FRICTION AND WEAR PROPERTIES OF POLYMERIC COMPOSITE MATERIALS FOR BEARING APPLICATIONS

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ABSTRACT

This paper presents a study on the tribological properties of two locally developed polymeric composite materials for bearing applications. Unidirectional reinforcements by linen and jute fibers are used, each in turn, in unsaturated polyester resin. Friction and wear tests are carried out, in dry conditions, on a pin-on-disc machine. The experimental results revealed that the reinforcement volume fraction as well as orientation have considerable effect on friction and wear of polyester composites.

Keywords Tribological Properties, Polymetric composite materials.

1. INTRODUCTION

The recent reports on the shortage of metals and deblition of mineral resources has encouraged many scientists to look for new and alternative non conventional materials [1-3]. Among these, composites and fiber reinforced polymeric materials were the most attractive. One advantage which encouraged research workers to focus on composites is the diverse range of mechanical and tribological properties that can be obtained using different types of reinforcements in different orientations with different volume fractions. Increased attention was therefore directed towards the utilization of different locally available fibers.

In bearing applications several polymer based fiber reinforced composite materials are now in use. However, the ease of manufacturing has always tempted scientists in different parts of the world to try locally available inexpensive fibers. The attempts of utilizing composite materials always raise the question "why shouldn't it be locally manufactured?". This usually ends up with another question concerning the suitability of locally available fibers for reinforcement purposes and to what extent they satisfy the specifications of good reinforced-plastic bearing material. The present work represents an attempt to produce and evaluate the characteristics of an alternative material using locally available textile fibers in Egypt, for sliding bearing applications.

The experimental investigations on polymeric composites have shown that the wear and friction behaviour of such materials exhibits anisotropic characteristics. However, there are some disagreement as to its effect [4-6]. Moreover, studies on the effector of sliding velocity on wear rate and coefficient of friction revealed some discrepancies. Such discrepancies may be explained by reviewing the material and testing conditions in each case [7-13].

The effect of fiber volume fraction on both wear and friction has been investigated [9,11,14-16]. Lhymn et al [9] showed that wear rate increases with increasing fiber volume fraction in glass-fiber-PBT composite but the coefficient of friction is found to be independent of the fiber volume fraction. Lhymn also studied the effect of orientation on the specific wear rate/fiber volume fraction relation using water as a lubricant. His results also showed that the coefficient of friction increases with increasing fiber volume fraction.

In response to the two questions raised

earlier in this introduction, the present study aimed at developing composite materials, with appropriate triabological as well as mechanical properties, for bearing applications using locally produced constituents.

2. EXPERIMENTAL

2.1. *Materials*

Unsaturated polyester, resin type ETERSET 2504 APTS, manufactured by Eternal Chemical Co. Ltd. is used as a matrix material. It has, among other advantages, low pressure moulding capabilities which makes it particularly valuable for large component manufacture at relatively low cost compared with other thermosetting resins. Methyle Ethyle Ketone peroxide (55% concentration) is used as a catalyst with 1% by weight Peroximon K1 hardener. Two types of fibers, locally produced and commercially available, namely Linen and Jute, are used as fibrous reinforcement to develop the Linen Fiber-Polyester Composite (LF-PC) and Jute Fiber-Polyester Composite (LF-PC).

The reinforced polyester composite specimens are fabricated by the open moulding (casting) process following the main principles adapted by Abdel-Aziz [17] and Aggag [18]. In order to ensure the reliability and reproducibility of the results obtained, it is necessary to fabricate all specimens under the same conditions. For this reason, a long rod is to be fabricated in each cast to get various types of specimens from the same rod. Details of the used mould and the method to set a certain volume fraction are given by Aggag [18]. Fiber volume fraction percentages used are 5,12,21 and 33% for linen and 13 and 15% for jute.

2.2. *Test Specimens*

Test specimens are prepared from the two fabricated composite materials. For each percentage of fiber volume fraction three types of test specimens are prepared to satisfy the three orientations illustrated in Figure (1). All specimens are cut from their corresponding rods and sized in cuboidal geometry by polishing using emery papers, with water as a coolant, to eliminate possible heat effects on specimen structure. The final size is 3 x 5 x 15 mm.

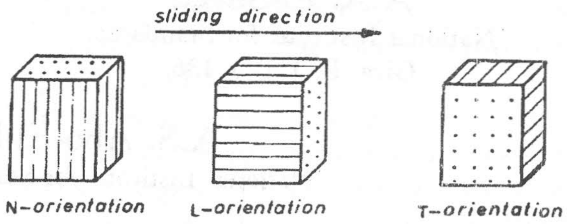


Figure 1. Test specimens with three fiber orientations.

2.3 *Instrumentation*

Friction and wear tests are carried out using a conventional pin-on-disc machine [19]. The design ensures two salinet features, namely the provision of wide range of sliding velocities encountered in practice and the precise measurements of the tangential friction force during the tests. The first is achieved through the use of a variable speed D.C. motor. The disc rotating speed could be controlled, hence the sliding velocity, using a feed back control unit to guarantee constant speed irrespective of torque variations. The second feature is ensured by using a high precision force measuring system which consists of a strain gage load-cell which is calibrated against a secondary standard force transducer.

2.4. *Test procedure*

Wear and friction tests are carried out using a counterface disc machined from a 57 HRC steel plate to an outer diameter of 150 mm and a thickness of 19 mm. The disc is polished resulting in a surface roughness of 0.15 um (CLA). A running in period is allowed up to the steady state where the value of the coefficient of friction corresponding to the specific volume fraction/fiber orientation under consideration is taken. Each recorded value is the average result of at least 5 tests on the same volume fraction/fiber orientation.

Tests are carried out on specimens of the two composite systems developed, in dry conditions, at low and high energy values (pressure-Velocity [PV] product) [20]. This limit Figure (2), in a given environment, enables the designer to determine the limiting operating conditions, i.e. the applied load, sliding speed and temperature. Two values for PV are chosen, namely 0.61 and 1.65 PMa.m/sec.

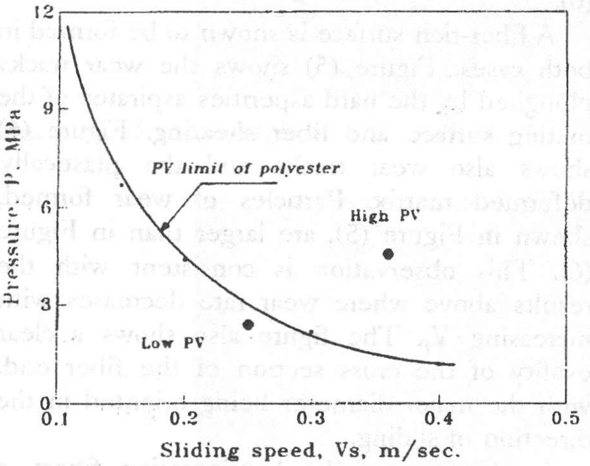


Figure 2. PV limit of pure polyester [20].

3. RESULTS AND DISCUSSION

3.1 *LF-PC friction coefficient at low value*

Figure (3) shows the variation of the coefficient of friction u with the volume fraction V_f of the LF-PC tested at low PV value in the three fibers orientation directions. The standard deviation of each one of the plotted values varied between 0.020 and 0.039. In the case of normal oreinetation (N) the Figure shows a slight increase of coefficient of friction (u_N) as the fiber volume fraction (V_f) increases. This increase may be accounted for by the assumption that the adhesion junctions formed on the surface require higher frictional force for shearing since the fibers are deeply embedded in the matrix material.

In the longitudinal orientation (L), u_L decreases steadily as V_f increases up to a values of about 12.5% then it reaches almost a constant value indicating that this is a threshold value of u_L. The decrease in u_L at lower values of V_f may be due to the relative ease of detachment of the outer layer of the fibers from the matrix when compared with the u_N since the fibers in this case are parallel to the sliding direction and sliding surface.

The coefficient of fraction u_T in the transversal direction also exhibits a similar behaviour to that in the L-orientation case. The decrease in u_T at the beginning can also be attributed to the ease of detachment of the fibers from the matrix. The initial decrease of the friction coefficient u_T, at the lower values of V_f, is almost equal to the decrease in u_L. This may be explained as follows; when the fiber-rich-surface increases in the contacting area, the friction coefficient may decrease. This is shown clearly in the Figure, where u_N is greater than u_L and u_T. Similar results were previously obtained with cotton-polyester composites [11] and with kevlar-epoxy composites [5].

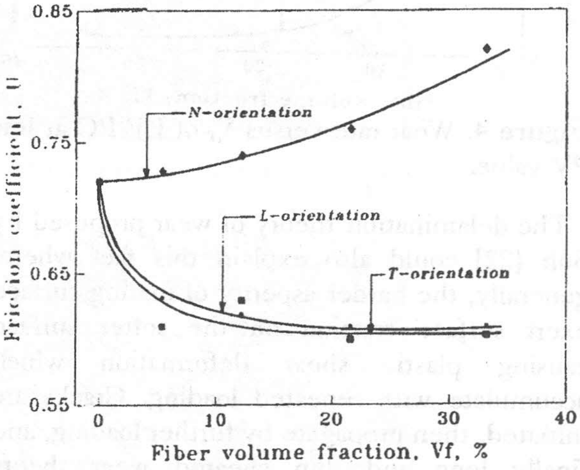


Figure 3. Coefficient of friction versus V_f of LF-PC at low PV value.

3.2 *LF-PC wear rate at low PV value*

Figure (4) shows the behaviour of LF-PC of different fiber volume fraction in wear tests. The standard deviation of each of the plotted values varied between 0.48×10^{-8} and 7.65×10^{-8} gm/cm. The figure indicates a clear tendency of wear rate to decrease with the increase in fiber volume fraction in the three cases of fiber orientations.

In the case of N-orientation fibers, the wear rate (w_N) decreases as V_f increases. The decrease in w_N is considerable up to a value for fiber volume fraction V_F of about 12.5% after which w_N remains nearly constant. The difficulty of extracting the long fibers, from the bulk material in the N-oreinetation, seems to be the main reason for the decrease of the wear rate. The fibers with this orientation are clearly in the best position to resist detachment from the bulk materials [21].

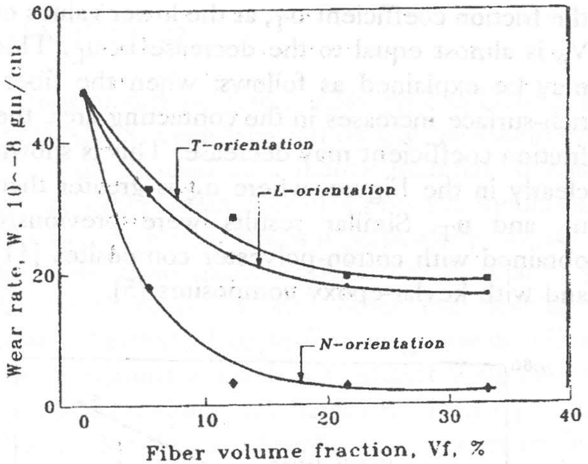


Figure 4. Wear rate versus V_f of LF-PC at low PV value.

The delamination theory of wear proposed by Suh [22] could also explain this fact where, generally, the harder asperity of mating surface exert surface traction on the softer surface causing plastic shear deformation which accumulate with repeated loading. Cracks are initiated, then propagate by further loading, and finally long and thin sheared wear sheets delaminate. In the case when fibers are oriented normal to the sliding surface and the sliding direction, the fibers diminish the crack propagation process by further loading, and this could well be a reason of diminishing the wear rate by this considerable amount [5]. In addition, the possible formation of a fiber rich surface reinforces the contacting surface and diminishes the wear rate.

In the present experiments, the fibers do not instantaneously break, due to its flexibility, but bend and become inclined to the direction of the sliding while still attached to the bulk. This process results in a fiber-rich-surface on the sliding surface. Moreover, polyester, which is more brittle, breaks when friction forces are applied. This causes an increase in the percentage of fibers on the contact surface, and consequently a decrease in the overall wear rate. Scanning Electron Microscope (SEM) results support such explanation. SEM photographs of the worn surface of normal oriented specimens with different V_f are shown in Figures (5) and (6).

A fiber-rich surface is shown to be formed in both cases. Figure (5) shows the wear tracks ploughed by the hard asperities aspirates of the mating surface and fiber shearing. Figure (6) shows also wear tracks and the plastically deformed matrix. Particles of wear formed, shown in Figure (5), are larger than in Figure (6). This observation is consistent with the results above where wear rate decreases with increasing V_f. The figure also shows a clear ovality of the cross section of the fiber end, with the major diameter being oriented in the direction of sliding.

In the case of the L-orientation fibers, a decrease in wear rate occurs as V_f increases as shown in Figure (4). The fibers in this case are oriented parallel to the sliding surface and also to the sliding direction. In this position the fiber can be easily detached from the matrix, hence it is observed that the decrease in wear rate in this case is much smaller than that observed in the case where sliding is in the N-orientation. Figure (7) shows SEM photographs of the worn surface of such specimens. The photographs show the wear tracks on the surface where the worn surfaces also exhibit plastically deformed matrix and fiber bulking from matrix.

In the case of the T-orientation fibers, a decrease in the wear rate also occurs by increasing V_f, as indicated in Figure (4), in which wear becomes nearly constant at V_f>12.5%. The observed decrease in wear rate is smaller than that observed in both the N-orientation and the L-orientation cases. These results agree well with those obtained by Sung and Suh [5] on graphite fiber-epoxy composites. Figure (8) shows SEM micrograph of the worn surface of LF-PC specimen tested in the T-orientation at low PV value. The photographs show the wear tracks on the surface. The worn surface also exhibit plastically deformed matrix and fiber bulking from the matrix.

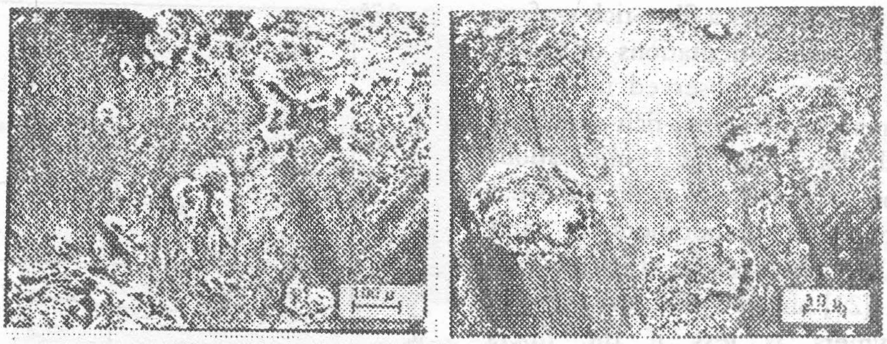


Figure 5. SEM micrograph of worn surface of 12% LF-PC (N oriented fibers) at low PV value.

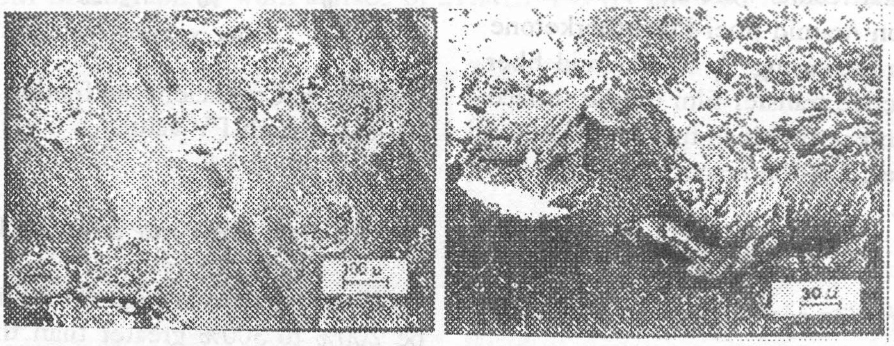


Figure 6. SEM micrograph of worn surface of 21% LF-PC (N oriented fibers) at low PV value.

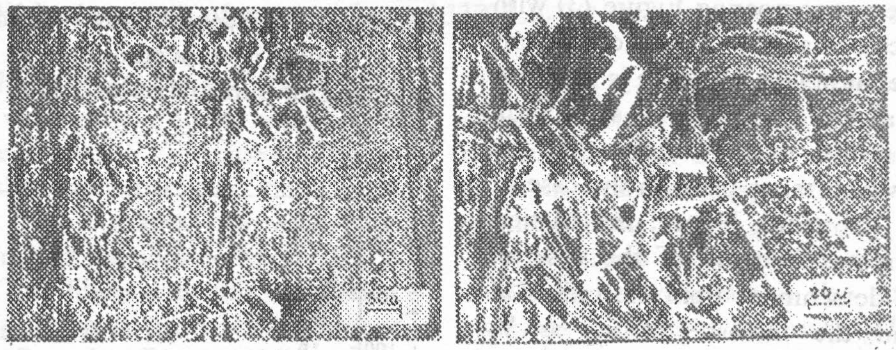


Figure 7. SEM micrograph of worn surface of 33% LF-PC (L oriented fibers) at low PV value.

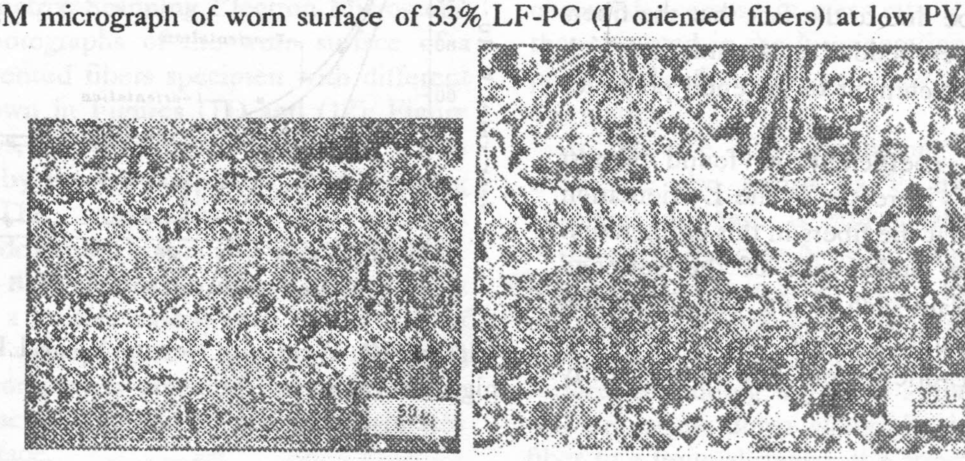


Figure 8. SEM micrograph of worn surface of 33% LF-PC (T oriented fibers) at low PV value.

In the present experiments a fiber-rich surface is observed in the three orientations of fibers; larger fiber-rich surface is observed in the N-orientation whereas smaller fiber-rich surface is observed in both the T and the L-orientation. Such observation is consistent with the wear rate results obtained experimentally and confirmed by SEM photographs (Figures (6,7) and 8). Tanaka [23] showed that the wear of fiber filled-polymers is less if the fibers composing the fiber-rich surface have good wear resistance. Similar results were also obtained by cirion et al [8] on Aramid fiber-Polyetherketone composites. On increasing V_f, the Aramid fiber created an effective transfer film on the surface of the steel counter part which further enhanced the wear resistance of the respective composite system.

3.3 *LF-PC Friction coefficient at high PV value*

Figure (9) shows that u_N increases as V_f increases. However, comparing Figure (3) with Figure (9) indicate that the friction coefficient of pure polyester at height PV value is less than that observed at low PV value to start with. This decrease is due to the softening of the surface matrix which takes place in the case of sliding at high PV value. Hence, the friction coefficient decreases because of the ease of matrix material detachment from the bulk. On the other hand the increase of u_N as V_f increases may be due to the fact that the fibers in this case are embedded in the matrix which prevent easy detachment of softened polyester from the matrix.

The friction coefficient is found almost unchanged as V_f increases in the L-orientation case. The fact that the fibers in this oreinetation could easily be pulled out of the softened matrix may explain such result. The figure also shows that u_T exhibits similar behaviour to that of u in the L-orientation but with slightly higher values.

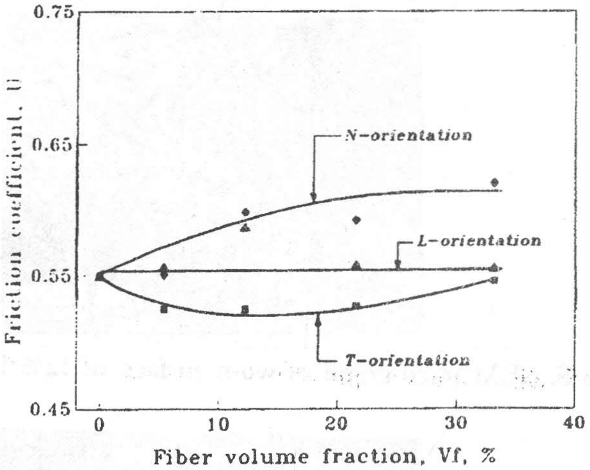


Figure 9. Coefficient of friction versus V_f of LF-PC at high PV value.

3.4 *LF-PC Wear rate at high PV value*

The wear rate al high PV value is found to be 200% to 300% greater than that at low PV value for the same volume fraction percentages and orientation direction as indicated by the comparison between Figure (4) and Figure (10). This results is expected due to the thermal softening of pure polyester.

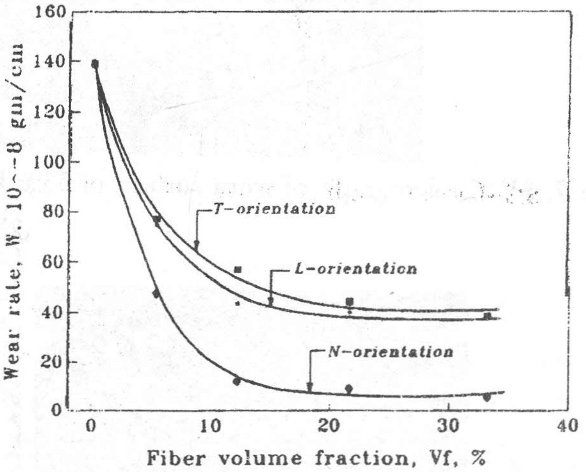


Figure 10. Wear rate versus V_f of LF-PC at high PV value.

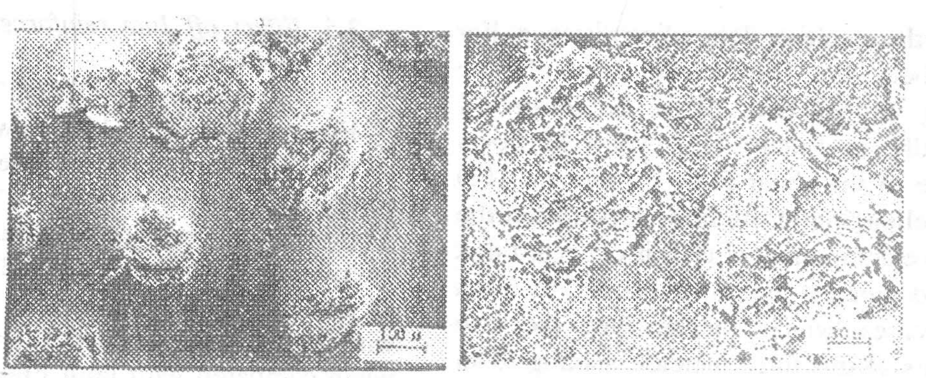


Figure 11. SEM micrograph of worn surface of 21% LF-PC (N oriented fibers) at high PV value.

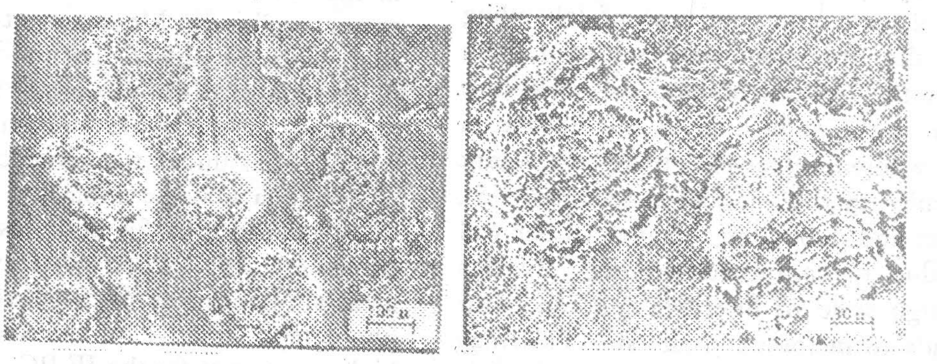


Figure 12. SEM micrograph of worn surface of 33% LF-PC (N oriented fibers) at high PV value.

The figure shows that, for the N-oriented fibers, the high value of w_N, due to softening of polyester, decreases as V_f increases. This is attributed to the fact that the long fibers embedded in the matrix prevent the catastrophic failure of the softened polyester at sliding surface. The fibers with this orientation are in the best position to prevent detachment from the matrix. Scanning Electron Microscope (SEM) photographs of the worn surface of a normal oriented fibers specimen with different V_f are shown in Figures (11) and (12). Figure (11) shows, worn surface and wear tracks ploughed by the hard aspirates of the mating surface. The worn surface also exhibits plastically deformed matrix and wear formations. The fiber-rich surface is seen to have been formed to a greater extent than in the case of the low PV value. Figure (12-a) shows the initial aspirates completely smeared over the surface and the tracks ploughed by the hard aspirates on the surface.

Figure (12-b) shows that the wear of fiber is caused by shear and wear sheet formation. It can also be seen that the section of the fiber takes an oval like shape with major diameter oriented in the sliding direction.

When fibers are oriented in the L-orientation a decrease in wear rate is also observed as V_f increases as shown in Figure (10). However, the observed decrease in wear rate is smaller than that observed in the N-orientation case. In this position the fiber can be easily detached from the matrix.

In the case of T-orientation, a decrease in wear rate also occurs as V_f increases. The observed decrease is still smaller than that observed in the case N-orientation but more or less equals to that observed in the case of L-orientation (Figure (10)). It is expected that when fibers are oriented normal to the sliding surface, debonding will occur at the surface and will propagate down along the length of the fiber to a finite distance; the stronger the fiber the longer the resulting debonding distance. For weaker fibers, the fiber break occurs before debonding propagation. This is illustrated schematically in Figure (13). Wear of fibers occurs due to the shear force component (Fs) whereas debonding of the fiber depends on the tensile force component (Ft). It is expected that when V_f decreases the force carried by each fiber increases which means that the two components of this force increase leading to an increase in debonding, shear of the fiber and wear rate. When fibers are oriented parallel to the sliding surface as in transverse or longitudinal orientation, initiation of debonding occurs at the fiber-resin interface at a finite depth from the surface.. Initiation of cracks may also occur at the surface or at the fiber-resin interface, where the tensile stress component perpendicular to the surface is maximum [5]. The cracks and debonding length of fiber will increase due to continuous loading. By this process large scale of fiber bulking can occur which leads to increased wear rate. This may apply with no appreciable difference between transverse and longitudinal orientation. However, the debonding tendancy occurs more in the transverse case which agrees with the obtained results.

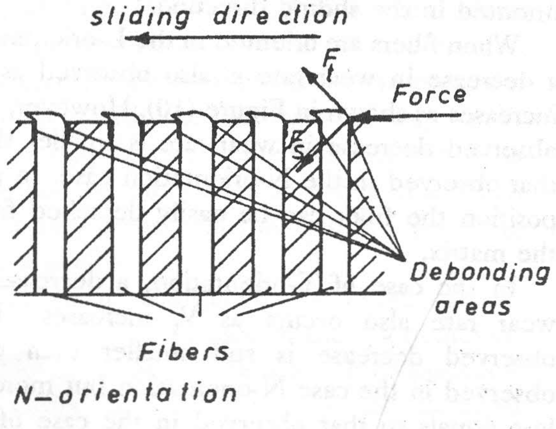
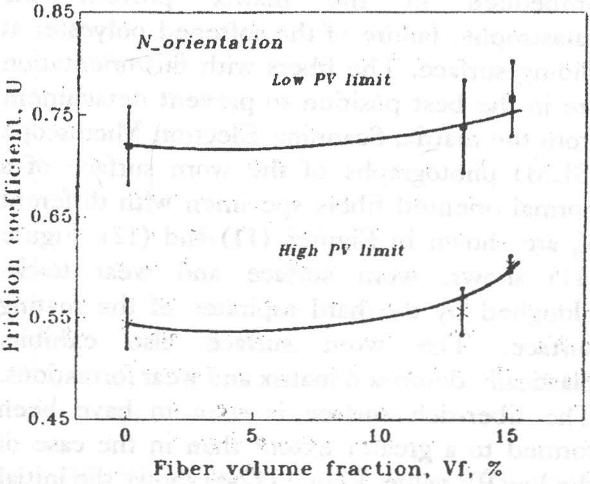


Figure 13. Schematic representation of failure mode in unidirectional continuous fiber reinforced composite.

3.5 *Effect off Jute reinforcement on friction and wear*

Figures (14) and (15) show the results of friction and wear tests on Jute fiber-polyester composite (JF-PC) At low and high PV values. The variation of u and w with the three fiber orientations with respect to sliding direction for all tests is plotted. Figure (14), when compared with both Figure (3) and (9) and Figure (15) when compared with both Figures (4) and (10) show that both the coefficient of friction and ear rate of JF-PC exhibit similar behaviour to that in the case of LF-PC when tested under the same conditions. Moreover, it can be shown from such comparison that the wear rate of the orientation of JF-PC is slightly higher than that obtained in the same orientation of LF-PC when tested under the same conditions. Such phenomena may be explained by viewing the SEM photographs for both cases. Figure (16), compared with Figure (5) reveals that smaller areas of fiber rich surface are present in the first photograph, relative to the second, indicating higher wear rate for the JF-PC. Figures (17) and (18) show the wear track, ploughed by hard aspirates of the mating surfaces, wear particles, plastically deformed matrix and fiber bulking from the matrix for T-oriented and L-oriented specimens respectively.



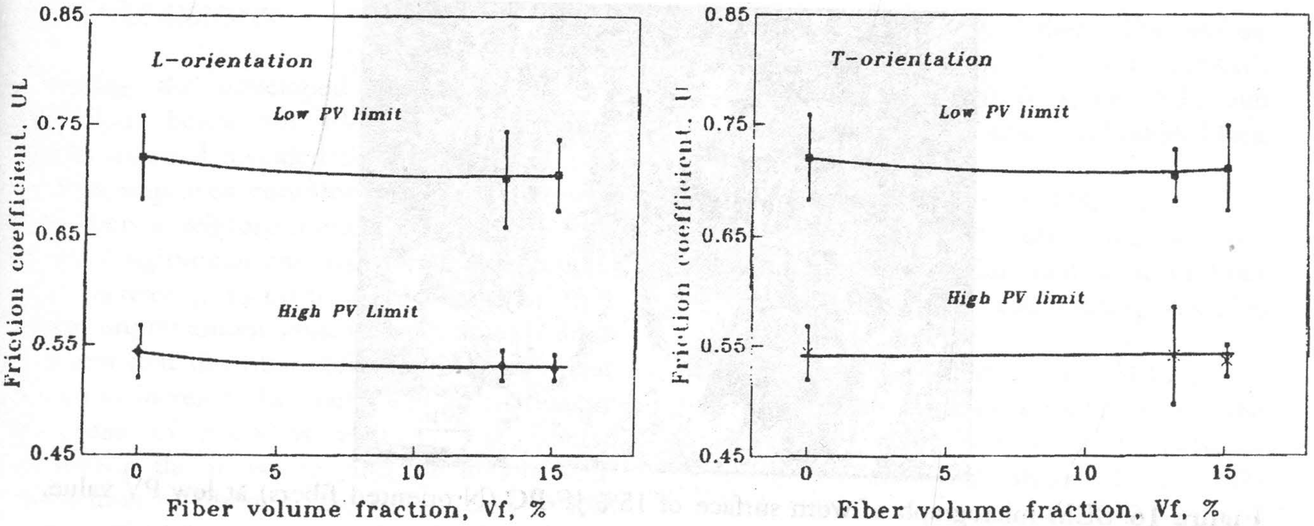


Figure 14. Coefficient of friction versus V_f of LF-PC at low and high PV values.

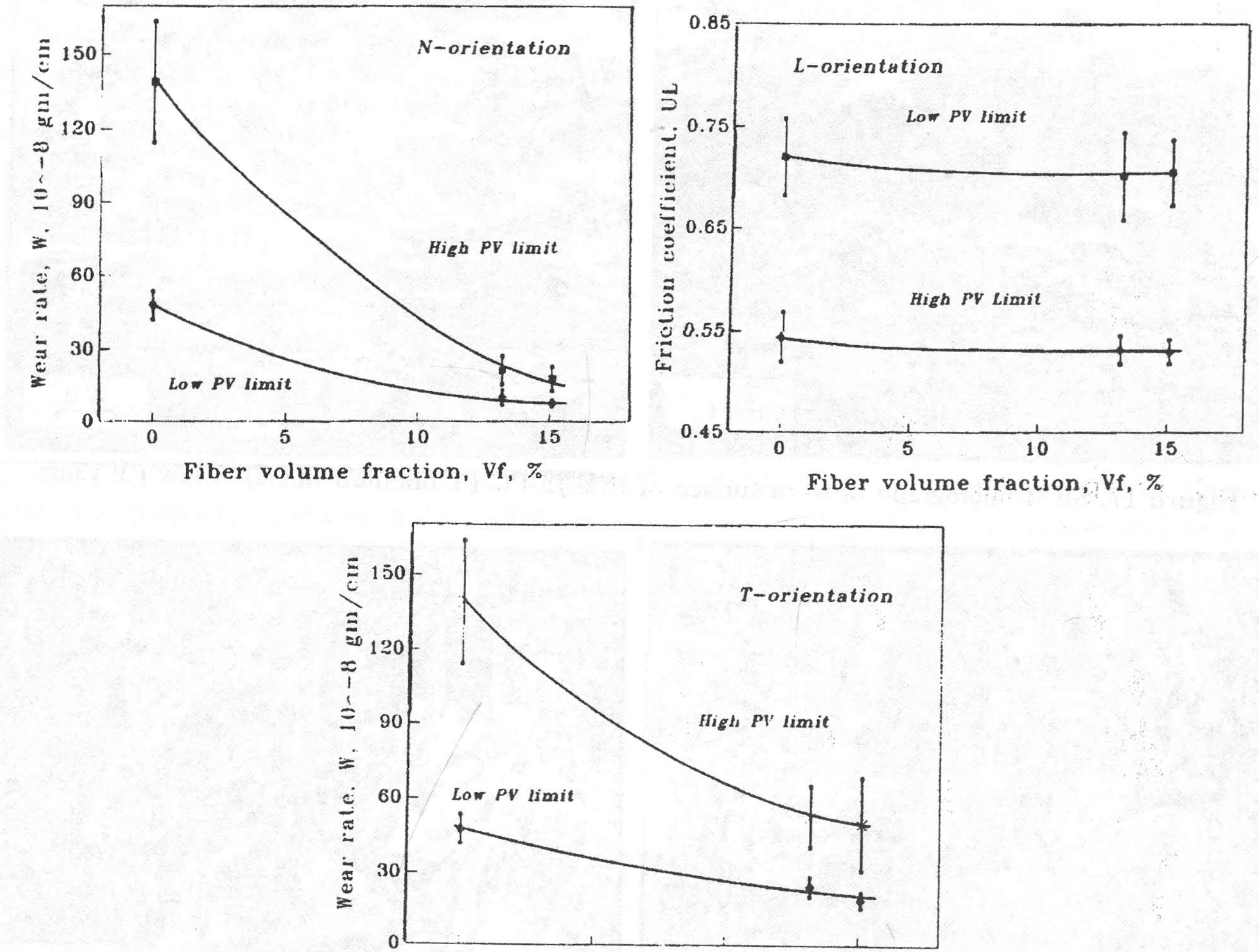


Figure 15. Wear rate versus V_f of JF-PC at low and high PV values.

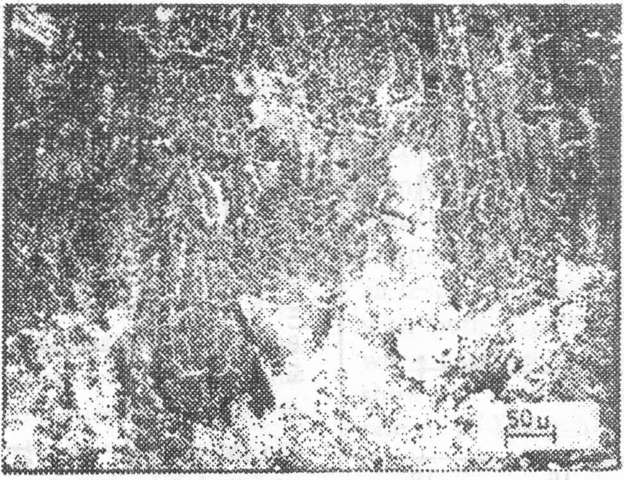


Figure 16. SEM micrograph of worn surface of 15% JF-PC (N oriented fibers) at low PV value.

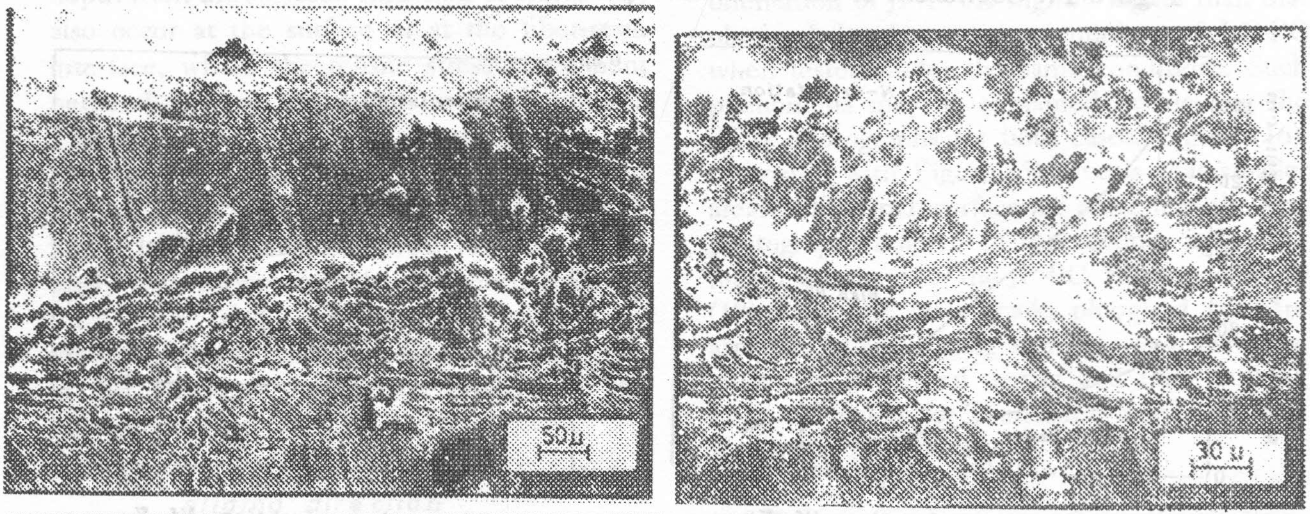


Figure 17. SEM micrograph of worn surface of 15% JF-PC (T oriented fibers) at low PV value.

Figure 18. SEM micrograph of worn surface of 15% JF-PC (T oriented fibers) at low PV value.

4. CONCLUSIONS

Testing the developed composites in dry conditions below the PV limit of the pure matrix material revealed that the coefficient of friction improves considerably, using linen or jute fibers as reinforcement (LF-PC and JF-PC) in the longitudinal and transferase orientation, with increasing V_f up to a percentage of 15% where improvement senses on the other hand it is found that the fibers oriented in the normal direction increase the coefficient of friction in the case of linen as well as jute fibers. Moreover, the transverse and the longitudinal orientation of fibers in the LF-PC and JF-PC system yield lower wear rate than that of the matrix material and the normal orientation fibers give its lowest rate at a value of 15% V_f.

Testing the developed composites in dry conditions above the PV limit of the pure matrix material revealed that the coefficient of friction is not significantly improved using either linen or jute fibers for reinforcement in both the longitudinal and the transferase orientation cases., It gets even worse in the case of normal orientation. On the contrary the wear rate improves as the volume fraction increases in both composite systems. As in the low PV case, the normally oriented fibers give the lowest wear rate; but at 20% V_f.

The size of the resulting wear debris decreases as the fiber volume fraction increases. In all cases the polyester matrix is shown to fail by the formation of wear plateau within a plastically deformed zone. The extent of such localized zones however depends on a fiber plucking off mechanism of both longitudinal and transverse orientations and fiber debonding in normally oriented fibers.

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