover, the buoyancy and emulsification effects caused large and small droplets of lubricating oil (Fig. 12(c)) in the water environment. Together with wood debris, these weakened the formation and lubrication effects of the lubricating oil film, so that the COF of NPWM in water was higher than that under the dry condition, with a difference of 0.022 (Figs. 12(a-2) and 12(b-2)).

5 Conclusions

The NPWM was verified its potential to work as a new natural oil-impregnated material by using its porous structure in this paper. Different NPWM friction responses after soaking and fluorination-soaking treatments in PAO10 and PAO40 lubricating oil infusion environments were revealed. More lubricating oil was stored in the NPWM porous structure because the fluorination-soaking treatment greatly enhanced the property of NPWM to absorb lubricating oil; therefore, the formation of a satisfactory lubricating film on the contact surfaces not only led to a more
than 50% reduction in friction responses but it also contributed to the most stable and lowest friction process even after long-time friction. However, although significant COF reductions occurred in NPWMs after the fluorination-soaking treatment in water medium, the lubrication condition was weakened because of the varying occurrence of oil in water; therefore, it was not as evident as that of dry friction. It is reasonable to believe that the knowledge gained herein not only verifies the strong potential of NPWM to be used as a new oil-impregnated material in the engineering field but also provides a novel methodology for the design of artificial friction materials with satisfactory properties for the storage of lubricating oil.

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