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Wear characteristics of thermoset composite under high stress three body abrasive

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Abstract

Three body abrasive wear of chopped strand mat glass fibres reinforced polyester (CGRP) was studied for three principal orientations of the fibres, i.e. parallel orientation (P-O), anti-parallel orientation (AP-O) and normal orientation (N-O). The tests were carried out under high stress conditions. A correlation between the specific wear rate and mechanical properties was established. As a result, CGRP composite exhibited better wear characteristic in P-O as opposed to in AP-O and N-O. Different wear mechanisms were observed on the worn surfaces of the materials, including pitting, micro- and/or macro-cracks, as well as breakage and debonding of the fibres.

Keywords: Glass, Polymers, SEM, Abrasive Wear, mechanical properties.

1. Introduction

Abrasive wear takes place when a solid object is loaded and slid against particles of another material with a similar or higher hardness [1]. Abrasive wear mechanisms can occur in three principle modes: micro-cutting, wedge-forming and plowing. Many factors control the abrasive wear degree, such as design parameters, operating conditions, characteristics of abrasion, and material properties [2]. Understanding the abrasive wear behaviour is imperative from a tribological and commercial standpoint. Abrasive wear is recognized as the most important among all forms of wear since it contributes to almost 63% of the combined cost for wear in industries [3]. Although abrasive wear of fibre polymeric composites is the subject of a large body of literature, the wear process in polymeric composite is still not well understood [4, 5]. Abrasive wear can occur in two-body abrasion (2B-A), three-body abrasion (3B-A), and/or both in the case where removed debris play the role of third body particles [6]. In practical applications, three-body abrasion is far more prevalent than that of its two-body counterpart [4,7]. Due to the extensive applications of polymeric composite materials, the 3B-A wear property has gained attention from many researchers in the past few years [5, 8-14]. Moreover, three-body abrasion is the major problem of agricultural machine and mining components [12].

Three-body abrasion modes are basically divided into high and low stress. For both types, the composite sample is pressed against a rotating or sliding counterface and during the tests, particles flow in the rubbing area. The type of the counterface material determines the kind of abrasion obtained, i.e. high stress in the case of metal and low stress in the case of rubber. For low stress abrasion of polymeric composites, many attempts have been made to understand the tribobehaviour of various materials at several operating parameters, and the efforts continue. In [5, 14], the low stress three-body abrasion of polyester composites reinforced with randomly distributed short glass fibres has been studied, and it was found that increasing the size of the abrasive particles and the applied load worsened the wear property of the composite. Meanwhile, increasing the sliding velocities reduced the wear rate, and increasing the volume fraction of the glass fibres, according to the high energy theory, improved the wear properties, whereby a higher energy was required to facilitate the failure in the fibrous regions. The wear mechanism was predominated by matrix failure, pitting, cracks and grooves. In research [12, 13], the effect of fibres, solid lubricants and applied load on the 3B-A characteristics of polyaryletherketone (PAEK) composites showed that the ketone/ether ratio highly influenced the wear resistance of the composites especially at a higher load (12 N). Surprisingly, the addition of fillers and/or fibres to the PAEK worsened its 3B-A characteristics. Moreover, carbon fibres provided a poorer support for the PAEK composites as compared to glass fibres. SEM images displayed a similar wear mechanism as shown in [5], i.e. pitting and grooves. In a recent work [11], the effect of woven glass and carbon fabric on the 3B-A wear performance of epoxy composites has been studied for a normal orientation at low stress conditions. This investigation indicated that an increase of the sliding distance caused an increase in the volume loss and a reduction in the specific wear rate. Meanwhile, increasing the applied load reduced the specific wear rate at longer sliding distances. Due to the exposure of fibres to the rubbing area, less support was found for the epoxy matrix. Moreover, carbon fibres showed less wear material removal due to the high interfacial adhesion with the epoxy matrix.

On the other hand, many attempts have been made to establish a relation between mechanical and tribological properties. Specifically, most of the research accomplished on polymeric composites tested in three body abrasive tests has attempted to find a correlation between mechanical properties (tensile strength, elongation and hardness) and the abrasive wear characteristics [4, 5, 7, 12-16]. However, the influence on the wear performance is not consistently beneficial as suggested by [13] with regard to reported arguments and contradictions. For instance, in a vast range of research efforts [4, 15-17], a poor relation has been found between the mechanical properties and the 3B-A wear rate of twenty polymeric materials. However, in another study, it has been found that the hardness played a main role in controlling the abrasive wear [4]. Therefore, certain investigations have attempted to combine more than one mechanical property to one product in order to identify a better relation [12, 13]. When combining more than one factor, some found that the relation between the mechanical and tribological properties was highly in agreement with certain published reports [18-21], they were contradictory to others [15-17]. It has been proposed through the published works to correlate the abrasive wear results of polymeric composites to the mechanical properties.

From the above studies, it is found that less work has been carried out on 3B-A wear at high stress condition; whereas, in practical applications, such as mining, farming as well as in dusty environments, polymeric components are subjected 3B-A at high stress against metal for instance in bearings, slides, seals, and bushes. Under such circumstances, high stress abrasion takes place and therefore, more attention should be paid to this type of wear. The current work comes to investigate the three body abrasive wear properties of chopped strand mat glass fibre reinforced polyester (CGRP) composite, subjected to high stress. In addition, it studies the possibility of establishing a correlation between the mechanical and tribological properties of the composite.

2. Materials and Experiments

2.1 PREPARATION OF COMPOSITES

Polyesters composite was developed based on chopped strand mat (CSM) glass fibres (450g/m2 R-glass). Orthophalic unsaturated polyester (Revesol P9509) is used in the current work which is cured by adding methylethylketone peroxide (MEKP) as a catalyst. The glass fibre mats were supplied by Kong Tat Company (Malaysia). Details of the fabrication method, compositions and properties of CGRP composite have been given elsewhere [22]. The specimens with sizes of 25 × 58 × 20 mm^3 were machined from a plate of size 250 × 250 × 25 mm^3 and the sliding was performed on an area of 25 × 58 mm^2.

2.2 Experimental details

A new tribo-test-machine was developed. Fig. 1 shows a three dimensional view of the machine, which was designed with the aid of CATIA software (Computer Aided Three dimensional Interactive Application). Three body abrasive (3B-A) experiments, using a sand/steel wheel configuration, were performed on the developed machine. The hopper provided sand at a desired flow rate, through a control valve, to the interface. To ensure that most of the sand particles go through the interface area, two side plates were used to direct the abrasive particles to the interface during the tests.

The experiments were performed against a stainless steel (AISI 304) counterface at an initial roughness of 0.12 μm Ra. The sand was collected from the beach of Alor Gajah at the Melaka city in Malaysia. The sand particles were sieved (in the size range of 500-900 μm), cleaned, washed and dried in an oven for 24 hours at 40 ^{o}C, **Fig. 1b**. The sand flow was, for all test conditions, fixed at a rate of 4.5 g/sec. The 3B-A tests was conducted at two rotational speeds (50 and 100 rpm corresponding to 0.576 and 1.152m/s, respectively) for a 180 s test duration. The applied load was in range of 5 N -20 N. The chopped strand mat glass fibre reinforced polyester (CGRP) composite was tested in three principle orientations with respect to the sliding direction, i.e. Parallel (P-O), Anti-Parallel (AP-O and Normal (N-O), **Fig. 2**. In parallel orientation (P-O), the composite is oriented in away where the fibre mats is parallel to the sliding direction and the applied load; while, in AP-O, the sliding direction is perpendicular to the fibre mats. In normal orientation (N-O), the fibre mats are parallel to the counterface plane; while, the applied load is perpendicular to the fiber mats.

It should be mentioned that three tests were run per test condition, and the averages were determined. After that, wear rates were determined with respect to the applied load, i.e. mg/N. Scanning electron microscopy SEM (JEOL, JSM 840) was used to observe the worn surfaces of the specimens after each test. Before taking the micrographs, the worn surface was coated with a thin layer of gold through ion sputtering (model JEOL, JFC-1600).

3. Results and discussion

3.1 Wear rate and friction coefficient of polyester composite based on glass fibres

The wear rate and friction coefficient of the chopped strand mat glass fibres (CGRP) composite three different orientations (P-, AP-, and N-orientations) versus the applied load (5-20 N) at two rotational speeds of 50 and 100 rpm are shown in **Figs. 3 and 4**. In general, increasing the applied load decreases the wear rate, especially at higher rotational speeds, **Fig.3b**. At a lower speed, the effect of the applied load is insignificant. The results at low rotational speed are in agreement with those reported [5] on CGRP tested in N-O under low stress against a rubber wheel. Meanwhile, the decrease in the wear rate with an increasing the applied load at higher rotational speeds is consistent with other published works [23-25]. However, other reported works [7,12,13] showed no influence of the applied load on the wear rate of the composite. The reduction of the wear rate with increasing applied load could be due to the fact that the apparent contact area was greatly increased at higher applied loads compared to at the lower ones. Increasing the apparent contact area allows a large number of sand particles to encounter the interface and share the stress. This, in turn, leads to a steady state or reduction in the wear rate.

The 3B-A results of the CGRP composite indicate that a better wear performance for the composite is produced in the P-O. In N-O, the wear results are poor compared to those obtained for P-O and AP-O. In P-O and AP-O, the abrasion was simultaneously initiated on the hard and soft phases of the composite. In this situation, the glass fibres were exposed to the interface throughout the entire test. It has been reported that the presence of glass fibres in the interface reduces the wear rate [5]. On the other hand, in the case of the N-O, the abrasion started through contact with the softer phase (polyester). This contributed to severe matrix damage as reported in [5, 14] when the CGRP composite was tested in N-O.

In [14], it is suggested that, under low stress 3B-A, the sand particles behaved in one of the following ways. From free fall, the sand particles gained energy from the rubber wheel and then struck the composite surface, which would result in the formation of pits. Secondly, the abrasive particles were embedded in the rubber wheel, transforming the three body abrasion into multipass two body abrasion. Thirdly, the particles roll at the interface causing plastic deformation to the composite. In the current work, at high stress abrasion, the counterface is steel, which is much harder than rubber. Consequently, there was only one way for the sand particles to move in the contact area, which was to gain high energy from the steel wheel and strike the composite surface. After that, the particles moved in one of two ways, either roll in the contact zone causing pitting on the composite surface, or penetrate into the composite surface causing micro- and/or macro-cracks on the surface. Both mechanisms were identified by the CSM glass fibre orientations. In N-orientation, all reported works on polyester and epoxy multilayer glass fibre composites [5, 14, 13] have concluded that, at the initial stage of the abrasion, the particle penetrated the soft outer layer of the composite (matrix) due to the lower hardness. Once the matrix layer was removed, the harder phase of the composite (fibres) was exposed to the rubbing area which acted as a protector leading to a reduction in the removal of material. However, breakage, debonding, as well as pull-out of fibres have been bserved at longer sliding distances. In the case of high stress 3-BA, the damage on the composite surface in N-O could be different and severer due to the high energy barrier caused by the particles. In this case, the sand particles penetrated deeply into the composites, causing fracture at the outer soft layer (polyester). As a result, the CSM glass fibres layer is exposed to the rubbing process. This could cause delamination and breakage the fibre layers.In the P-O and AP-O, the contact of the particles with the composite surface differed from that in N-O due to the fibres being exposed to the contact from the start of the test. This assisted in reducing the material removal from the composite surface during the sliding, where the glass fibres had a higher hardness than the polyester, thus explaining the poor wear results of the composite in N-O compared to in the P and AP-orientations.

With regards of the frictional performance of the CGRP composite, **Fig. 4** shows that increasing the applied load reduces the friction coefficient of the CGRP in the P-O and AP-O.

Meanwhile, in N-O, the friction coefficient increased when the applied load was increased. The Fig. indicates that the friction coefficient of the composite in different orientations is reduced in the following order N-O > AP-O > P-O. Sometimes, the higher friction coefficient indicates a higher wear resistance. The current study on the CGRP composite in 3B-A at high stress showed the opposite, i.e. a lower friction was associated with the lower wear rate. It seemed that the wear and frictional characteristics were controlled by the type of motion that the particles underwent at the interface, i.e. either sliding or rolling. In the case of rolling, a lower friction coefficient and wear rate were measured, whereas these values were supposedly higher during sliding.

3.1.1 SEM observations on CGRP

Parallel-orientation

Fig. 5 shows the worn surface of the CGRP composite tested in P-O at different loads and rotational speeds. At a low applied load (5 N), **Fig. 5a**, the damage was more dominant in the resinous regions than in the fibrous ones. Pitting (marked as "Pi") in the resinous regions and micro-cracks (marked as "Cr"), especially in the area close to the CSM glass fibres can be observed. The fibres seemed to be loose, although there was no sign of fibres pulled out. At a higher applied load (10 N) and a low rotational speed (50 rpm), **Fig. 5b**, both the polyester and fibre regions were damaged. Breakage (marked as "Br") and delamination (marked as "De") of the fibres occurred as well as fracture (marked as "Fr") of the polyester, initiated by micro- or macro-cracks. Under severe test conditions (of 20 N and 100 rpm), **Fig. 5c**, a massive removal of material took place in the resinous region, and breakage occurred in the fibrous one and it seemed that broken fibres were worn away. This could explain the higher wear rate found at the higher speed, as illustrated in **Fig 3**.

Anti-parallel-orientation

Fig. 6 shows the micrographs of the worn surface of the CGRP composite tested in AP-O at different applied loads and rotational speeds. **Fig. 6a** shows the damage of the composite worn surface at 10 N and 50 rpm. Under this condition, the composite surface was highly deteriorated and the predominant wear mechanism was pitting in the resinous regions and breakage in the fibrous ones. At a 50 rpm rotational speed and 20 N applied load, **Fig. 6b**, debonding and delamination of the fibres occurred, causing the fibres to become loose and easily removed. At a 20 N applied load and 100 rpm rotational speed, larger sizes of polyester debris were present on the surface and the fibres seemed to be worn away. This was associated with micro- and macro-cracks, distorted grooves and pitting in certain areas.

Judging from the observations on the worn surfaces of the composite in P-O (**Fig. 5**) and in AP-O (**Fig. 6**), the damage in the fibrous region was more evident in AP-O, where the resinous region close to the CSM glass fibres was substantially removed. This, in turn, allowed the particles to attack the fibres and damage them. On the other hand, in the case of P-O, the particle movement was parallel to both the hard and soft layers of the composite and somehow caused less damage to the fibres. This could explain the higher removal of material in AP-O compared to in P-O.

Normal-orientation

The worn surfaces of the composite tested in N-O at different applied loads and 50 rpm rotational speed are shown in **Fig. 7.** The Fig. illustrates a substantial damage on the composite surface, i.e. the detachment of CSM glass fibres, removal of the polyester layer and debonding of fibres. This indicates that the sand particles penetrated deeply into the composite. Comparing the micrographs of the composite, in the three orientations (Figs. 6-8), it can be concluded that there was a relatively high amount of material removal in N-O, which supports the results shown in **Fig. 3**.

4. Correlation of 3B-A with Mechanical Properties

Arguments and contradictions have been reported with regard to the correlation between mechanical properties and the 3B-A wear performance of a composite, [13]. For instance, work reported by [4, 18] showed a poor relation between the mechanical properties (*S, e,* and *H)* and the 3B-A wear rate of twenty polymeric materials, where *S* represents the ultimate strength, *e* the elongation at the break, and *H* the hardness. When considering the properties individually, it has been found that the hardness played a main role in controlling the abrasive wear [4]. However, other researchers found otherwise [15-17]. Therefore, a combination of more than one mechanical property in one product (such as *Se, SeH* and *He*) was found to give better correlation [12, 13]. When combining more than one factor, it has been seen that a lower *Se* and a higher hardness yielded high wear rates for all the selected materials. While this result agreed well with some published work [4, 17-21], it was contradictory to others [15-17].

The compression strength could have a stronger influence on the 3B-A wear property than the tensile strength. Whereby the load is applied in the form of compression thereby pressing the specimen toward the sand particles at the interface. This attracted the attention to explore the possibility of a correlation between the mechanical properties, including the compression strength, and the specific wear rates of the composites. Some of the previous work on polyester composite based on oil palm fibres [26, 27] is needed here to establish the some graphs. In the previous work, 3B-A wear behaviour of untreated and treated oil palm fibres reinforced polyester (UT-OPRP, and

T-OPRP) composites were reported. The mechanical properties of the previous and current composites are listed in **Table 1**.

Table 1 Various mechanical results of CGRP, UT-OPRP and T-OPRP composites, as well as NP.

Material	Tensile strength MPa	Tensile modulus GPa	Elongation %	Comp. Strength MPa	Hardness SD
Neat Polyester (NP)	25	1.3	2.5	28	6.8
CGRP	85	1.6	6.3	51	9.62
UT-OPRP	35	1.7	4.3	57.6	6.9
T-OPRP	45	1.65	3.2	60	7.52

The steady state values of the specific wear rate (W_S) of all the materials at 50 rpm and 10 N are plotted against various products of the mechanical properties such as S_Te^{-1}, HSe^{-1} and S_C^{-1}, in **Figs. 8&9**, Here, S_Te^{-1}= ultimate strength multiplied by the elongation at the break, HSe^{-1} the ultimate strength multiplied by the elongation at the break and the hardness and S_C^{-1} corresponded to the compression strength. **Fig. 8 a&b** shows the correlation between S_T and W_S, as well as HS_Te and W_S. The figure indicates that there was a stronger correlation between W_S and HS_Te than when considering the ultimate tensile strengths individually.

Fig. 9 shows the compression strength (S_C) as well as the product of all the factors against W_S for the materials. **Fig. 9a** displays that when considering the compression strength alone, one obtains a better correlation than when including other factors (whether in combination or individually). Furthermore, by combining all the mechanical properties (HS_TeS_C), less correlation with the W_S can be noticed, **Fig. 9b**. It can be concluded that in such polymeric composite materials, the compression strength plays the main role in controlling the 3B-A wear property. The higher the compression strength, the lower was the specific wear rate. At the same time, the hardness and elongation had more influence on the abrasive property compared to the tensile strength.

5. Conclusions

After conducting the experimental work and discussing the results, few points can be drawn as follows:

1. The CGRP composite exhibited better wear characteristics when it was tested in P-O. There was less damage to the fibrous regions as opposed to in AP-O and N-O.
2. Different wear mechanisms were observed on the worn surfaces of the materials, including pitting, micro- and/or macro-cracks, fracture in the matrix as well as breakage and debonding of the fibres.
3. A correlation between wear and mechanical properties is established. Better correlation, between specific wear rate and mechanical properties as one product, is found compare to the ultimate tensile strengths individually. Tensile strength showed no remarkable influence on the wear property, while, hardness and elongation at the break had more affect. On the other hand, it is found that the specific wear rates and mechanical properties were in close relation when the compression strength was considered.

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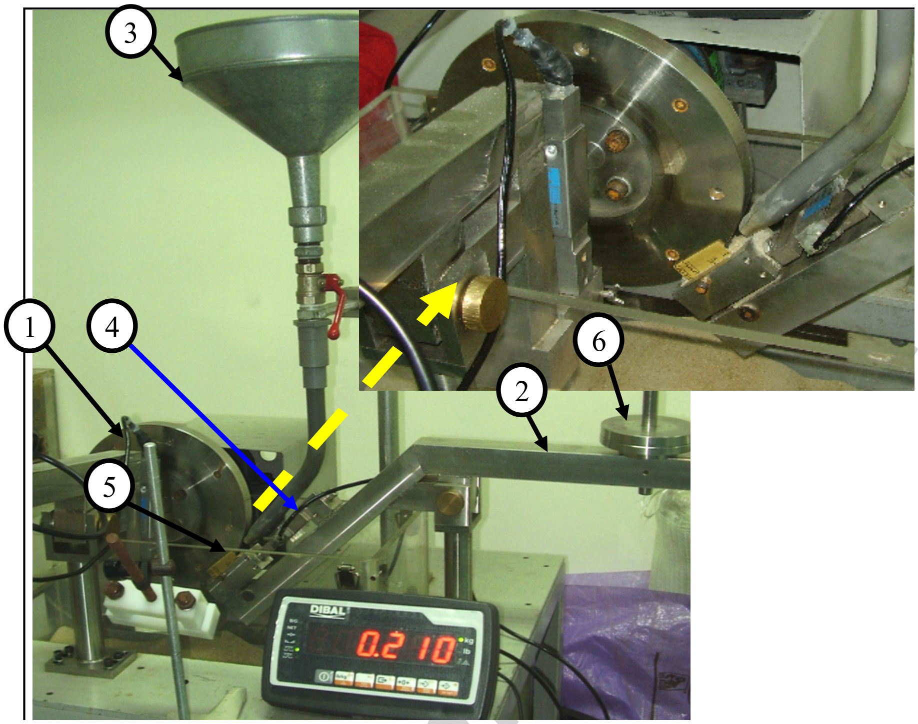
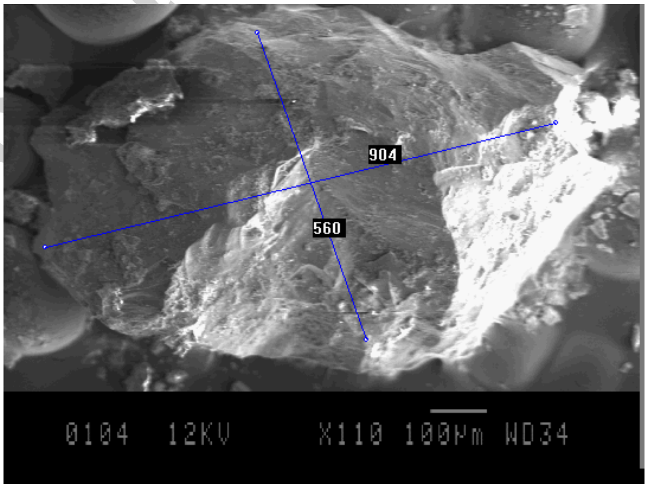
T-OPRP	65	1.65	3.2	60	7.52



1-Counterface, 2-load lever, 3- Sand hopper -, 4-Load cells, 5-Specimen,6-Dead weights

a) The tribo-test machine running in 3B-A mode.



b) SEM micrograph of the sand used for the 3B-A tests.

Fig. 1 A three dimensional drawing of the new tribo-test machine with the used sand particles

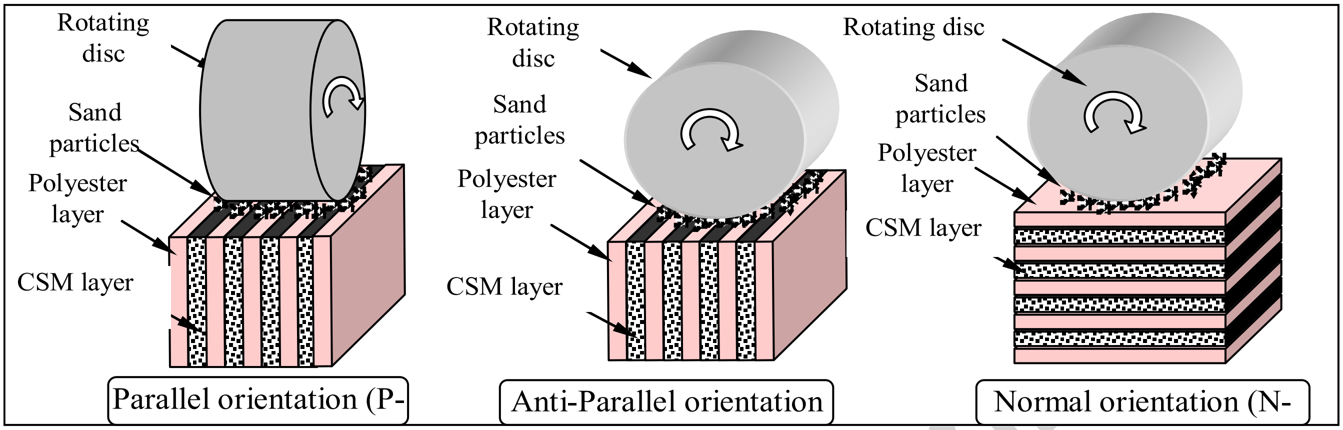


Fig. 2 The CGRP composite tested in different orientations

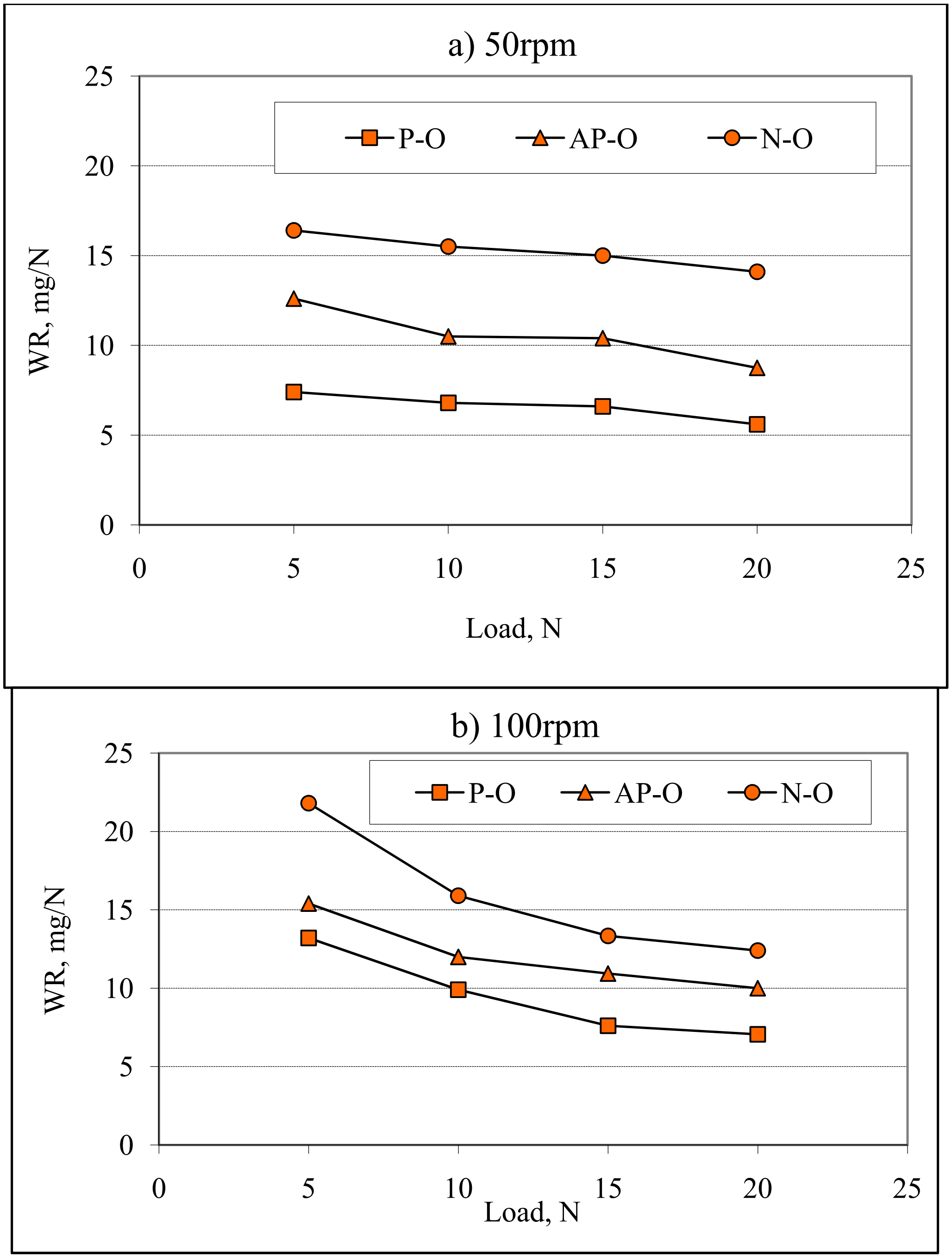


Fig. 3 The 3-BA wear rate vs. the applied load for the CGRP composite in three orientations at 50rpm and 100 rpm rotational speeds.

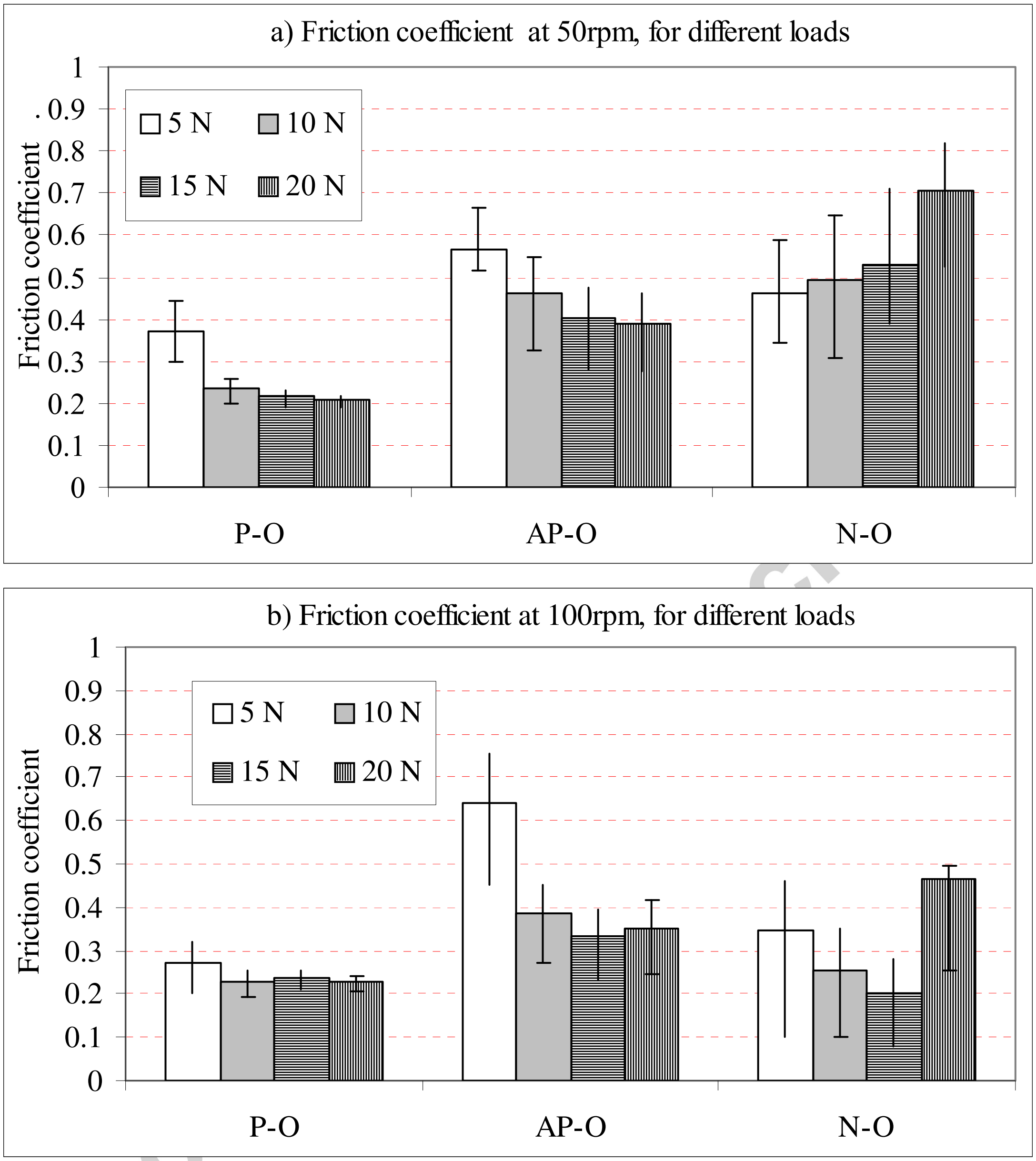
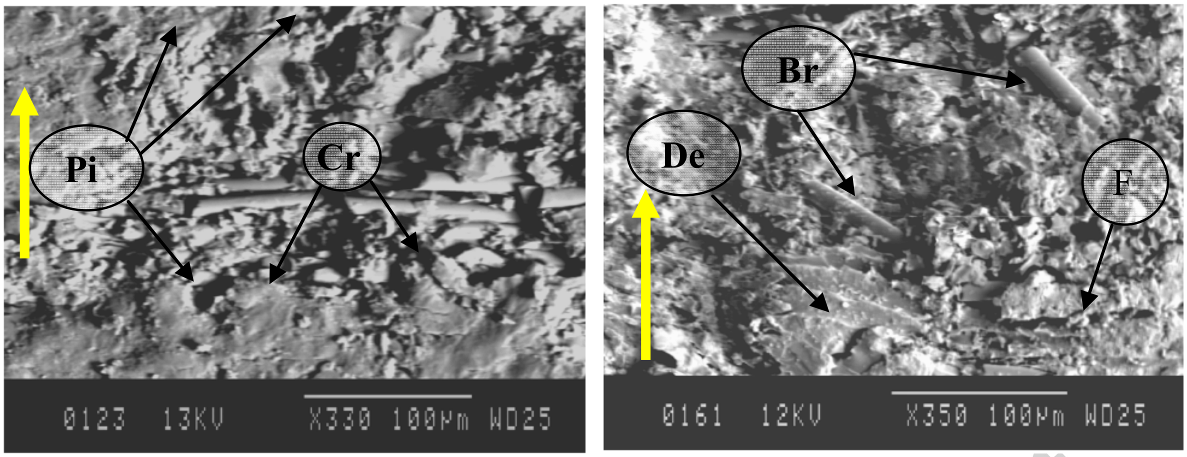
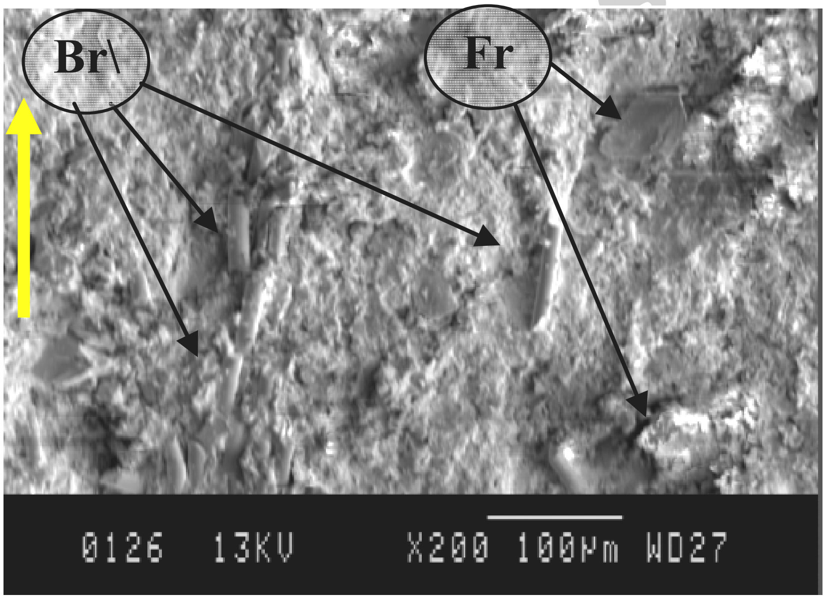


Fig. 4 The friction coefficient of the CGRP composite in three orientations at different applied loads and rotational speeds.



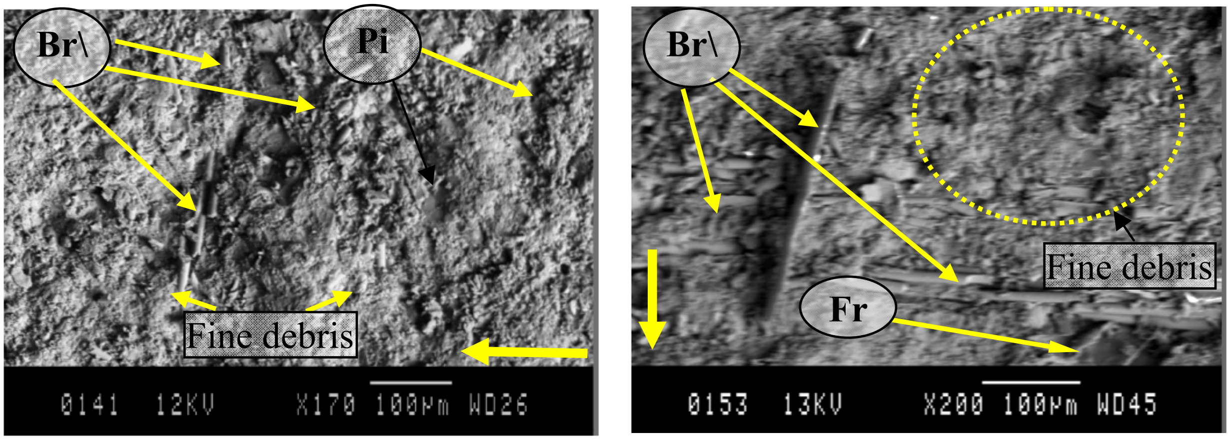
a) At 5 N, 50 rpm

b) At 10N, 50rpm



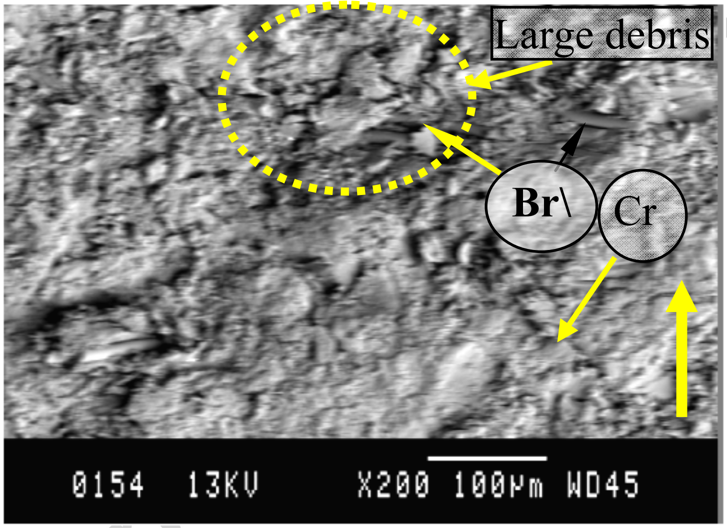
c) At 20N, 100rpm

Fig. 5 Micrographs of the worn surfaces of CGRP tested in P-O at different applied loads and rotational speeds.



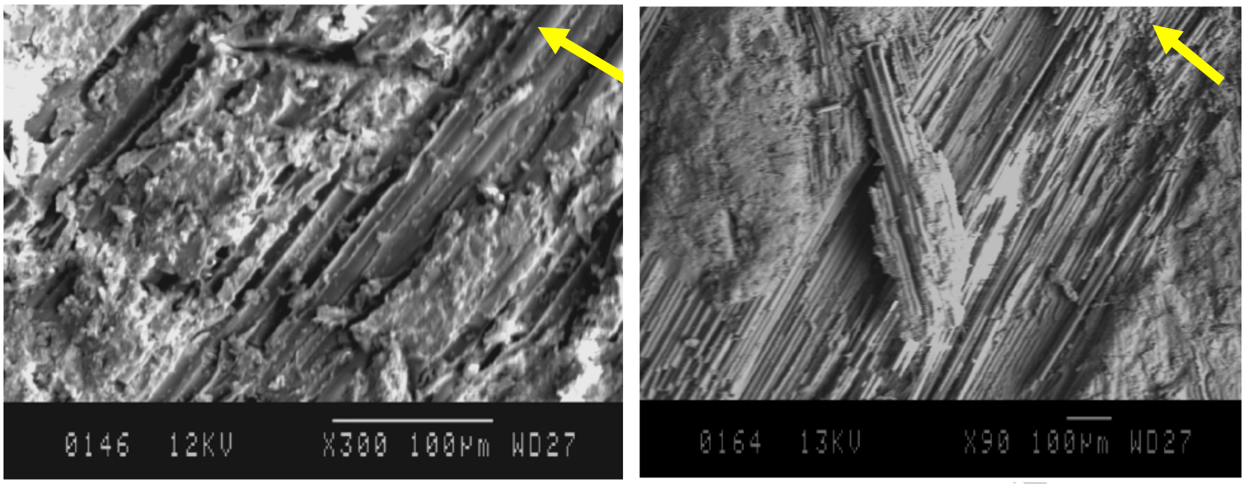
a) 10N, 50rpm

b) At 20 N, 50 rpm



c) At 20N, 100rpm

Fig. 6 SEM micrographs of the worn CGRP surface tested in AP-O at different applied loads and rotational speeds.



a) 5N, 50rpm

b) At 20N, 50 rpm

Fig. 7 SEM micrographs of the worn CGRP surfaces tested in N-O at different applied loads and rotational speeds.

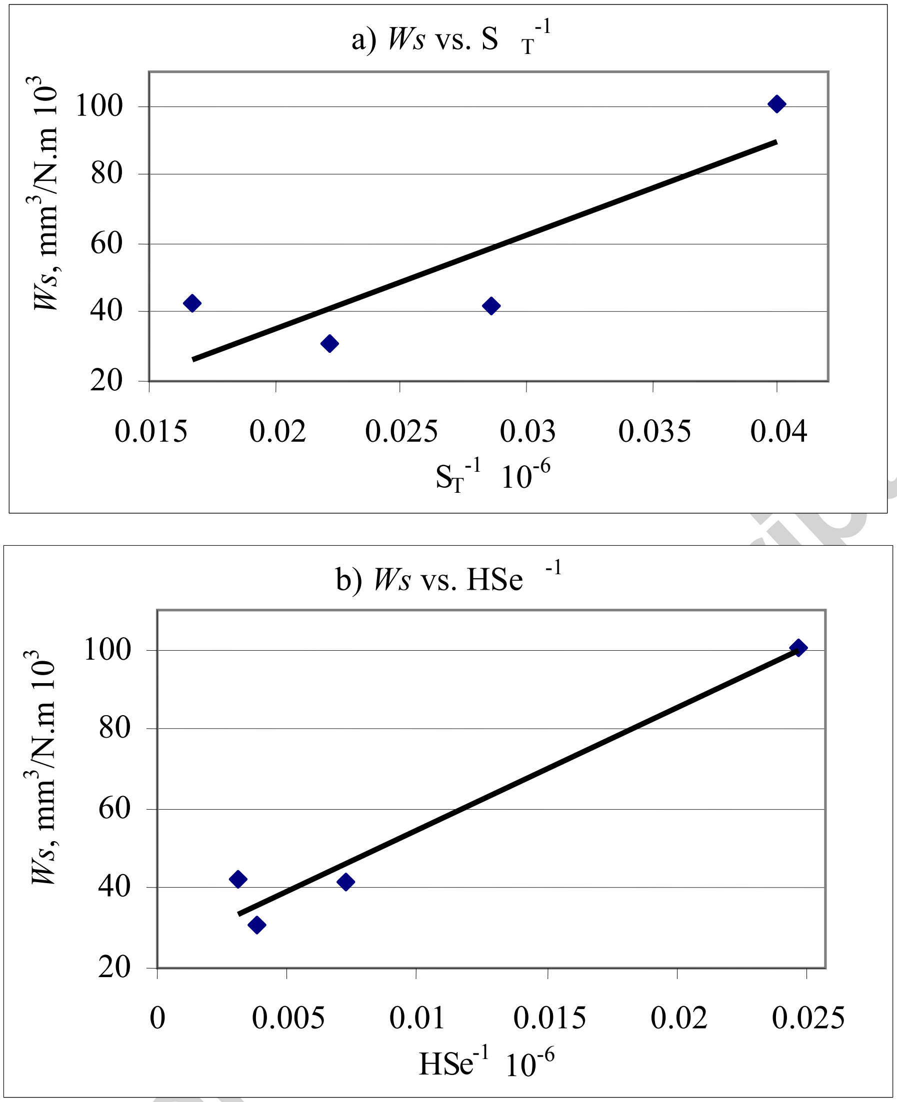


Fig. 8 The specific wear rate as a function of various S_T^{-1} and HS_Te^{-1} of the neat polyester, as well as the CGRP, T- OPRP and UT-OPRP composites in P-O.

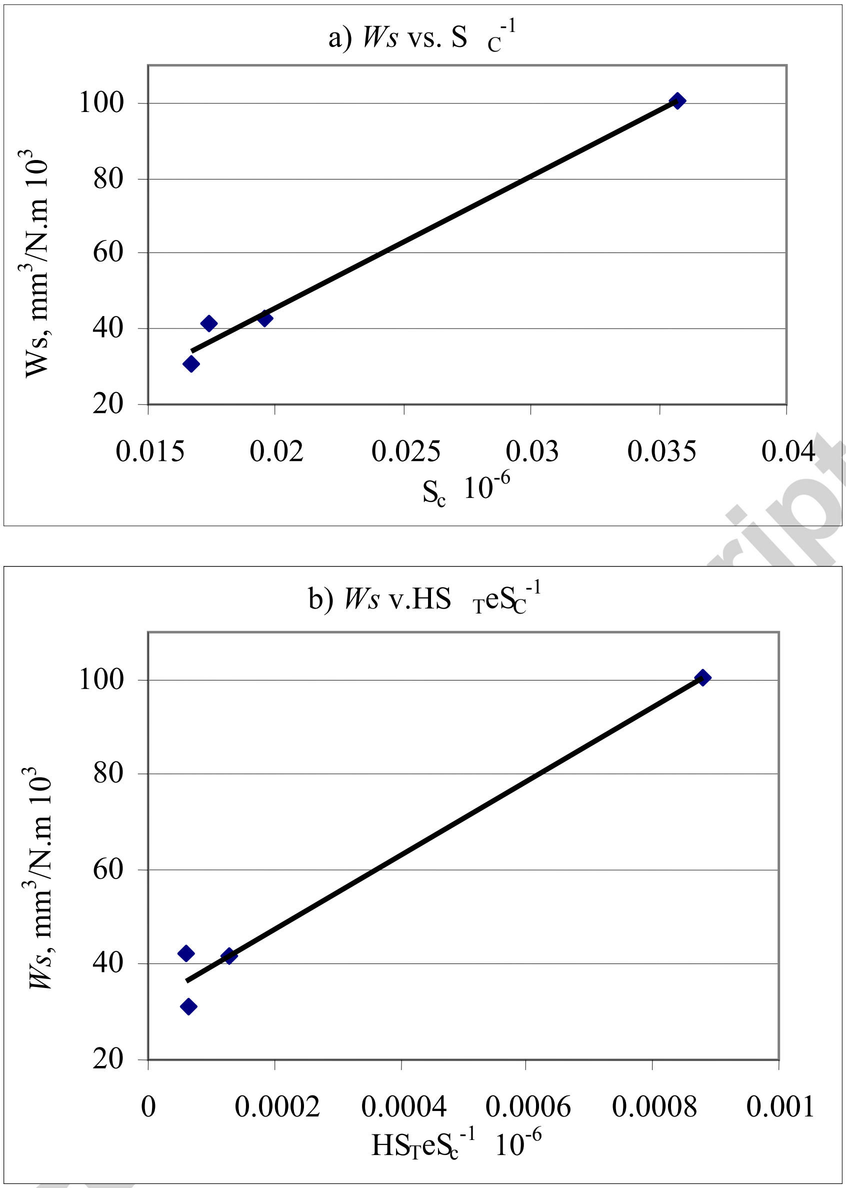
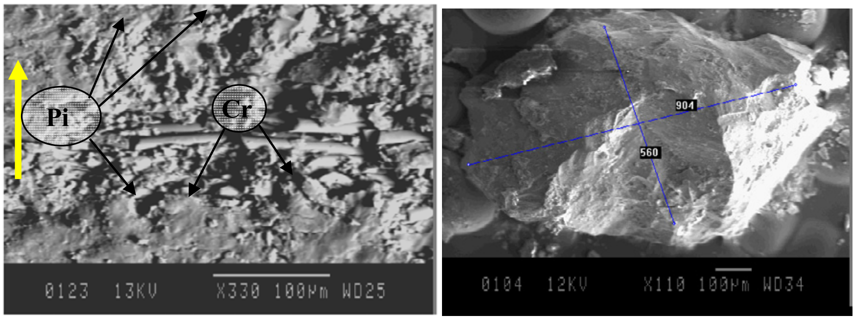


Fig. 9 The specific wear rate as a function of various S_C^{-1} and $HS_TeS_C^{-1}$ of the neat polyester, as well as of the CGRP, T- OPRP and UT-OPRP composites in P-O.

Graphical Abstract



Highlights

• Fibre orientation influences the three body abrasion behaviour •Speed and load influence the wear characteristics •Wear mechanisms in three body abrasion are pitting, cracks, fracture in the resinous regions, and breakage of fibres. •There is good correlation between mechanical and wear properties