

Comparative Analysis of Wear Behaviour of Commercial Polymeric Pipe Materials under Different Sliding Environments

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STUDENT DECLARATION

This is to certify that the thesis entitled, “**Comparative Analysis of Wear Behaviour of Commercial Polymeric Pipe Materials under Different Sliding Environments**” is an outcome of the investigation carried out by the author under the supervision of **Dr. S. Reaz Ahmed**, Department of Mechanical Engineering, BUET. This thesis or any part of it has not been submitted to elsewhere for the award of any other degree or diploma or other similar title or prize.

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SUPERVISOR CERTIFICATION

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I wish them success in their future life.

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ABSTRACT

The current study was conducted to compare the wear behaviour and frictional nature of three commonly used commercial polymers namely, uPVC (Unplasticized polyvinyl chloride), High Density Polyethylene (HDPE) and Acrylic. The aim was to find out the effect of various loads at various sliding distances on wear characteristics and frictional nature of the materials. A vertical pin-on-disk method was used throughout the experiment. All experiments were carried out in normal ambient conditions of relatively high summer temperatures (approximately 30°C) and high relative humidity (80%). The sliding velocity was kept at 0.6397 m/s and the sliding distance was varied from 192.423 m to 4618.152 m. The loads were 0.025 kg, 0.5 kg, 1.0 kg, and 2.0 kg respectively. The experiments were done in three different surface mating conditions, dry, wet and clay-water. It was verified that the weight loss increased with increase in sliding distance and load. Density and hardness of the different polymers were also measured. Also it was studied to see whether the wear behaviour and frictional resistance had any correlation to each other and it was found that there was no noticeable relationship between wear rate and friction coefficient (μ). However both the frictional coefficient and wear rate varied with load. Different surface mating conditions (dry, wet and clay-water) showed effect on the friction coefficient (μ) and wear rate as well. It was found that in general friction coefficient (μ) of HDPE was least of the three in all experimental conditions, while acrylic had the highest, and uPVC fell in between. The wear behaviour also showed a similar trend in that HDPE had the least wear for a given load at a particular sliding distance and at a specified surface mating condition while Acrylic showed the most wear with uPVC falling in between. The reason behind the excellent wear and frictional behaviour of HDPE is due to the difference in the crystallinity of the three polymers. HDPE is almost fully crystalline in nature while Acrylic is almost fully amorphous and uPVC has higher portions of crystalline region compared to acrylic. Generally the higher the crystallinity the better the frictional and wear characteristics of any material. Optical microscopic analysis of the specimen, dust and disk was also made. EDX and ESM observations were also made which showed that uPVC was most affected by oxidation followed by HDPE and then Acrylic.

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1. INTRODUCTION

1.1 Background

In modern times the advent and development of plastic, polymer and polymer-science has had a significant effect on both the commercial sector and everyday life. These plastics are generally formed by many organic molecules called monomers coming together and forming large branched or un-branched chains (polymers). Plastics and polymers are used in almost every industry and also in manufacturing common household items. Everything from heavy duty commercial pipes to chairs, bottles and even medical equipment like the syringes are made from plastics and polymers. And so it is very important to investigate the nature and properties of these plastics under a variety of working conditions so that their response in actual service can be predicted, and their lifetime enhanced. Among these properties tribological nature is of special interest for commercial polymers, as in many practical cases these materials tend to be elements of various real-life tribological systems. Common commercial polymers which are of special interest for this study are Unplasticized Polyvinyl Chloride (uPVC), High Density Polyethylene (HDPE) and Polymethyl methacrylate (PMMA). By comparing the tribological system responses (friction and wear characteristics) of these polymers and by identifying internal (structural) and external (service/test conditions) factors which dictate these responses appropriate areas of their use can be found. Some of these important structural factors are the chain length and degree of branching of the polymers, cross-linkage of the chains, nature of the cross-linkage in the said chains, chain entanglement and the presence of special functional groups in the chain, degree of crystallinity which is the percentage of amorphous and crystalline zones in the material. Among service factors mating surface conditions (i.e. lubricated or non-lubricated), temperature at the interface, load, speed, counter body roughness, transfer-layer formation at the interface, chemical interaction with the environment and the nature of relative motion among the sliding pair are of special interest.

1.2 Literature Review

For this study a look at the current state of knowledge in the fields of polymer tribology and polymer crystallography is necessary. There have been attempts to mathematically model wear characteristics of materials in field of tribology be they polymer or not. The most well-known of these models was given by *Archard*; according to this theory the

volume removed is proportional to both the applied load and sliding distance but varies inversely with the hardness of the softest contacting surface [1]. Another model of interest is Reye's hypothesis which states that the volume of the removed debris due to wear is proportional to the work done by friction forces [2]. *Viswanath* and *Bellow* in recent years have developed a wear model specifically for polymers [3]. Their aim was to develop an empirical wear equation which relates volume loss of a polymer to the operating conditions, properties of the polymer, and counter-face roughness [3].

The most important external factor which directly influences the wear and frictional nature of polymers is the development of the "Transfer layer" also called "The third-body" at the contact zone as stated by *Godet* [4]. *Jintang* also found the same furthermore he also found that the friction and wear properties of polymer were closely related to adhesion strength and covering extent of the transfer film [5]. He also concluded that the transfer film formation itself was governed by polymer structure characteristics, tribochemical reactions and friction conditions [5]. *Rhee* and *Ludema* also studied the mechanisms of transfer layer formation [6]. From their study they came to the conclusion that transfer film forms more readily on roughened surfaces and that it (transfer layer) can exist in a solid state and in a low viscosity or fluid state, each state controls friction and wear of the polymer in a different way [6]. Also it is worth mentioning that condition at the mating surfaces like presence of lubrication also has a profound effect on tribological properties and these properties vary with use of one lubricant to another [7].

Interface Temperature also plays a significant role on polymer friction and wear characteristics, as they are far more sensitive to temperature than metals and ceramics. Elevated temperatures can cause changes in viscoelastic properties of the polymers and often times increase friction in these transition temperature ranges as stated by *Ludema, Tabor* [8]. Other researchers studied the Effect of counter face Materials on interface temperature and friction coefficient of GFRE composite under dry sliding contact. They found that when sliding against Hardened steel (HS) the temperature at the interface was much higher than when sliding against Cast iron (CI) or Aluminium (Al). As a result they concluded that the type of counter face material greatly influences both interface temperature and friction coefficient [9]. In this case it seems that hardness of the counter face material plays a significant role in the interface temperature of a tribological system with harder materials causing greater temperature rise.

As stated above different structural aspects of the polymer chains, their arrangement and nature also dictate the tribological system responses. One of these aspects is the presence of side groups in the polymer chains. *Satyanarayana, Sinha* and *Shen* studied the effects of these side groups on tribological properties. They found that without the presence of bulky side groups polymers show low coefficient of friction and wear [10].

Like side groups another important structural factor which plays a role in the nature of polymers undergoing friction and wear is the presence of cross linkage among the chains. In fact not only does the presence of cross linkage in polymers effect their behaviour but also the nature and type of the cross linkage (random cross linkage and ordered cross linkage) plays a significant role in their behaviour as stated by *Chiu, Barry, Perry, Sawyer* and *Phillpot*. They found that as cross linkage increases so does the frictional force generated [11]. And lastly the factor which is most responsible for unique tribological responses of different polymers is the crystallinity or the degree of crystallinity of the material in question. It is the ratio between the crystalline and amorphous zones in a polymer. Generally higher the degree of crystallinity the better the wear and fractional resistance of the polymer along with improved interfacial properties, better thermal resistance and greater hardness. *Cartledge* and *Baillie* have shown this in their study [12].

Polymers selected for this study are Unplasticized Polyvinyl Chloride (uPVC), High Density Polyethylene (HDPE) and Poly methyl methacrylate (PMMA). Not a lot of studies regarding the comparison of the three materials have been done. A few notable studies concerning these three materials are now cited. *Wang, Pan, Wang* and *Zhang* studied the tribological properties of TPU/PVC blends with chrome-plated steel under dry sliding conditions [13]. *Xianqiang, Michael* and *Klaus* prepared Microfibrillar reinforced composites (MFCs) from polyethylene terephthalate (PET) and high density polyethylene (HDPE) and studied the tribological properties [14], while others studied the effect of weathering on tribological properties of an acrylic melamine automotive nano composite [15].

1.3 Objective of the Research

From the previous discussion it is quite clear that lot of work has been done on understanding the mechanics and factors involved in general polymer tribological behaviour. Also effort has been given in improvement the polymers in question (uPVC, HDPE and Acrylic) by manufacturing of polymer composites however, not much research has been done in understanding and comparing the wear and frictional nature of these three materials as to the proper areas of application of these can be found instead of making costly composites. So it is the aim of this paper to investigate these three polymers on their frictional and wear characteristics by subjecting them to wear under different sliding environments. The objectives of this research are as follows,

- a. To study the wear characteristics and frictional behaviour of the polymers in different sliding environment.
- b. To highlight the reasons for the different wear and frictional characteristics of the polymers.
- c. To study the microstructure of the polymers before and after wear by means of optical microscope, SEM and EDX.
- d. To correlate these results with earlier found results.

2. MATERIALS AND METHODS

2.1 Materials & Sample Preparation

The test materials used in the current study are Acrylic (Poly methyl methacrylate), High Density Polyethylene (HDPE) and Unplasticized Polyvinyl Chloride (uPVC). All three samples were taken from commercially available pipes, the chemical composition and physical properties of all three polymers are listed in tables at the end of this section. The figures below show the three pipe sections from which the test specimens were made.

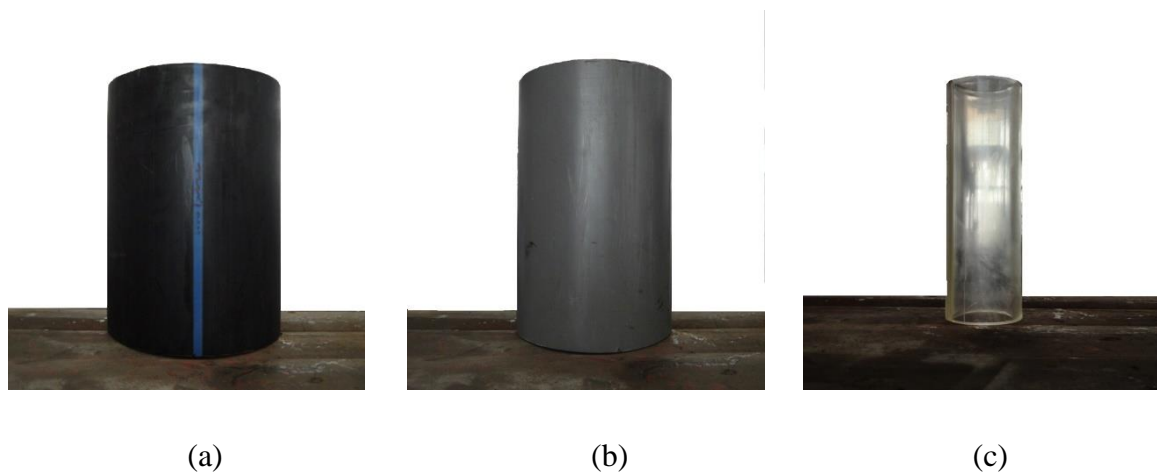


Figure 2 .1 Photographs of (a) HDPE Pipe section, (b) uPVC Pipe section, (c) Acrylic pipe section

Mild steel disks were used as counter-body. The relative roughness of the disks was about $2\mu\text{m}$. And hardness was around HB 126. Acetone ($\text{CH}_3\text{-CO-CH}_3$) was also used as an organic cleaning agent to clean the samples after preparation.

For the test samples were made from strips of materials cut from the pipe sections. The dimensions of the test specimens were 8mm large diameter; 12 mm length and 5mm small diameter were made. Approximately 30 pieces of samples were made for each material totalling at 90 samples combined for all the materials. After sample preparation each sample was polished with emery papers of grade 600, 800, 1200, 1500 and fine polished with velvet and aluminium oxide (Al_2O_3) on polishing wheel. Later the samples were wiped with acetone to remove any residual particles. The figures show the process in the sample making from cutting the pipe samples to the finished samples. As well as the general dimensions of the samples made.

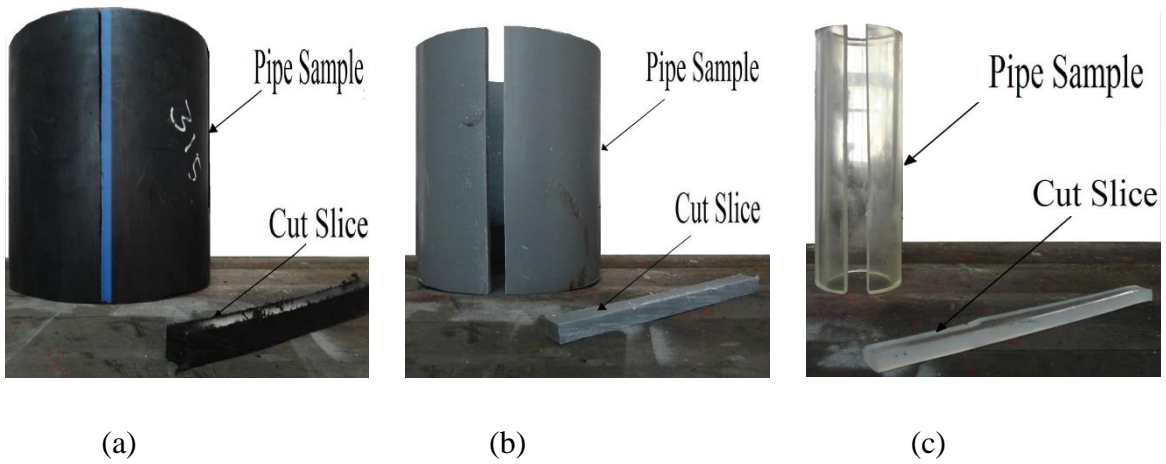


Figure 2.1.2 Photographs showing cut sections of (a) HDPE, (b) uPVC, (c) Acrylic

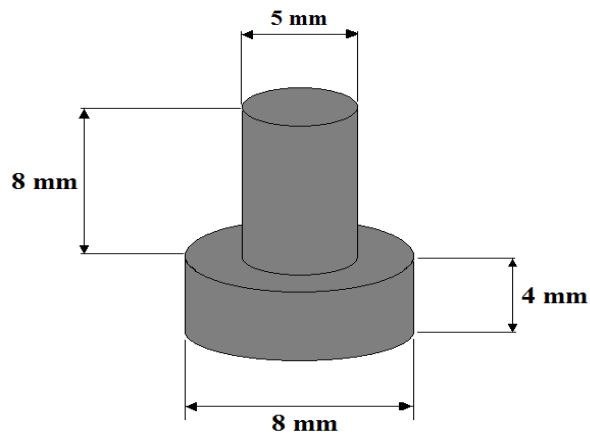


Figure 3.1.3 Dimensions of the test sample

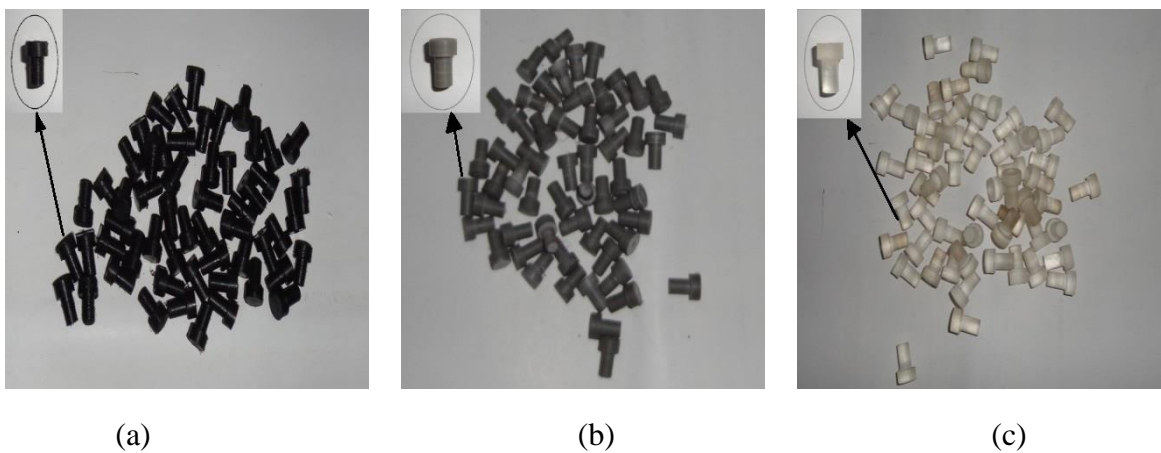


Figure 2.1.4 Photographs of Prepared wear test samples of (a) HDPE, (b) Acrylic, (c) uPVC

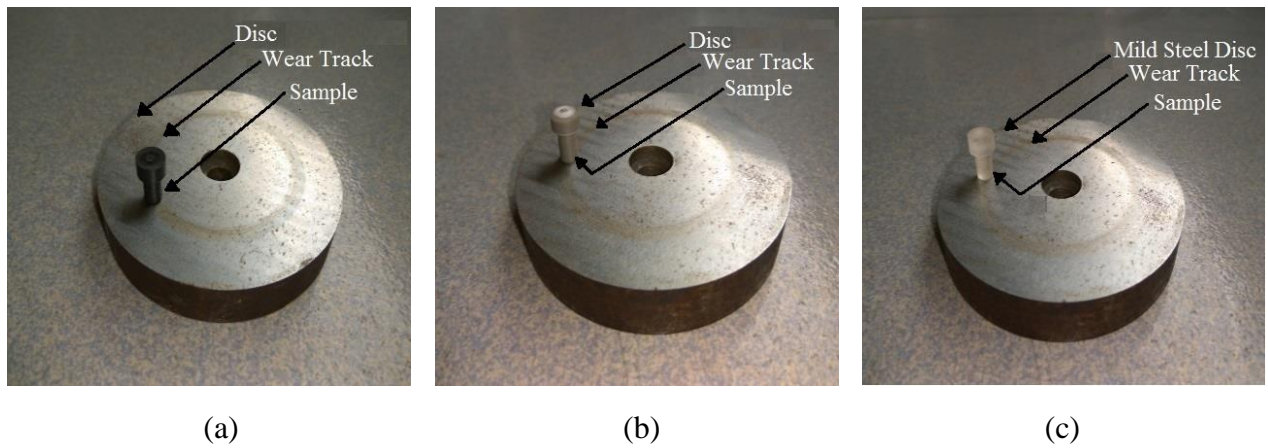


Figure 2.1.5 Photographs of (a) HDPE sample, (b) uPVC sample, (c) Acrylic sample on mild steel disc

2.2. Test Procedure

There are various methods for wear and frictional testing. For this experiment a “Horizontal pin-on-disk” type set-up was used. ASTM Standard G99-05 was followed throughout. Also a digital scale of sensitivity of $1/10000^{\text{th}}$ of a gram was used to measure the weight loss. The figures following show the set up used.



Figure 2.2.1 (a) Test apparatus, (b) Digital scale

During wear test the rotational speed of the rotating mild steel disk was kept constant at 250 RPM. The sliding velocity (v_c) as a result was also at a constant value of 0.6397433m/s. The applied loads on the specimen were 2.45 N, 4.9 N, 9.81 N and 19.62 N (0.025, 0.5, 1.0, and 2.0 kg). The sliding distance was varied from 192.423 m to 4618.152 m. Ambient average temperature and humidity were about 35°C and 80% respectively.

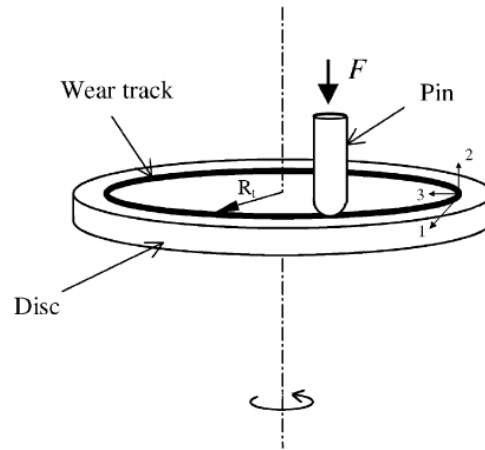


Figure 2.2.2 Schematic of “pin-on-disk” method [16]

The specimens were first subjected to dry sliding condition and then chronologically to wet and clay water environments. In all cases the wear rate and frictional forces were recorded and made in to graphical representations as weight loss vs. distance graph, wear rate vs. distance graph, frictional coefficient vs. distance and average frictional coefficient vs. load graphs. From all these graphs conclusions were drawn as to the effect of different conditions on wear and fictional properties and also as to the differences among the responses of the different polymers to the same operating conditions. Variations in the graphs due to subtle variations in test conditions were also accounted for.

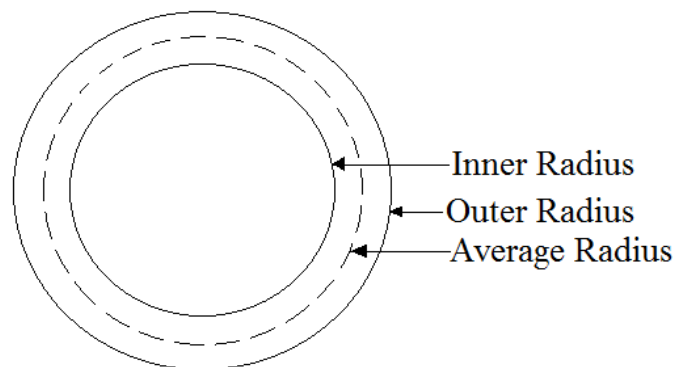


Figure 2.2.3 Average radius (R_m) of wear track

The determination of sliding velocity was done by first finding the average radius of the wear track (R_m) and then calculating the average perimeter travelled ($2\pi R_m$) by the specimen and then multiplying by r.p.m (N) to finally get the average sliding velocity. Sliding distance is just sliding velocity multiplied by time run ($v_c t$) by the specimen

$$v_c = (2\pi R_m N) / 60000 \text{ (m/s)} \dots\dots\dots(i)$$

$$\pi = 3.1416$$

$$N = 250 \text{ r.p.m.}$$

$$S_d = v_c t \text{ (m) ('t' is in seconds)}$$

The determination of wear rate was done by measuring weight loss (Δw) after each test and the distance run during the test. Frictional coefficient (μ) was determined by taking the reading from the load cell (F_{cell}) and then dividing it by the applied load (m.g).

$$\Delta w = W_{initial} - W_{final} \dots\dots\dots(ii)$$

$$\text{Wear rate} = \Delta w / S_d \dots\dots\dots(iii)$$

$$\mu = F_{cell} / m.g \dots\dots\dots(iv)$$

Dust from the test was also gathered and studied under optical microscope at various magnifications (25X, 80X); the scratches on the counter body were also studied. And finally SEM investigation of the worn surfaces of the samples run 192.423 m and 4618.152 m were taken.

2.3 List of Chemical Composition, Physical properties and Structures

Table 2.3.1 Chemical composition of the different polymers [17]

Name	% of C	% of H	% of Cl	% of O
HPDE	86	14	-	-
uPVC	38.4	4.8	56.8	-
Acrylic	60	8		32

Table 2.3.2 Physical and mechanical properties of the polymers

Name	Ultimate tensile Strength, S_{ut} (MPa) [17]	Shore D Hardness [Experimental]	Density (kg/m ³) [Experimental]
HPDE	37	59	941.7
uPVC	50	71	1533.8
Acrylic	114	76	1223.7

Table 2.3.3 Chemical name, Commercial name and Chemical Structures

Materials	Chemical Name [17]	Commercial Name [18]	Chemical Formula	Monomer
Acrylic	Polymethyl methacrylate	Perspex, Acrylic glass, Plexiglas, Acrylite, Lucite, Kamax	$-(C_5O_2H_8)_n-$	$C_5H_8O_2$ (Methyl methacrylate)
HDPE	High Density Polyethylene	Alkathene, Polythene, Alathon, Fortiflex, Hostalen	$-(CH_2-CH_2)_n-$	$CH_2=CH_2$ (Ethylene)
uPVC	Unplasticized Polyvinyl Chloride	Darvic, Simona	$-(CH_2-CHCl)_n-$	$CH_2=CHCl$ (Vinyl Chloride)

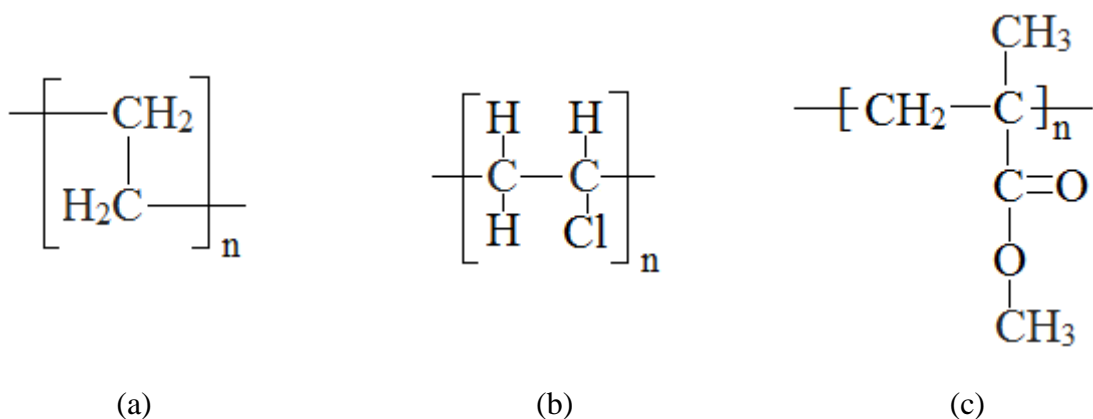
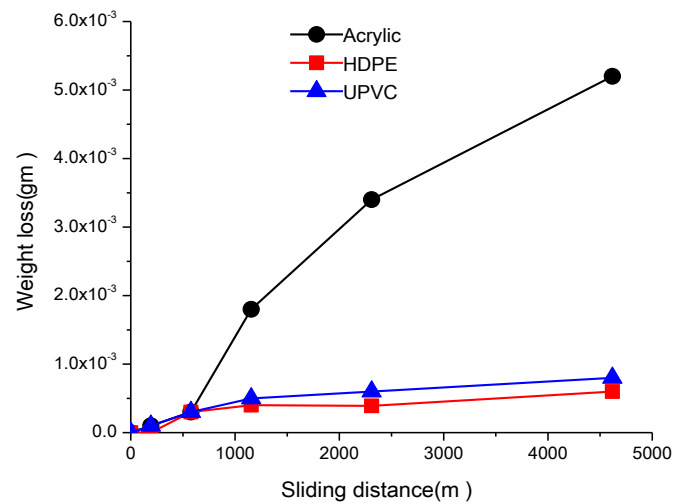


Figure 2.2.4 Chemical Structure of (a) HDPE, (b) uPVC, (c) Acrylic

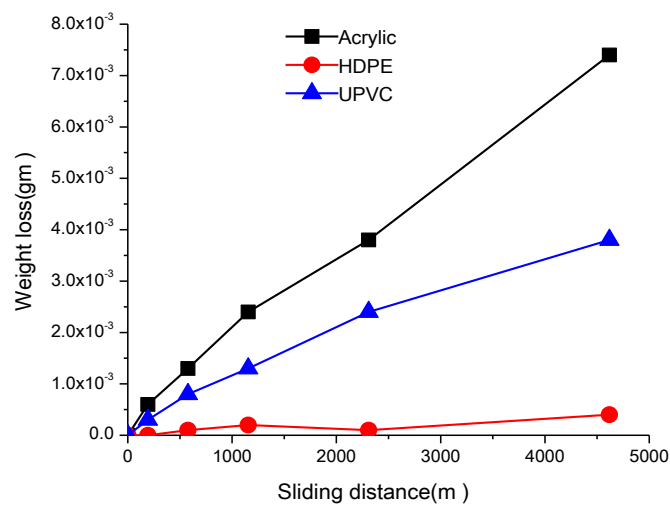
3. RESULTS AND DISCUSSION

3.1 WEAR TEST

WEIGHT LOSS vs. DISTANCE CURVES (DRY SLIDING ENVIRONMENT)

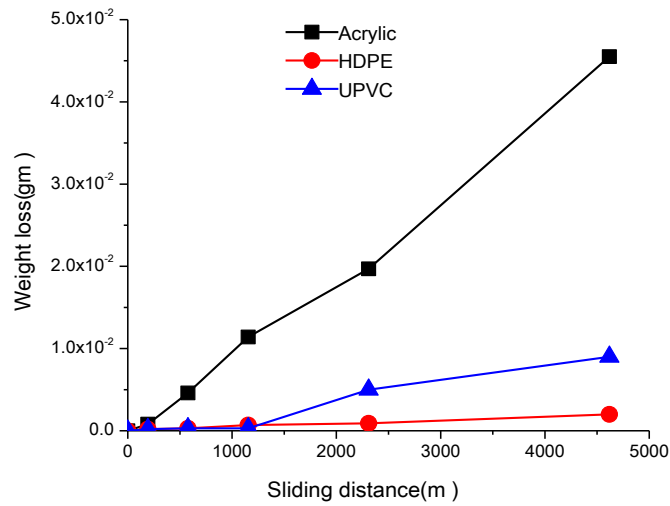


(a)

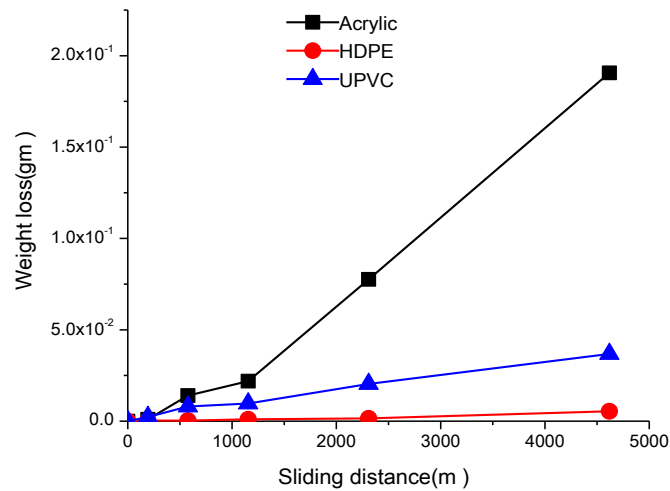


(b)

Figure 3.1.1 Change of weight loss with sliding distance in dry sliding environment at (a) 0.025 kg load; (b) 0.5 kg load in dry sliding environment 250 rpm and sliding velocity of 0.6397 m/s



(a)



(b)

Figure 3.1.2 Change of weight loss with sliding distance in dry sliding environment under (a) 1 kg and (b) 2 kg load at 250 rpm and with sliding velocity of 0.6397 m/s

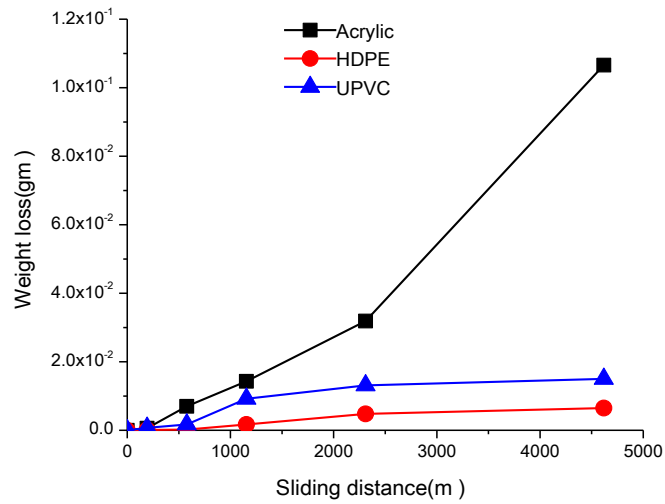
From the figures above it can be seen that the weight loss increases as sliding distance increases for all loads. It is also seen that the weight loss of Acrylic at any load is exceptionally higher than that of uPVC or HDPE. The weight loss curves for both uPVC and HDPE are always comparably closer relative to Acrylic except for at 0.5 kg load where uPVC shows more of a difference compared to HDPE. The maximum weight

losses of Acrylic, uPVC, and HDPE at 0.025 kg of load are 0.0055, 0.0008 and 0.0006 gm respectively. At 0.5 kg of load they are respectively 0.0074 gm for Acrylic, 0.0038 gm for uPVC and 0.0004 gm for HDPE. Similarly at 1 kg load they are 0.0455 (Acrylic), 0.009 (uPVC), 0.002 (HDPE). And finally at 2 kg is 0.1905 gm (Acrylic), 0.0368 gm (uPVC), 0.0054 gm (HDPE). In all of the curves, weight loss increases with increase in sliding distance.

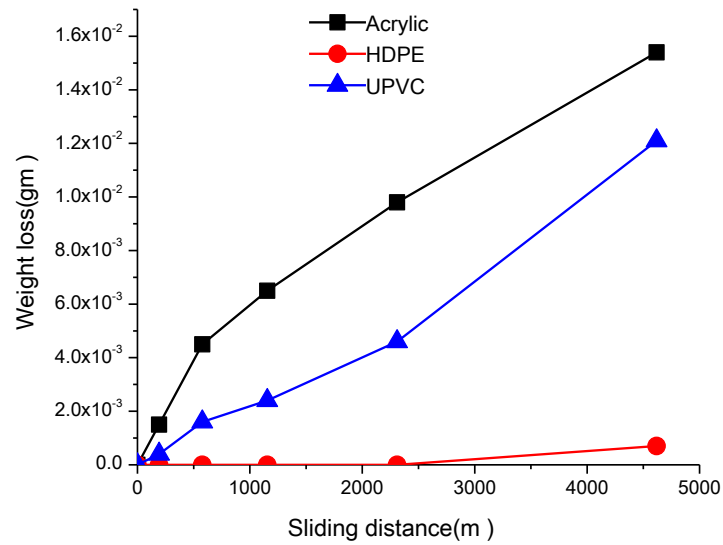
In general the behaviour of uPVC and HDPE curves tend to have similar values, this can be explained by the fact that both their molecular structures are more organized compared to Acrylic. HDPE gives the least wear as it is almost fully crystalline in structure (the chains are highly linear with little side branching and are organized in almost parallel layers); the molecular structure of uPVC is a mixture of both crystalline and amorphous zones. The crystalline zones come from the presence of partially charged chloride group ($\text{Cl}^{\delta-}$) and hydrogen group ($\text{H}^{\delta+}$) wanting to line themselves up in parallel chains. The presence of these ordered structures give both HDPE and uPVC better resistance to abrasive wear caused by the mild steel disk as they have strong cohesion among their chains. It can be noted that the amorphous regions in the uPVC come from the fact that the chloride group is quite large and it interrupts the ordered alignment of the chains. Acrylic is fully amorphous in its structure with little to no crystalline zones, causing in much less cohesive forces among the chains and as a result being more susceptible to abrasive wear.

In all the curves in the initial stages the weight loss tends to be erratic in nature (in between the sliding distances of 577.269-1154.538 m). This can be explained by the fact that at the initial stages there is a formation of an intermediate medium between the counter face and the sliding material consisting of the wear particles generated by the shearing action of the disc called "Transfer Layer". When this transfer layer becomes fully developed the increase in weight loss is almost linear and any sudden changes in this layer show up as a fluctuation from this linear nature. Also interface temperature plays a key role in the weight loss. If the interface temperature rises above its glass transition temperature for some reason then there will be softening of the material at the interface and as a result more material will be deposited due to thermal fatigue than expected, decrease in temperature will have the inverse effect. Increased temperature will also cause oxidation of the material at the interface resulting in more wear.

WEIGHT LOSS vs. DISTANCE CURVES (WET AND CLAY –WATER SLIDING ENVIRONMENT)



(a)



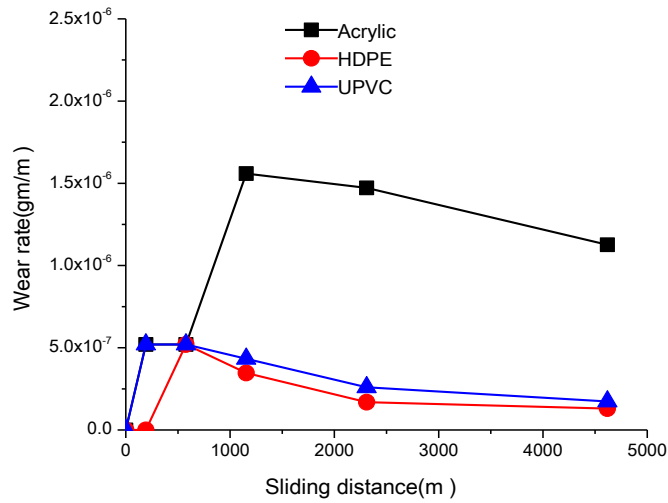
(b)

Figure 3.1.3 Variation of weight loss against sliding distance under 2 kg load with (a) wet sliding environment, (b) clay-water sliding environment at 250 rpm and with a sliding velocity of 0.6397 m/s

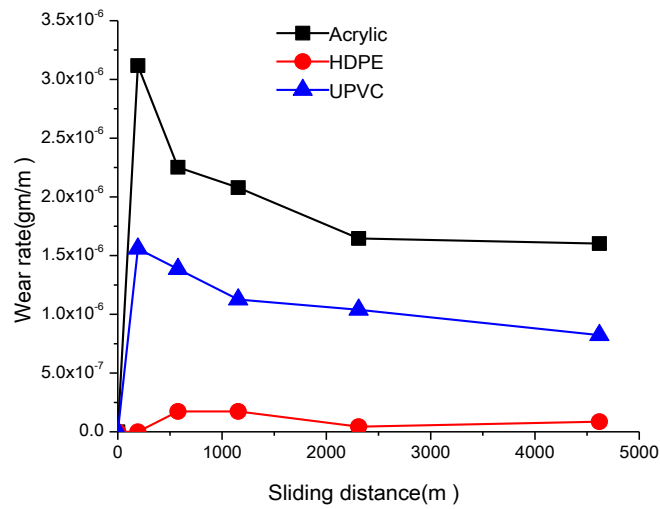
In wet condition the curves show a similar trend as in dry condition the only difference being that the maximum weight loss is always less for the same load in dry condition, 0.11 gm compared to 0.20 gm for Acrylic, 0.015 gm compared to 0.0368 gm for uPVC. Only HDPE shows exception from this behaviour. In that in both wet and dry cases the weight loss is almost same.

Weight loss curve for the clay-water sliding condition gives the most erratic behaviour as both uPVC and Acrylic fluctuate randomly with no apparent relationship against sliding distance. However HDPE still retains its nature as it exhibits the least wear even compared to wet environment. This apparent fluctuation in weight loss in the presence of 5% Bentonite clay solution can be explained by the fact that the particles in the solution are uneven and not of the same size, furthermore the solution composition may not also be homogeneous throughout as it exhibits a tendency to form precipitate when not continuously stirred in a uniform way. As a result at different stages, clay film of marginally different composition may come into contact with the test material and counter face causing the sudden rises and lowering in the weight loss values. Also the clay film may cause wear and corrosion on the counter face itself causing steel particles to come into the interface and thus suddenly increasing the weight loss value. In general the weight loss in the presence of clay-water at the interface is lower as the Bentonite clay is quite viscous and forms a better lubricating film reducing wear and weight loss.

WEAR RATE vs. SLIDING DISTANCE (DRY SLIDING ENVIRONMENT)

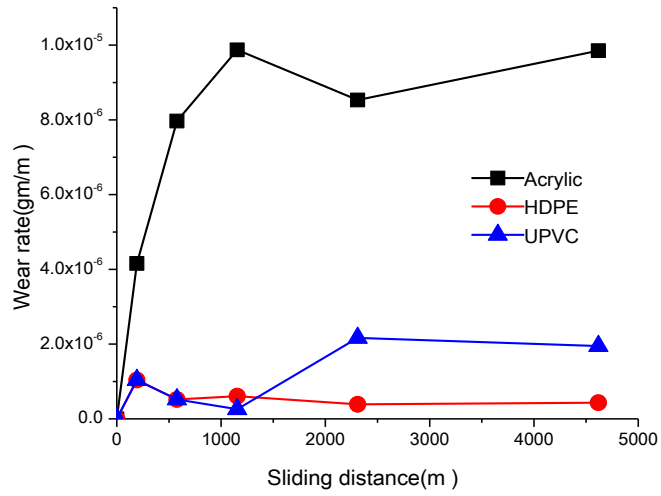


(a)

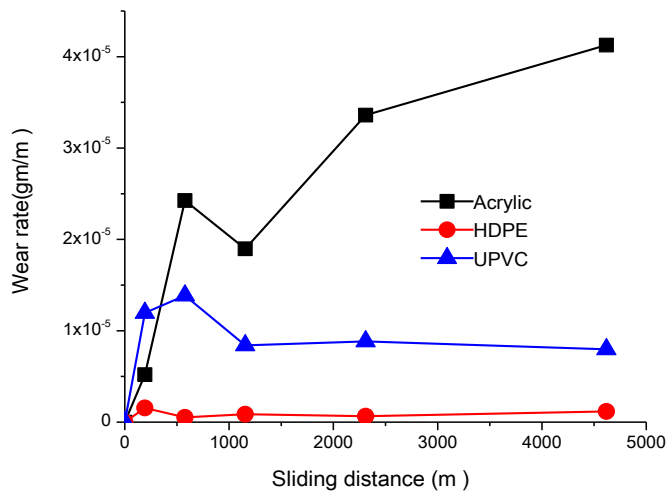


(b)

Figure 3.1.4 Variation of wear rate with sliding distance under (a) 0.025 kg load and (b) 0.5 kg load with dry sliding condition at 250 rpm and sliding velocity of 0.6397 m/s



(a)



(b)

Figure 3.1.5 Variation of wear rate with sliding distance under (a) 1 kg load and (b) 2 kg load with dry sliding environment at 250 rpm and sliding velocity of 0.6397 m/s

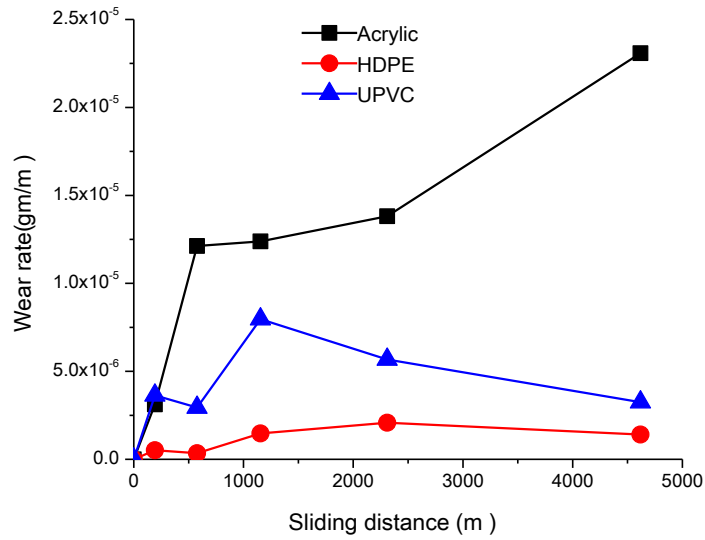
From the wear rate curves it can be seen that at dry condition the wear rate first fluctuates and then attains a constant value. Acrylic and uPVC show more fluctuations in compared to HDPE which always attains a steady state value after some time sliding. Furthermore the wear rate of HDPE is always less than that of the other two.

The general nature of the curves to fluctuate in the beginning stages and then attain a fairly constant value can be explained as follows; As sliding is initiated the specimen surface is in direct contact with the metal counter face resulting in a high rate of wear as the hardness of the steel disk is more than that of the polymers. As running continues the specimen starts to deposit particles on the counter face as a result the slope of the wear rate curve fluctuates until there is a definite amount of transfer layer material on the counter face, at this point there is no more growth in the transfer layer and the wear rate becomes constant.

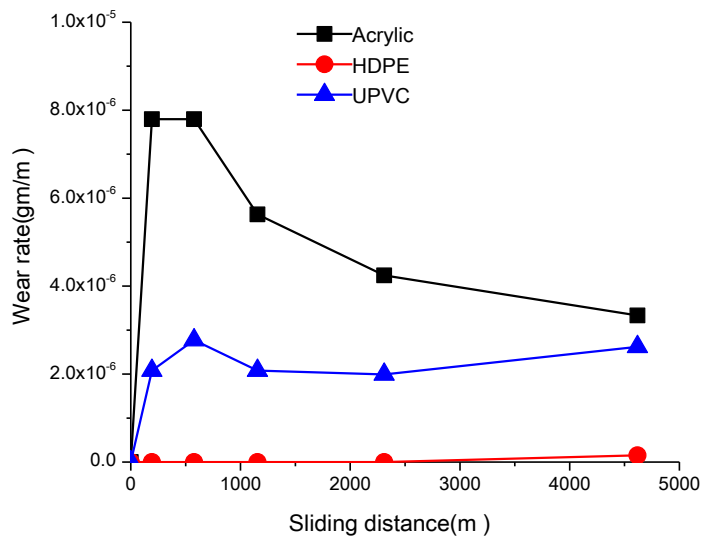
For uPVC and Acrylic there is also some variation in the steady state phase of the curves. These variations in the curves can be explained by the fact that the interface temperature does not remain constant through the experiment. Changes in temperature can lead to unwanted chemical reactions in the interface transfer layer altering its thickness and composition causing the variations in the wear rate curves.

Furthermore the structures of the Acrylic and uPVC are mostly amorphous resulting in uneven amount of material to be deposited at different time which causes small variations in the steady state transfer layer. In general the more crystalline the polymer less the deviation shall be from the ideal nature as described above. It is verified from looking at the curves as HDPE follows the ideal behaviour most closely followed by uPVC and then Acrylic.

WEAR RATE vs. SLIDING DISTANCE (WET SLIDING ENVIRONMENT AND CLAY-WATER SLIDING ENVIRONMENT)



(a)



(b)

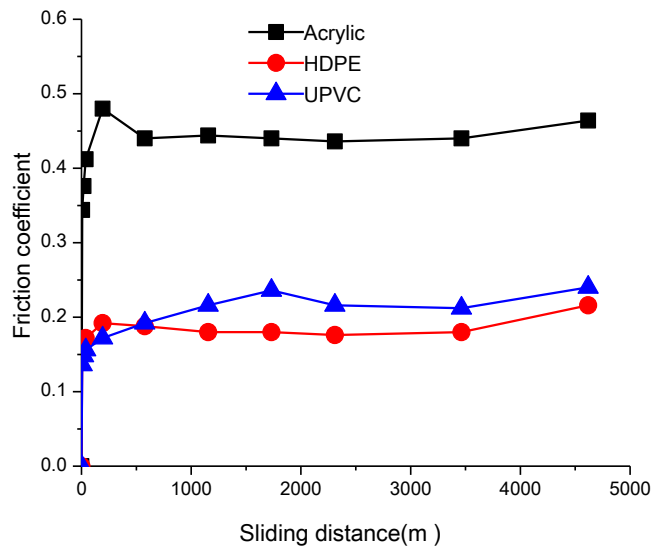
Figure 3.1.6 Variation of wear rate against sliding distance under (a) 2kg load and wet condition; (b) 2kg load and clay-water condition at 250 rpm and sliding velocity of 0.6397 m/s

The curves in the wet condition also shows the general nature as described above only with random variations occurring these random variations can be explained due to the fact that the fluid film thickness changes with time and also the temperature of the fluid film changes with ambient temperature fluctuations effecting the wear rate of the materials. When the fluid film thickens there is less wear and thus less wear rate is observed and when fluid film thins out there is more wear and thus more wear rate is observed. Also it is possible that wear debris and other particles from surrounding environment get entrapped in the fluid film and thus changes in the wear rate occur.

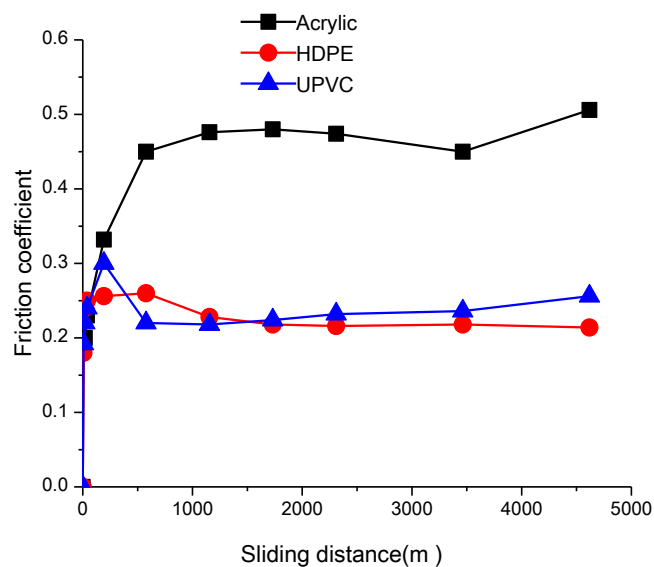
For clay condition again it can be seen that wear rate of HDPE is least and that the nature of the curve follows the above described behaviour more closely compared to Acrylic and UPVC. Random changes in the wear rate of both UPVC and Acrylic can be observed; once again this can be attributed to clay particles interacting with the materials differently at different times and chemical interaction occurring between the clay particles, the counter face and the test materials.

3.2 FRICTION TEST

FRICTION COEFFICIENT vs. SLIDING DISTANCE CURVES (DRY SLIDING ENVIRONMENT)

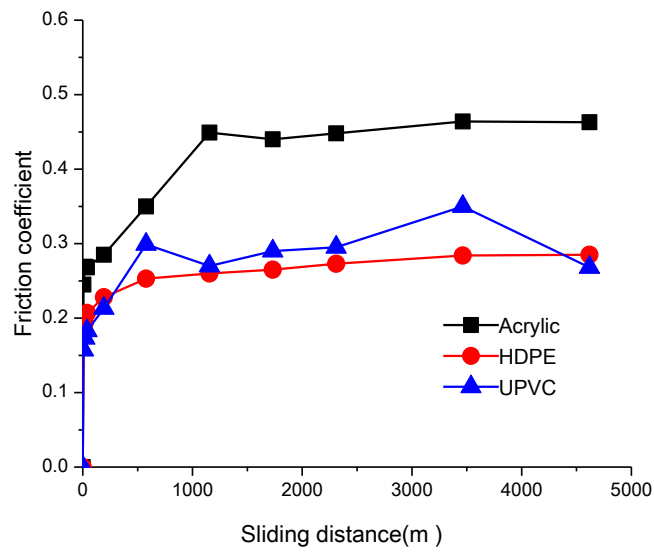


(a)

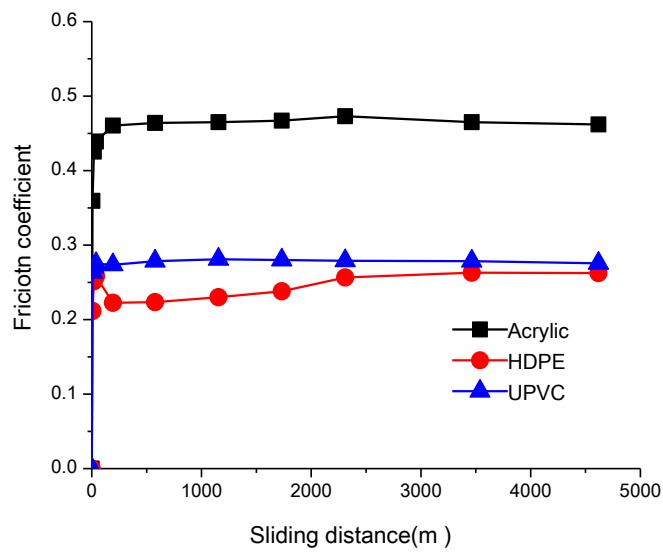


(b)

Figure 3.2.1 Variation of friction coefficient with sliding distance under (a) 0.025 kg load and (b) 0.5 kg load in dry sliding environment at 250 r.p.m and sliding velocity of 0.6397 m/s.



(a)



(b)

Figure 3.2.2 Variation of friction coefficient with sliding distance under (a) 1 kg load and (b) 2 kg load in dry sliding condition at 250 r.p.m and sliding velocity of 0.6397 m/s.

From the above figures it can be seen that in general all the curves have two distinct regions. First the friction coefficient (μ) rises sharply and then attains a constant value. The graphs also show that in general the rise of the frictional coefficients to steady state value is in about 192.423 m (5 min) to 577.260 m (15min) of distance run. It is also observed that frictional coefficient for Acrylic is always the greatest for any given sliding distance at a certain load.

The nature of the curves can be explained by the fact that as the specimen is tested, sheared particles form a transfer film on the surface of the counter body. The formation time and thickness of this transfer film as well as the interaction of this transfer film with both the test material and counter body is what primarily determine the nature of the curves [6]. When sliding is first initiated the contact is primarily between the asperities of the counter face of the steel disk and the sample at hand. During sliding at initial this stage there is abrasive wear and test material is plastically deformed and sheared off from the test specimen. As a result in the initial stages the value of the friction coefficient (μ) increases sharply. As sliding continues a thin layer of particles is deposited on the steel disk surface as shearing of material at the interface is reduced. It is this layer of material which forms the "Transfer layer". This transfer film then essentially acts as a medium between the disk and sample. And the sliding material at this point is in contact with particles of the same material as itself. The transfer film reaches a steady thickness contributing to the constant nature of the curve [6].

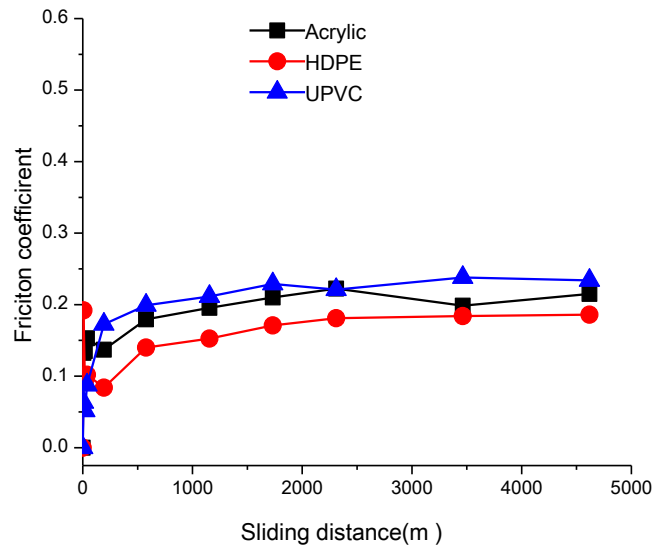
Some deviations can be seen from this general behaviour of a sharp rise phase and a steady state phase. These deviations can also be explained due to the nature of the transfer film. Among other factors the heat transfer at the interface also plays an important role. In figure (b) of 0.5 kg load it can be seen that Acrylic attains a steady state value much slower (at 500 m of distance run as opposed to 192.4 m) than it did in fig (a) of 0.025 kg load. Same was seen in figure (c) of 1kg load as acrylic attained steady state at about 1000 m of sliding distance as opposed to 192 m in case of 0.025 kg load. In both cases the curves raise very sharply indicating rapid change in friction coefficient, then instead of a steady state phase there is a period of slow less steep rise followed by a relative steady state phase with fluctuations about a mean value. As a result both the curves attain a steady state value at a much greater distance run compared to 0.025 kg load. At 2 kg load however, no such unexpected fluctuations are not present. Similarly it can be seen that uPVC also exhibits this erratic behaviour of fluctuating from this steady state value. At

0.025 kg load friction coefficient for uPVC also shows a similar behaviour. While at 0.5 and 1 kg load only random fluctuations about a steady state value are present. These fluctuations are less observed in case of HDPE for all loads.

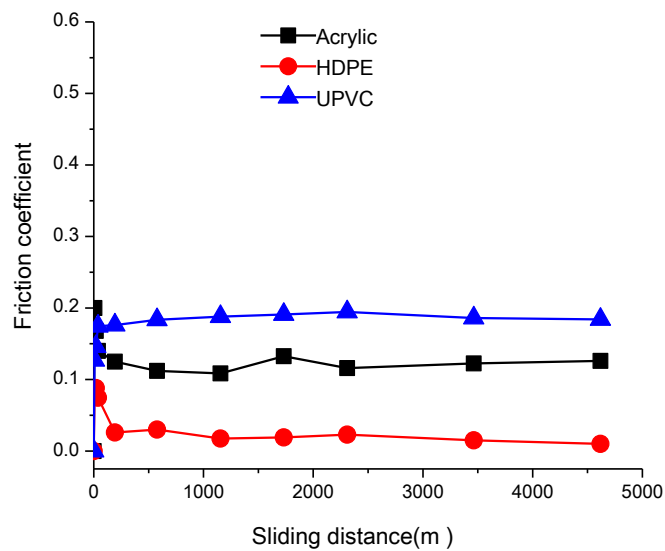
This erratic behaviour may be explained due to the changes in the transfer layer thickness. In the case of Acrylic at 0.5 kg and 1 kg load and also uPVC at 0.025 kg the period of slow rise of frictional coefficient following the rapid rise phase and preceding the steady state phase can be explained as follows; as the sliding distance increases initially so does the amount of sheered material deposited at the interface. At this point the particles themselves are of different sizes and are distributed unevenly on the mild steel disk. As further sliding takes place the particles are subjected to further wear and start to form a more evenly distributed film across the counter face. The individual particles themselves also take on a more uniform size through out and start to fill the asperities on the mild steel disk. The rate of wear particle generation also slows down as this layer acts as a sort of separating medium causing a slow rise of the frictional coefficient also heat generated at the interface causes the deposited layer to soften resulting in the diminished rate of rise. After some time the transfer layer becomes stable and film of relatively constant thickness and composition is formed. As a result the nature of interaction between the surfaces becomes unchanging constituting in the steady frictional coefficient (μ) phase.

The second type of variation seen in the curves which is the variation about the some steady state value can be explained by unwanted changes in the transfer layer and interface temperature which may be due to external factors not controlled in the test. Where there is a sudden jump in value it indicates that at that point the transfer layer has thinned out for some reason, may be that the temperature has suddenly fallen causing a change in the visco-elastic behaviour. Where there is a sudden fall in frictional coefficient the transfer layer thickens as wear rate increases for some reason perhaps due to surface fatigue and local failure as caused local variations in the arrangements of grains or polymer chains or perhaps chemical interactions with air (O_2) due to increased interface temperature.

FRICITION COEFFICIENT vs. SLIDING DISTANCE CURVES (WET AND CLAY –WATER SLIDING ENVIRONMENT)



(a)



(b)

Figure 3.2.3 Friction coefficient vs. sliding distance at (a) 2 kg load and wet sliding environment; (b) 2 kg load and clay-water sliding environment

For wet and clay conditions it can be seen that the general nature of the curves are the same as in the dry condition with the expectation that the coefficient of friction for both cases is lower. The values for coefficient of friction are in the range of 0.180-0.223 for Acrylic, 0.140-0.180 for HDPE and 0.199-0.238 for uPVC for wet environment. For clay environment the ranges are, 0.112-0.132 for Acrylic, 0.010-0.030 for HDPE and 0.194-0.183 for uPVC in the steady state phase.

Here too there is a phase where the friction coefficient rises sharply and then a phase when friction coefficient becomes time (distance) independent. The steep unsteady phase is due to the fact that in initial stages the liquid or clay film has just started to form and once the surface layer has fully formed the value of the friction coefficient stabilizes.

It can also be seen that in wet condition the fluctuation in the value of frictional coefficient is quite random and frequent though the magnitude of the deviations are not so high compared to dry condition, this is due to the change in the liquid film nature (viscosity) and thickness caused by heat transfer changes at the interface (the variation in temperature of the fluid film due to heat generation and dissipation from the frictional forces) and also from the slight change in the centrifugal forces acting on the film due to small variations in the supplied voltage to the motor (minor speed changes). If the thickness of the film increases at any point or the viscosity decreases due to lowering of temperature then the frictional coefficient will also decrease the increase in viscosity due to rise in temperature or reduction in film thickness will have the inverse effect.

An interesting phenomenon is also found in the wet conditions is that the difference in the friction coefficients becomes much narrower ; though HDPE still holds the least values of frictional coefficients. The curves for uPVC and Perspex almost coincide with each other. This indicates that under the influence of wet sliding environment Acrylic and uPVC both have similar characteristics. The water used in this experiment is dematerialized water meaning there are no foreign particles or chemical species present in the water. In the presence of 5% Bentonite clay solution however an interesting result is obtained as the curves for uPVC and Acrylic switch their places as uPVC shows the greater frictional coefficient for any load. These effects can be explained due increased attraction between uPVC and the clay particles due to the presence of semi polar chloride group as well as increased adhesion between the clay particles and the steel counter face.

AVARAGE FRICTION COEFFICEINT vs. LOAD CURVE

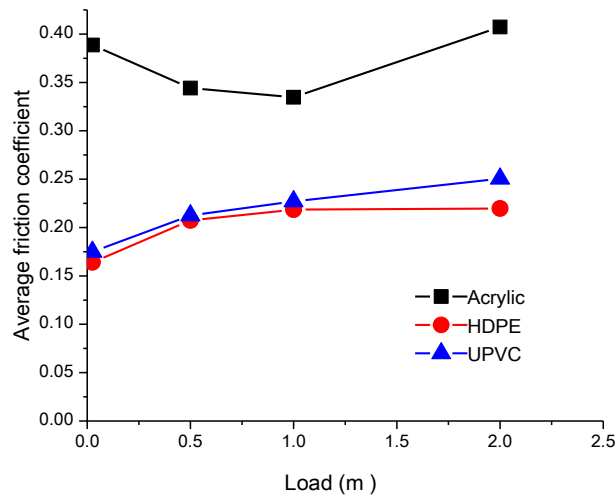


Figure 3.2.4 Average friction coefficient vs. load at dry condition, 250 rpm and sliding velocity of 0.6397 m/s

It can be seen that the highest friction factors for any load belong to Acrylic, then followed by uPVC and then HDPE. Also it can be seen that the average friction factors for uPVC and HDPE over the entire load range (0.025, 0.5, 1, and 2 kg) are much lower than for Acrylic. The friction coefficient (μ) for Acrylic varies from 0.388 at .25 kg to 0.407 at 2 kg, while coefficient (μ) for HDPE varies from 0.164 at .25 kg to 0.219 at 2 kg. And finally friction coefficient (μ) for uPVC is 0.175 at .025 kg and 0.250 at 2 kg. Overall the friction factor increases as the load is increased with only Acrylic showing a decrease in coefficient at 0.5 kg and 1 kg.

The higher frictional coefficient (μ) of Acrylic can be explained due to the fact that it is an amorphous solid.^[1] Meaning that there is no regular crystal structure, the polymer chains are arranged disorderedly except for over short distances.^[1] This lack of a well-defined crystal structure means that when the sliding surface of the specimen is cut by the sheering action of the rotating disk, an uneven rough surface is produced which in turn gives rise to higher friction factor for the material.

Also it can be seen that the coefficient of Acrylic at 0.025 kg is about .39 but then drops to .35 at 0.5 kg and further drops to 0.339 at 1 kg. This unexpected behaviour is due to the fact that Perspex is amorphous and forms wear particles much faster compared to the

other two polymers as a result the separated particles form a layer of dust between the disk and the sample much more rapidly which acts as a layer of solid lubricant causing a drop in the factor at relatively low loads. At higher loads (2 kg) the dust layer is not formed due to the increased load as a result the friction coefficient rises sharply to above 0.4.

The frictional coefficient (μ) for HDPE is the least of the three with uPVC falling in between. On close inspection of the graph it is found at lower loads (0.025, 0.5 and 1 kg) the frictional coefficient (μ) of the uPVC and HDPE are comparable) but at high load (2 kg) differ considerably (0.20 for uPVC and 0.25 for HDPE). This variation can be explained due the difference in their polymer chain arrangement and crystal structure. UPVC is also an amorphous solid but unlike Perspex which is completely amorphous; uPVC chains have associated with them a strong dipole moment which gives rise to a more ordered crystal structure to uPVC compared to Perspex. The following figure demonstrates this.

As a result of this strong dipole force uPVC is much harder and when worn by the disk exposes a much smoother and uniform surface compared to Perspex. But under increased load the dipole moments are not sufficient enough to maintain this semi-ordered nature causing higher frictional coefficients. HDPE on the other hand is a semi-crystalline polymer made up of crystalline and amorphous regions meaning that the chains in certain region align themselves into closely packed and very ordered arrangements of polyhedral shaped crystals called spherulites. And other portions have no definite molecular arrangement. The spherulites make up almost 90% of the structure while amorphous region only makes up 10%. This high degree of crystallization ensures a more even surface even after being subjected to the wear of the rotating disk giving a lower frictional coefficient even at higher loads.

COMPARISON OF AVERAGE FRICTION COEFFICIENT IN DIFFERENT SLIDING ENVIROMENT

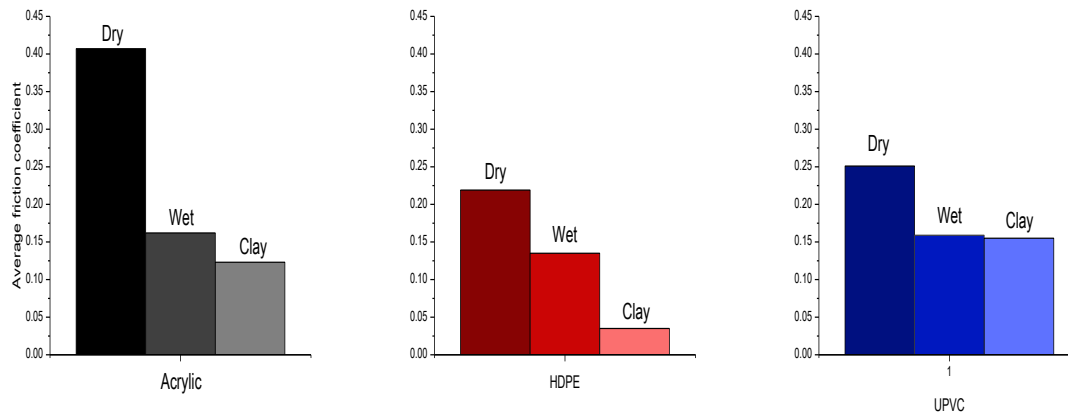
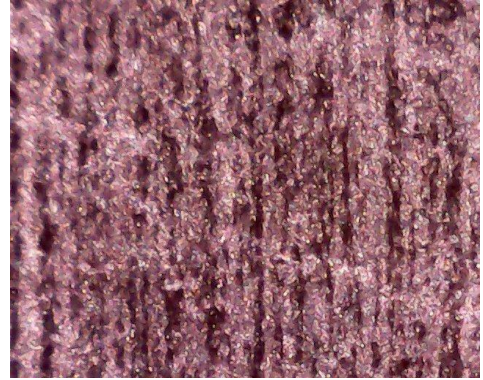


Figure 3.2.5 Average friction coefficient in different sliding environment of Acrylic, HDPE and uPVC

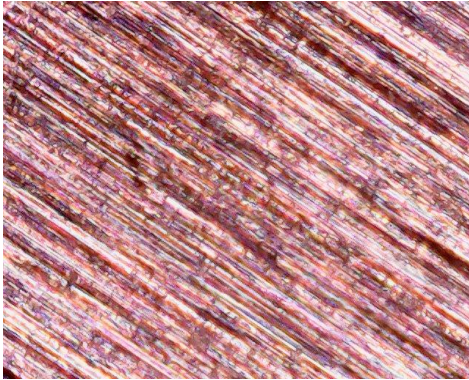
The average friction coefficient for all the three materials was found to be highest in the dry sliding condition followed by wet and then by clay water condition also it can be seen that for Acrylic and HDPE the change in friction coefficient from wet to clay water contact sliding condition is noticeable; 0.162 to 0.123 for Acrylic and 0.135 to 0.035 for HDPE but in the case of UPVC the difference is much less noticeable; 0.155 to 0.159.

The reason for clay environment giving the least value of coefficient of friction can be explained by the fact that the Bentonite clay has much higher viscosity than water and acts as a much better lubricant between the disk and specimen giving rise to much lower value of frictional coefficient for the most cases. Only UPVC almost exact same values for fraction coefficient in the wet and clay sliding contact. This can be due to the fact that there is some level of interaction between the chloride ($\text{Cl}^{\delta-}$) and the clay particles which are essentially oxide and silicates of Aluminium (Al). Also it can be seen that HDPE has the least value of frictional coefficient in clay contact indicating that the clay particles have no interaction on the molecular level with HDPE chains as expected because of HDPE having no polar nature at all. Acrylic has oxygen molecules in its chain structure which is highly electro negative and as a result may interfere with clay particles giving a higher frictional coefficient compared to HDPE.

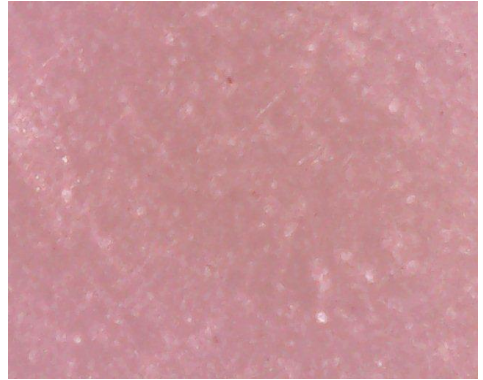
3.3 OPTICAL MICROSCOPIC OBSERVATION



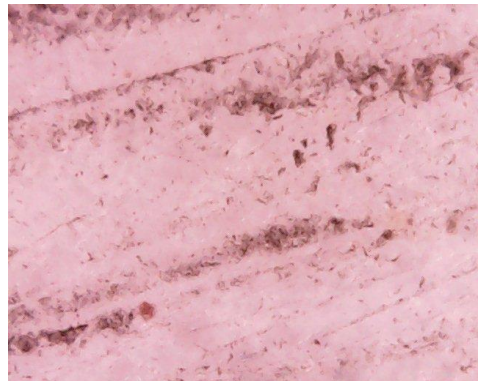
(b) HDPE



(c) Mild Steel Disc

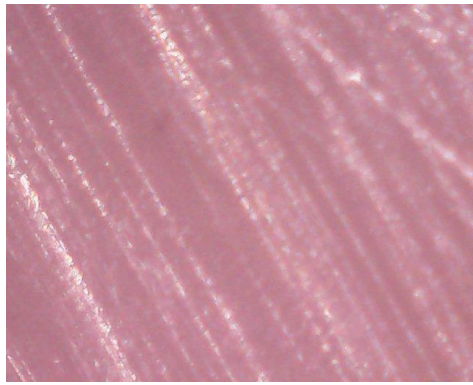


(d) uPVC

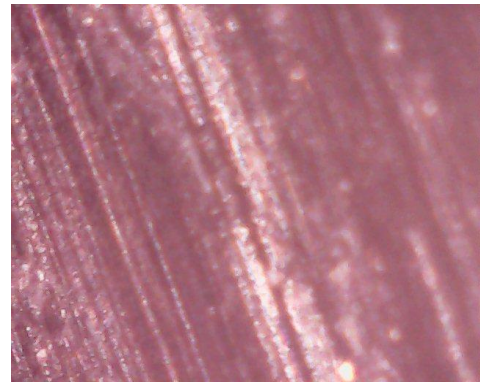


(e) Acrylic

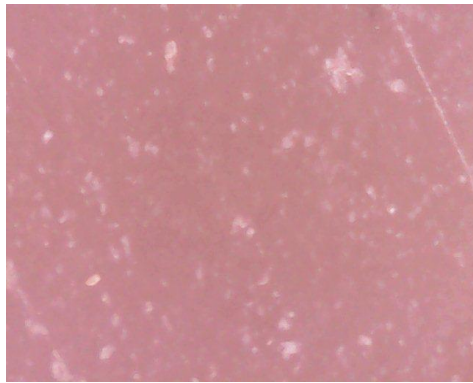
Figure 3.3.1 Optical micrographs (25X) of disc and sample surfaces



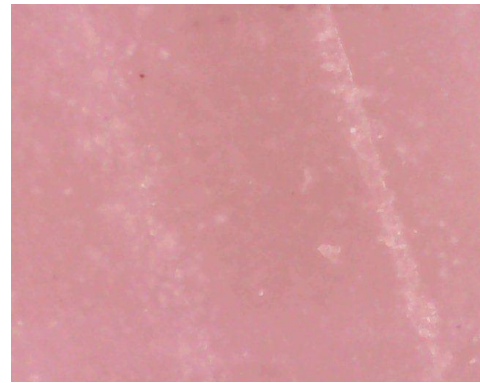
(a₁)



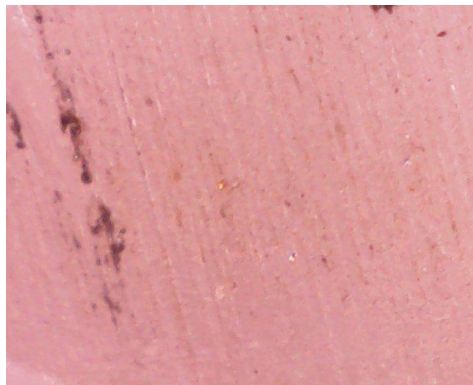
(a₂)



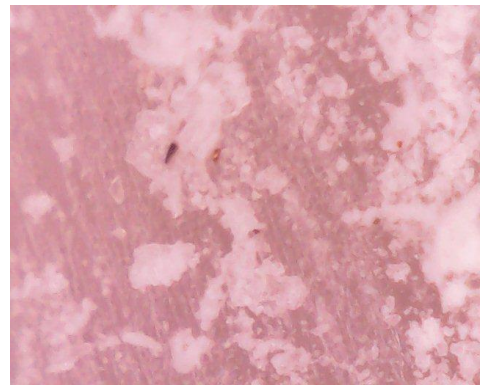
(b₁)



(b₂)

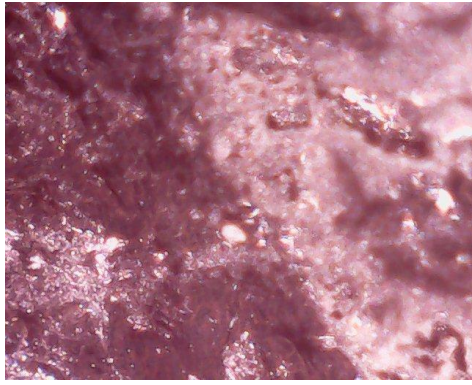


(c₁)

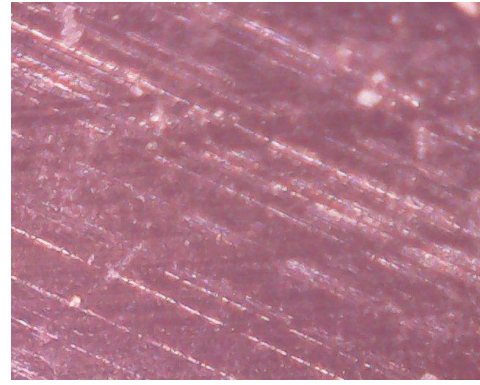


(c₂)

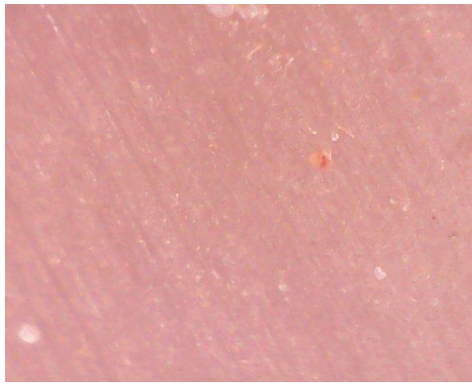
Figure 3.3.2 Optical micrographs (25X) of after wear of (a₁) HDPE 5 min sample, (a₂) HDPE 120 min sample, (b₁) uPVC 5 min sample, (b₂) uPVC 120 min sample, (c₁) Acrylic 5 min sample, (c₂) uPVC 120 min sample all with an applied load of 2 kg and dry sliding condition



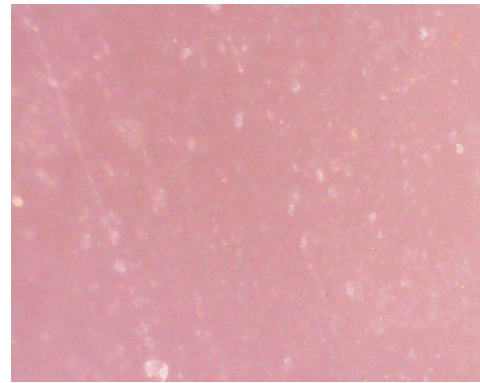
(a₁)



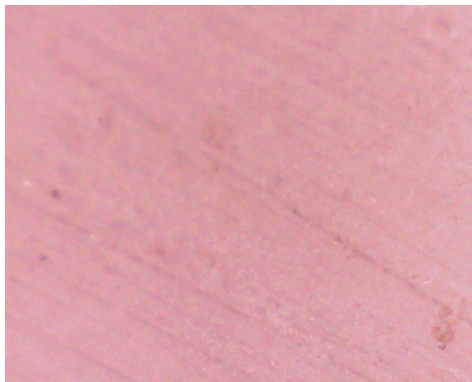
(a₂)



(b₁)



(b₂)

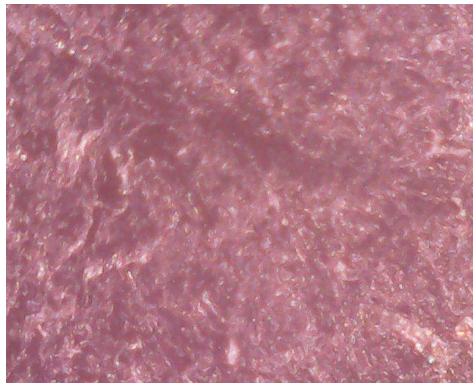


(c₁)

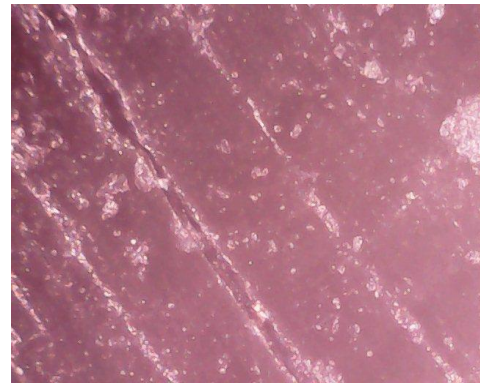


(c₂)

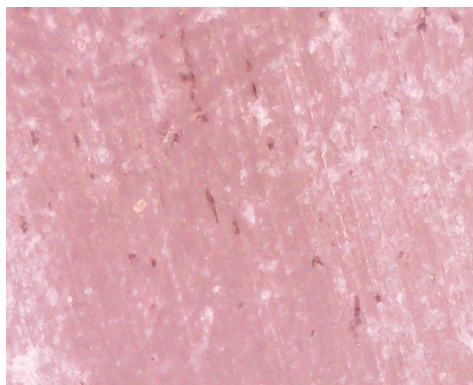
Figure 3.3.3 Optical micrographs (25X) of after wear of (a₁) HDPE 5 min sample, (a₂) HDPE 120 min sample, (b₁) uPVC 5 min sample, (b₂) uPVC 120 min sample, (c₁) Acrylic 5 min sample, (c₂) uPVC 120 min sample all with an applied load of 2 kg and wet sliding condition



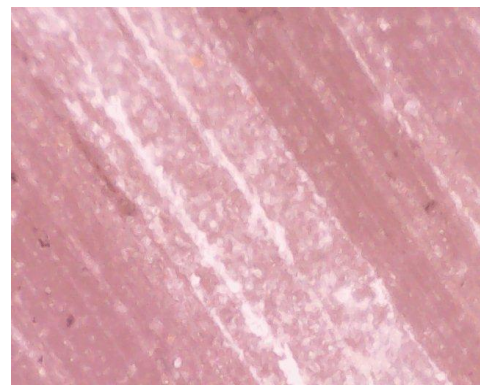
(a₁)



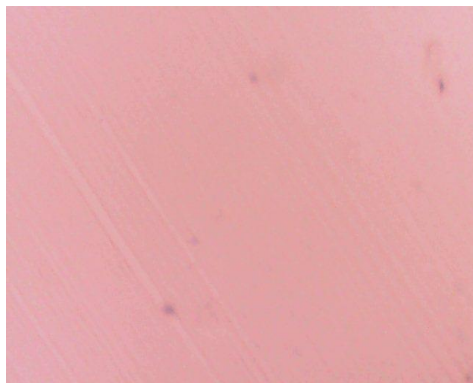
(a₂)



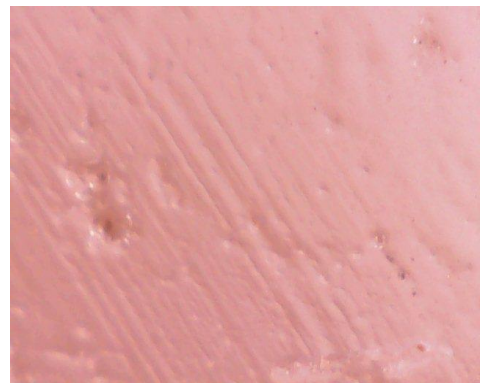
(b₁)



(b₂)



(c₁)



(c₂)

Figure 3.3.4 Optical micrographs (25X) of after wear of (a₁) HDPE 5 min sample, (a₂) HDPE 120 min sample, (b₁) uPVC 5 min sample, (b₂) uPVC 120 min sample, (c₁) Acrylic 5 min sample, (c₂) uPVC 120 min sample all with an applied load of 2 kg and sliding under clay water condition

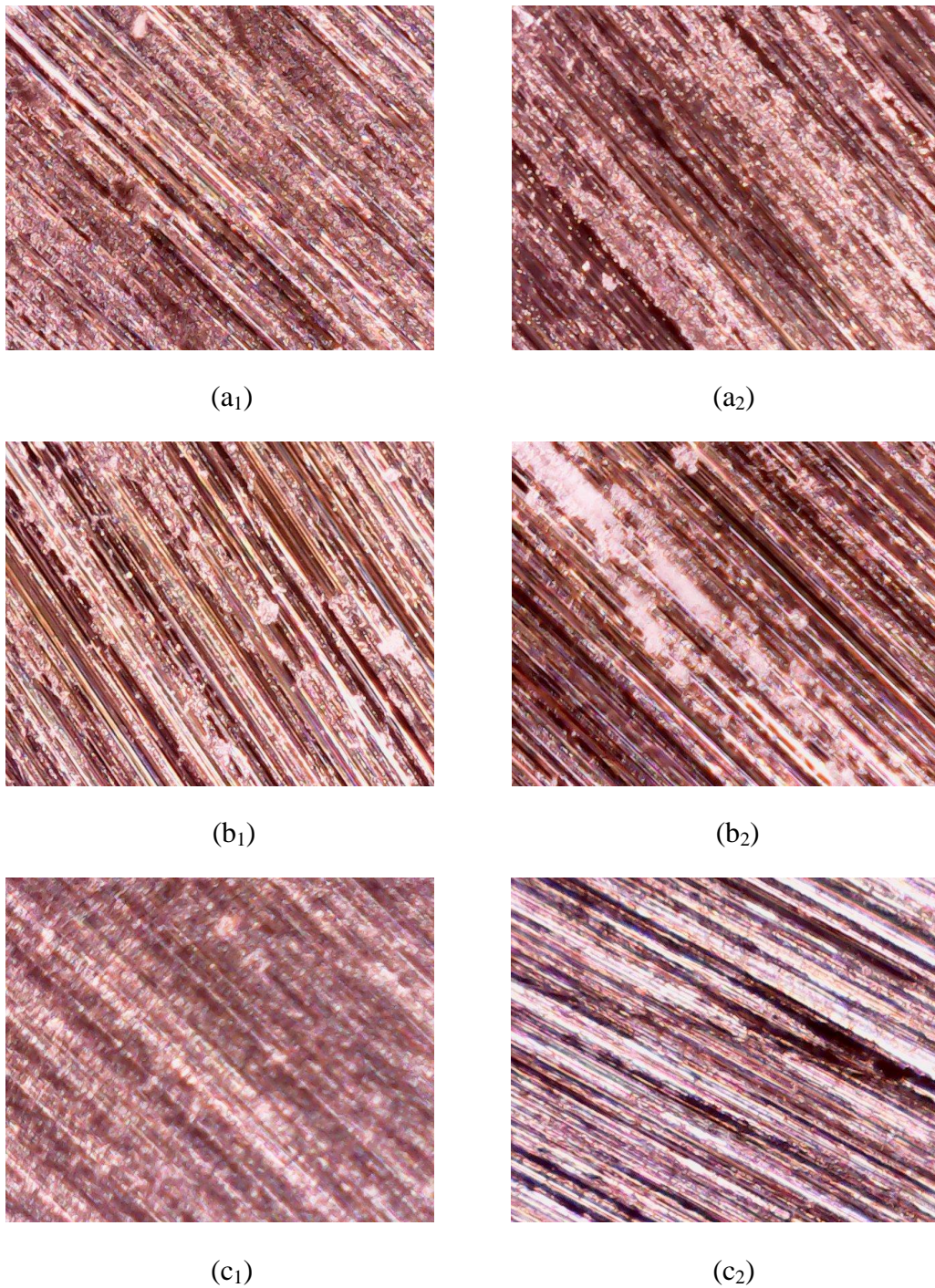
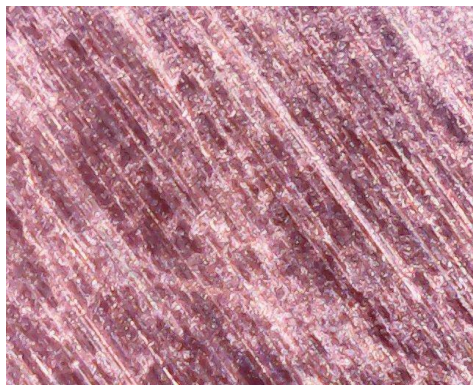
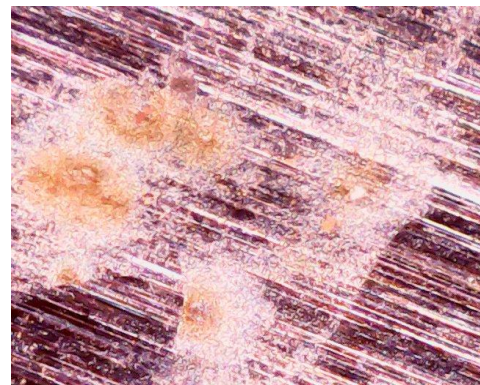


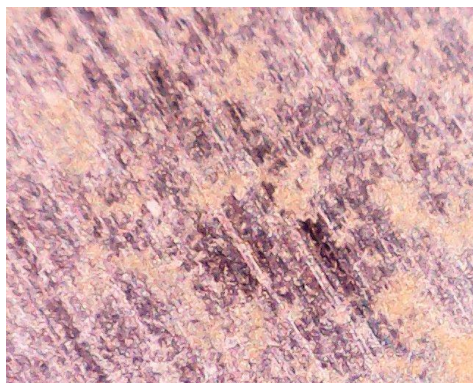
Figure 3.3.5 (a₁) HDPE 5 min disc, (a₂) HDPE 120 min disc, (b₁) uPVC 5 min disc, (b₂) uPVC 120 min disc, (c₁) Acrylic 5 min disc, (c₂) uPVC 120 min disc all with an applied load of 2 kg and dry sliding condition



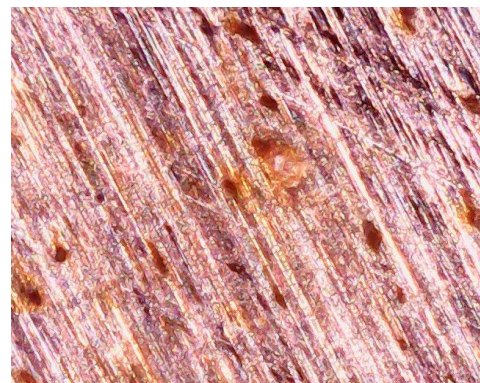
(a₁)



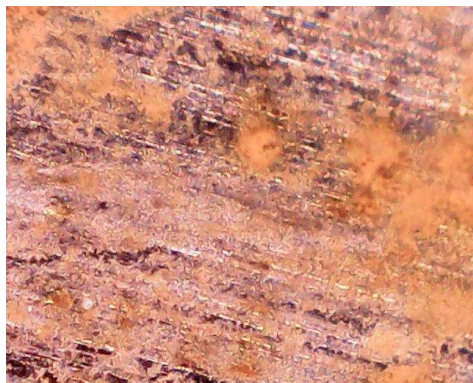
(a₂)



(b₁)



(b₂)



(c₁)



(c₂)

Figure 3.3.6 Optical micrographs (25X) of after wear of (a₁) HDPE 5 min disc, (a₂) HDPE 120 min disc, (b₁) uPVC 5 min disc, (b₂) uPVC 120 min disc, (c₁) Acrylic 5 min disc, (c₂) uPVC 120 min disc all with an applied load of 2 kg and wet sliding condition

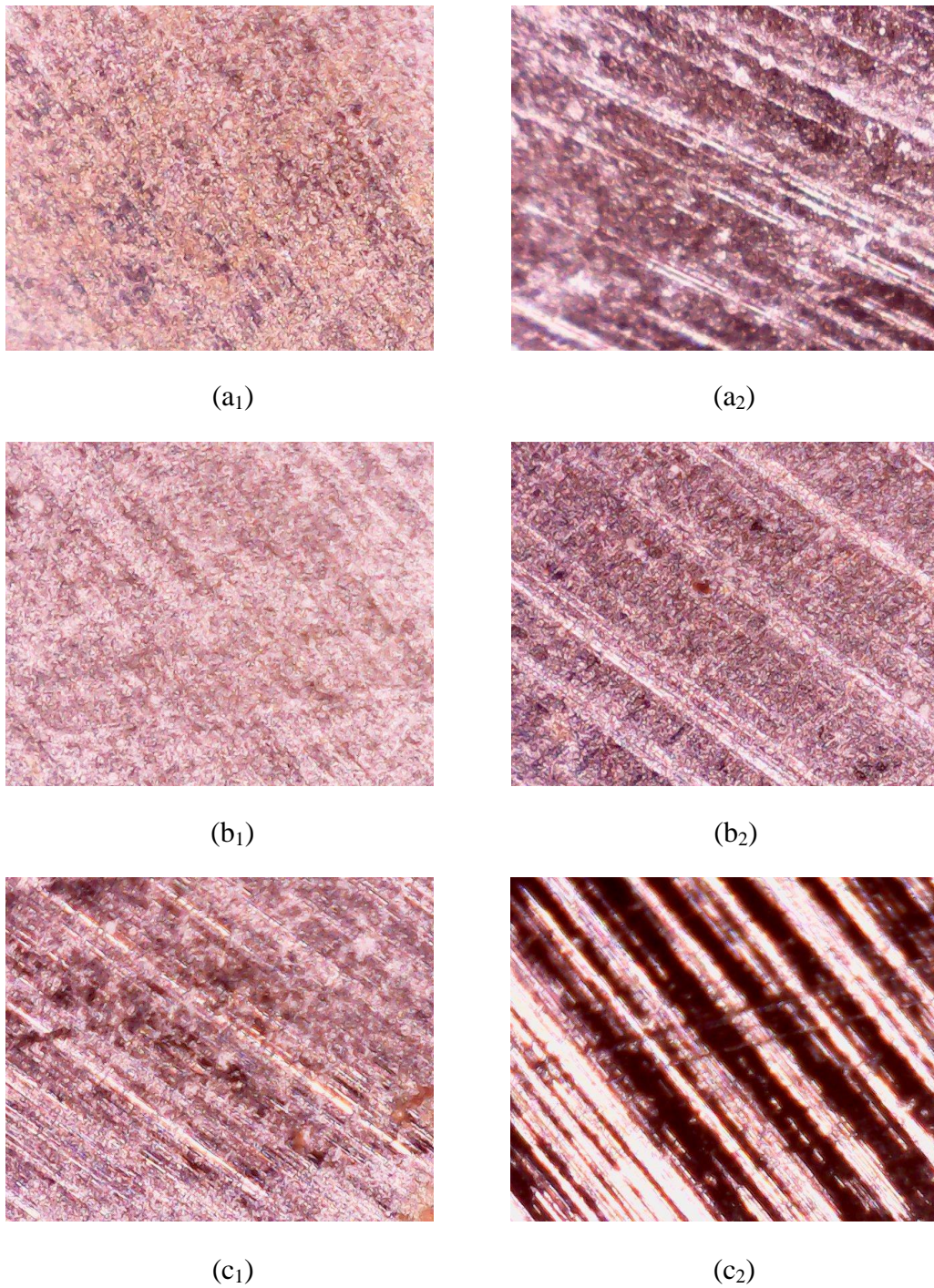
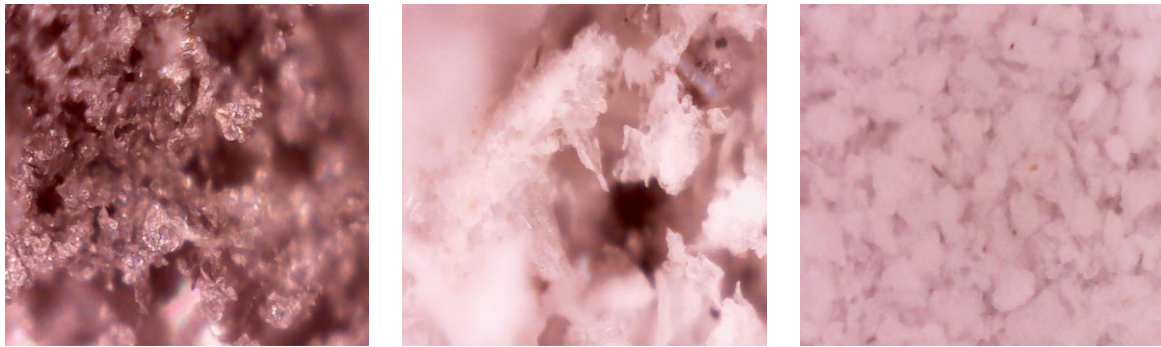


Figure 3.3.6 Optical micrographs (25X) of after wear of (a₁) HDPE 5 min disc, (a₂) HDPE 120 min disc, (b₁) uPVC 5 min disc, (b₂) uPVC 120 min disc, (c₁) Acrylic 5 min disc, (c₂) uPVC 120 min disc all with an applied load of 2 kg and sliding under clay water condition

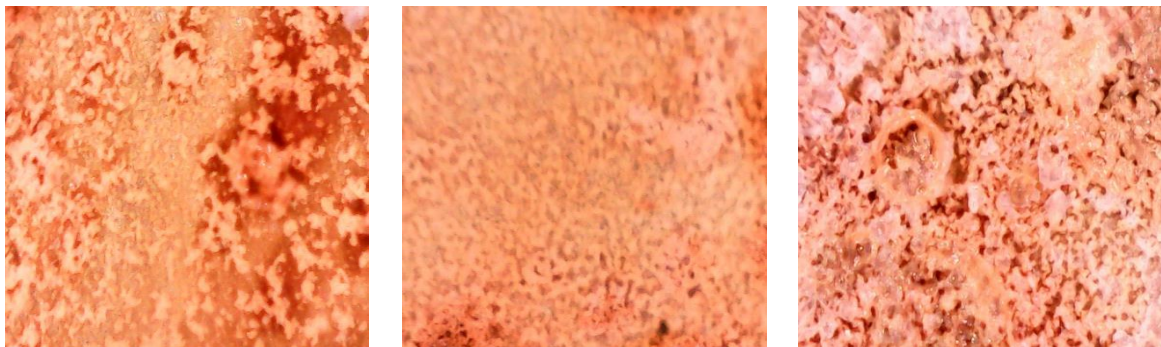


(a)

(b)

(c)

Figure 3.3.7 Optical micrographs (25X) of (a) HDPE dust, (b) uPVC dust, (c) Acrylic dust all with an applied load of 2 kg and dry sliding condition (120 min.)



(a)

(b)

(c)

Figure 3.3.8 Optical micrographs (25X) of (a) HDPE dust, (b) uPVC dust, (c) Acrylic dust all with an applied load of 2 kg and wet sliding condition (120 min.)



(a)

(b)

(c)

Figure 3.3.8 Optical micrographs (25X) of (a) HDPE dust, (b) uPVC dust, (c) Acrylic dust all with an applied load of 2 kg and sliding under clay water condition (120 min.)

From the above observations it can be noted that after testing the inspection of the surface of the specimens indicate the different way in which wear has been impacted on them, Perspex sample was covered with small fine scratches all over while uPVC was covered with less scratches but they reached much deeper in the. HDPE surface was also covered with scratches but much less than that of other materials also the scratches themselves were not too deep, As conditions changed to wet these scratches became much shallower on all three of the materials, in the presence of clay water sliding condition all three polymers showed signs of oxidation and absorption of the clay content as evident from the change in colour change of the test specimens. Also in clay water condition, it was found that the uPVC had more scratch marks and crevices on its surface than that of Perspex and HDPE agreeing with the earlier found result that friction is more in clay water condition for uPVC compared to Perspex. The nature of the dust of these three materials is Acrylic has powdered dust with many grains of different size. uPVC is much less grainy and much more laminar and HDPE is almost totally laminar string like, from these observations it is explainable that HDPE has a much more ordered structure, then comes uPVC and finally Acrylic has no definite structure at all. It is also seen that HDPE leaves little scratches on the counter face and Acrylic leaves much more scratches with uPVC falling in between.

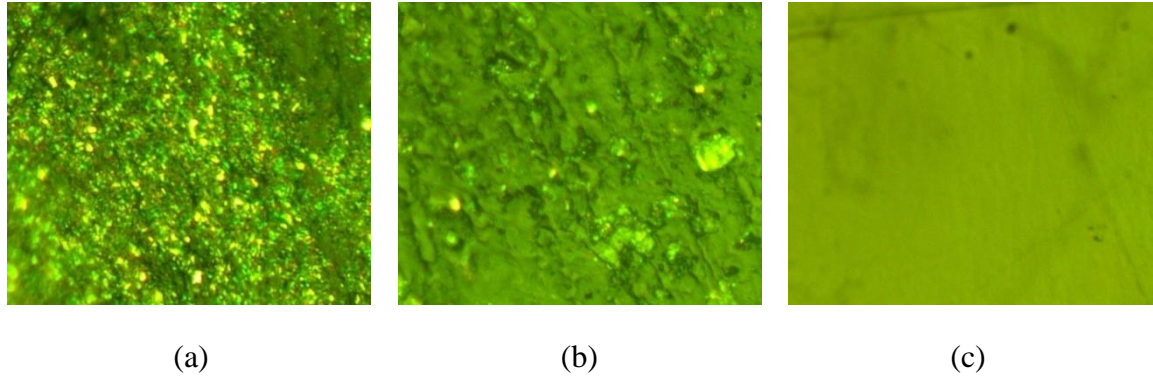
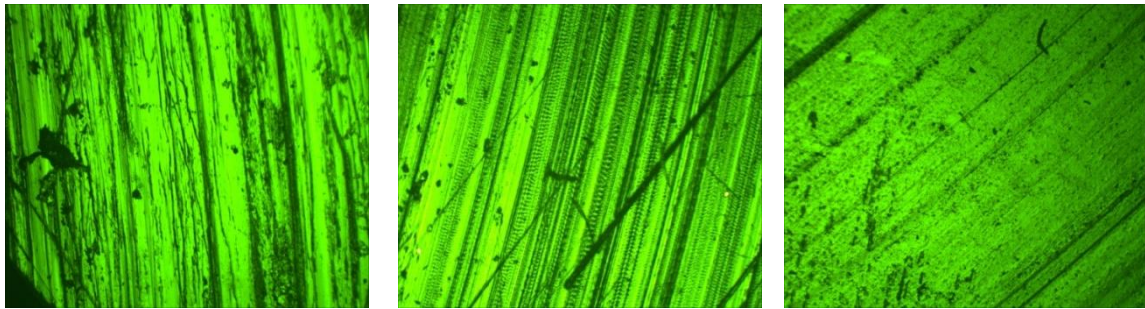


Figure 3.3.10 Microstructures of (a) HDPE, (b) Acrylic and (c) uPVC after polishing (160X)

The above figure is taken at a greater magnification for all the three materials after fine polishing. It is evident that HDPE has more uneven surface finish even after fine polishing. This can be explained by the fact that the laminar arrangement and dense packing of the HDPE chains results higher adhesion in the material giving more resistance to material removal by abrasive means. uPVC has much less surface irregularities as the large chloride groups which prevent the forming of large crystalline, ordered groups to some extent as a result cohesion between the chains is much less. In Acrylic the irregularities are virtually non-existent. This is because Acrylic is totally amorphous polymer and the chains are much wider apart resulting in the least amount of adhesion between the chains and lowest resistance to abrasive wear.

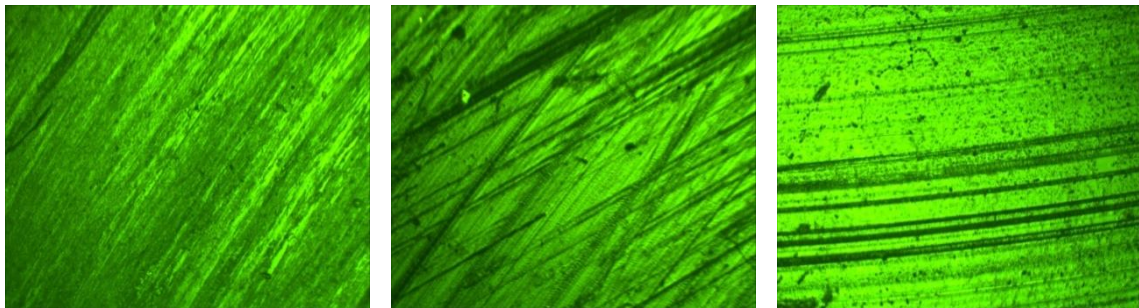


(a)

(b)

(c)

Figure 3.3.11 Optical micrographs of worn surfaces in dry sliding contact after 5 min run time with an applied load of 2 kg under 80X magnification of (a) Acrylic, (b) HDPE and (c) uPVC

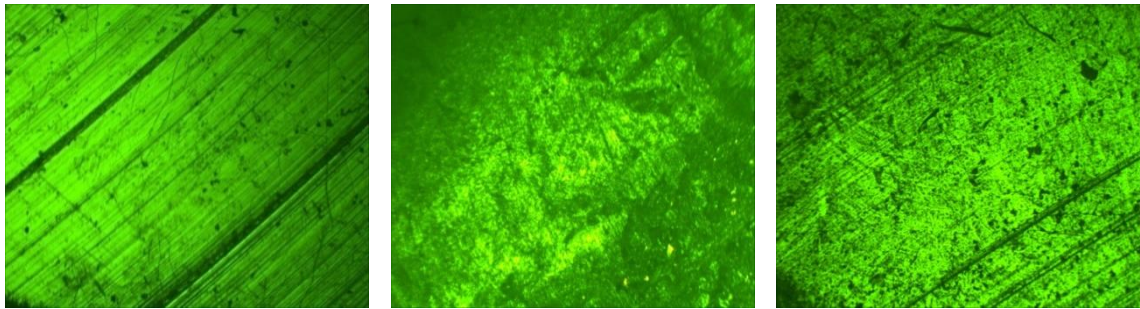


(a)

(b)

(c)

Figure 3.3.14 Optical micrographs of worn surfaces in dry sliding contact after 2 hour run time with an applied load of 2 kg under 80X magnification of (a) Acrylic, (b) HDPE and (c) uPVC

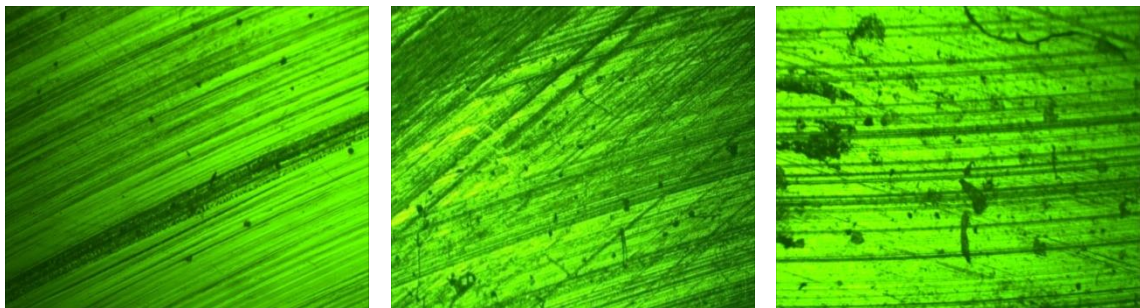


(a)

(b)

(c)

Figure 3.3.12 Optical micrographs of worn surfaces in wet contact after 5 min run time with an applied load of 2 kg under 80X magnification of (a) Acrylic, (b) HDPE and (c) uPVC



(a)

(b)

(c)

Figure 3.3.15 Optical micrographs of worn surfaces in wet contact after 2 hour run time with an applied load of 2 kg under 80X magnification of (a) Acrylic, (b) HDPE and (c) uPVC

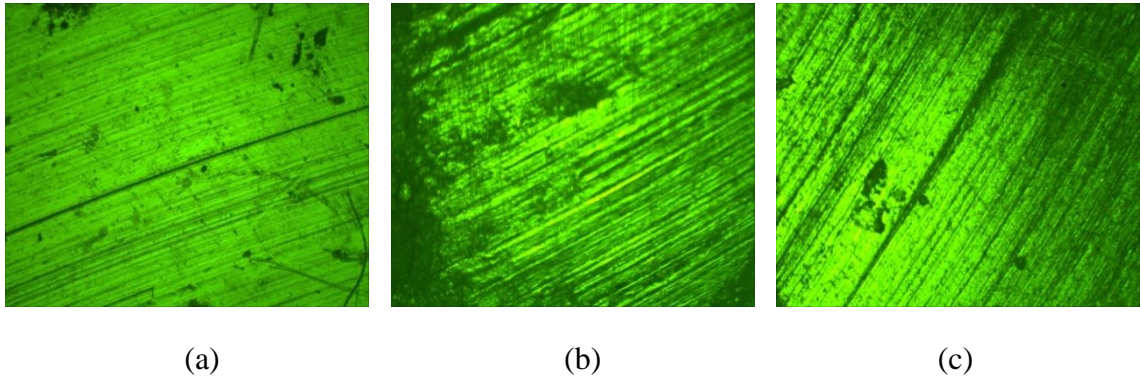


Figure 3.3.13 Optical micrographs of worn surfaces under clay water sliding condition after 5 min of run time with an applied load of 2 kg under 80X magnification of (a) Acrylic, (b) HDPE and (c) uPVC

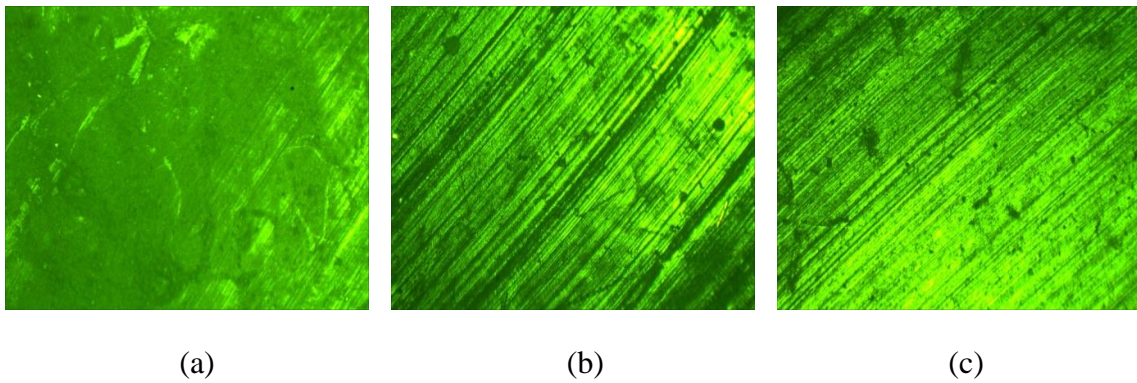
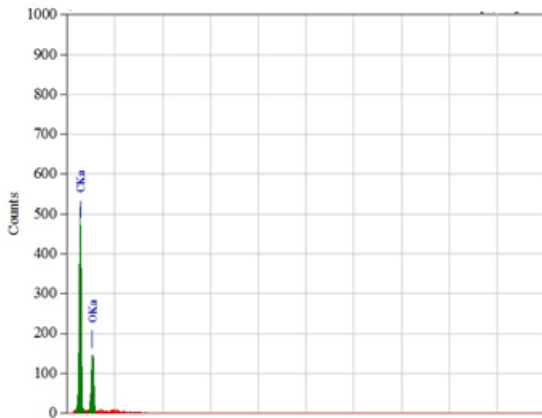
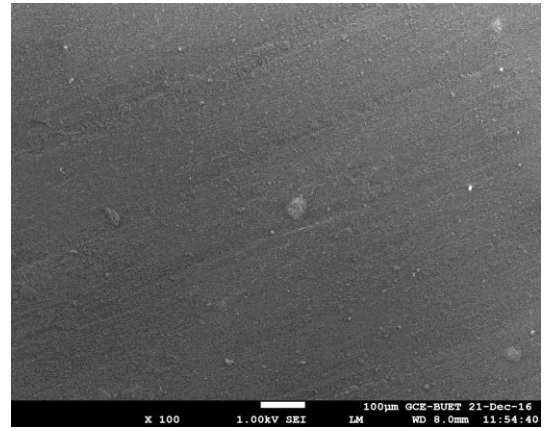
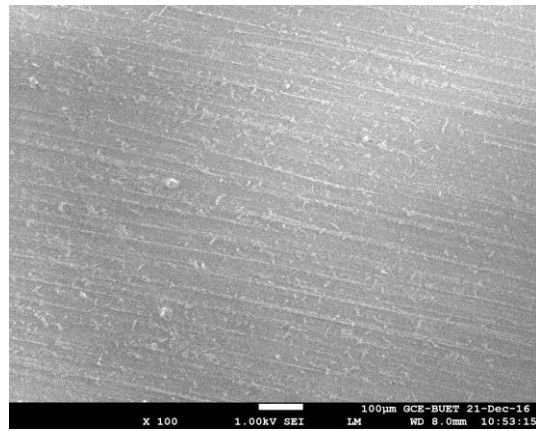


Figure 3.3.16 Optical micrographs of worn surfaces sliding under clay water condition after 2 hour run time with an applied load of 2 kg under 80X magnification of (a) Acrylic, (b) HDPE and (c) uPVC

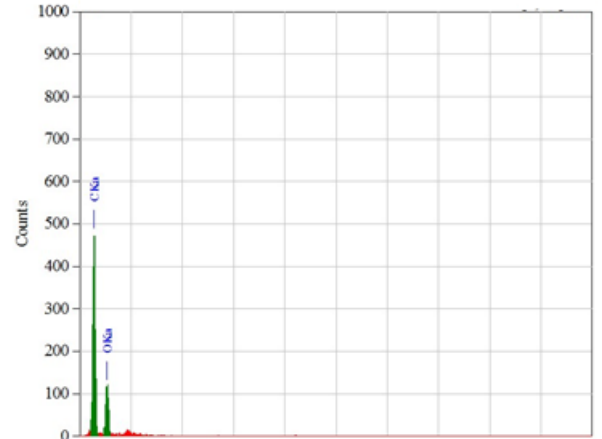
From the above images it is clear that increasing the load has an impact on worn surfaces. The number of scratches increases for all the materials. It can also be observed that at higher load the surfaces of the materials show more visual indications of chemical wear. Also it can be seen that the scratches are most prominent in the dry condition with random crevices and deep marks spread throughout. In both clay water and wet condition the deep marks as seen in dry sliding condition are much less visible also the marks appear to be more orderly. The least amount of scratch marks are seen on the clay water samples for both 5 min and 120 min samples with much less shallower scratch marks compared to the other two conditions. This may be explained due to the fact that the clay mixture is more viscous compared to water so under testing it can form a far better lubricating film compared to water and no lubricating film compared to dry condition. The many fine scratches on the clay water sample compared to the erratic and sudden scratch marks on the dry and wet samples may be explained by the fact that the clay mixture has suspended in it fine clay particles which are distributed evenly in the mixture causing the more even pattern of scratches.

3.4 SEM AND EDX OBSERVATIONS



Element	(keV)	Mass%	Sigma	Atom%	Compc
C K	0.277	67.07	0.64	73.07	
O K	0.525	32.93	0.98	26.93	
Total		100.00		100.00	

(a)



Element	(keV)	Mass%	Sigma	Atom%	Compu
C K	0.277	69.03	0.66	74.81	
O K	0.525	30.97	0.99	25.19	
Total		100.00		100.00	

(b)

Figure 3.4.1 SEM micrograph and EDX analysis of Acrylic sample (a) before and (b) after wear at 2 kg load and dry condition

The EXD profile indicates that the major elements present in the acrylic sample are carbon, C (67.07% by mass) and oxygen, O (32.93% by mass), The percentage of hydrogen is negligible.

After wear the acrylic sample exhibits a higher percentage of carbon, C (69.03 % by mass) and a reduced percentage of oxygen, O (30.97 % by mass). This overall higher percentage of carbon and lower percentage of oxygen indicates that oxidation has not

been significant in the wear process; this is backed by the almost clear debris collected with little signs of chemical wear.

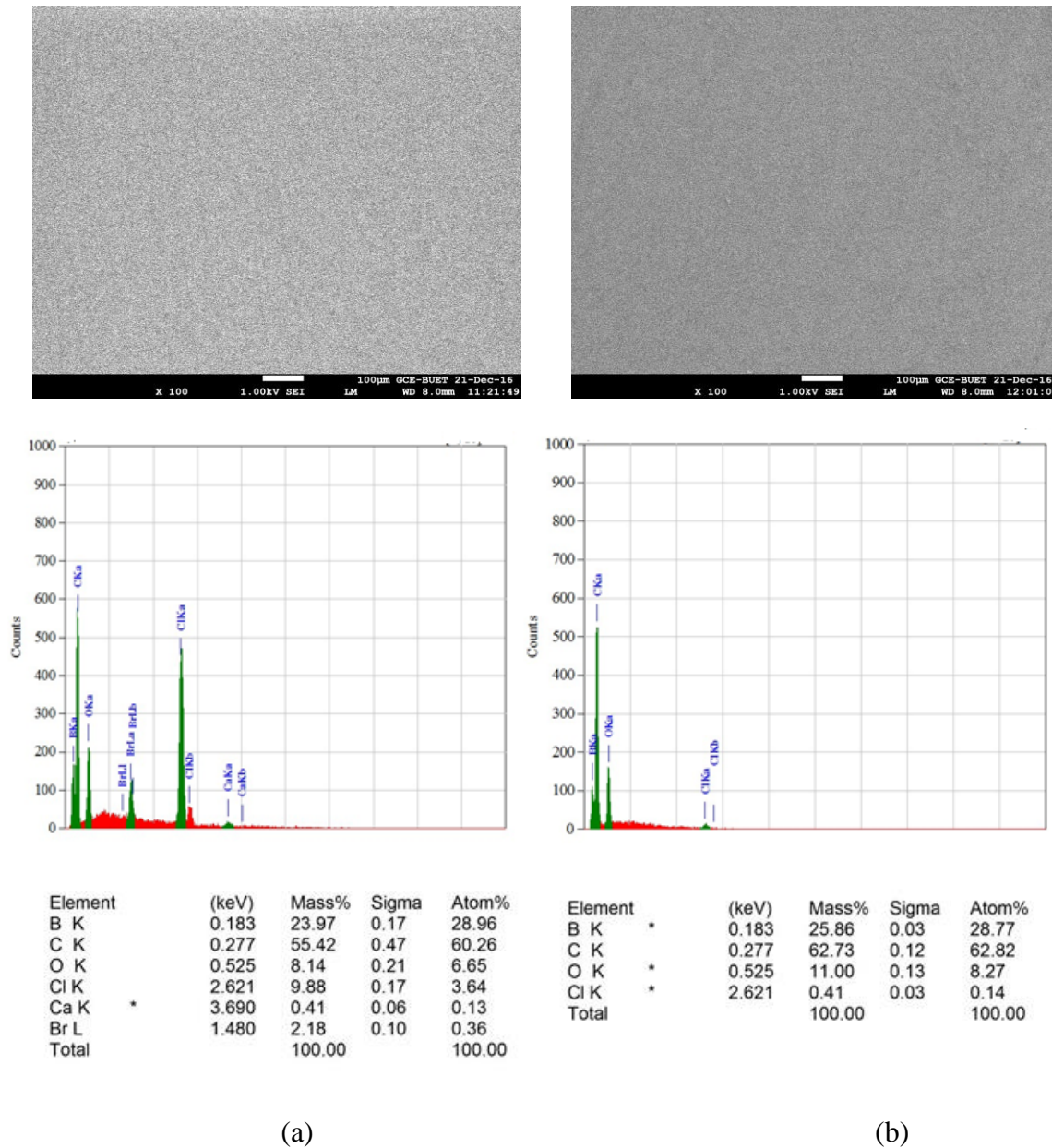


Figure 3.4.2 SEM micrograph and EDX analysis of uPVC sample (a) before and (b) after wear at 2 kg load and dry condition

From the EDX analysis it can be clearly seen that in the case of UPVC the main constituents are C 55.42 % by mass, B 23.97 % by mass and Cl 9.88 % by mass. Other constituents are O 8.14%, Br 2.18 % and Ca 0.41 %.

After wear it can be seen that carbon content rises to 62.73 % and oxygen (O) content also rises to 11.00 % while chlorine content (O) reduces to 0.41 %. Since the oxygen content rises it is safe to say that oxidation occurs and is a dominant factor in the wear process.

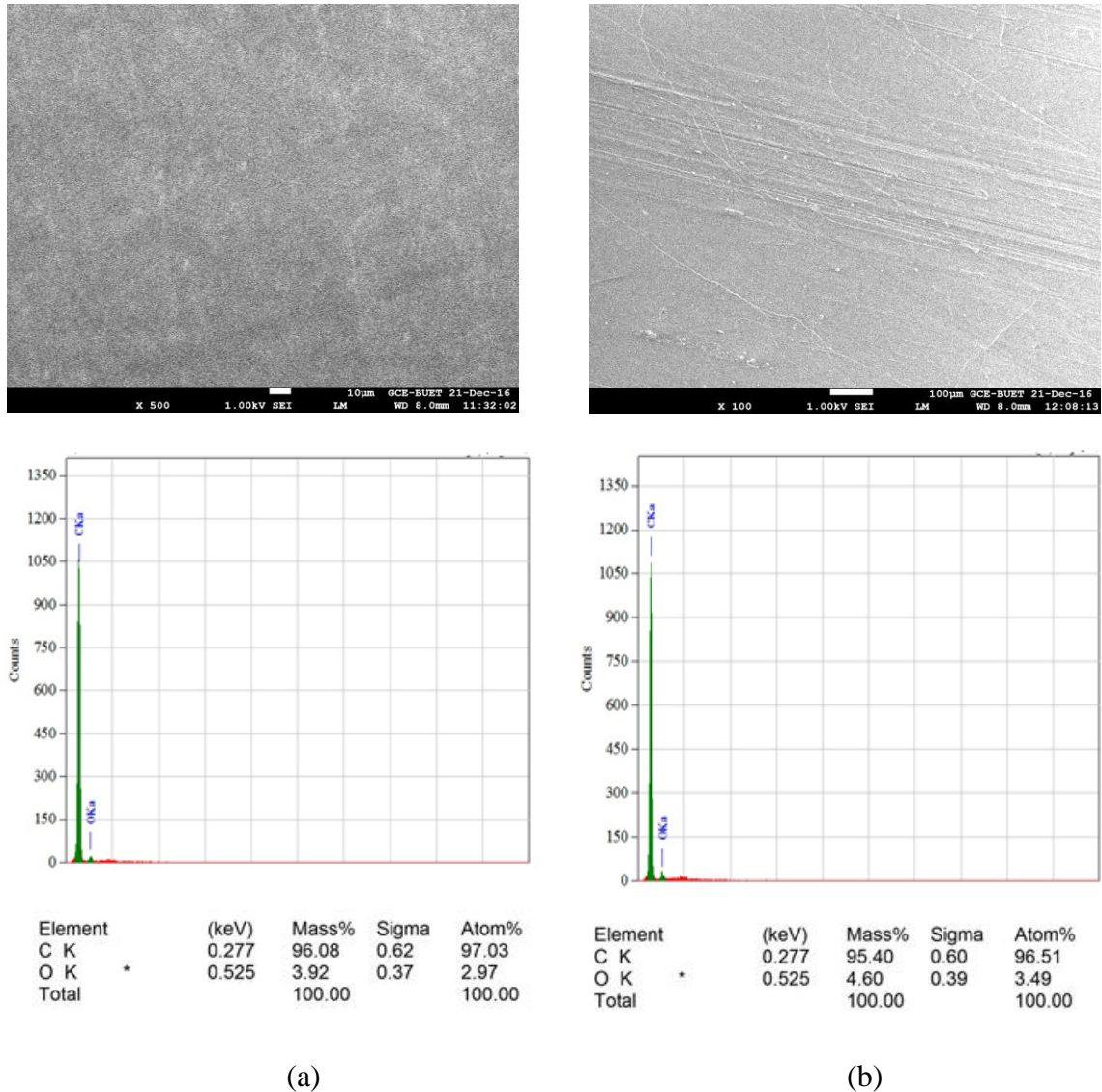


Figure 3.4.3 SEM micrograph and EDX analysis of HDPE sample (a) before and (b) after wear at 2 kg load and dry condition

The major elements of HDPE are also carbon, C (96.08% by mass) and oxygen, O (3.92% by mass), the high % of carbon is because of the structure of HDPE.

In the case of HDPE the oxygen (O) content increases after wear to 4.60% by mass revealing that some oxidation has taken place and that oxidation plays a key role in the formation of the steady state transfer layer after wear at the initial condition has taken place. Also the oxide formation in this case is much less than for UPVC indicating a better resistance to weathering in actual practices though it is more than acrylic.

4. CONCLUSIONS

In conclusion it was verified that the weight loss increased almost linearly with sliding distance, wear rate first fluctuates to a maximum value and then drops to steady value. Wear rate and weight loss also increase with increase in the load applied. The nature of the polymer structure influences greatly its behaviour and also that crystalline HDPE has better frictional and wear characteristics than UPVC and Acrylic. Studying the worn surface of the materials and the counter body surface also shows that HDPE leaves fewer scratches on the surface and that it is harder to wear compared to UPVC and Acrylic. Chemical interaction affects all three of the polymers. It is also seen that environmental factors and other factors can change the response of the tribo system in any manner. The results can be summarized as;

- I. HDPE has the least wear and is least affected by friction due to it having a highly linear, densely packed chains with less side branching.
- II. Acrylic is completely amorphous and thus is affected the most by friction and wear.
- III. uPVC has crystalline zones as well as amorphous zones so it exhibits behaviour in between HDPE and Acrylic.
- IV. EDX and SEM results show that Acrylic is least affected by oxidation. Followed by HDPE and finally uPVC. SEM also shows the oxide formation on the HDPE and uPVC in the form of small white spots and strips is much more than Acrylic.
- V. Optical microscopic observations show that the scratches on the HDPE sample are the least dense, Acrylic has the most amount of scratches and uPVC falls in between correlating with the earlier results obtained in the friction and wear test.

5. RECOMMENDATION FOR FUTURE WORK

A few aspects of this research was limited, if these can be improved a more accurate study can be made, they are-

- I. Testing more samples would result in more data points which would give more complete results.
- II. The study was conducted in an open environment. If the surrounding environmental conditions could be more controlled it would reduce outside interference and more accurate results.
- III. The application of water and clay for the experiment was done by hand, a future set up could be made so that these can be done in a more controlled way ensuring exact surface mating conditions at all times further eliminating source of variation.
- IV. The number of test materials can also be increased to include different types of polymers so that a more through and detailed knowledge as to what factors in structure effect wear and friction conditions.
- V. The number of surface mating conditions can also be increased so that the test emulates real life conditions more accurately

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