Investigation of tribological, physicomechanical, and morphological properties of resin-based friction materials reinforced with Agave americana waste

Siyang Wu*, Jian Zhuang†, Qian Wu‡, Hongyan Qi‡, Jiale Zhao†† and Mingzhuo Guo‡‡

1 Key Laboratory of Bionic Engineering (Ministry of Education, P. R. China), Jilin University, 5988 Renmin Street, Changchun 130022, People’s Republic of China
2 College of Biological and Agricultural Engineering, Jilin University, 5988 Renmin Street, Changchun 130022, People’s Republic of China

* Authors to whom any correspondence should be addressed.

E-mail: zhaojl@jlu.edu.cn and guomingzhuo@outlook.com

Keywords: Agave americana fiber, friction materials, tribological property, morphological characterization

Abstract

In recent years, natural fibers and their composites have attracted the attention of researchers due to environmental awareness and sustainable development. It is crucial to identify new natural fibers as potential reinforcement in polymer composites. This study was aimed to investigate the potential use of Agave americana fibers as a reinforcing component in resin-based friction materials. The tribological, physicomechanical, and morphological characteristics of materials containing different A. americana fiber contents were systematically evaluated. Experimental results indicated that fiber addition effectively improved the fade resistance, recovery behavior, and wear resistance of these materials. From the perspective of overall performance, a friction composite containing 5-wt% fibers possessed the optimal friction stability and wear resistance, exhibiting a fade rate of 13.6%, recovery rate of 97.5%, and sum wear rate of 2.340 × 10⁻⁷ cm³ N⁻¹ m⁻¹. Furthermore, sample worn surface morphologies were examined by scanning electron microscope, which revealed that appropriate fiber inclusion helped in the formation of secondary contact plateaus on friction surfaces. In addition, this fiber content significantly reduced abrasive and adhesive wear, which were conducive to good tribological behaviors of friction materials. This research provided a promising method for environment-friendly applications of A. americana waste.

1. Introduction

Fiber materials are widely used in automotive transport systems as brake pads/liners to control the deceleration and immobilization of vehicles quickly and reliably [1]. Fiber materials are multi-ingredient composites composed of binders (phenolic resin, nitrile butadiene rubber powder, crumb rubber, calcium oxide, etc.), fibrous reinforcements (aramid fibers, Prosopis juliflora fibers, mullite, basalt fibers, mineral fibers, etc.), friction modifiers (lubricants and abrasives, like graphite, antimony sulfide, iron sulfide, red mud, iron powder, etc.), and fillers (inert and functional, like barium sulfate, vermiculite powder, granite powder, friction dust, china clay, etc) [2–5]. Generally, more than 10–20 raw ingredients are used in friction materials to achieve a certain set of performance requirements, such as good friction stability, low fade, moderately high recovery, low noise generation, no vibration, and excellent wear resistance, as well as low wear of friction counterparts under different operating conditions [6–8]. Among these various ingredients, fibrous reinforcements are often considered essential components for maintaining thermal stability, mechanical strength, and toughness, along with altering the tribological behaviors of friction materials [9]. Asbestos fibers were once used as reinforcement in friction material industry earlier because of their availability and excellent thermal resilience. The usage of asbestos fibers has been banned since they were proved as carcinogenic materials [10]. Thereafter, the human-made synthetic fibers such as glass, ceramic, and aramid fibers, etc, metallic fibers such as steel, copper, and brass
fibers, etc., as well as combinations thereof, have been utilized in friction materials as substitutes for traditional asbestos fibers [11]. However, these synthetic fibers showed adverse effects on the environment during disposal due to their non-biodegradable nature. The heavy metallic fibers also have a disadvantage that their wear debris formed during braking process can cause immense danger to the aquatic life [12]. Considering the above problems, the need for green friction materials using biodegradable and renewable fibers is gaining wider importance.

With improved environmental protection and sustainable development consciousness, natural fibers, especially plant fibers, have received intense attention as potential reinforcements for composite materials [13, 14]. Plant fibers, such as from Leucas Aspera, Prosopis juliflora bark, Areva Javanica, hemp, bamboo, rattan, flax, sisal, and corn stalk, provide several significant advantages over synthetic fibers, including wide availability, biodegradability, renewability, light weight, relatively low cost, no or minor irritation to human eyes, skin, and respiratory system, high-specific mechanical properties, satisfactory acoustic insulation characteristics, and environment-friendly features [15–21]. Thus, many studies have been performed concerning the effects of the type, length, aspect ratio, relative content, orientation, and surface modification of plant fibers on the tribological, mechanical, thermal, and physical behaviors of friction composite materials.

Xu et al [22] have developed brake friction materials reinforced with sisal fibers and examined the effects of fiber content on tribological properties. They found that composite materials with a sisal fiber/resin ratio at 4/3 (by wt) exhibited optimal friction and wear behaviors. The friction coefficient of sisal fiber–brake materials shows relatively low fluctuation rates under different temperature conditions, compared to asbestos and steel/mineral fiber reinforced materials. Nirmal et al [23] have fabricated bamboo fiber-reinforced epoxy composites (BMBFRE) and evaluated the influence of fiber orientation (random, parallel, and antiparallel) on adhesive wear and frictional performance under dry conditions. They found that BMBFRE composites in antiparallel orientation exhibited superior wear resistance and friction behaviors at different sliding velocities compared to random and parallel orientations. The specific wear rate, friction coefficient, and interface temperature of antiparallel oriented BMBFRE composites were improved by ~60, 46.4, and 34.7%, respectively, in comparison to neat epoxy composites. El-Tayeb [24] have reported the preparation and tribological assessment of polyester composites based on sugarcane fibers under dry sliding conditions. They concluded that sugarcane fibers have positive effects on enhancing composite friction coefficient and wear resistance properties, yielding them a promising reinforcement material for tribological applications. Similarly, the naturally derived filler materials such as crab, periwinkle, scallop, palm kernel, and cashew nut shells were investigated and evaluated to develop the environment-friendly friction composite materials [10, 12, 25, 26].

Despite the above advantages of natural fibers, the hydrophilic nature and poor interfacial bonding between fibers and matrix limits the usage of natural fibers in composite materials. In order to overcome these issues, various surface modifications known as chemical treatment on natural fibers were proposed by researchers such as alkaline treatment, benzylation treatment, acetylation treatment, and silanization treatment, etc [27–29]. Among these chemical treatments, alkaline treatment has proved to be an efficient and cost-effective method, which can remove the hydrophilic constituents in fibers and improve the compatibility of reinforcement fibers with the hydrophobic matrix, leading to the enhancement of composite properties [29]. Hence, alkaline treatment was chosen as the fiber modification method in the current study.

Agave americana, belonging to the Agavaceae family, is native to Central America and Mexico, and has been successfully introduced and cultivated in Southwest and South China [30]. A. americana is widely known for its application in pulque (an alcoholic beverage) production and the resulting discarded leaves estimated to account for ~46% of the harvested plant, representing a large quantity of underutilized plant fiber resources [31]. These fibers, as lignocellulosic fibers, are mainly composed of cellulose, lignin, and hemicellulose and have been used in several applications, including in ropes, twines, yarns, textiles, and handicrafts [32, 33]. However, to the best of our knowledge, few studies have been conducted regarding the use of these fibers as reinforcing fibers in composite materials, particularly in brake friction composite materials, in spite of the fact that these fibers have interesting physical and mechanical properties, including high strength, low density, high extensibility, and high rupture energy [30, 34].

Therefore, this study focused on the preparation and performance evaluation of A. americana fiber-reinforced resin-based friction composite materials. For this purpose, five friction materials with varying fiber content were fabricated using a hot-press molding method. Then, the obtained friction materials were characterized in terms of physical, mechanical, and tribological properties. In addition, worn surface morphologies were examined and analyzed to reveal wear mechanisms in these materials. These results will not only help expand the potential application of A. americana waste, but also provide a basis for the design and development of new ecofriendly brake friction materials.
2. Experimental details

2.1. Fiber preparation

*A. americana* leaves were obtained from Kunming (Yunnan Province, China). The leaves were cleansed with distilled water and the leaf margin and tip thorns removed. After air-drying, the leaves were ground to pieces and screened with a 40–60 mesh (0.425–0.250 mm) sieve. The real images of *A. americana* leaves and fibers are shown in figure 1. Subsequently, the prepared fibers were subjected to surface treatment. They were soaked in 6-wt% aqueous NaOH for 60 min, followed by 2-wt% aqueous H₂SO₄ for 20 min, repeatedly rinsed with distilled water, and finally oven-dried at 70 °C to constant mass. The morphologies of raw and treated fibers are shown in figure 2.

2.2. Sample preparation

Five friction composite materials were prepared in this study and their detailed compositions are summarized in table 1. Among these raw materials, *A. americana* fibers and compound mineral fibers were used as reinforcing ingredients. Phenolic resin was used as a binder. Graphite, petroleum coke, antimony sulfide, and zinc stearate were used as lubricants. Alumina and porous iron powder were used as abrasives. Vermiculite powder, friction powder, and barium sulfate were used as particulate fillers. These composite materials were designated FMS-0, FMS-2.5, FMS-5, FMS-7.5, and FMS-10, depending on their *A. americana* fiber content (wt%). The preparation of friction composite samples was performed by mixing, hot-pressing, and post-curing, and the specific procedure conditions are presented in table 2. The mixing sequence of ingredients involved in this study is given in table 3. The resulting composite samples were finally machined into preset dimensions for physicomechanical and tribological tests (figure 3).
2.3. Physicomechanical characterization

The physicomechanical performances of the prepared composite samples were characterized in terms of density, hardness, and impact strength. Density measurements were carried out based on Archimedes drainage.
principle, hardness assessed using a HRSS-150 Rockwell hardness instrument, and impact strength was evaluated on an XJ-40A impact testing instrument. Hardness and impact strength tests were performed as per Chinese National Standards GB/T 5766–2007 and GB/T 5764–2011, respectively.

2.4. Tribological characterization

The tribological behaviors of composite samples were characterized in terms of friction coefficient, fade and recovery, and wear rates. Tribological tests were performed using a JF150D-II constant-speed friction tester (Wanda Machinery, Changchun, China, figure 4). The friction tester mainly consisted of control, loading, heating, cooling water, friction testing, and power systems. The samples were press-fitted onto the surface of counterpart disk using a pressurizing device, and the corresponding applied load was adjusted by the loading system. The counterpart disk was driven to rotate by a motor, and the frictional force between the samples and counterpart disk was detected by a tension-compression sensor. The temperature during the test was monitored using a thermocouple sensor and was controlled and regulated by the heating and cooling water systems. A whole test was composed of two parts: fade and recovery procedures. Detailed test procedures are described in table 4, based on Chinese National Standard GB/T 5763–2008. The friction coefficient (μ) was recorded automatically and wear rate (W) was calculated according to the following formula [35]:

$$W = \frac{1}{2\pi R} \times \frac{A}{N} \times \frac{\Delta h}{f}$$  \hspace{1cm} (1)

where $A$ (mm$^2$) is the area of the composite sample, $\Delta h$ (mm) the thickness change of the sample, $R$ (mm) the horizontal distance between the disk and sample centers (here, $R = 150$ mm), $N$ the disk rotational number, and $f$ (N) the average friction force.
The friction coefficients decrease temporarily at elevated temperatures and should be regained at lower temperatures, which are referred to as fade and recovery, respectively. These characteristics are essential for performance evaluation of friction materials. The fade \( F \) and recovery \( R \) rates were calculated according to the following formulas respectively [36]:

\[
F = \frac{(\mu_{100^\circ C} - \mu_{350^\circ C})}{\mu_{100^\circ C}} \times 100\%
\]

\[
R = \frac{\mu_{100^\circ C}}{\mu_{350^\circ C}} \times 100\%
\]

where \( \mu_{100^\circ C} \) and \( \mu_{350^\circ C} \) are the sample \( \mu \) at 100 and 350 \( ^\circ \)C during the fade procedure, respectively; \( \mu_{100^\circ C} \) the sample \( \mu \) at 100 \( ^\circ \)C during the recovery procedure.

### 2.5. Worn surface morphology characterization

After completion of tribological tests, worn surface morphologies of these materials were characterized by means of an EVO18 scanning electron microscope (SEM; Carl Zeiss AG, Oberkochen, Germany). Prior to SEM observation, samples were gold sputtered to enhance surface conductivity.

### 3. Results and discussion

#### 3.1. Physicomechanical properties

The experimental evaluation of the physicomechanical properties of these friction material samples were performed in triplicate to minimize error, and the corresponding test results are given in figures 5(a)–(c). Sample densities exhibited a downward trend with increased fiber content, with FMS-0 samples exhibiting the highest density and FMS-10 the lowest (2.34 and 2.10 g cm\(^{-3}\), respectively; figure 5(a)). It can be attributed to the factor that the density of \textit{A. americana} fibers was relatively low compared with other ingredients, and when the total mass of the friction composite samples remained unchanged, adding \textit{A. americana} fibers reduced the overall density of the polymer composites. This is in accordance with the previous research of Nishino \textit{et al} [37] for their study on the kenaf fibers reinforced composites.
The friction behavior of friction materials is directly related to the security and stability of automotive braking [42]. Friction testing was conducted to evaluate the effect of fiber content on changes in friction coefficient. The friction coefficients of FMS-0, FMS-2.5, FMS-5, FMS-7.5, and FMS-10 as a function of temperature during the fade and recovery processes showed that sample coefficients increased as the temperature increased from 100 to 150 °C and then decreased as the temperature rose to 350 °C (figure 6(a)). The increased friction coefficient might have been due to the glass transition of the binder resin in the composites [43]. The subsequent high temperature decreased friction coefficient was ascribed to the heat fade effect caused by thermal decomposition of organic components, including binder resin, compound mineral fibers, and organic fibers, at elevated temperatures [36, 44]. It was interesting to note here that the friction coefficients of the tested samples were in the range of 0.38–0.51, which was in conformity with the Chinese national standard.

During the recovery process, the friction coefficients of all samples initially increased by decreased temperature from 300 to 200 °C and then decreased with further temperature decrease to 100 °C (figure 6(b)). The recovery performance of friction materials was found to be affected by both wear debris alteration and surface layer morphology [45]. At high test temperatures, high friction coefficients were mainly attributed to wear debris formation, leading to the counterpart disk scraping. However, lower friction coefficients at lower test temperatures were primarily correlated with rheological changes between wear debris and surface layer morphology [6]. In addition, it was worth pointing out that fluctuations in friction coefficients were in a relatively stable range (0.40–0.48), which was beneficial to braking stability of friction materials [42].

The friction coefficient changes of these samples were further evaluated by determining the fade and recovery rates of composite samples. The order of fade rate was clearly FMS-0 > FMS-10 > FMS-7.5 > FMS-

![Figure 6. Friction coefficient of friction composite samples during the fade (a) and recovery (b) processes.](image-url)
2.5 > FMS-5 and the recovery rate order FMS-5 > FMS-2.5 > FMS-7.5 > FMS-10 > FMS-0 (figure 7). Sample FMS-5 presented the lowest fade rate and highest recovery rate (13.6 and 97.5%, respectively), demonstrating excellent fade resistance and recovery properties. However, sample FMS-0 had the worst performance among all samples, with a fade rate of 22.4% and recovery rate of 85.6%. These results suggested that the inclusion of these fibers improved the friction behaviors of resin-based friction materials and, in particular, sample FMS-5 showed optimal friction stability during the entire testing series.

3.2.2. Wear performance
Wear resistance, an important parameter for determining the service life of friction composites, has been found to be primarily dependent on the test temperature as well as material composition [41]. The observed variation in wear rate with test temperature showed that sample wear rates experienced a significant increasing trend with increased test temperature (figure 8(a)). This might have been due to the fact that thermal deformation and decomposition of the resin binder could cause weakening of interfacial interactions between the resin matrix and ingredients. Thus, the ingredients became loose and sometimes detached from the matrix, consequently resulting in increased wear rate [46, 47]. Similar trends have been reported by Lee et al [48] and Ji et al [44]. Notably, the wear rate of sample FMS-0 was clearly higher than other samples, especially at elevated temperatures. In addition, the sum wear rates of these samples were in the order FMS-0 > FMS-10 > FMS-2.5 > FMS-7.5 > FMS-5 (figure 8(b)). Sample FMS-5 exhibited the lowest sum wear rate \(2.340 \times 10^{-7} \text{ cm}^3\text{N}^{-1}\text{m}^{-1}\) followed by FMS-7.5, while FMS-0 achieved the highest \(2.705 \times 10^{-7} \text{ cm}^3\text{N}^{-1}\text{m}^{-1}\). These results suggested that fiber incorporation effectively enhanced the wear resistance of these composites, with 5-wt% fiber contents appearing to be the optimal proportion from the wear performance point of view.
understand the above observations, the wear mechanisms involved needed to be investigated, the details of which were presented in the section below.

3.3. Worn surface analysis

The tribological properties of friction materials are closely associated with their corresponding worn surfaces \[49\]. Here, worn surface characterizations were carried out by SEM observation to understand the effects of \textit{A. americana} fibers on wear mechanisms and tribological behaviors. SEM micrographs of worn surfaces of samples showed that the worn surface of sample FMS-0 exhibited the roughest surface topography and possessed the most wear debris, scratches, and grooves, as well as spalling pits, which corresponded to the highest wear rate of these composites (figure 9(a)). The scratches and grooves have been reported to be surface damage phenomena associated with hard particles and debris \[50\]. Generally, hard particles from resin wear debris behaved as third-body abrasives, which nicked and destroyed the worn surface, producing typical abrasive wear characteristics. In addition, cold soldering joints were easily produced between the matrix surface and counterpart disk, which then detached from the surface when subjected to shear forces, thus leading to the formation of spalling pits, indicating adhesive wear behavior \[51\]. The wear mechanisms for sample FMS-0 were thought to be predominantly abrasive and adhesive wear.

Worn surface morphologies of samples reinforced with \textit{A. americana} fibers, including samples FMS-2.5, FMS-5, FMS-7.5, and FMS-10, clearly showed relatively smoother worn surfaces, compared to FMS-0.
(figures 9(b)–(e)). Specifically, FMS-2.5 surfaces exhibited plenty of wear debris, microcracks, scratches, and grooves, together with broken fibers, which could have accounted for its high wear rate. The presence of microcracks was thought to be due to an unstable pressure and temperature field generated on the friction surface, as well as discrepancies in the thermal expansion coefficients of different zones, leading to typical fatigue wear characteristics [50]. For sample FMS-5, a high amount of secondary plateaus, some fine wear debris, and a few slight scratches were found on the worn surface, with polished fibers showing only a little breakage, which indicated a preferable interface adhesion between the fibers and composite matrix. The secondary contact plateaus formed on friction surfaces were believed to contribute to enhanced friction stability and wear resistance performances of this sample type [40]. The presence of secondary contact plateaus was mainly due to the accumulation and compaction of wear debris under the combined action of shearing forces, normal pressure, and friction heat [52, 53]. The present observations might have correlated with the optimal tribological behaviors observed in sample FMS-5 and, in particular, with its lowest wear rate. Worn surfaces of sample FMS-7.5 were covered with some particles and debris pieces, shallow parallel scratches, bare fibers, fiber-shedding pits, and a few secondary contact plateaus, which agreed with its slightly reduced wear resistance with respect to sample FMS-5. For FMS-10, numerous wear particles and debris, obvious scratches and grooves, microcracks, and fiber-shedding pits were observed on worn surfaces, which are indicative of aggravated wear of the friction surface. The reason for this observation was that too many fibers in the friction material negatively affected the fiber-matrix interface bonding strength, which then easily allowed fiber pullout and shedding under applied frictional forces, resulting in increased wear rate [35].

4. Conclusions

This study evaluated the possibility of using A. americana fibers as reinforcement fibers in friction composite materials. The effects of fiber content on the tribological, physicomechanical, and morphological characteristics of prepared fiber-reinforced friction materials were examined. The main conclusions drawn were:

(1) As A. americana fiber content increased, the density and hardness of the obtained composite materials exhibited a downward trend, while impact strength showed no specific changes and sample FMS-7.5 presented the maximum impact strength, at 0.491 J cm$^{-2}$, followed by sample FMS-5, at 0.478 J cm$^{-2}$.

(2) The incorporation of A. americana fibers apparently improved the fade resistance and recovery properties of the composite samples. Remarkably, the best friction stability was obtained in sample FMS-5, with a fade rate of 13.6% and recovery rate of 97.5%.

(3) A. americana fibers were also effective for enhancing the wear resistance of resin-based friction materials. Notably, among all tested samples, sample FMS-5 (sum wear rate: $2.340 \times 10^{-7}$ cm$^{3}$ N$^{-1}$ m$^{-1}$) exhibited the best performance, followed by sample FMS-7.5 ($2.426 \times 10^{-7}$ cm$^{3}$ N$^{-1}$ m$^{-1}$).

(4) The SEM results revealed that appropriate fiber addition (specifically 5-wt%) not only facilitated secondary contact plateau formation on friction surfaces, but also significantly reduced abrasive and adhesive wear, which explained the improved tribological performances of these samples.

Overall, the obtained results of the present study provided evidence that adding A. americana fibers appropriately improved the tribological, physicomechanical, and morphological properties of the polymer composites. Thus A. americana fibers can be effectively used as reinforcing components in the development of resin-based brake friction composite materials, which expanded the environment-friendly application of A. americana waste.

Acknowledgments

The research was financially supported by the National Key Research and Development Project of China (No. 2018YFA0703300), the Natural Science Foundation of China (No. 52075215), the China Postdoctoral Science Foundation (No. 2020M670854), and the Science and Technology Development Plan Project of Jilin Province (Nos. 20190301023NY, 20190701055GH, and 20200404008YY).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
References

[1] Manoharan S, Vijay R, Singaravelu D L and Kchauo M 2019 Experimental investigation on the tribo-thermal properties of brake friction materials using various forms of graphite: a comparative study Arab. J. Sci. Eng. 44 1459–73
[2] Manoharan S, Krishnan G S, Babu L G, Vijay R and Singaravelu D L 2019 Synergetic effect of red mud-iron sulfide particles on fade-recovery characteristics of non-asbestos organic brake friction composites Mater. Res. Express 6 035311
[3] Rajan B S, Balaji M A S and Saravanan K S 2018 Effect of chemical treatment and fiber loading on physico–mechanical properties of Prospis juliflora fiber reinforced hybrid friction composite Mater. Res. Express 6 035302
[4] Manoharan S, Shihab A I, Alendrar A S A, Babu L G, Vijay R and Singaravelu D L 2019 Influence of recycled basalt-aramid fibres integration on the mechanical and thermal properties of brake friction composites Mater. Res. Express 6 115310
[5] Mahale V, Bijwe J and Sinha S 2019 Efforts towards green friction materials Tribol. Int. 136 196–206
[6] Li Z, Liao W, Zhou H, Hou S, Zhuang Q, Li J and Jin H 2018 Effects of the shapes and dimensions of mulitle whisker on the friction and wear behaviors of resin-based friction materials Wear 406 118–25
[7] Ozuruk B and Ozuruk S 2011 Effects of resin type and fiber length on the mechanical and tribological properties of brake friction materials Tribol. Lett. 42 339–50
[8] Hinrichs R, Soares M R F, Lamb R G, Soares M R F and Vasconcellos M A Z 2011 Phase characterization of debris generated in brake pad coefficient of friction tests Wear 270 515–9
[9] Bakhout M, Cristol A L, Desplanques Y and Elleuch R 2015 Impact of the glass fibers addition on tribological behavior and braking performances of organic matrix composites for brake lining Wear 330 507–14
[10] Rajan B S, Balaji M A S, Noorni A B M A, Khatteeb M U H, Harirharasakthisudan P and Doss P A 2019 Tribological performance evaluation of newly synthesized silane treated shell powders in friction composites Mater. Res. Express 6 085317
[11] Mustafa A, Abdollam M F B, Shuhimi F, Ismail N, Amiruddin H and Umebora N 2015 Characterization and verifcation of kenaf fibres as an alternative friction material using Weighted Decision Matrix method Mater. Des. 67 577–82
[12] Singaravelu D L, Vijay R and Filip P 2019 Influence of various cashew friction dusts on the fade and recovery characteristics of non-asbestos copper free brake friction composites Wear 426 1129–41
[13] Shah D U 2013 Developing plant fibre composites for structural applications by optimising composite parameters: a critical review J. Mater. Sci. 48 6083–107
[14] Shalwan A and Yousif B F 2013 In state of art: mechanical and tribological behaviour of polymeric composites based on natural fibres Mater. Des. 48 14–24
[15] Vijay R, Manoharan S, Arjun S, Vinod A and Singaravelu D L 2020 Characterization of silane-treated and untreated natural fibres from stem of Juncus aspera J. Nat. Fibers 1–17
[16] Rajan B S, Saibalalaji M A and Mohideen S R 2019 Tribological performance evaluation of epoxy modified phenolic FC reinforced with chemically modified Prospis juliflora bark fiber Mater. Res. Express 6 075313
[17] Md J A, Saibalalaji M A, Rajan B S and Liu Y 2019 Characterization of alkaline treated Arenga javanica fiber and its tribological performance in phenolic friction composites Mater. Res. Express 6 115307
[18] Ramesh M, Palanikumar K and Reddy K H 2017 Plant fibre based bio-composites: Sustainable and renewable green materials Renew. Sust. Energ. Rev. 79 556–64
[19] Shah D U, Schubel P J, Licence P and Clifford M J 2012 Hydroxyethylcellulose surface treatment of natural fibres: an alternative preparation and optimization for composites applicability J. Mater. Sci. 47 2709–17
[20] Saha P, Manna S, Chowdhury S R, Sen R, Roy D and Adhikari B 2010 Enhancement of tensile strength of lignocellulosic jute fibers by alkali-steam treatment Bioreos. Technol. 101 3182–7
[21] Ettaati A, Mehdizadeh S A, Wang H and Pathar S 2014 Vibration damping characteristics of short hemp fibre thermoplastic composites J. Reinfr. Plast. Comp. 33 330–41
[22] Xin X, Xu Y, C G and Qing L F 2007 Friction properties of sisal fibre reinforced resin brake composites Wear 262 736–41
[23] Nirmal U, Hashim J and Low K O 2013 Adhesive wear and frictional performance of bamboo fibres reinforced epoxy composite Tribol. Int. 67 122–33
[24] El-Tayeb N S M 2008 A study on the potential of sugarcane fibers/polyester composite for tribological applications Wear 265 233–35
[25] Singaravelu D L, Rahul R M, Vijay R, Manoharan S and Kchauo M 2019 Development and performance evaluation of Eco-frieNdly crab shell powder based brake pads for automotive applications Int. J. Auto. Mech. Eng. 16 6502–23
[26] Rajan B S, Balaji M A S and Ab M A N 2019 Effect of silane surface treatment on the physico-mechanical properties of shell powder reinforced epoxy modified phenolic friction composite Mater. Res. Express 6 065315
[27] Vijay R, Manoharan S, Vinod A, Singaravelu D L, Sanjay M R and Siengchin S 2019 Characterization of raw and benzoyl chloride treated Impomea pes-caprae fibers and its epoxy composites Mater. Res. Express 6 095307
[28] Vijay R, Singaravelu D L, Vinod A, Sanjay M R, Siengchin S, Jawaid M, Khan A and Parameswaranpillai J 2019 Characterization of raw and alkali treated new natural cellulosic fibres from Tridax procumbens Int. J. Biol. Macromol. 125 99–108
[29] Sentharmarai Kannan P and Kathiresan M 2018 Characterization of raw and alkali treated new natural cellulosic fiber from Coccusia grandis L. Carbohyd. Polym. 186 332–43
[30] Mshali S, Jaoudi M, Sakli F and Drem J Y 2015 Study of the mechanical properties of fibers extracted from Tunisian Agave americana L. J. Nat. Fiber 12 552–60
[31] Hernández-Hernández H M, Chanona-Pérez J J, Vega A, Ligerio P, Mendoza-Pérez J A, Calderón-Dominguez G, Terrés E and Ferrera-Rebollo R R 2016 Acetosolv treatment of fibers from waste agave leaves: influence of process variables and microstructural study Ind. Crop. Prod. 86 163–72
[32] Mylamn K and Rajendran I 2011 Influence of fibre length on the wear behaviour of chopped agave americana fibre reinforced epoxy composites Tribol. Lett. 44 75–80
[33] Basu G, Roy A N, Satapathy K K, Abbas S M J, Mishra L and Chakraborty R 2012 Potentiality for value-added technical use of Indian sial Ind. Crop. Prod. 36 33–40
[34] El Oudiani A, Chaabouni Y, Mshali S and Sakli F 2011 Crystal transition from cellulose I to cellulose II in NaOH treated Agave americana L. fibre Carbohydr. Polym. 86 1221–9
[35] Ma Y, Wu S, Tong J, Zhao X, Zhanj J, Liu Y and Qi H 2018 Tribological and mechanical behaviours of rattan-fibre-reinforced friction materials under dry sliding conditions Mater. Res. Express 5 035101
[36] Ma Y, Wu S, Zhanj J, Tong J, Xiao Y and Qi H 2018 The evaluation of physico-mechanical and tribological characterization of friction composites reinforced by waste corn stalk Materials 11 901
[37] Nishino T, Hirao K, Koter M, Nakamae K and Inagaki H 2003 Kenaf reinforced biodegradable composite Compos. Sci. Technol. 63 1281–6
[38] Ma Y, Wu S, Zhanj J, Tian Y, Qi H and Tong J 2019 The effect of lignin on the physicomechanical, tribological, and morphological performance indicators of corn stalk fiber-reinforced friction materials Mater. Res. Express 6 105325
[39] Boz M and Kurt A 2007 The effect of Al2O3 on the friction performance of automotive brake friction materials Tribol. Int. 40 1161–9
[40] Ma Y, Wu S, Zhanj J, Tong J and Qi H 2019 Tribological and physico-mechanical characterization of cow dung fibers reinforced friction composites: an effective utilization of cow dung waste Tribol. Int. 131 209–11
[41] Wang Z, Hou G, Yang Z, Jiang Q, Zhang F, Xie M and Yao Z 2016 Influence of slag weight fraction on mechanical, thermal and tribological properties of polymer based friction materials Mater. Des. 90 76–83
[42] Ma Y, Liu Y, Wang L, Tong J, Zhanj J and Jia H 2018 Performance assessment of hybrid fibers reinforced friction composites under dry sliding conditions Tribol. Int. 119 262–9
[43] Wu Y, Zeng M, Xu Q, Hou S, Jin H and Fan L 2012 Effects of glass-to-rubber transition of thermosetting resin matrix on the friction and wear properties of friction materials Tribol. Int. 54 51–7
[44] Ji Z, Jin H, Luo W, Cheng F, Chen Y, Ren Y, Wu Y and Hou S 2017 The effect of crystallinity of potassium titanate whisker on the tribological behavior of NAO friction materials Tribol. Int. 107 213–20
[45] Kumar M and Bijwe J 2010 NAO friction materials with various metal powders: tribological evaluation on full-scale inertia dynamometer Wear 269 826–37
[46] Cai P, Wang Y, Wang T and Wang Q 2015 Effect of resins on thermal, mechanical and tribological properties of friction materials Tribol. Int. 87 1–10
[47] Wang Z Y, Wang J, Cao F H, Ma Y H, Tej S and Guštáv F 2019 Influence of banana fiber on physicomechanical and tribological properties of phenolic based friction materials Mater. Res. Express 6 075103
[48] Lee J J, Lee J A, Kwon S and Kim J 2018 Effect of different reinforcement materials on the formation of secondary plateaus and friction properties in friction materials for automobiles Tribol. Int. 120 70–9
[49] Wang F and Liu Y 2014 Mechanical and tribological properties of ceramic-matrix friction materials with steel fiber and mullite fiber Mater. Des. 57 449–55
[50] Correa C E, Betancourt S, Vázquez A and Gañan P 2015 Wear resistance and friction behavior of thermoset matrix reinforced with Musaceae fiber bundles Tribol. Int. 87 57–64
[51] Betancourt S, Cruz L J and Toro A 2011 Effect of the addition of carbonaceous fibers on the tribological behavior of a phenolic resin sliding against cast iron Wear 272 43–9
[52] Eriksson M and Jacobson S 2000 Tribological surfaces of organic brake pads Tribol. Int. 33 817–27
[53] Menapace C, Leonardi M, Perricone G, Bortolotti M, Straffelini G and Gialanella S 2017 Pin-on-disc study of brake friction materials with ball-milled nanostructured components Mater. Des. 115 267–98