

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

185,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Tribological Properties of Polyester Composites: Effect of Vegetable Oils and Polymer Fibers

Ibrahim Refaay Ahmed and Ali Waheed Yousry

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/39230>

1. Introduction

Short fiber reinforced polymer composites are nowadays used in numerous tribological applications. In spite of this fact, new developments are still under way to explore other fields of application for these materials and to tailor their properties for more extreme loading conditions. [1]. Polyester composites are commonly used nowadays in industrial applications such as bearing materials, brake pads materials, flooring materials and so on. The references given at the end of this chapter describe some of these developments. [2]. Further approaches in designing polymeric composites in order to operate under low friction and low wear against steel counterparts are described. In this work polyester composites was reinforced with graphite or polymer fibers filled with some vegetable oils are proposed to be used as self-lubricated materials, so friction coefficient and wear rates were measured. Due to the great changes in technology that occurred in the last century, a large number of components fabricated in engineering polymers and composites have been used; substituting the most traditional metals in diverse applications, attaining in many cases better advantages as reduction of maintenance costs, save in weight and higher freedom for designing. Some examples of applications can be cited as: self-lubricant bearings, linear guides, mechanical seals, bushings, bearings cages, transporting belts, gears, and pulleys. These components are in turn more required in the aspects of mechanical resistance, fatigue strength and resistance to wear. [3]. Analysis of the wear resistance of polymeric fibres requires a better understanding of both their abrasive scratch behaviour and their frictional response. [4]. Fiber Reinforced Plastics (FRP) are widely used as structural materials in industrial applications, for example, marine boats, automobiles and bathtubs due to their light weight, high degree of rigidity and superior moldability.[5]. Polymers have been favorably introduced as sliding materials in offshore structures for over ten years because of good wear resistance. Mainly under high loads, surface plasticity

contributes to low friction, which is favorable for a reduction in dissipated sliding energy. [6]. In industrial applications, the increase in using composite materials means that it is necessary to know their behaviour under working conditions. Wear is an important parameter and its experimental behaviour must be known. [7]. Polymers are frequently used in tribological applications because of their self-lubricating ability and loadability. However, most research on their friction and wear mechanisms is performed on small-scale test samples under relatively low normal loads. [8]. As polymers generally possess good self-lubricating abilities through the formation of a polymer transfer film or 'third body', they are also used in industry as sliding materials in gears, slides and bearings. While polyamides or polyethylene are most commonly used, they should be replaced by polyesters for obtaining higher temperature and fatigue resistance because of the stiffening action of the aromatic phenylene group. [9]. Fibre-Reinforced-Polymer composites are used particularly in the automotive and aircraft industries and the manufacture of spaceships and sea vehicles. [10]. There are the two main characteristics which make these materials attractive compared to conventional metallic designs. They are of relatively low density and they can be tailored to have stacking sequences to provide high strength and stiffness in directions of high loading, [11]. Composite materials consist of a resin and reinforcement chosen according to desired mechanical properties and the application, [12]. Polyesters are also commonly used as matrix materials, particularly with glass-fibre-reinforcement. Polyester is an economic material that has high chemical resistance and is resistive to environmental effects. It has high dimensional stability and low moisture absorption. Low-volume-fraction glass-fibre/ polyester composites with a wide range of colors have been in use for a long time. The production technologies for thermoset glass/polyester composites are easier and cheaper than those for other glass/resin materials. Glass-fibre-reinforced polymer with thermoset polyester resin is an attractive material that is economically desirable. Its application at low temperatures and under service terms is easy when this material is compared to advanced polymer composites with a complex molecule structure, high strength and working under terms of difficult service, [13].

1.1. Adhesion bonds

When two surfaces are brought into contact, the surface forces of attraction and repulsion act between the atoms and molecules of two approaching surfaces. Due to these forces the bonds formed between the contacting surfaces are followed by junctions developed on the real contact spots. Formation and rupture of the junctions control the adhesion component of friction. For the majority of polymers, the hydrogen bond develops at very short distance in polymers containing the groups OH, COOH, NHCO and others, in which the hydrogen atom is linked with an electronegative atom. Under favorable conditions two approaching atoms are linked together by a common proton providing a strong and stable compound. The junctions sheared under the applied tangential force result in the frictional force. That is, work done by the frictional force results from breakdown of the interfacial bonds. In general case, the interfacial junctions (their formation, growth and fracture) are influenced by nature of the surfaces, surface chemistry and stresses in the surface layers (loading conditions). The interfacial junctions together with products of their fracture and the highly deformed layers where shear deformation is localized, were named by Kragelskii as a 'third body', [14].

1.2. Real contact area

When two surfaces approach each other, their opposing asperities with maximum height come into contact. As the load increases, the new pairs of asperities with lesser height make contact forming individual spots. The overall area of these spots is known as the real contact area (RCA). When simulating the real contact concept with plastics, the temperature and sliding velocity should be taken into account. [15].

1.3. Wear of polymers

1.3.1. Wear modes

The changes in surface layer arise from mechanical stresses, temperature and chemical reactions. Polymers due to their specific structure and mechanical behavior are more sensitive to these factors. The local temperature at the interface may be substantially higher than that of the environment, and may also be enhanced at the asperity contacts by transient 'flashes' or 'hot-spots'. The temperature exerts an influence on wear of polymers. Thus, it was shown that a number of polymers sliding against steel pass a minimum at characteristic temperature. The great diversity of the mechanisms and their interrelation make impossible the rigorous classification of wear processes. It is generally recognized that the most common types of wear of polymers are abrasion, adhesion, and fatigue. [16].

a. Abrasive wear

The key aspect of abrasive wear relates to cutting or plowing of the surface by harder particles or asperities. These cutting points may either be embedded in the counter-face, or loose within the contact zone. The former case is commonly called two-body abrasion, and the latter, three-body abrasion. Abrasion displays scratches, gouges, and scoring marks on the worn surface, and the debris produced by abrasion frequently take on the appearance of fine cutting chips similar to those produced during machining, although at a much finer scale. Most of the models associated with abrasive wear incorporate geometric asperity descriptions, so that wear rates turn out to be quite dependent on the shape and apex angles of the abrasive points moving along the surface. The sources of the abrasive solid are numerous, and the nature of the abrasive wear in a given tribosystem will depend to some extent on the manner in which the abrasives enter the tribosystem: whether they are present in the original microstructure as hard phases, enter the system as contaminants from outside, or generated as debris from the contact surfaces as they wear. There are two distinct modes of deformation when an abrasive particle acts on the plastic material. The first mode is plastic grooving, often referring to as ploughing, in which a prow is pushed ahead of the particle, and material is continually displaced sideways to form ridges adjacent to the developing groove. No material is removed from the surface. The second mode is named cutting, because it is similar to micromachining and all the material displaced by the particle is removed as a chip. In the case of three-body abrasion the free abrasive readily penetrates the polymeric surface which begins to operate as an emery cloth resulting in increasing the wear of counter surface, [17].

b. Adhesion wear and friction transfer

Adhesion wear results from the shear of the friction junctions. The fundamental mechanism of this wear is adhesion, important component of friction outlined above. This wear process evolves in formation of adhesion junction, its growth and fracture. A distinguishing feature of this wear is that transfer of material from one surface to another occurs due to localized bonding between the contacting solid surfaces. It was noted that the transfer of polymer is the most important characteristic of adhesive wear in polymers. It is reasonable that the processes associated with other wear types (fatigue, abrasion and so on) accompany the adhesive wear. The phenomenon of friction transfer is observed for nearly all materials (metals, ceramics, and polymers) and their combinations. The point is that whether the transfer produces an influence on tribological behavior of the friction pair. In this case, the consequences of material transfer may be significantly distinct. If small particles of micrometer size are transferred from one surface to the other, then wear rate varies to only a small extent. Under certain conditions, the situations take place when thin film of soft material is transferred onto the hard mating surface, for example, polymer on metal. [18].

c. Fatigue wear

Fatigue is known to be a change in the material state due to repeated (cyclic) stressing which results in progressive fracture. Its characteristic feature is accumulation of irreversible changes, which give rise to generation, and development of cracks. The similar process takes place at friction accompanying nearly all the wear modes. A friction contact undergoes the cyclic stressing at rolling and reciprocal sliding. In addition, each asperity of friction surface experiences sequential loading from the asperities of counter surface. As a consequence, two varying stress fields are brought about in surface and sub-surface regions with different scales from the diameter of apparent contact area in the first case to that of local contact spot in the second. These fields are responsible for material fatigue in these regions that leads to the generation and propagation of cracks and the formation of wear particles. This process is named friction fatigue. Unlike the bulk fatigue, it spans only surface and sub-surface regions. The loss of material from solid surfaces owing to friction fatigue is referred to as fatigue wear. It has been known that the fatigue cracks are initiated at the points where the maximum tangential stress or the tensile strain takes place. [19].

2. Experimental work

The investigation of wear and friction was carried out to examine the effect of adding vegetable oils and fibers on the tribological behavior of polyester.

2.1. Description of test rig

Experiments were carried out using "pin-on-disc" test rig, figure 1. It consists of a rotary horizontal steel disc of 170 mm diameter and 5 mm thickness driven by variable speed motor, Specimen holder, this holder fastened to the load cell, loading plat at which the normal loads were applied, and digital screen attached to the load cell.



Figure 1. Pin-on-Disk Tribometer

2.2. Test specimens

Test specimens were formed in shape of cylindrical pins of 5 mm diameter and 30mm height, Fig. 2.

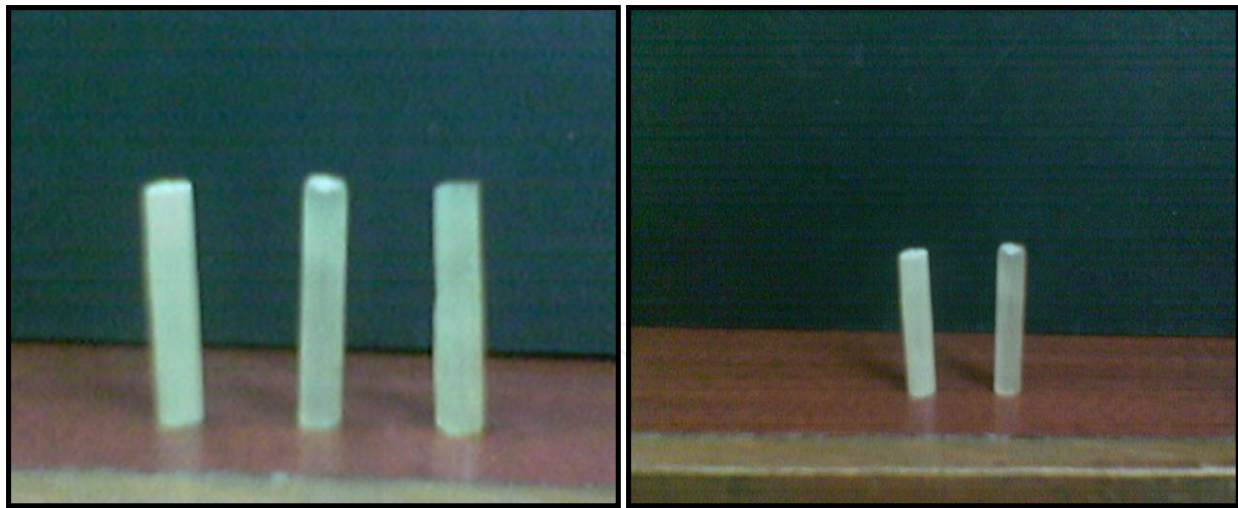


Figure 2. Test Specimens

2.3. Preparation of test specimen

Polyester was mixed with vegetable oils in volumetric ratio from 1 to 10% for unfilled specimens, or filled by some fibers with volumetric ratio from 1 to 5% for filled specimens after well mixing the mixture was molded into a paper mold then left it for two days for solidification before tests.

2.4. Experiments

Tests were carried out at room temperature and normal level of humidity by means of "pin-on-disc" tribometer. Polyester composites were held in specimen holder and loaded against the rotating steel counterface, due to the contact between composites and steel disc a tangential force try to resist the rotating disc, this force depending on the friction coefficient of composites and it was monitored by the digital screen. These forces measured at 190 rpm (0.696 m/s) under variable normal loads 4, 6, 8, and 10 N. friction coefficient calculated by dividing the friction force by the applied load. Wear was determined by measuring the change in composite volume before and after adhesion between the composites and the steel counterface for 5 minutes at 20 N normal load and counterface rotational speed of 100 rpm (0.366m/s). The following equations explain the calculations of wear and friction coefficient.

$$\text{Wear} = \text{Volume loss} = \Delta V = (L_1 - L_2) * A \quad (1)$$

$$\text{Friction coefficient} = \mu = F_f / F_n \quad (2)$$

Where,

L_1 = Length of specimen before test, mm.

L_2 = Length of specimen after test, mm.

A = Friction surface area = $(\pi/4) d^2$, mm².

d = Specimen diameter, mm.

F_f = Friction force N, and

F_n = Normal force N.

3. Results and discussion

Test specimens were divided into two groups, unfilled and filled polyester, the first one divided into three groups according to the type of oil as follows:

1. Polyester impregnated by olives oil.
2. Polyester impregnated by corn oil.
3. Polyester impregnated by sunflower oil.

Each composite divided into two subgroups according to the filler type as follows:

1. Composite filled by polyamide fiber.
2. Composites filled by polytetrafluoroethylene PTFE fiber.

3.1. Unfilled polyester

3.1.1. Frictional behavior of polyester impregnated by olives oil

Friction coefficient decreases to 0.35 with increase of oil contents to 10% by volume of olives oil under low applied loads, it seems that there is an oil film generates at the friction surface and increases with oil content increase, which may be responsible for friction reduction, figure 3.

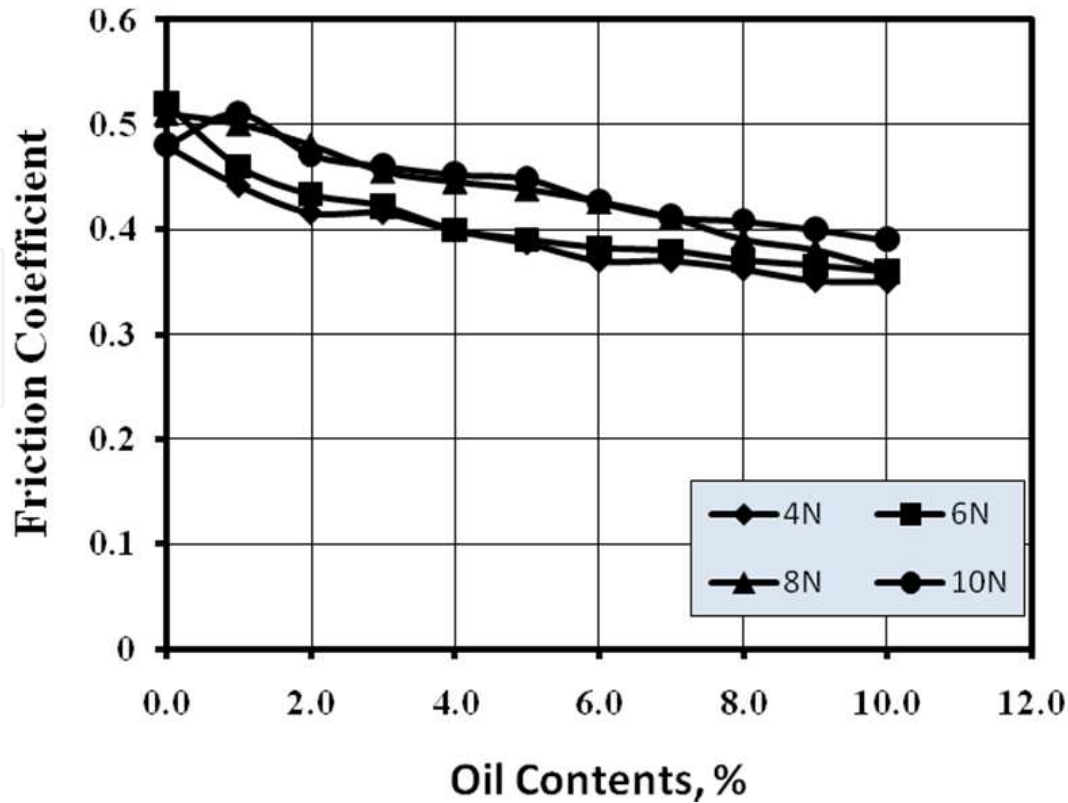


Figure 3. Frictional behavior of polyester impregnated by olives oil

3.1.2. Frictional behavior of polyester impregnated by corn oil

Increases of corn oil in composites decrease friction coefficient to minimum at maximum oil percent and low applied loads, figure 4. It seems that the increase in oil content increases oil film at friction surface which decreased the friction coefficient.

3.1.3. Frictional behavior of polyester impregnated by sunflower oil

Figure 5. shows that the increase of oil contents in composites decreases friction coefficient to 0.33 for composites of 10% by volume of sunflower oil, beside it shows that there is low effect of applied load in friction coefficient; it seems that the increase in sunflower oil contents increases surface hardness of composite which may be responsible for friction reduction.

3.1.4. Wear results of polyester impregnated by vegetable oils

Figure 6. shows that increase of olives, corn or sunflower oils in polyester composites decreased wear drastically to very little values in compare with polyester specimens free of oils, the amount of wear decreased from 3.37 mm³ for free polyester to 0.3 mm³ for composite impregnated by 10 vol. % sunflower oils. This can be attributed to the formation of oil film in the contact area which responsible for wear reduction as well as increase of surface hardness for specimens impregnated by sunflower oils.

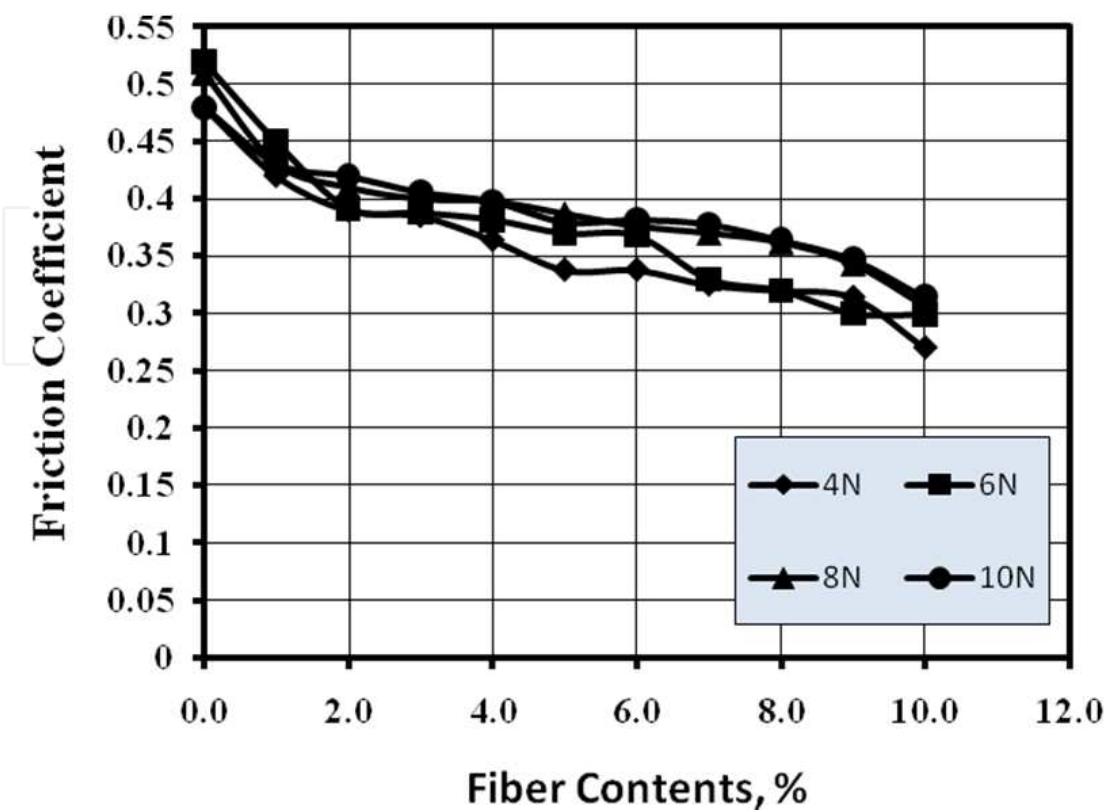


Figure 4. Frictional behavior of polyester impregnated by corn oil

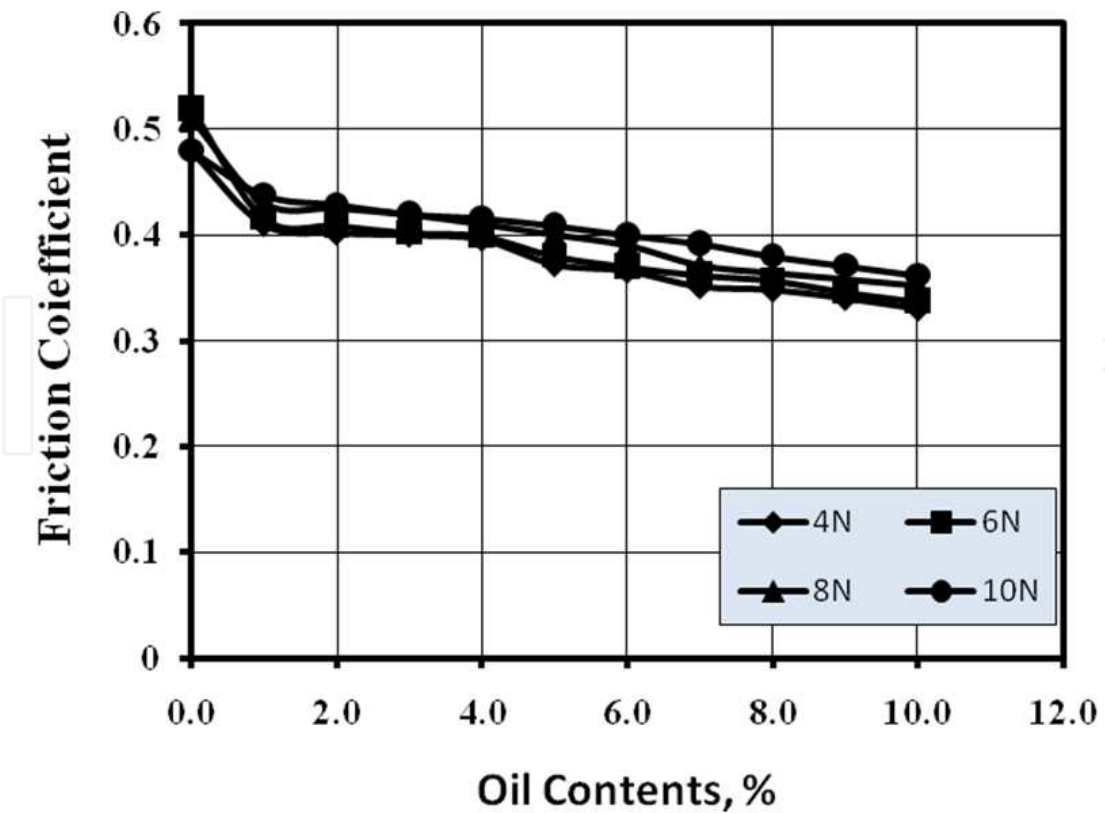


Figure 5. Frictional behavior of polyester impregnated by sunflower oil

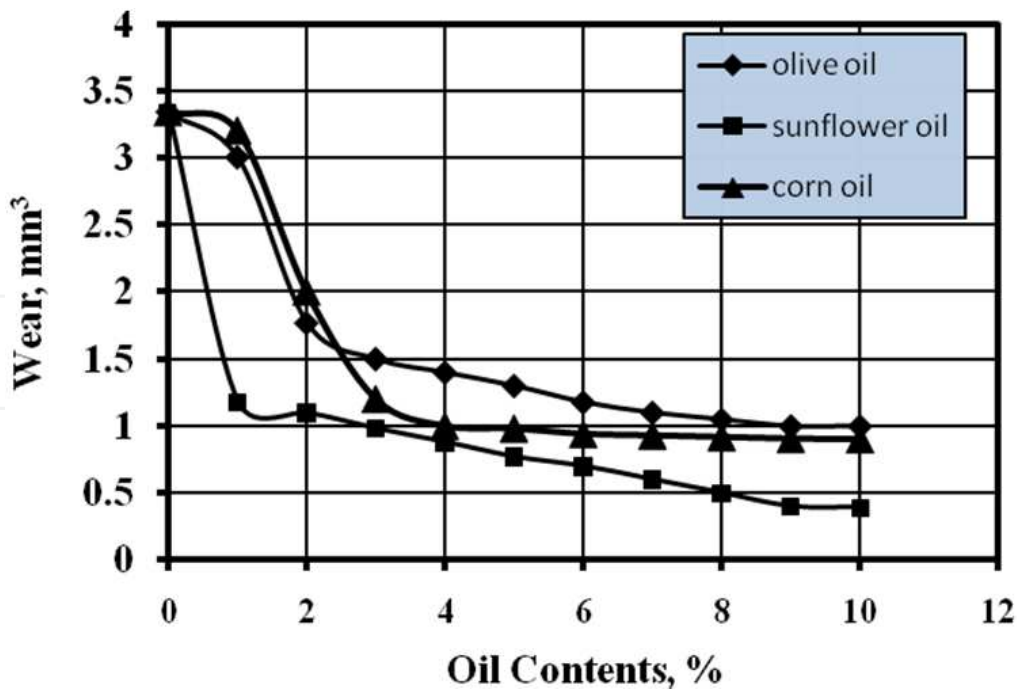


Figure 6. Wear results of polyester impregnated by vegetable oils

3.2. Polyester composites reinforced with polyamide fiber

3.2.1. Frictional behavior of polyester composite free of oil

Figure 7. shows that the increase in fiber content for composite free of oil decreases friction coefficient to 0.22 for composite of 4 % polyamide contents, under 4N. Beside it shows there are great effect for applied loads on friction results. It seems that the increase in fiber content increases the polyamide layer on the friction surface which may be responsible for friction reduction.

3.2.2. Frictional behavior of polyester composites impregnated by olives oil

Friction results of composite impregnated by olive oil shown in figure 8. Increase of fiber contents decreases friction coefficient to 0.183 for composite of 5% fiber content under 6N. This figure shows that there were low effects of applied loads in friction results. The effects of oil increasing in composite shows outstanding friction results, friction coefficient decreases to 0.153 for composite of 1 % fiber content and 10% by volume of olives oil. This recommended these composite as good bearing material under high loads, fig. 9.

3.2.3. Wear results of polyester composites impregnated by olives oil

Wear results of composite impregnated by 5 and 10 % oil content shows remarkably decreases in wear of composite contain 10 % oil content , it reached to 0.196 mm³ for composite of 4 % fiber content, fig. 10., it may be attributed to the ability of oil film at frictional surfaces to reduce polyester transfer to counterface. That reduce composites wear.

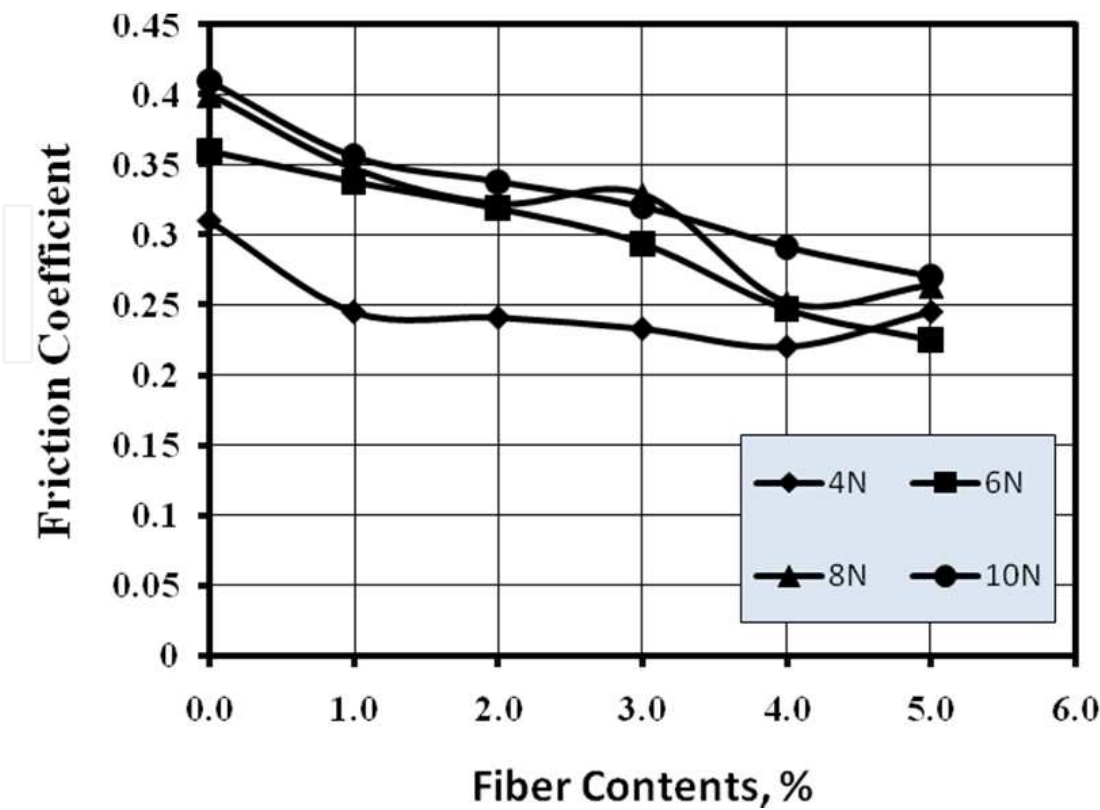


Figure 7. Frictional behavior of polyester composite free of oil reinforced by polyamide fiber

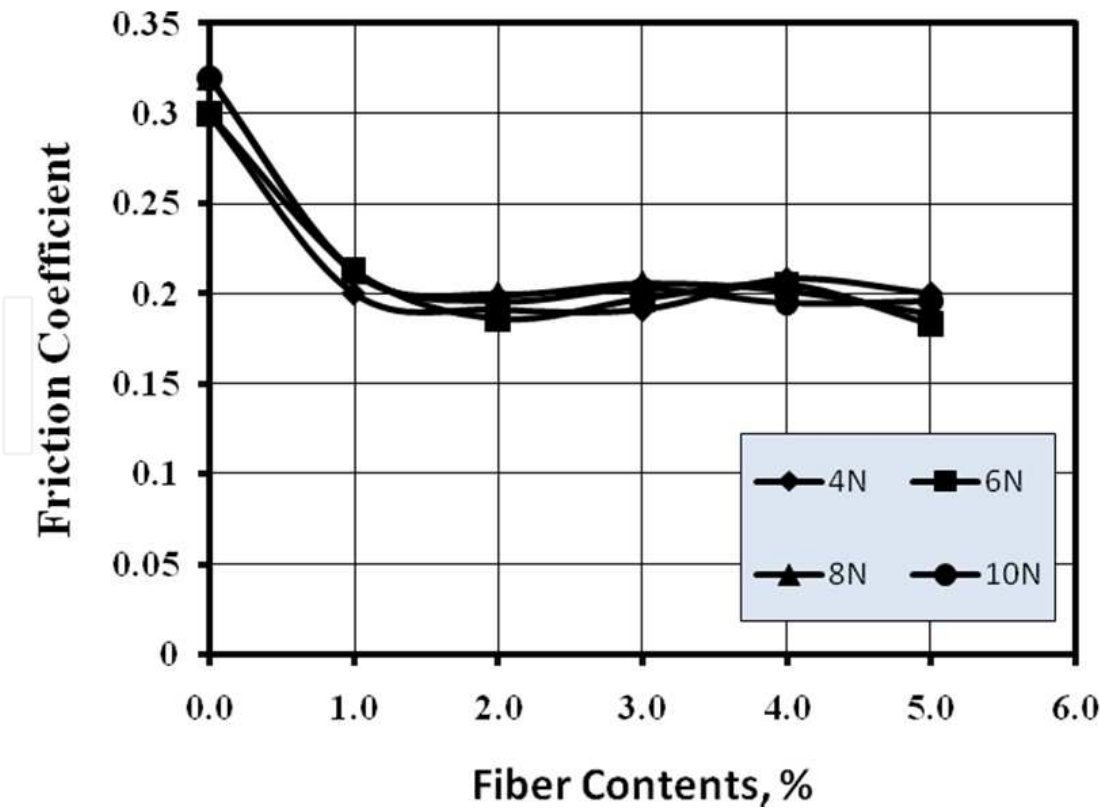


Figure 8. Frictional behavior of polyester composite impregnated with 5.0 vol. % olives oil

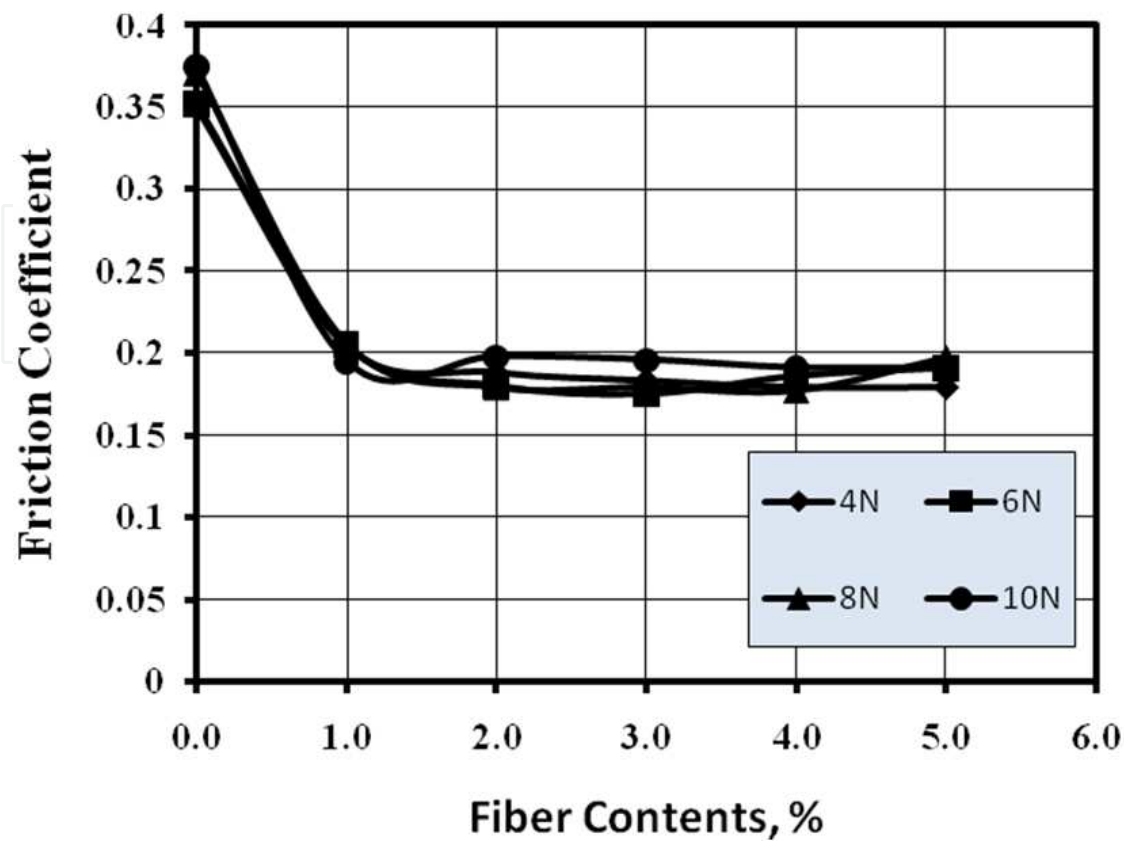


Figure 9. Frictional behavior of polyester composite impregnated with 10 vol. % olives oil

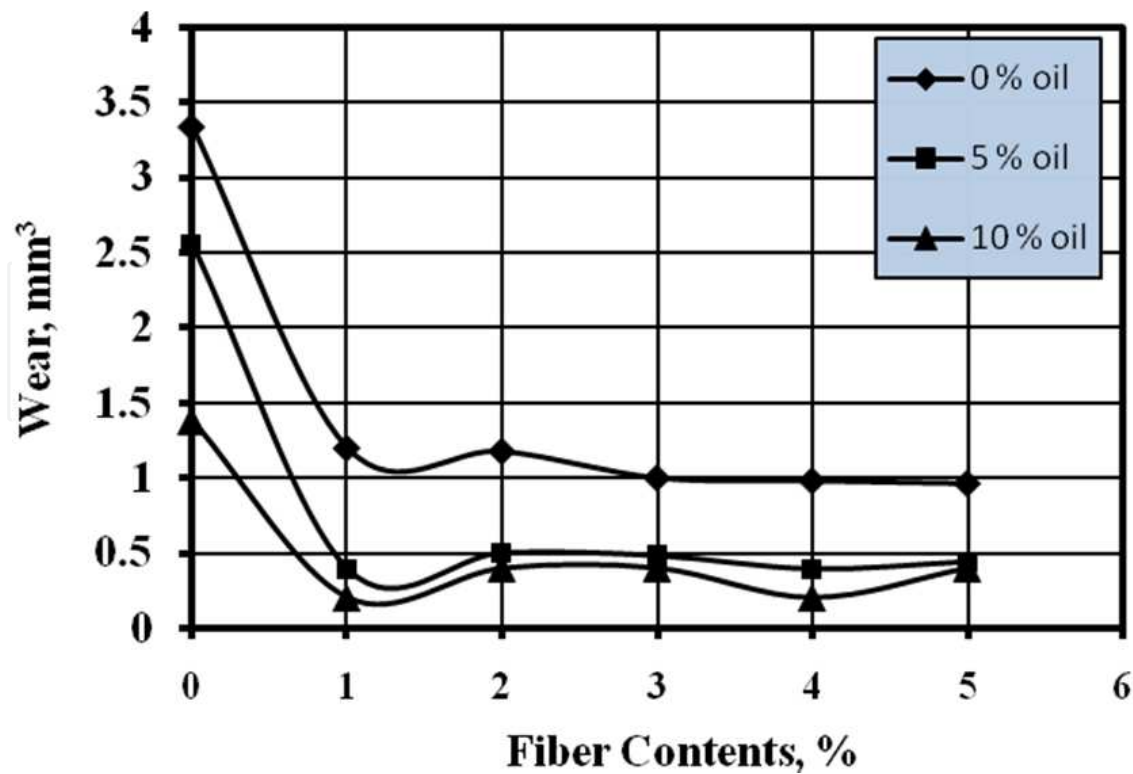


Figure 10. Wear of polyester composite impregnated by olives oil

3.2.4. Frictional behavior of polyester composites impregnated by corn oil

Increase of corn oil in composite shows great effect especially with fiber content increasing this was represented in figure 11. It shows that the friction coefficient was decreased to 0.187 for composite of 4 % fiber content. It may be attributed to the increase of oil layer at friction surface. Furthermore, it could be stated that the effect of applied load was decreased in high fiber composite contents. Composite impregnated by 10% by volume of corn oil shows good friction results as fiber content increase, friction coefficient decreases to 0.17 for composite of 5 % fiber content under 10N, fig. 12., beside it show that there is low effect of applied load on friction results. These results recommended those composite as good bearing material.

3.2.5. Wear results of polyester composites impregnated by corn oil

Wear results of composite free of oil shows decrease trend with increasing of fiber content, it may be attributed to the ability of polyamide layer for decreases polyester transfer to counterface. Composite impregnated by 5 and 10% by volume of oil content shows significantly decreases in wear to 0.215 mm³ for composite of 5 % fiber content and 10% oil content, it seems that the increase in oil content increases the presence oil layer which may be responsible for wear reduction, fig. 13.

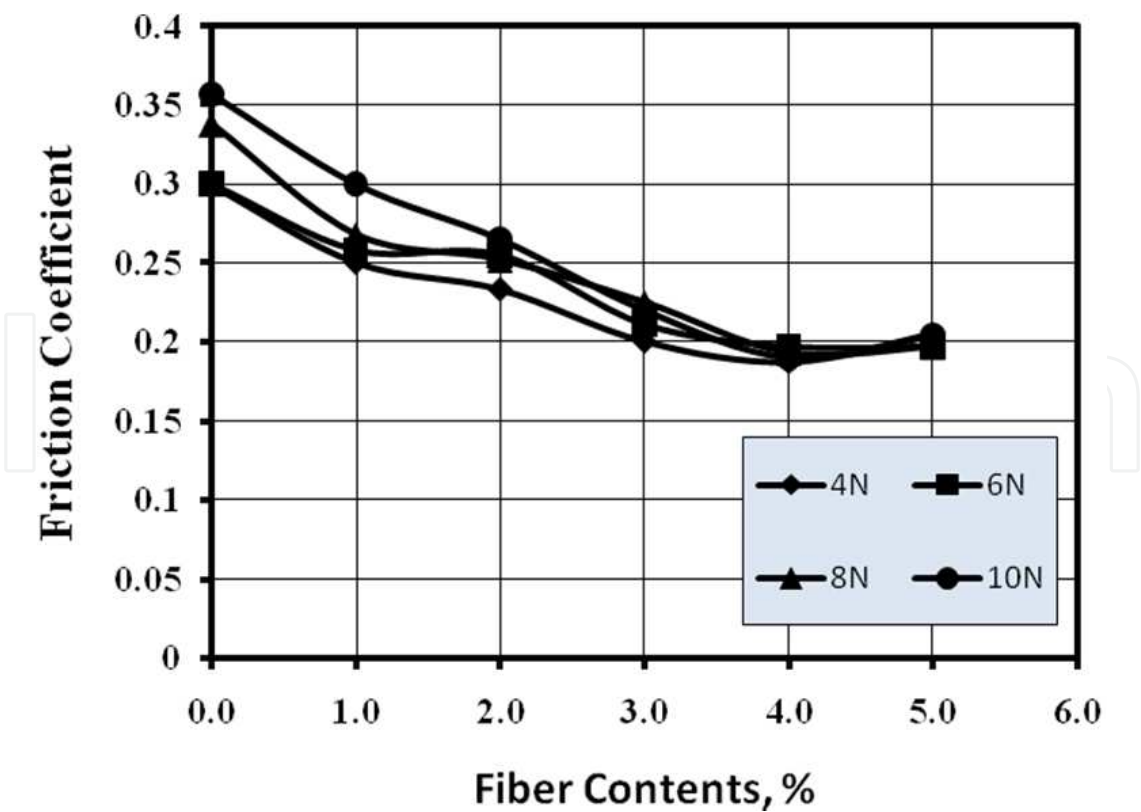


Figure 11. Frictional behavior of polyester composite impregnated with 5.0 vol. % corn oil

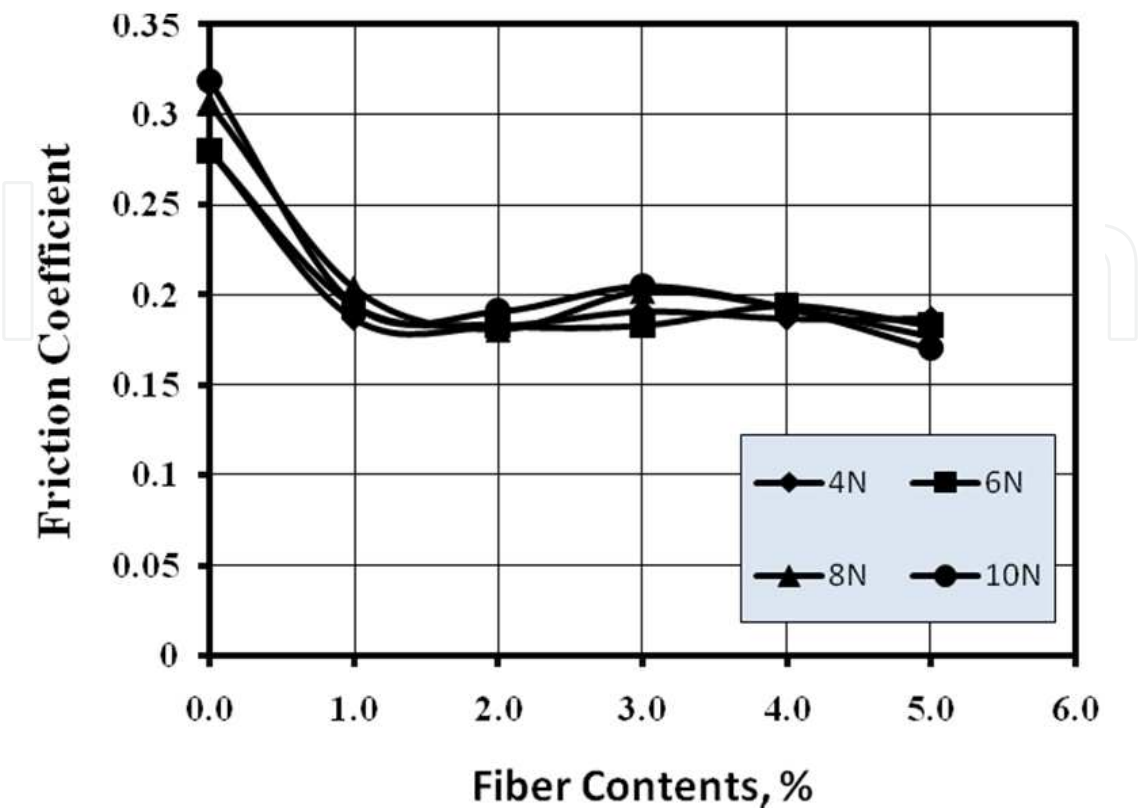


Figure 12. Frictional behavior of polyester composite impregnated with 10 vol. % corn oil

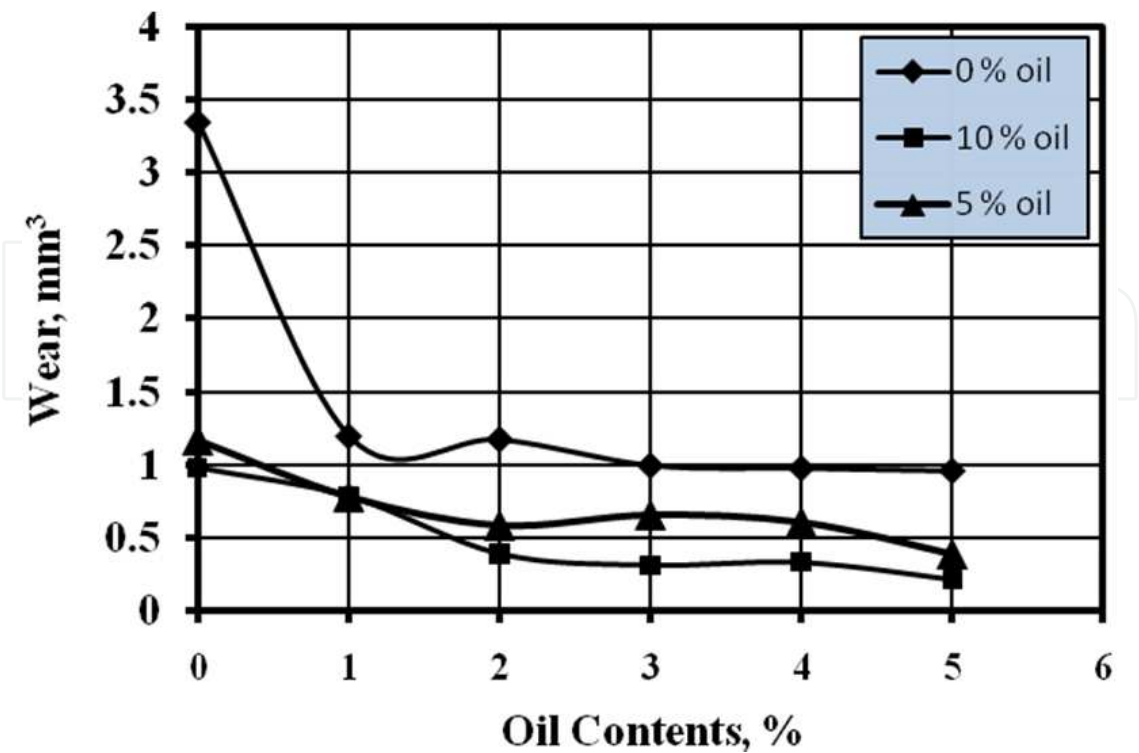


Figure 13. Wear of polyester composite impregnated by corn oil

3.2.6. Frictional behavior of polyester composites impregnated by sunflower oil

Friction coefficient of 4 % fiber composite content impregnated by 5 % sunflower oil under load of 8N was decreased to 0.177, figure 14. Composite impregnated by 10 % sunflower oil content shows good friction results, friction coefficient decreases to 0.166 for composite of 4 % fiber content under 4N, fig 15. beside low effects of applied load in friction coefficient. It seems that increase of sunflower oil in polyester composite increased its hardness and decreased friction coefficient.

3.2.7. Wear results of polyester composites impregnated by sunflower oil

Wear results for composite impregnated by 5 and 10 % sunflower oil were shown in figure 16. it could be stated that increasing the oil content decreased wear value to 0.196 mm³ for composite of 10 % oil content and 5 % fiber content.

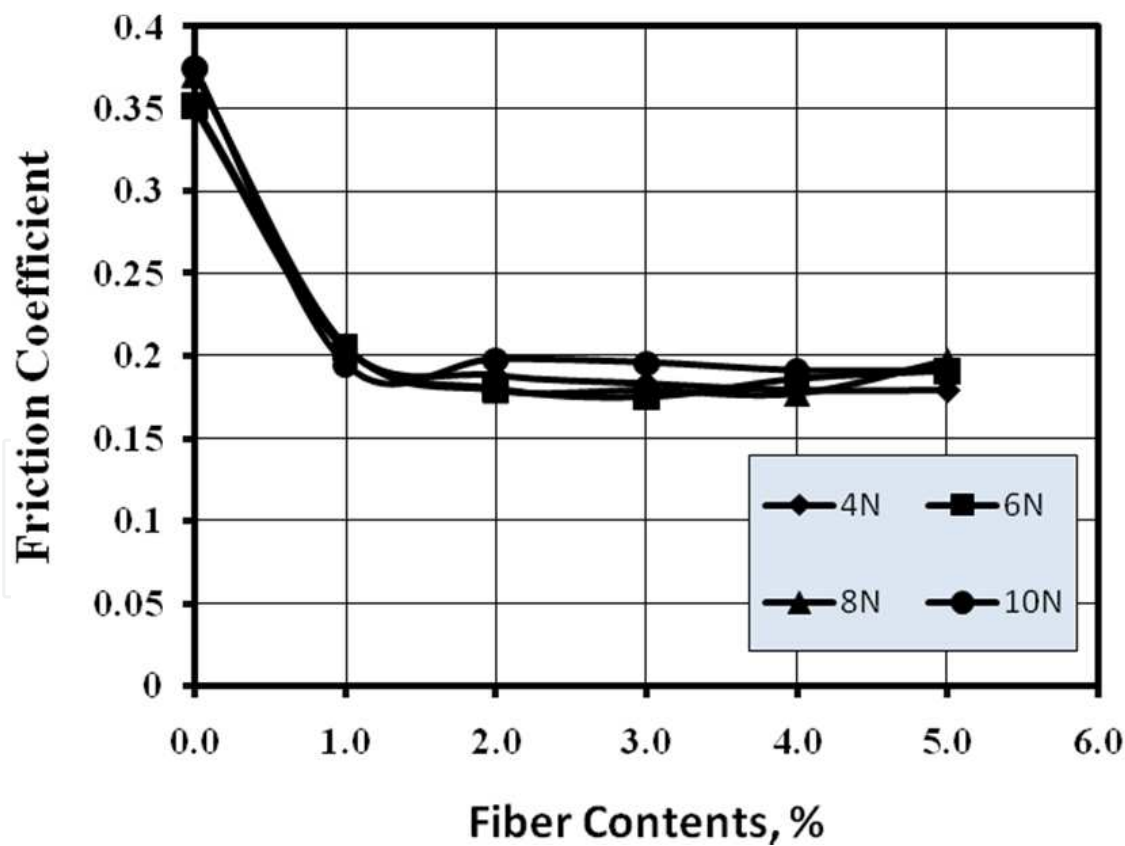


Figure 14. Frictional behavior of polyester composite impregnated with 5.0 vol. % sunflower oil

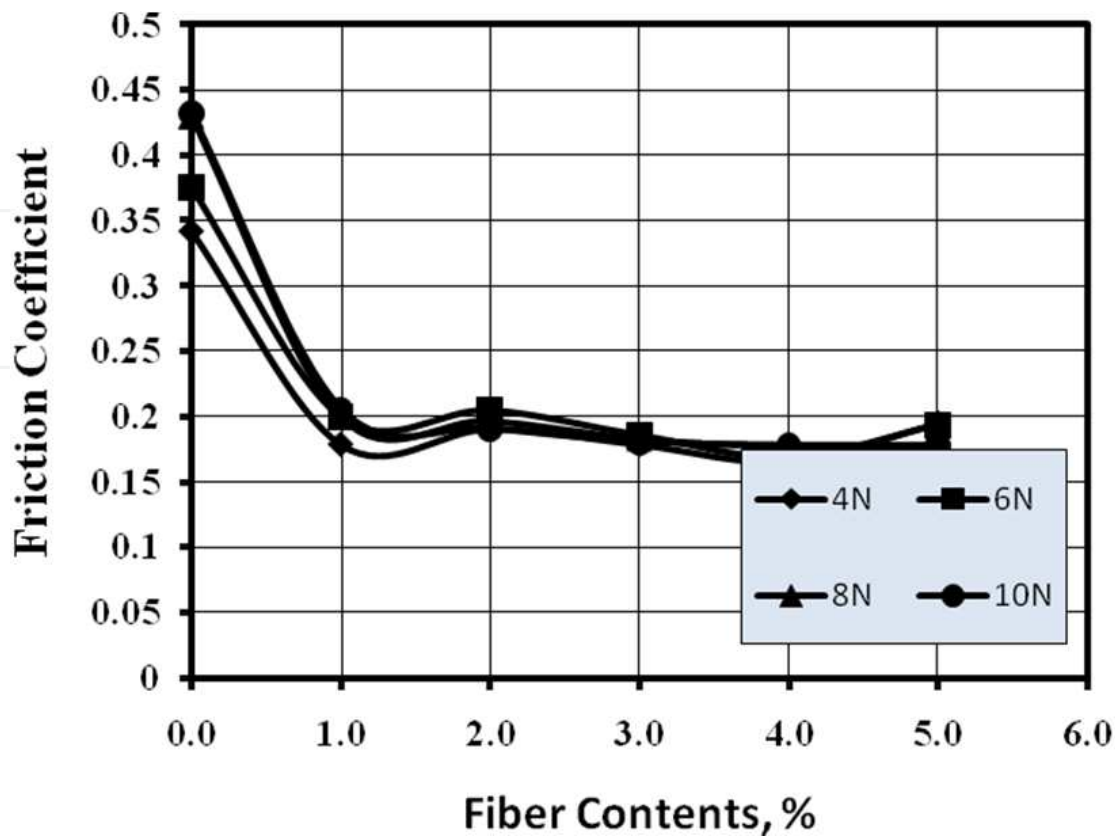


Figure 15. Frictional behavior of polyester composite impregnated with 10 vol. % sunflower oil

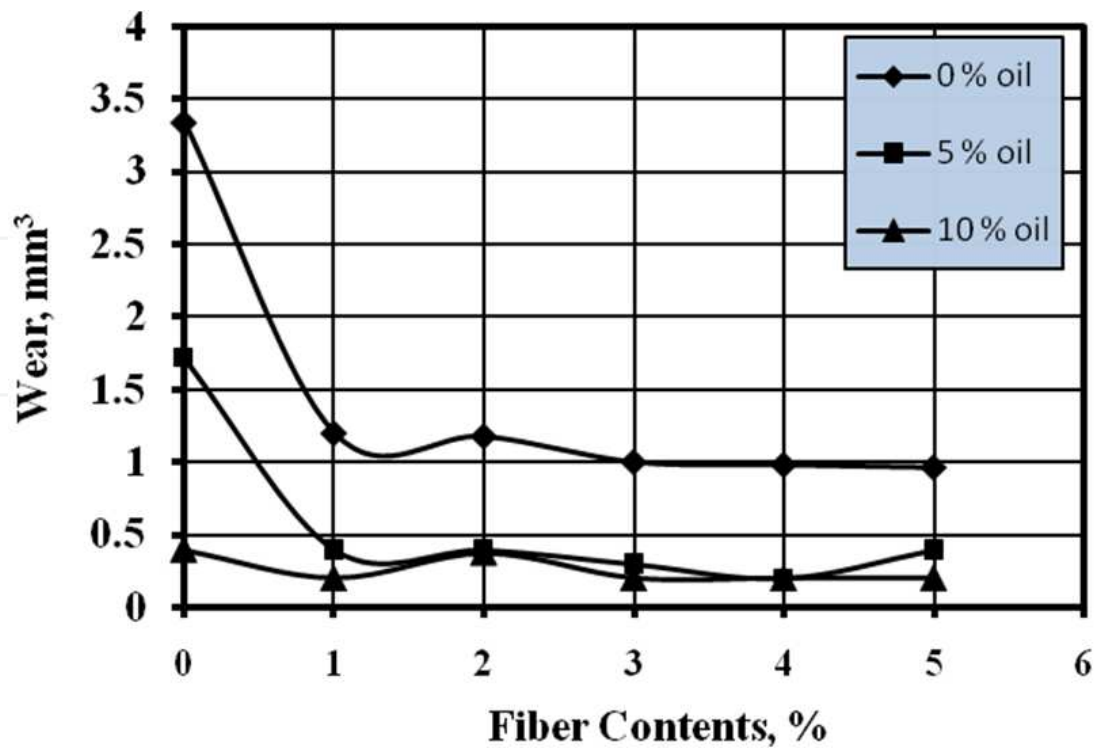


Figure 16. Wear of polyester composite impregnated by sunflower oil

3.3. Polyester composites reinforced by PTFE fiber

3.3.1. Frictional behavior of polyester composite free of oil

Frictional behavior of composite free from oil was shown in figure 17. It could be noted that the increasing of fiber content decreases friction coefficient to 0.257 for composite of 5 % PTFE fiber content under 4N. It may be interpreted by the increase of PTFE layer on the contact area which behaved as solid lubricant layer and reduced friction coefficient.

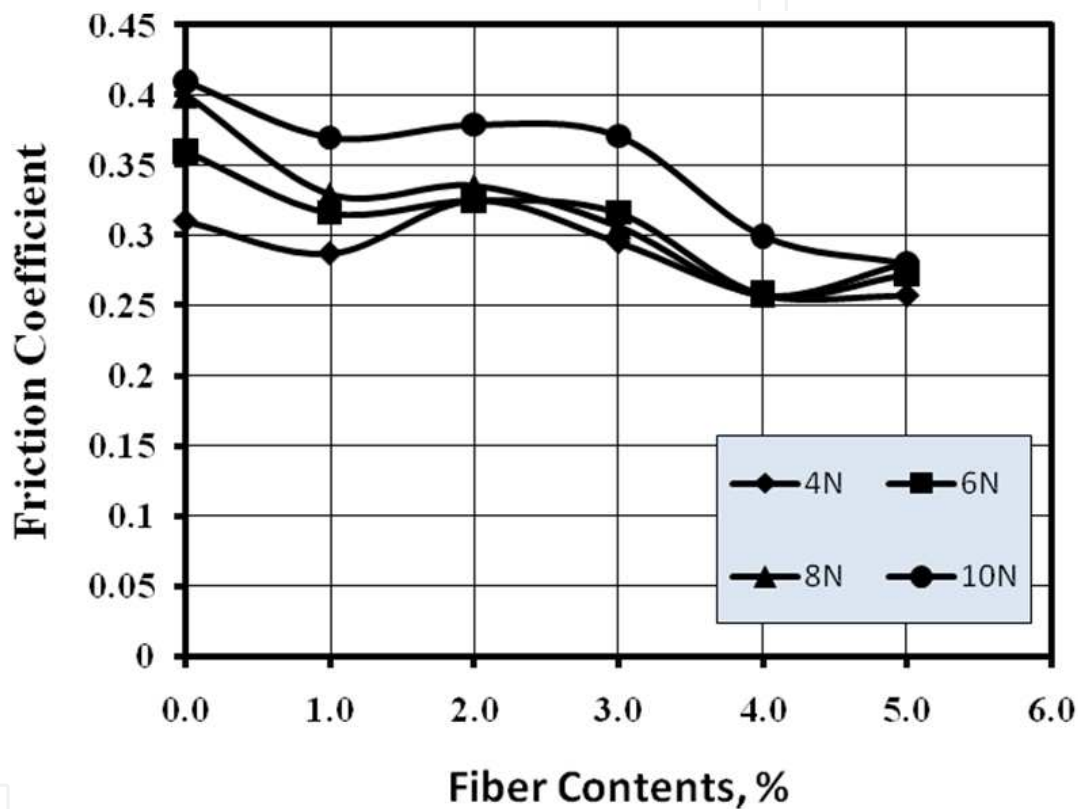


Figure 17. Frictional behavior of polyester composite free of oil reinforced by PTFE fiber

3.3.2. Frictional behavior of polyester composites impregnated by olives oil

Friction results for composite impregnated by 5 % olive oil was shown in figure 18., it shows that the increase in fiber content decreases friction coefficient to 0.165 for composite of 5 % fiber content under 4N. Figure 19. shows that increase of olive oil contents to 10 vol. % decreases friction coefficient remarkably to 0.152 for composite of 5 % fiber content under 4N. It seems that the increase in oil content increased the presence of oil layer at friction surface which may be responsible for friction reduction. These results recommended those composite as good bearing material.

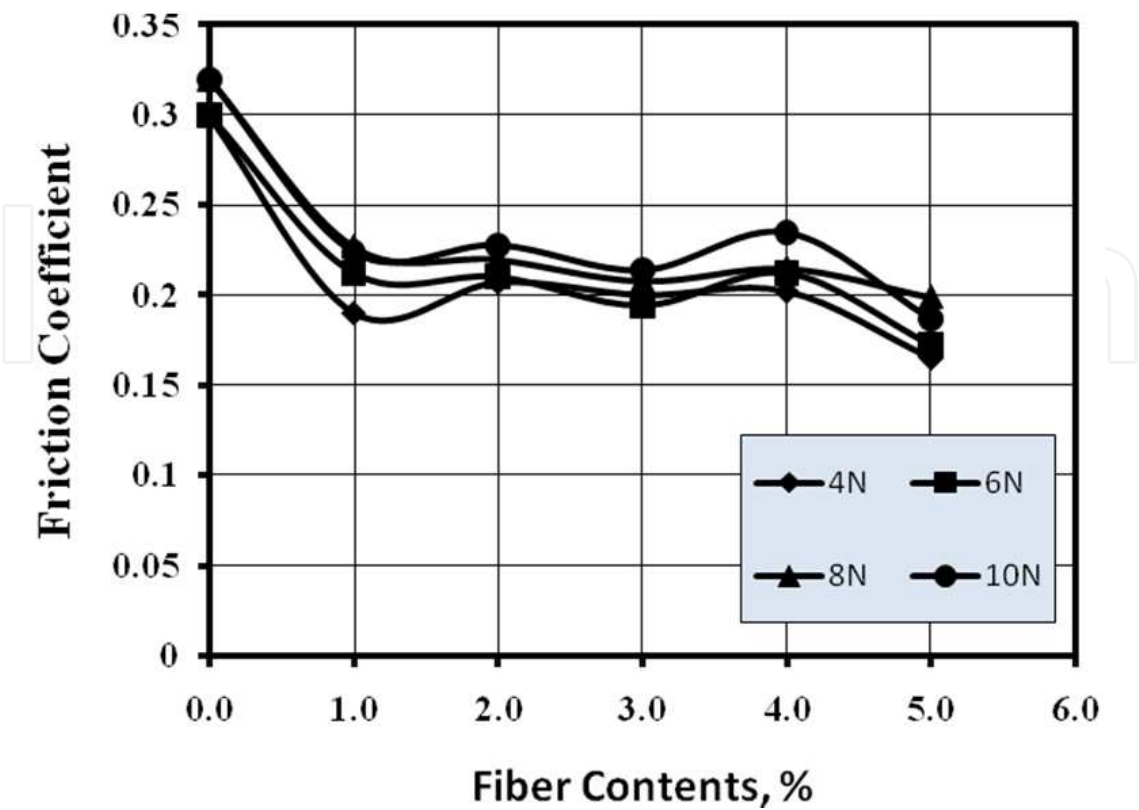


Figure 18. Frictional behavior of polyester composite impregnated by 5.0 vol. % olives oil

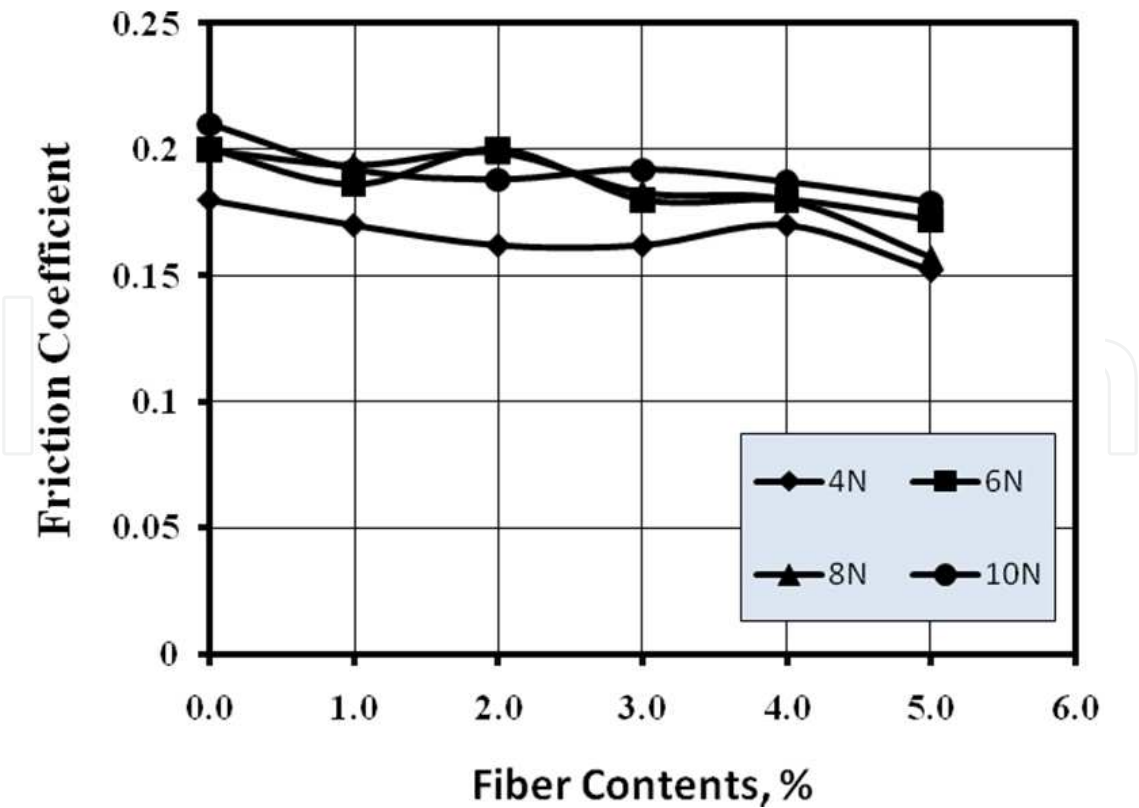


Figure 19. Frictional behavior of polyester composite impregnated by 10.0 vol. % olives oil

3.3.3. Wear results of polyester composites impregnated by olives oil

Figure 20. shows that the increase in oil content decreased the wear value to 0.315 mm³ for composite of 3 % PTFE fiber content and 10 % oil content. It may be interpreted by increase of oil contents decreased polyester transfer and reduce wear.

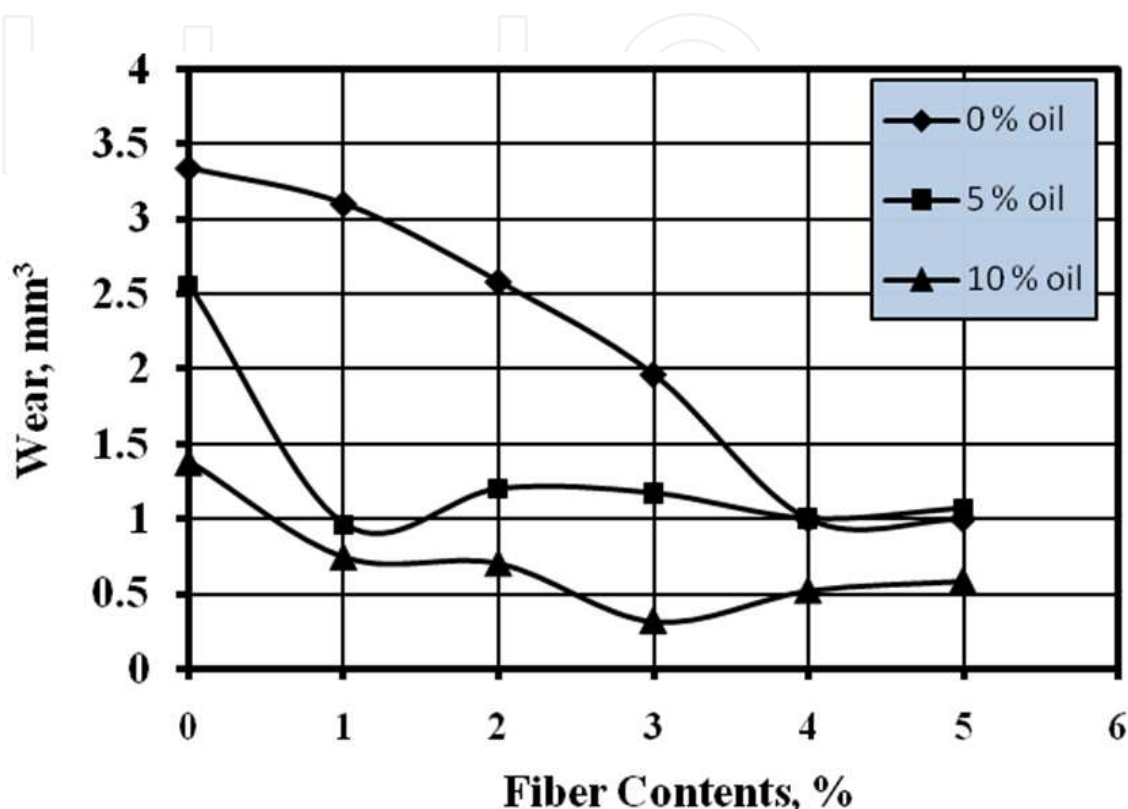


Figure 20. Wear of polyester composite impregnated by olives oil

3.3.4. Frictional behavior of polyester composites impregnated by corn oil

Composite impregnated by 5 % corn oil shows remarkably decreases in friction coefficient with increases of PTFE content; it reached to 0.172 for composite of 5 % fiber content under 6N figure 21. It may be attributed to the ability of corn oil film to reduce adhesion between composite and counterface. This may be responsible for friction reduction. Friction coefficient decreases in composite impregnated by 10 % oil content to 0.182 for composite of 5 % fiber content, figure 22.

3.3.5. Wear results of polyester composites impregnated by sunflower oil

Wear results decreases with increases of oil content it reaches to 0.283 mm³ for composite of 2 % fiber content and 10 % oil content. It may be attributed to the ability of PTFE layer and the presence oil film to reduce friction as well as polyester transfer to counterface. Figure 23.

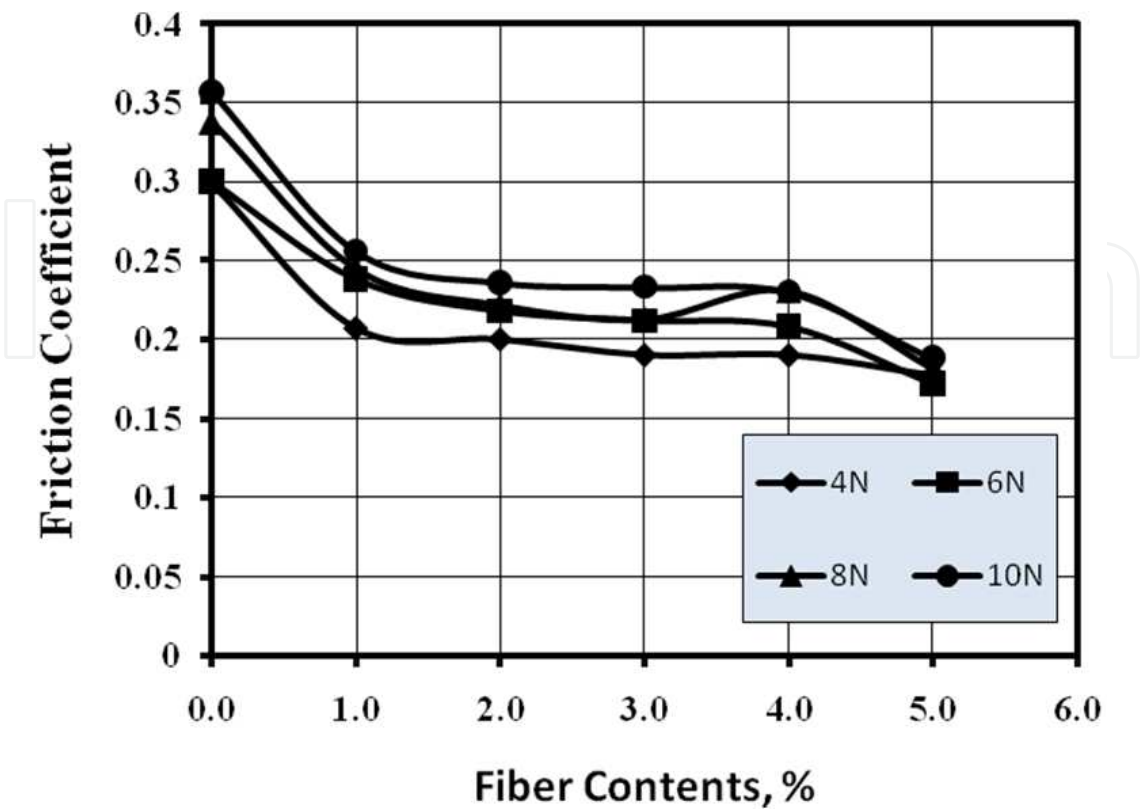


Figure 21. Frictional behavior of polyester composite impregnated by 5.0 vol. % corn oil

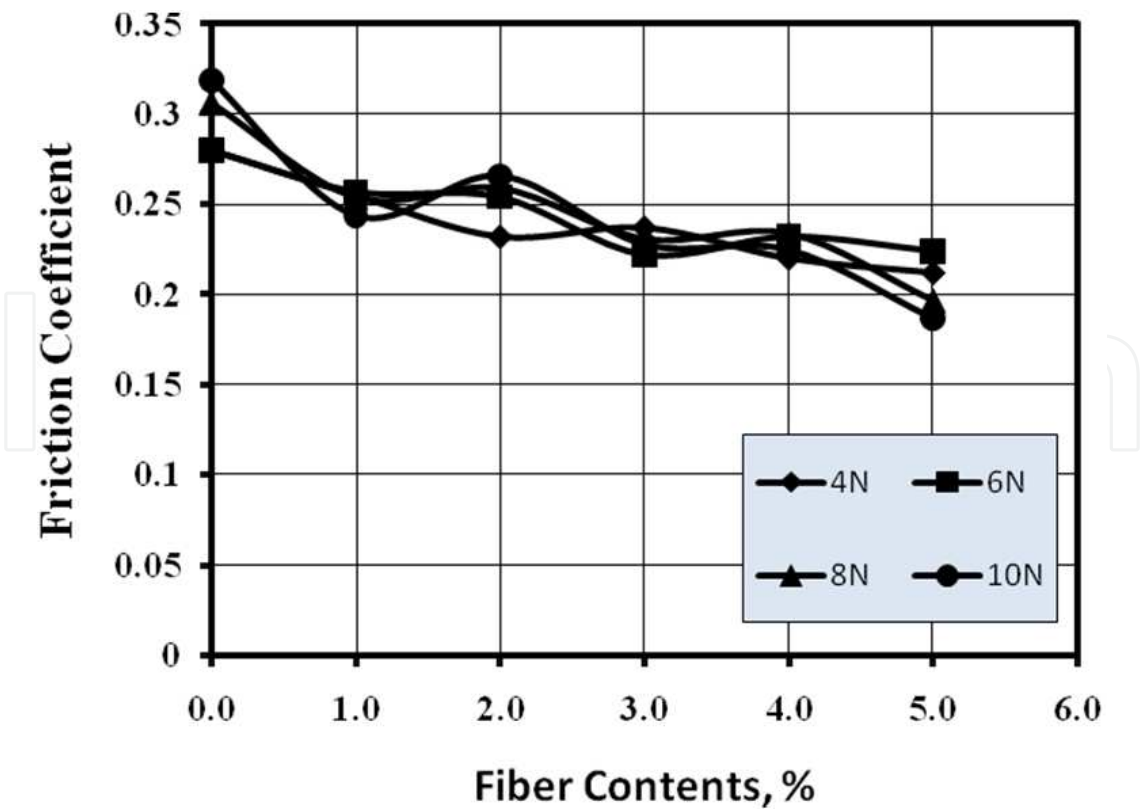


Figure 22. Frictional behavior of polyester composite impregnated by 10.0 vol. % corn oil

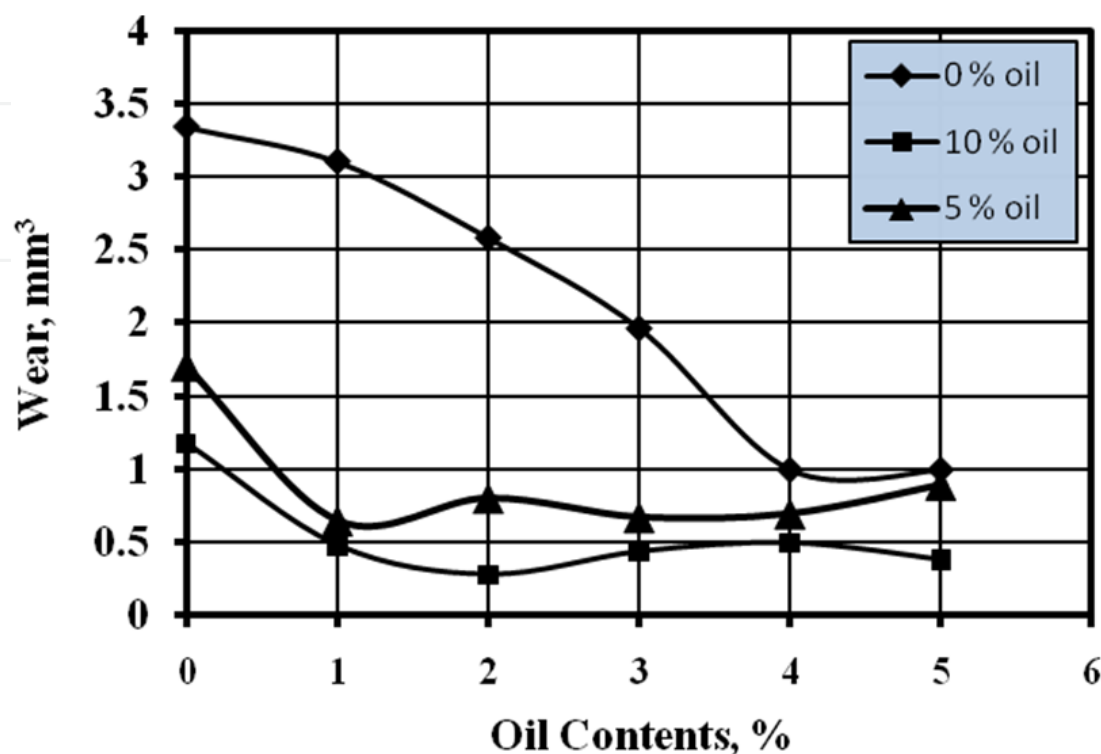


Figure 23. Wear of polyester composite impregnated by corn oil

3.3.6. Frictional behavior of polyester composites impregnated by sunflower oil

Friction results of composites impregnated by 5 % sunflower shows decreases in friction coefficient to 0.185 with increase of PTFE content to 5 % under 10N, figure 24. The reached results showed that there were low effect of applied loads on friction coefficient. It seems that the increase of sunflower oil increases composite hardness. This may be responsible for friction reduction. Composite impregnated by 10 % sunflower oil shows slightly increases in friction coefficient in comparing with composite impregnated by 5 % sunflower. But friction coefficient decreases with increasing of fiber content to 0.2 for composite of 5 % fiber content under 10N figure 25.

3.3.7. Wear results of polyester composites impregnated by sunflower oil

Composite of fiber content impregnated by 5 and 10% of sunflower oil decreased the value of wear to 0.347 mm³. Especially for composite of 10 % oil content and 5 % fiber content. It may be attributed to the ability of sunflower oil to reduce polyester transfer to counterface and reduce wear. Figure 26.

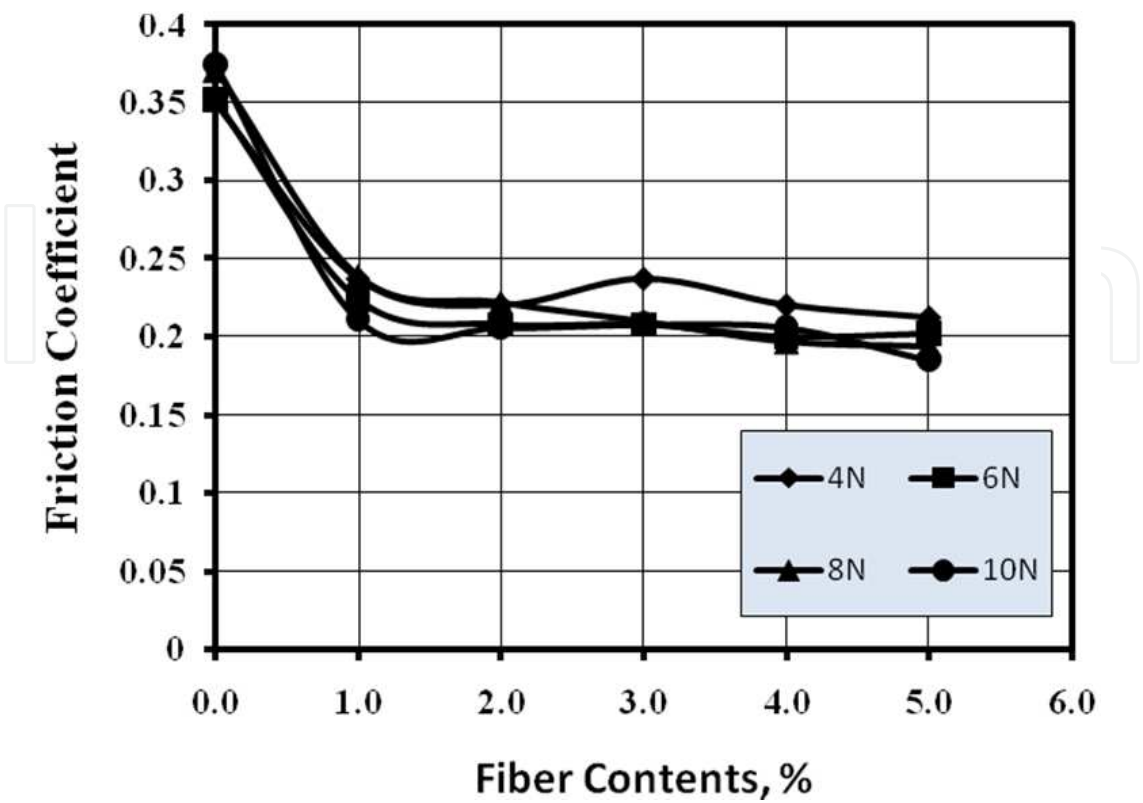


Figure 24. Frictional behavior of polyester composite impregnated by 5.0 vol. % sunflower oil

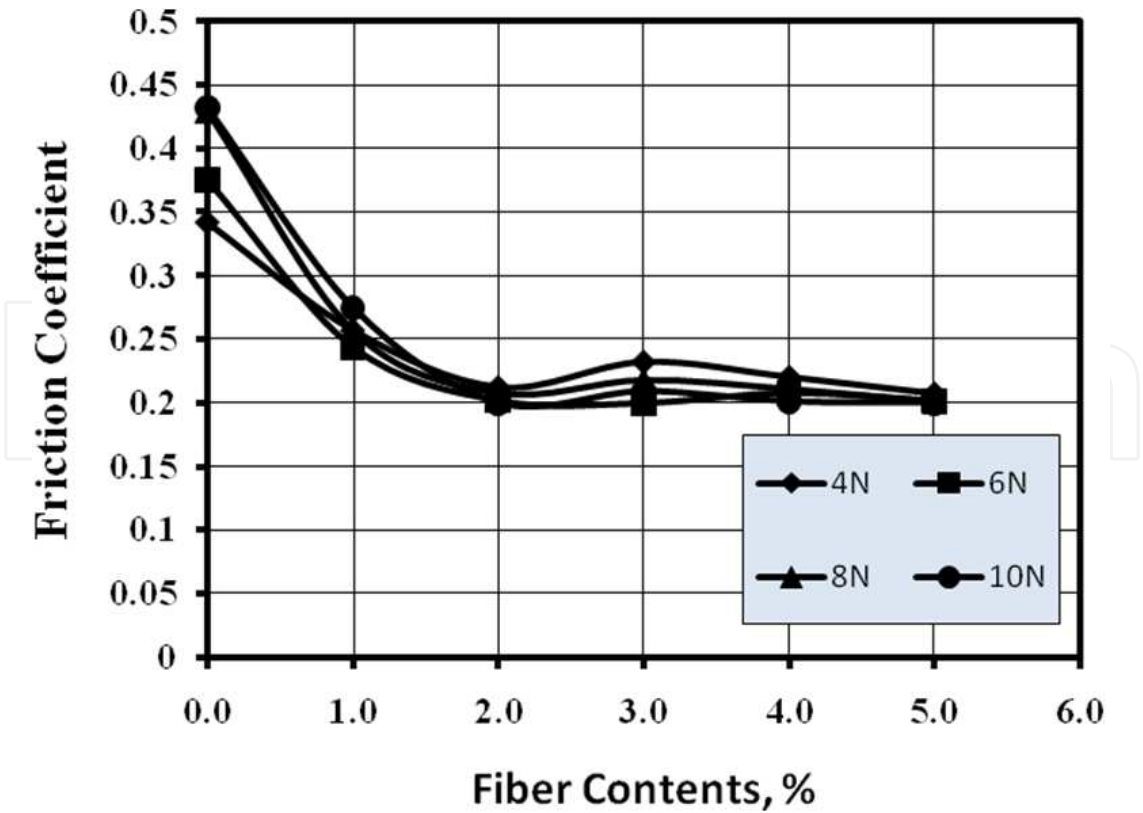


Figure 25. Frictional behavior of polyester composite impregnated by 10.0 vol. % sunflower oil

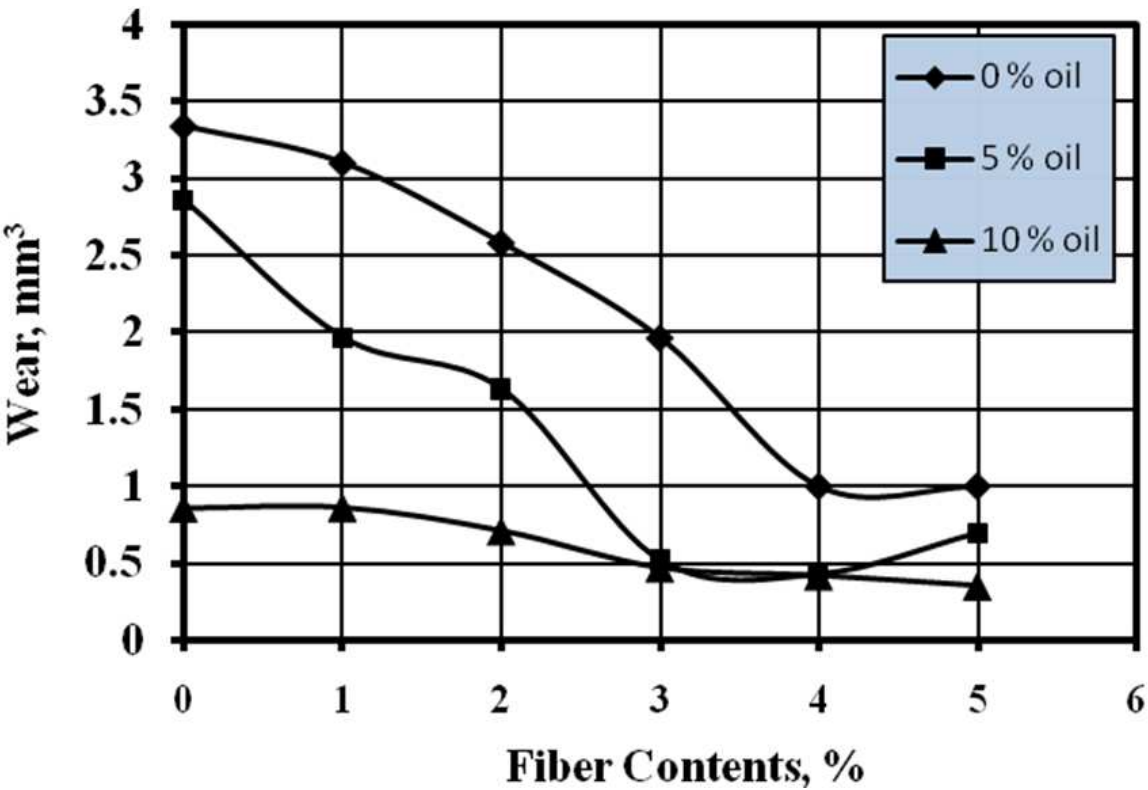


Figure 26. Wear of polyester composite impregnated by sunflower oil

Composite	VHR
Free polyester without oils	11.28 x 10 ⁶ N/mm ²
Composite impregnated by corn oil	11.43 x 10 ⁶ N/mm ²
Composite impregnated by glycerin oil	13.77 x 10 ⁶ N/mm ²
Composite impregnated by olive oil	13.92 x 10 ⁶ N/mm ²
Composite impregnated by paraffin oil	09.68 x 10 ⁶ N/mm ²
Composite impregnated by sunflower oil	24.22 x 10 ⁶ N/mm ²

Table 1. Micro hardness for test specimens

These results confirmed the previous results of friction and wear. The consistency of friction with applied load can be interpreted on the basis that hardness increases with addition of sunflower oil to composite, and consequently the plastic deformation decreases, this recommended composite impregnated by sunflower oil as very good bearing material especially under high loads.

4. Conclusions

Polyester composites filled with vegetable oils and reinforced by polymer fiber shows low friction coefficients and low wear rates, which recommended these composites for industrial applications such as self-lubricated materials.

5. Future work

Polyester composites reinforced with some agricultural wastes are proposed to be used in industrial applications.

Author details

Ibrahim Refaay Ahmed

Faculty of engineering, Beni-Suif University, Egypt

Ali Waheed Yousry

Faculty of engineering, Minia University, Egypt

6. References

- [1] Klaus F., Zhong Z. , Alois K., "Effects of various fillers on the sliding wear of polymer composites", *Composites Science and Technology* 65 (2005) pp 2329–2343.
- [2] Karger-Kocsis J., Zhang Z., "Structure–property relationships in nanoparticle/semi-crystalline thermoplastic composites". *Mechanical properties of polymers based on nanostructure and morphology*, New York: CRC Press; (2005) pp. 547–596.
- [3] Hutchings I. M., "Wear-resistant materials: into the next century", *J. Mat. Sci. Eng.*, (1994) pp.185–195.
- [4] H. Czichos, D. Klaffke, E. Santner, M. Woydt, *Advances in tribology: the materials point of view*, *Wear* 190 (1995) 155–161.
- [5] Gauthier C, R. Schirrer. Time and temperature dependence of the scratch properties of poly(methylmethacrylate) surfaces. *Journal of Materials Science* 2000;35(9):2121–30.
- [6] Inoue, Kaoru Miyake, Yuochi, Development of the chemical recycling technology of glass fiber reinforced PA6 Parts, SAE Paper, No 01-0694 2001 (in English).
- [7] J.R.T. Branco, S.V. Campos, Wear behaviour of thermally sprayed PET, *Surf. Coat. Technol.* 120–121 (1999) 476.
- [8] Samyn P., Baets P., "Friction of polyoxymethylene homopolymer in highly loaded applications extrapolated from small-scale testing", *Tribol. Lett.* 19 (2005) pp. 177–189.
- [9] Zheng S. F., Weng G.J., "A new constitutive eq. for the long-term creep of polymers based on physical aging", *Eur. J. Mech. A21* (2002) pp. 411–421.
- [10] Beake B. D., Leggett G. J., Shipway P. H., "Nanotribology of biaxially oriented poly(ethylene terephthalate) film", *Polymer* 42 (2001) p. 7025.
- [11] Neogi S., Hashmi S. A. R., Chand N., "Role of PET in improving wear properties of PP in dry sliding condition", *Bull. Mater. Sci.* 26 (2003) p.579.
- [12] Franklin S. E., "Wear experiments with selected engineering polymers and polymer composites under dry reciprocating sliding conditions", *Wear* 251 (2001) 1591.
- [13] Hashim P., Nihat T., "Investigation of the wear behaviour of a glass-fibre-reinforced composite and plain polyester resin", *Composites Science and Technology* 62 (2002) pp. 367–370

- [14] Tsukruk V., Nguen T., Lemieux M., Hazel J., Weber W., Shevchenko V., et al., "Tribological properties of modified MEMS surfaces. In: Bhushan B, editor. Tribology issues and opportunities in MEMS. Dodrecht: Kluwer Academic Publishers; (1998) pp. 607–614.
- [15] Dutta N., Karak N., Dolui S. K., "Synthesis and characterization of polyester resins based on Nahar seed oil", *Progress in Organic Coatings* 49 (2004) pp. 146–152
- [16] Liu Y., Schaefer J. A., "The sliding friction of thermoplastic polymer composites tested at low speeds", *Wear* 261 (2006) pp. 568–577.
- [17] Liu Y., Hild W., Kitsche M., Doering S., Lasse S., Hungenbach G., Scherge M., Schaefer J. A., "Tribological performance of selected bearings and bearing materials used for nanopositioning, in: D., Dowson, et al., *Life Cycle Tribology: 31st Lyon-Leeds Symposium on Tribology, Tribology and Interface Engineering Series No. 48* (2005) Elsevier, pp. 739–750.
- [18] Sawyer W. G., Freudenberg K. D., Bhimaraj P., Schadler L. S., "A study on the friction and wear behavior of PTFE filled with alumina nanoparticles", *Wear* 254 (2003) p. 573.
- [19] McCook N. L., Burris D. L., Bourne G. R., Steffens J., Hanrahan J. R., Sawyer W. G., "Wear resistant solid lubricant coating made from PTFE and epoxy", *Trib. Let.* 18 (2005) p. 119.