Proceedings of the Estonian Academy of Sciences,
2022, **71**, 2, 186–193
https://doi.org/10.3176/proc.2022.2.03
Available online at www.eap.ee/proceedings

COMPOSITES MATERIALS AND SUSTAINABILITY

Tribological and circular economy aspects of polypropylene/cotton fibre hybrid composite

Abrar Hussain[a*], Vitali Podgursky[a], Dmitri Goliandin[a], Maksim Antonov[a], Rahul Kumar[a], Nikhil Kamboj[a], Ramin Rahmani Ahranjani[a], Mart Viljus[a], Tahir Ahmad[b], Muhammad Mubashir Farid[d], Muhammad Mujtaba Abbas[e], Andres Krumme[f] and Illia Krasnou[f]

[a] Department of Mechanical and Industrial Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia
[b] Department of Mechanical Engineering, Universitat Politechnica De Catalunya (UPC)-Barcelona Tech, Barcelona, Spain
[c] Department of Mechanical Engineering, The Superior University Lahore, Lahore, Punjab, Pakistan
[d] Department of Mechanical Engineering, Faculty of Engineering, Lahore Leads University, Lahore, Pakistan
[e] Department of Mechanical Engineering, University of Engineering and Technology, New Campus Lahore 54890, Pakistan
[f] Department of Materials and Environmental Technology, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

Received 4 June 2021, accepted 1 October 2021, available online 16 May 2022

Abstract. The circular economy is emerging as green technology solution for polymer and composite industries. However, the use of circular economy as an industrial practice is still a global challenge. In this article, polypropylene-cotton hybrid composite was developed using different amounts of cotton fibre waste (0, 10, 30, 40 wt%). Scanning electron microscope (SEM), tribometer, Rockwell hardness tester and binocular microscope were used for investigations of composite surface, hardness and coefficient of friction (COF). The mean coefficient of friction values was 0.64, 0.75, 0.88 and 0.94 for pure propylene, 10, 30 and 40% of cotton reinforced composites, respectively. The scanning electron microscopy characterization of hybrid composite revealed the voids, porosity and asperities due to random fibres orientation. The Rockwell hardness value of composites was increased due to rise of fibre fraction. Based on the COF values, hardness and surface characterization, polypropylene-cotton reinforced hybrid composite could be used functionally for thermal and sound applications.

Keywords: polymer composites, tribology, wear, cotton fibres, thermal conductivity, sound isolation, circular economy.

1. INTRODUCTION

Circular economy deals with industrial system to manufacture products with least waste [1]. The application of green technology has led to utilizing natural and artificial fibre-reinforced composites in civil, automobile and electronic industries. Commonly, injection moulding and extrusion processes are used for composites synthesis [2,3]. Composites are usually made up of fibres and matrix materials that bind fibres together. The matrix as a bulk material also provides reasonable abrasive, erosion and fatigue resistance against environmental impacts. The fibres impart strength and stiffness to composites materials [4].

Natural fibres are composed of hollow cellulose fibrils, lignin and hemicellulose. The amount of fibres has a direct impact on properties such as tensile strength, modulus of elasticity and hydrophilicity. The fibre-matrix interface acts as a binder, load transfer, fibre wettability improver, degradation resistor and mechanical properties controller. These properties favour the use of natural fibres in composites manufacturing industries. The synthetic fibres like polyesters, rayon, nylon and spandex are being replaced by natural fibres such as cotton, sisal, bamboo,

* Corresponding author, abhuss@taltech.ee

and hemp due to their low cost, biodegradability, non-toxicity and light weight [5,6].

The tribological studies of both synthetic and natural polymeric composite materials are rising. A lot of research work has been reported on the tribological performance of synthetic fibre reinforcement composites [7,8]. However, little work has been published for the tribological investigation of natural fibre reinforcement hybrid composites. A higher coefficient of friction has been reported for jute, cotton, sugarcane, and kenaf reinforcement composites [9]. The fibre orientation, percentage of fibre fraction, binding agent, nature of matrix polymer and nature of fibre polymer optimized the wear resistance, abrasion behaviour, fibre-matrix adhesion and wear rate of hybrid composite [10].

In this research work, polypropylene-cotton fibre (PP/CF) composite has been developed for the first time using compression moulding. Post-consumer cotton waste and polypropylene were used as reinforcement and matrix materials. The PP/CF composites were fabricated with various fibre contents for thermal and sound applications. The coefficient of friction was determined for practical applications. Neither binder nor mixing agents were added to ensure cost-effectiveness of the composite. The developed composites were tested and characterized by CETR tribometer, Rockwell hardness, Micro-Vickers, binocular and SEM microscopes, respectively. Moreover, the current study mainly focuses on the investigations of tribological behaviour of composites toward environmental impacts.

2. MATERIALS AND METHODS

2.1. Materials

Post-consumer cotton and virgin polypropylene materials were used for PP/CF composite development. The cotton polymer and polypropylene (PP) contribute to reinforcement and resistance behaviour of hybrid composite, respectively [11]. The purchased PP has 0.92 g/mL density, molecular weight (M_w) 120000 g/mol and 31 g/10 min melt flow index (ASTM D 1238). PP was chosen as matrix material due to reasonable fiber wettability, low fabrication temperature, and to provide a good tribological (damage) resistance. However, cotton polymer waste was milled using a developed prototype model. The machine was run at 300 rpm for 10 min. The cotton polymer was filtered using different sieves. The SEM was used for fibre size and diameter measurement. The cotton had 1.55 g/cm^3 density, 5–25% elongation range, 220 N tensile force, 270 N effective tensile force, 212 N breaking force and 237 g/m^2 weight.

The mixing temperature, time and speed were kept at 190 °C, 7 min and 80 rpm. Different amounts of cotton fibre (0, 10, 30, 40 wt%) were mixed with PP to fabricate a hybrid composite. Table 1 shows the formulation of composites.

Table 1. PP/CF hybrid composite formulation procedure

Cotton fibre content (wt%)	Matrix content (wt%)	Net weight of fibre (g)	Net weight of matrix (g)
0	100	0	300
10	90	30	270
30	70	90	210
40	60	120	180

2.2. Formation of hybrid composites

The post-consumer cotton woven fabric of the Estonian local garment industry was used as natural fibre reinforcement. The cotton wastes include similar yarn counts, weight, densities and fabric codes. Before milling, the cotton polymer was cut into small pieces with a shredding machine. After cutting, the direct grinding process was utilized for cotton disintegration into small fibres. The fibre length and diameter were measured using SEM.

The melt-mixing of cotton fibres and PP was done and plasticorder compounder was used under optimized manufacturing conditions for composite formation. The melting temperature, time, rotor torque and speed were controlled at 190 °C, 7 min, 60 Nm and 80 rpm. Initially, the weighed PP was funnelled inside the mixing chamber using a metallic tube. In the next step, the weighed cotton fibres were added. The matrix and fibres were mixed for 7 mins at 50 rpm. Finally, the composite was extruded in the form of a wire shape. The composite product was ground and milled into desired grain size. The ground composite was transformed into 1 mm, 3 mm and 6 mm thick square sheets using compression moulding. The heating time, pressure and temperature were kept at 7 min, 80 kg cm^{-2} and 190 °C, respectively. The compressed sheets were cooled at room temperature for 5 min.

2.3. Tribological and hardness testing methods

The sliding tests were performed using the ASTM G132-96 standard. Silicon carbide (SiC) sandpapers were used to study the COF [12]. The composites were cut into 5 × 5 × 15 mm small pins. The CETR UMT-2 tribometer was introduced for sliding. The speed, load, and sliding track distance were 0.1 m s^{-1}, 1 N and 70 mm, respectively. The composites pins covered periodically an 18 m linear abrasive path in 3 minutes. The wear tests were repeated five times for average COF values. The tests were performed at room temperature at relative humidity of 60%.

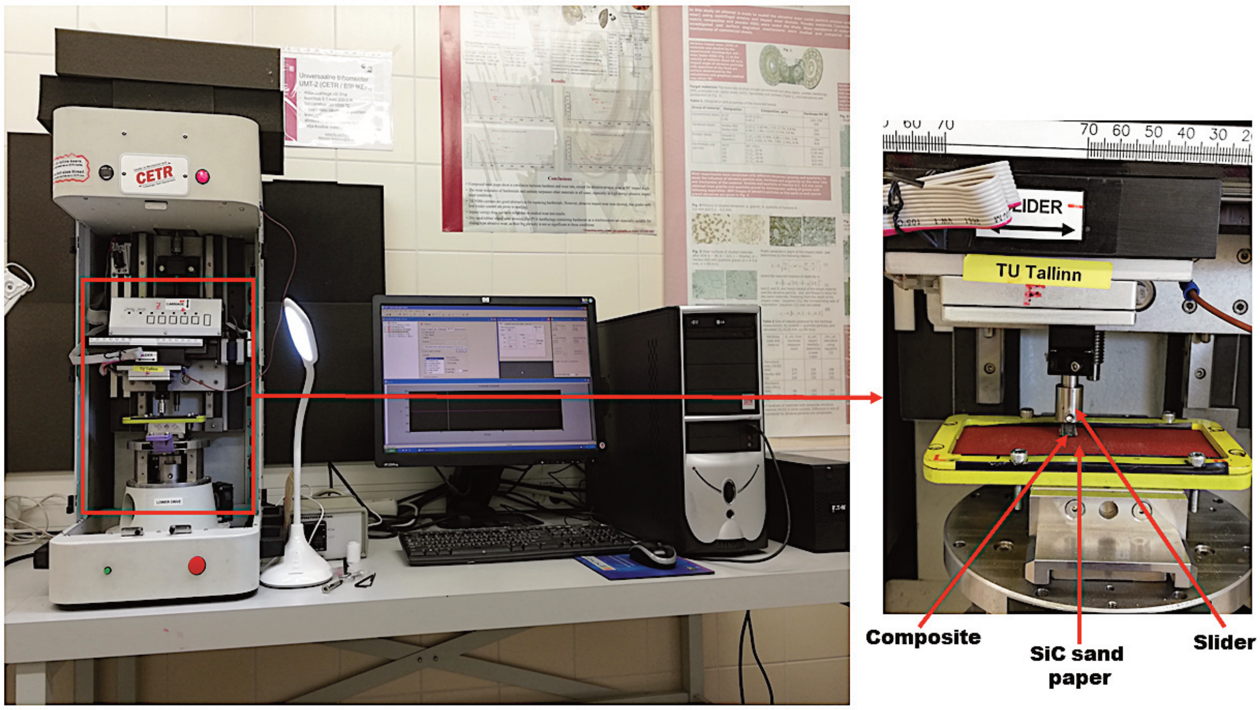

Fig. 1. Experimental setup for tribological investigations.

Rockwell hardness test (HR15W scale) was performed to measure composites surface hardness. The EN ISO 20392-2000 standard was used. The surface evaluation of PP/CF composite was done before and after tribology testing.

3. RESULTS AND DISCUSSION

The surface characterization of PP/CF was done using SEM. The matrix phase holds the fibres together, transfers the load, and protects from environmental impacts, distortion and damage. The thermoplastic PP provides lower degradation temperature and fibre wettability during processing as compared to another plastic matrix [2,10].

The cotton fibres were found to be randomly oriented and discontinuous. During the use of PP/CF composite material, cotton fibres impart strength, reinforcement and stiffness. Binocular and SEM microscopes were used for fibre length, diameter and area determination. About 20 to 50 random fibre fragments were selected manually for characterization. The fibre length varied from 1.5 to 6 mm, being about 3 mm in average. The labels 1, 2, 3 and 4 in Fig. 2a indicate the remains of yarn length up to 10 mm, interwind fibres, loose interwind fibres and fibre fraction of very short length (below 1 mm), respectively. According to the longitudinal view of fibres, the fibres have an irregular cylindrical shape. Moreover, the cotton fibre is composed of aligned microfibrils, lignin and hemicellulose. The structure was porous, it absorbed water and impurities. The microfibrils are attached to a core of fibre through lignin. The combination of these factors makes fibres structure porous naturally. The fibres during composite fabrication aligned themselves along the direction of panels and the porosity of fibres becomes minimum due to chemical and physical bonding with matrix material. Additionally, the SEM micrographs of pure PP and composites with 10%, 30% and 40% fibre loading are presented in Fig. 3a–d, respectively. Figure 3a shows the SEM micrograph of pure PP (reference material). The surface of reference materials has good surface finishing with almost minimum surface defects. Figure 3b–c show the same results with reasonable fibre distribution. However, an increase in fibre fraction produces internal voids, asperities and other surface defects due to poor bonding between matrix and cotton fibres, see Fig. 3d.

The effect of sliding distance, time and fibre fraction on COF is shown in Fig. 4a and b. The COF variations are shown in Table 2. The composite did not show constant response. The COF values were increased due to an increase in fibre contents. The higher fibre contents create asperities, voids and other surface defects. These surface

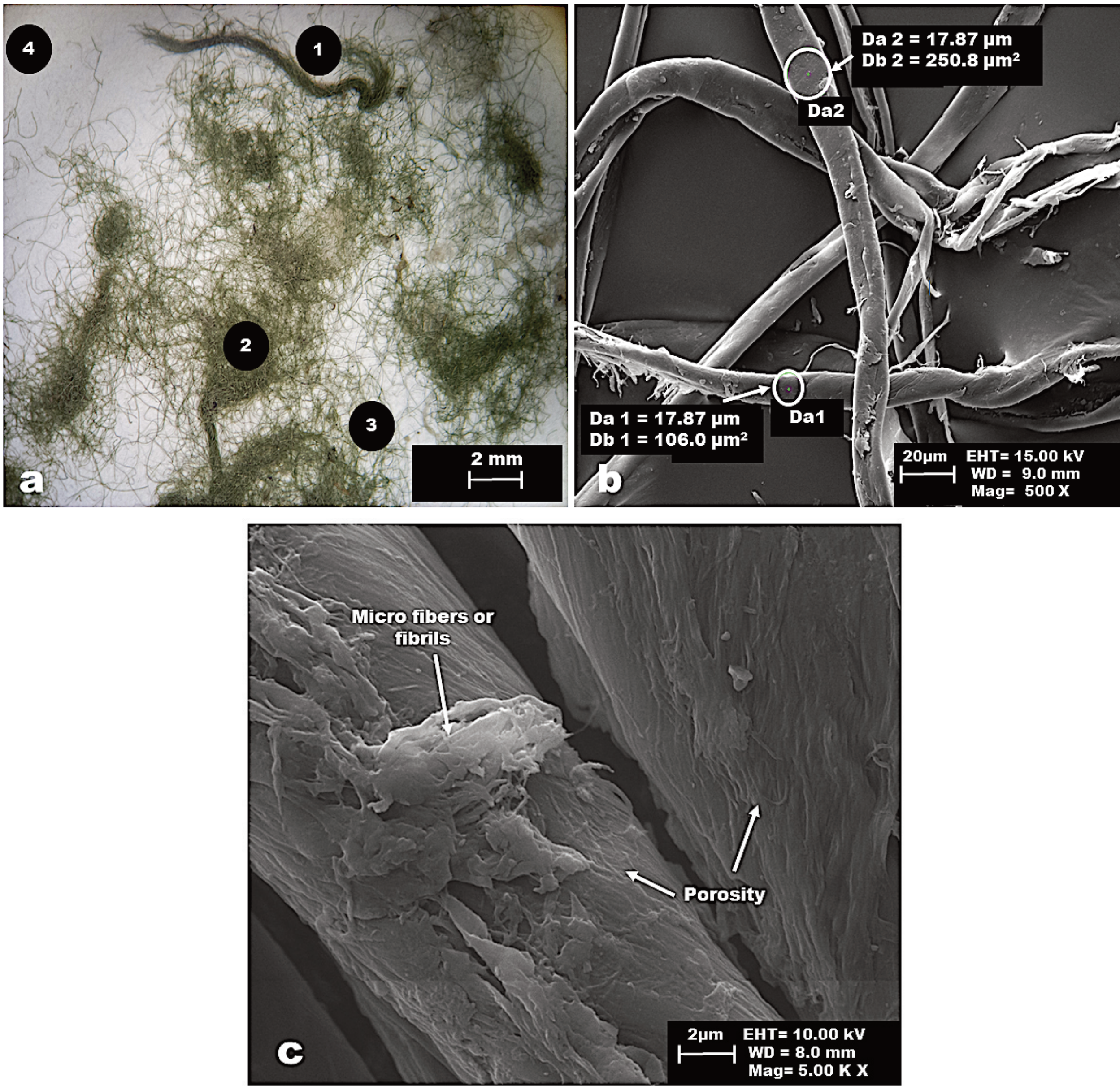

Fig. 2. Ground cotton fibers: (a) binocular optical image, (b) SEM image, (c) microfibrils and porosity on fibre surface.

defects produce resistance during interactions between composites and SiC sandpaper. According to Fig. 4b and Table 2, the value of COF increased from 0.75 to 1.22 due to an increase in fibre content. The increase in fibre fraction helps composite to produce resistance against elastic and plastic deformation [13]. Moreover, the cotton fibres present in PP matrix phase act as reinforcement phase.

Figure 5 demonstrates the effect of cotton fibres additions on the hardness of PP/CT hybrid composites. The Rockwell hardness value increased with an increasing amount of fibre fractions [14]. The obtained results were similar to some previous research. The fibre addition enlarged the composite resistance towards plastic deformation. Therefore, a rise in fibre fractions makes composite harder.

The SEM micrographs of PP/CF composites before and under the sliding condition at 0.1 m s^{-1} speed, 1 N applied load and 18 m sliding distance are shown in Fig. 6a and b. Some fibres of composites in the bundle were pulled out due to matrix damage and debonding of fibres. The pores, asperities, voids, debris are formed due

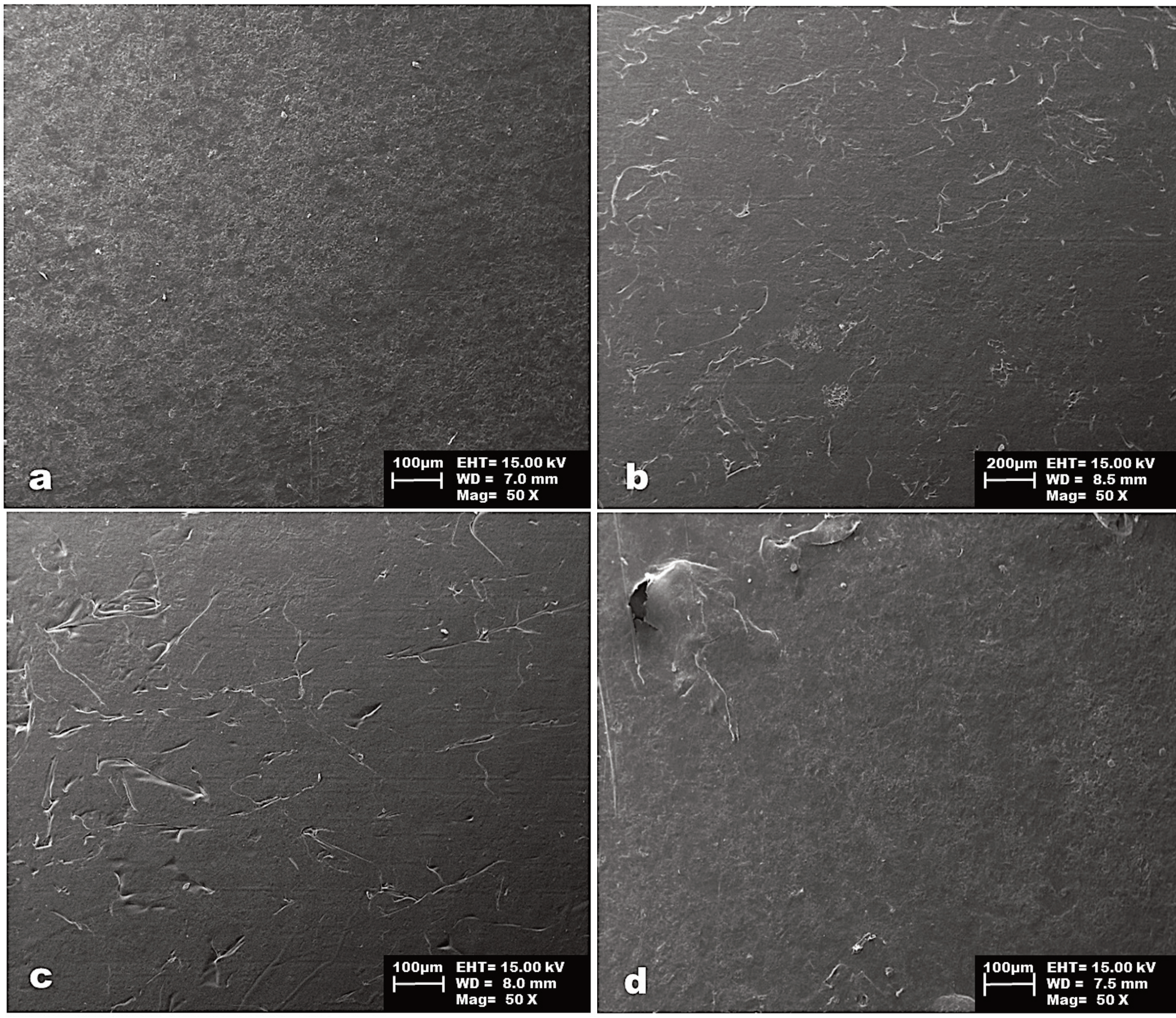

Fig. 3. SEM micrographs of pure PP and various composites fabricated through compression molding: (a) pure PP, (b) 10% cotton fibre fraction, (c) 30% fibre content and (d) 40% fibre content.

to random orientation of bundle of fibres, stress concentrations and thermal stresses [8]. These defects and effects cause physical bending, micro-cracks and severe damage to the surrounding of fibrous region.

The rough surface texture of cotton imparts a high degree of compactness and cohesion. The physical parameters like density, weight, porosity, twist factor play vital role. The higher weight and density offer huge compactness and low fibrillation. Therefore, random orientation and arrangement produce high porosity [8,14–17].

The thermal and sound properties majorly rely on the nature of fibre, porosity, voids and microstructure of composite. These defects along with cotton fibres trapped a large amount of air. Therefore, it slows down the thermal and acoustic behaviour of the developed composite.

The compression molding, sliding tribological testing, hardness testing and SEM characterization results make PP/CT hybrid composite suitable for thermal insulation and sound isolations for automotive and building applications. The mechanical evaluations play a vital role in transforming the open-system recycling into closed-system recycling (sustainable and green products) [18,19]. The conventional (open-system manufacturing) routes of polymer production do not provide the desired physical, surface, thermal, and chemical properties. However, the concept of closed-system manufacturing and recycling allow commercial industries to get desired mechanical properties [1,20].

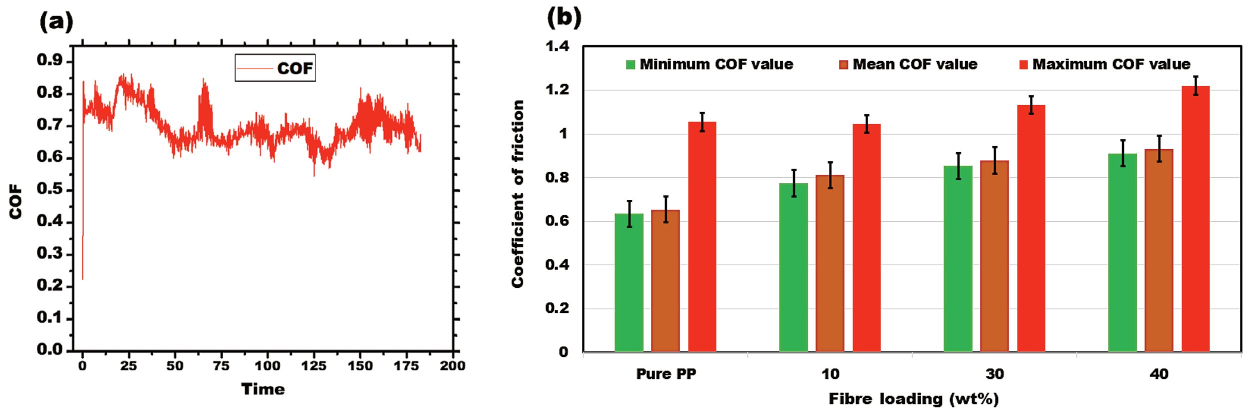

Fig. 4. (a) COF vs sliding time, (b) COF vs fibre loading for product design.

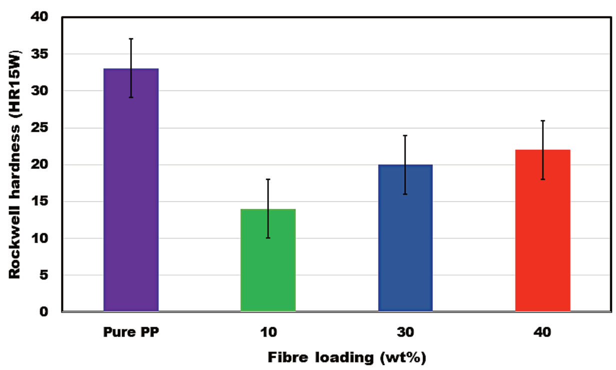

Fig. 5. Rockwell hardness and fibre loading relationship.

Table 2. PP/CF hybrid composite tribology response

Cotton fibre content (wt%)	Minimum coefficient of friction	Maximum coefficient of friction	Mean coefficient of friction
0	0.634	1.054	0.645
10	0.754	1.043	0.811
30	0.853	1.132	0.879
40	0.911	1.220	0.932

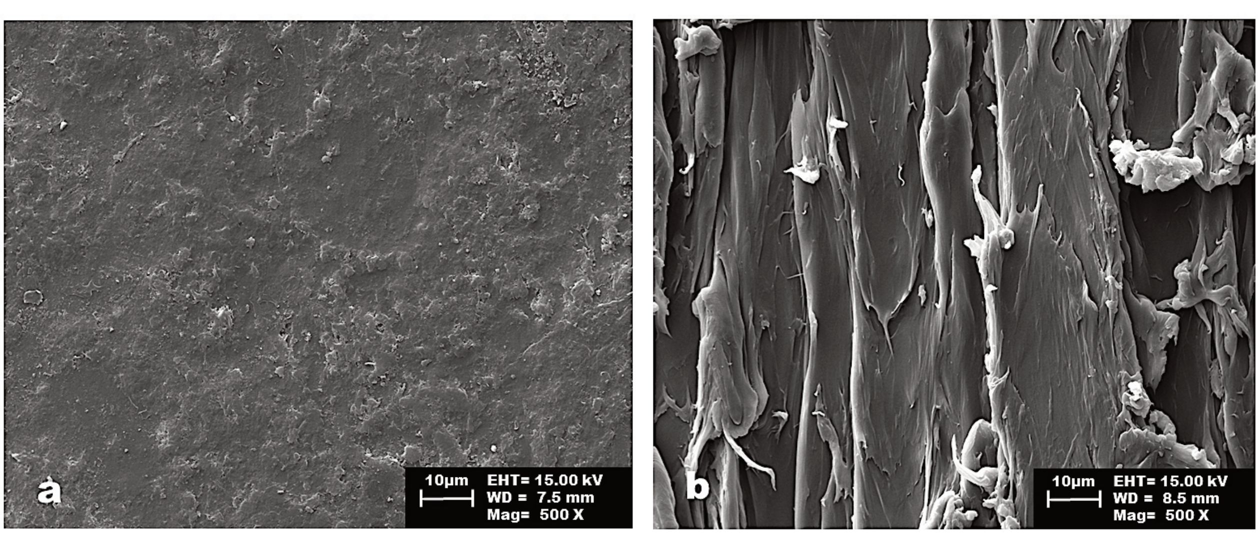

Fig. 6. PP/CF composites before (a) and after (b) sliding test.

4. CONCLUSIONS

The sustainable and cost-effective polypropylene-cotton fibre composite has been developed using compression moulding. The surface evaluation of composite was performed to investigate the coefficient of friction, surface hardness and surface defects. The matrix and fibres were shown reasonable protection against environmental impacts and wettability during processing, respectively. During SEM analysis, porosity, asperities and voids were detected as surface defects.

The minimum, average and maximum COF values of composites were found in the range of 0.65 to 1.05, 0.75 to 1.04, 0.85 to 1.35 and 0.91 to 1.22 for pure PP, 10%, 30%, and 40% amount of cotton fibres. The COF variations were found due to reported composite defects. Moreover, the Rockwell hardness values were 33 HR15W, 13 HR15W, 19 HR15W and 23 HR15W for pure PP, 10%, 30%, and 40% fraction of cotton fibres. The hardness value enhances due to the harder surface and fibre fraction. The PP/CT hybrid composites could be used as a sustainable and green technology candidate for automotive, industrial and construction applications.

ACKNOWLEDGEMENTS

The study was financially supported by Ministry of Research and Education, Republic of Estonia, and Tallinn University of Technology. The publication costs of this article were covered by the Estonian Academy of Sciences.

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Polüpropüleen-puuvillakiu hübriidkomposiidi triboloogilised ja ringmajanduslikud aspektid

Abrar Hussain, Vitali Podgursky, Dmitri Goliandin, Maksim Antonov, Rahul Kumar, Nikhil Kamboj, Ramin Rahmani Ahranjani, Mart Viljus, Tahir Ahmad, Muhammad Mubashir Farid, Muhammad Mujtaba Abbas, Andres Krumme ja Illia Krasnou

Polümeeri- ja komposiiditööstuses tõuseb üha enam esile ringmajandus kui rohetehnoloogiline lahendus. Ülemaailmselt on ringmajanduse rakendamine tööstuses siiski endiselt suur väljakutse. Antud uuringus töötati välja polüpropüleen-puuvill hübriidkomposiite, kasutades 0, 10, 30 ja 40 massiprotsenti puuvillakiu jäätmeid. Komposiitide pinna uurimiseks ning kõvaduse ja hõõrdeteguri mõõtmiseks kasutati skaneerivat elektronmikroskoopi, binokulaarmikroskoopi, tribomeetrit ja Rockwelli kõvadusmõõtjat. Puhta polüpropüleeni hõõrdetegur oli 0,64 ning 10%, 30% ja 40% puuvillakiu sisaldusega komposiitidel oli see vastavalt 0,75; 0,88 ja 0,94. Komposiitide elektronmikroskoopiline uuring näitas puuvillakiudude ebaühtlase jaotuse ja orientatsiooni tulemusel struktuuris tekkinud poore ja tühikuid. Komposiitide kõvaduse väärtused Rockwelli skaalas kasvasid koos puuvillakiudude osakaalu suurenemisega. Hõõrdeteguri, kõvaduse ja pinnauuringute põhjal võib puuvillakiuga tugevdatud polüpropüleen-hübriidkomposiite kasutada soojus- ja heliisolatsioonimaterjalidena.