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FRICTION BEHAVIOR OF CARBON FIBRES REINFORCED EPOXY FLOOR

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ABSTRACT
The present work discusses the effect of reinforcing epoxy by carbon fibres (CF) on the friction coefficient displayed by contact and separation as well as sliding of bare foot and foot wearing rubber contacting epoxy. The relationship between electrostatic charge (ESC) and friction coefficient will be discussed.

From experiments carried out in the present work, it was observed that ESC increases with increasing CF content. Besides, as the CF are close to the sliding surface ESC increases. It is known that the strength of the electric field inside the epoxy matrix is proportional to how much charge is generated on the friction surface. The significant ESC increase when the CF were close to the surface confirmed the presence of a magnetic field around the CF that is directly proportional to the current value and inversely proportional to the distance from the conductor. ESC generated during contact and separation as well as sliding of insulating materials can play a major role in adhesion energy and alter friction.

KEYWORDS
Friction coefficient, bare foot, rubber foot wear, epoxy reinforced by carbon fibres, electrostatic charge.

INTRODUCTION
There is an increasing demand to investigate proper solutions for reducing slip and fall accidents. The friction of footwear on floor coverings is responsible of the occurrence of slips and falls. The slip resistance is normally assessed on the bases of friction coefficient measured with footwear materials sliding against floors. The effect of rubber floor provided by cylindrical treads on the friction coefficient was investigated, [1]. Floor slip-resistance is quantified by the static friction coefficient. In the USA, the static friction coefficient of 0.5 has been recommended as the slip-resistant standard for unloaded, normal walking conditions [2]. Higher the static friction coefficient values may be required for safe walking when handling loads. In Europe, [3], it was suggested that a floor was ‘‘very slip-resistant’’ if the friction coefficient was 0.3 or more. A floor with

the friction coefficient between 0.2 and 0.29 was ‘‘slip resistant’’. A floor was classified as ‘‘unsure’’ if its friction coefficient was between 0.15 and 0.19. A floor was ‘‘slippery’’ and ‘‘very slippery’’ if the friction coefficient of was lower than 0.15 and 0.05, respectively. The subjective ranking of floor slipperiness was compared with the static friction coefficient (μ) and found that the two measures were consistent, [4, 5]. It was concluded that human subjects could discriminate floor slipperiness reliably. Many state laws and building codes have established that a static $\mu \geq 0.50$ represents the minimum slip resistance threshold for safe floor surfaces. Furthermore, the Americans with Disabilities Act Accessibility Guidelines [6] contain advisory recommendations for static friction coefficient of $\mu \geq 0.60$ for accessible routes (e.g. walkways and elevators) and $\mu \geq 0.80$ for ramps.

The effect of surface roughness, on the friction behaviour of recycled rubber tiles, was discussed, [7]. Experiments were carried out by the sliding of the bare foot against the tested rubber tiles of different thickness. It was found that friction coefficient slightly increased with increasing the tile thickness. In the presence of water on the sliding surface, rough surface displayed higher friction values than the smooth one. The effect, of rectangular and cross treads introduced in the rubber mats on friction coefficient when sliding against footwear, was tested, [8]. It was found that friction coefficient slightly decreased with increasing tread groove at dry, detergent wet and oily sliding due to the decreased contact area accompanied to the increased groove width of the rubber. At water wet sliding friction coefficient remarkably increased with increasing the tread groove. Oily sliding displayed very low values of friction coefficient. As the tread width decreased the friction values decreased due to the decrease of the contact area at dry, detergent wet and oily sliding. Friction coefficient of rubber sliding against different types of floor materials of different surface roughness was investigated under different sliding conditions: dry, water, water/detergent dilution, oil, water/oil dilution, [9]. The floor materials are parquet, polyvinyl chloride (PVC), epoxy, marble, cement and ceramic. Based on the experiments, it was found out that at dry sliding, friction coefficient decreased with increasing surface roughness. Epoxy displayed relatively higher friction than parquet and PVC, while cement tiles gave the highest friction coefficient. Ceramic showed relatively lower friction values than marble and cement. The effect of floor materials, on the generation of electric static charge and friction coefficient, was discussed, [10]. Marble displayed higher values than that observed for ceramic floor. Based on this observation it can be suggested to select floor materials according to their resistance to generate electric static charge.

Static friction coefficient displayed by rubber disc fitted by single groove sliding against ceramics was investigated, [11 – 14]. It was found that for dry sliding against ceramics, friction coefficient slightly increased with increasing load. For soft rubber friction coefficient slightly decreased with increasing normal load. In the presence of sand friction coefficient slightly decreased with increasing applied load. The effect of sand particles, on friction coefficient displayed by rubber sliding against ceramic tiles, was investigated, [15]. It was found that, at dry sliding, dust particles caused drastic decrease in friction coefficient. In this condition, it is recommended to use circular protrusion in the rubber surface. The friction behavior of ceramic tiles, as floor materials when soft

and hard rubbers slide against them, was described, [16]. Based on the experiments, it was found that at dry sliding soft rubber showed higher friction coefficient than hard one. The difference might be attributed to the extra deformation offered by soft rubber. Friction coefficient and electrostatic charge of epoxy composites filled by iron nanoparticles sliding against rubber to develop proper materials to be used as floor materials of high friction coefficient and low electrostatic charge were investigated, [17]. It was found that presence of sand particles on the sliding surfaces strongly affected the friction coefficient. Presence of sand decreased the electric static charge. The effect, of the filling materials on the friction coefficient of recycled rubber floors, was discussed, [18]. It was found that friction coefficient slightly increased with increasing the content of the filling materials. The lowest friction values were observed for tiles filled by 70 wt. % polyurethane. The porous recycled rubber tiles were inspected to be used for architectural applications as floor tiles, [19]. It was found that friction coefficient displayed by bare foot sliding against dry recycled rubber tiles slightly increased with increasing force reduction ratio. It seems that the presence of pores inside the rubber matrix is responsible for the extra deformation displayed by the porous recycled rubber and consequently the contact area between the foot and the tested floor materials increased.

The friction coefficient, of rubber semi-spherical balls of different diameter and hardness, was tested, [20]. Friction coefficient drastically decreased with increasing hardness when sliding against water, detergent and oil lubricated rubber. It showed significant increase with increasing the diameter of the semi-spherical protrusions. The effect, of the hardness and thickness of recycled rubber floor tiles on the friction coefficient, was tested, [21]. Based on the experimental observations, it was found that friction coefficient, displayed by sliding of rubber sole against dry floor tiles, drastically decreased with increasing the hardness of the tested floor tiles, while increased with increasing normal load. Friction coefficient of rubber sliding against polymeric indoor floor materials of different surface roughness was investigated under the following conditions: dry, water, water and soap, oil, water and oil, [22, 23]. It was found that, maximum friction values were observed at surface roughness ranging from 1.5 and 2.0 µm Ra. At water–soap lubricated sliding, the friction coefficient drastically decreased with increasing the surface roughness. At oil lubricated sliding, the maximum friction values were noticed at 4.0 µm Ra surface roughness. At water and oil lubricated sliding, smooth floor surface displayed very low values of friction coefficient (0.08) close to the ones observed for mixed lubrication where the two sliding surfaces are partially separated by a fluid film. The effect of surface roughness on the friction coefficient of ceramic rubbing against rubber and leather, was investigated, [24]. Friction coefficient of glazed ceramic floor decreased down to minimum then increased with increasing the surface roughness of the ceramic surface. Bare foot sliding against epoxy floor showed relatively lower voltage than that displayed by rubber footwear, where the maximum value reached 280 volts, [25]. Rubber footwear sliding against epoxy floor displayed consistent trend of friction coefficient with increasing load. The highest friction coefficient value was 0.86, while the lowest was 0.58. Sliding against PVC floor experienced lower friction coefficient than that observed on epoxy floor.

The aim of the present work is to investigate ESC generated from the contact and separation as well as sliding of bare foot and rubber footwear against epoxy floor that reinforced by CF. Besides, friction coefficient and its dependency on ESC are discussed.

EXPERIMENTAL

Experiments were carried out using test rig which shown in Fig. 2.1. It consists, mainly, of two load cell one places in horizontal position and other places in vertical position (horizontal load cell measured normal load while vertical one measured friction load). Also it consists of upper base that will covered by the flooring surface (ceramics), and lower base used to make test rig fixed on floor and not move during test running. Two monitors are connected to two load cell for reading normal and friction force.

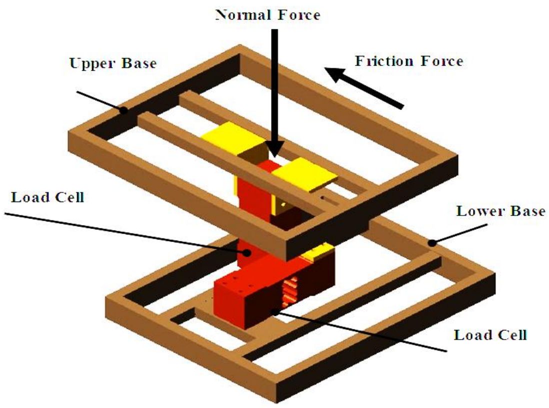
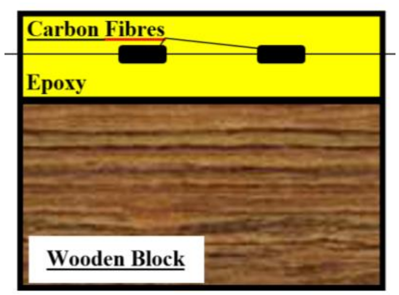
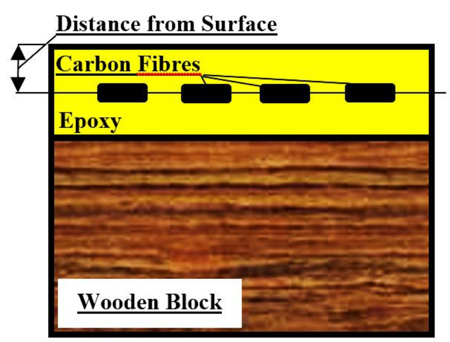


Fig. 1 Details of the test rig.

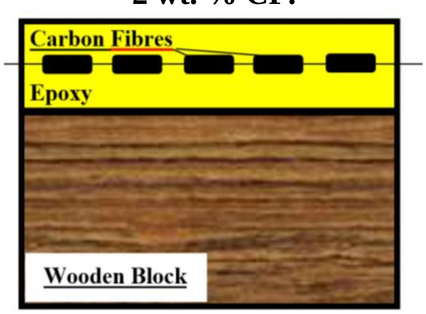
Fig. 2 ESC measurement device.



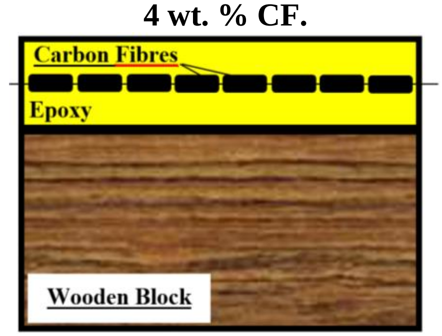
2 wt. % CF.



4 wt. % CF.



6 wt. % CF.



8 wt. % CF.

Fig. 3 Epoxy test specimens with different CF contents.

The effect of the tested parameters on friction coefficient of epoxy reinforced by carbon fibres (CF) such as content and distance from epoxy surface has been investigated. Epoxy test specimens have been prepared in the form of square sheets of 50 × 50 mm. The values of CF content used in experiment are 0, 2, 4, 6, 8 wt. % as illustrated in Fig. 3. ESC measurement has been carried out. First, epoxy specimens have been adhered on wooden block then cleaned to eliminate any dirt and dust and carefully dried before the test. The epoxy test specimens have been loaded against human skin and rubber at contact and separation as well as sliding conditions. During test running, horizontal and vertical load cell connected to two monitors read normal and friction load respectively. Friction coefficient is the ratio between friction and normal load. By taking five values for each test the values of friction coefficient can be calculated.

RESULTS AND DISCUSSION

The effect of CF content located at 1mm from the surface on ESC generated from contact and separation of epoxy and bare foot is shown in Fig. 4. ESC slightly increases with increasing CF content and normal load. Epoxy of 8 wt. % CF content displayed the highest value of ESC. The relatively low values of ESC may be attributed to the fact that bare foot conducts the ESC out of the contact surface. It is expected that electric field will be formed due the ESC formed on epoxy and bare foot surfaces.

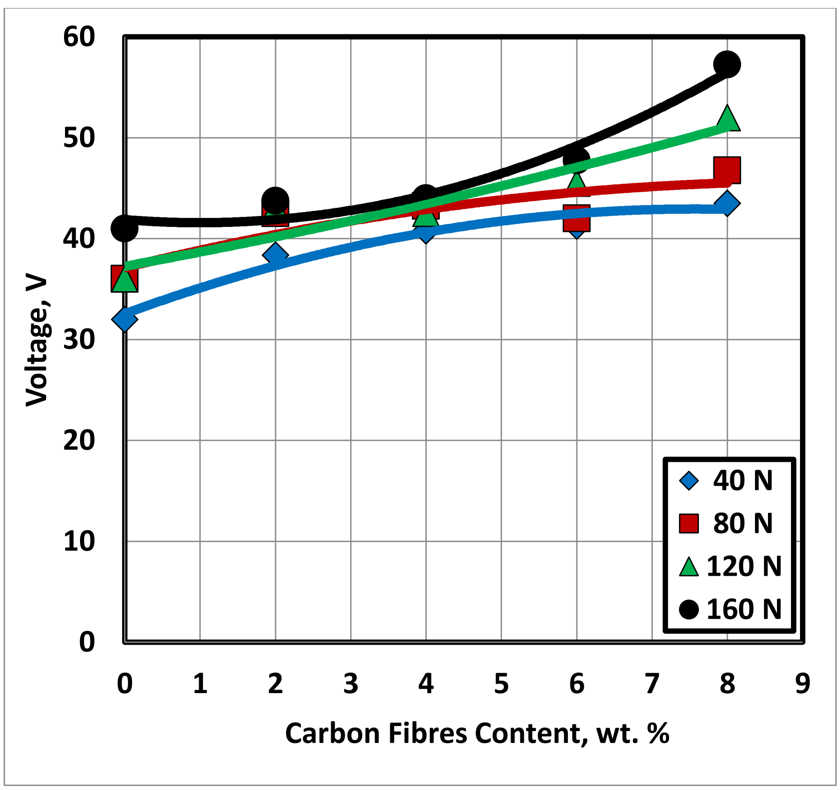


Fig. 4 Effect of CF located at 1 mm from surface on ESC for epoxy at contact and separation with bare foot.

ESC generated from the contact and separation of epoxy filled with CF at 5 mm distance from is shown in Fig. 5. The ESC slightly increased with increasing CF content, while significantly increased with increasing normal load. Values of ESC were relatively lower than that observed for closer CF to the contact surface. It seems that if the CF were closer to the surface, they were strongly influenced by the electric field and consequently the intensity of the ESC increased.

The effect of the distance of CF from the surface on the ESC generated from sliding of bare foot and test specimens is shown in Fig. 6. Significant decrease in ESC was observed as the distance of CF from friction surface increased. It is clearly seen that, as the content of CF increased, ESC increased. This behavior can be explained on the basis the generation of double layer of ESC on the two sliding surfaces. When two dissimilar materials are pressed or rubbed together, the surface of one usually becomes positively charged, while the other becomes negatively charged. The intensity of the generated charge depends on the pressure and velocity of rubbing. Once charged, the two surfaces attract each other. The distribution of charges on the sliding surfaces generates electric field. Epoxy as insulator contains a distribution of charges which are conserved. The double layer of the electric static charge generated on the sliding surfaces would generate an E-field inside the matrix of epoxy. Presence of CF inside epoxy matrix would generate extra ESC on the sliding surfaces. As CF are close to the surface the intensity of the electric field increases.

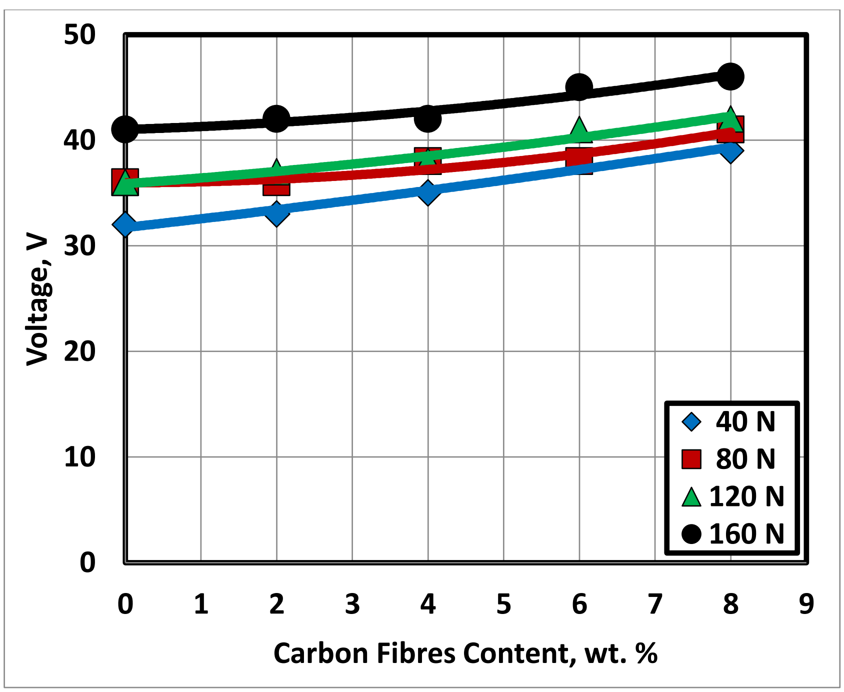


Fig. 5 Effect of CF located at 5 mm from surface on ESC for epoxy at contact and separation with bare foot.

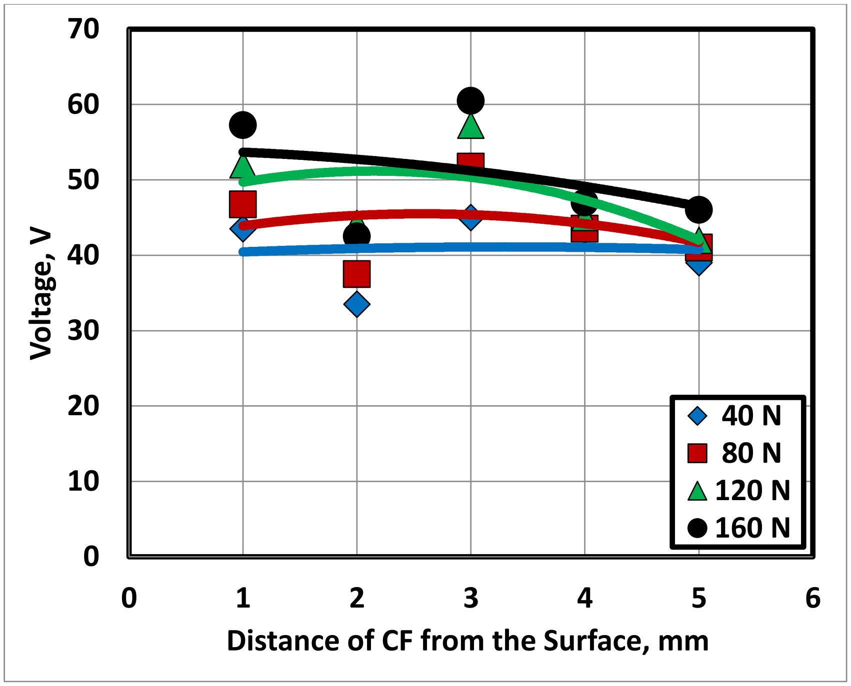


Fig. 6 Effect of the distance of CF from the surface on the ESC generated from contact and separation of bare foot and test specimens.

ESC generated from sliding of bare foot and test specimens and CF content is shown in Figs. 7 – 9. It was observed that, at sliding, the charge value was higher than that recorded for contact and and separation. It is clearly seen that ESC significantly increased up to maximum with increasing CF content. Values of the voltage depend on the applied normal load, where they increase with the increase of the load. As the distance of the CF from the friction surface increased voltage decreased. The highest and lowest voltage values were recorded for CF located at 1.0 and 5.0 mm far from the friction surface respectively, Figs. 7 and 8. Presence of CF inside epoxy matrix would generate extra electric static charge on the sliding surface. It is known that friction between two surfaces causes the object in the upper position of the triboelectric series to be charged positively (bare foot) and that in the lower position to be charged negatively (epoxy), where the different polarity means attraction. Also, the long gap between the two sliding materials in the series gives higher chance to exchange more charges (electrons) between the two surfaces rubbing each other. The relative voltage increase at sliding might be attributed to the increase of the mobility of the free electrons to one of the rubbed surfaces. Based on the fact that friction of epoxy against bare foot is accompanied by electrification, where one of the sliding surface gains positive ESC (bare foot), while the other (epoxy) gains negative charge. As a result of that, an electrostatic force is generated and this force influences the adhesion between the two surfaces. The magnitude of the electrostatic force is proportional to the ESC which depends on the rank of the rubbing surfaces in the triboelectric series.

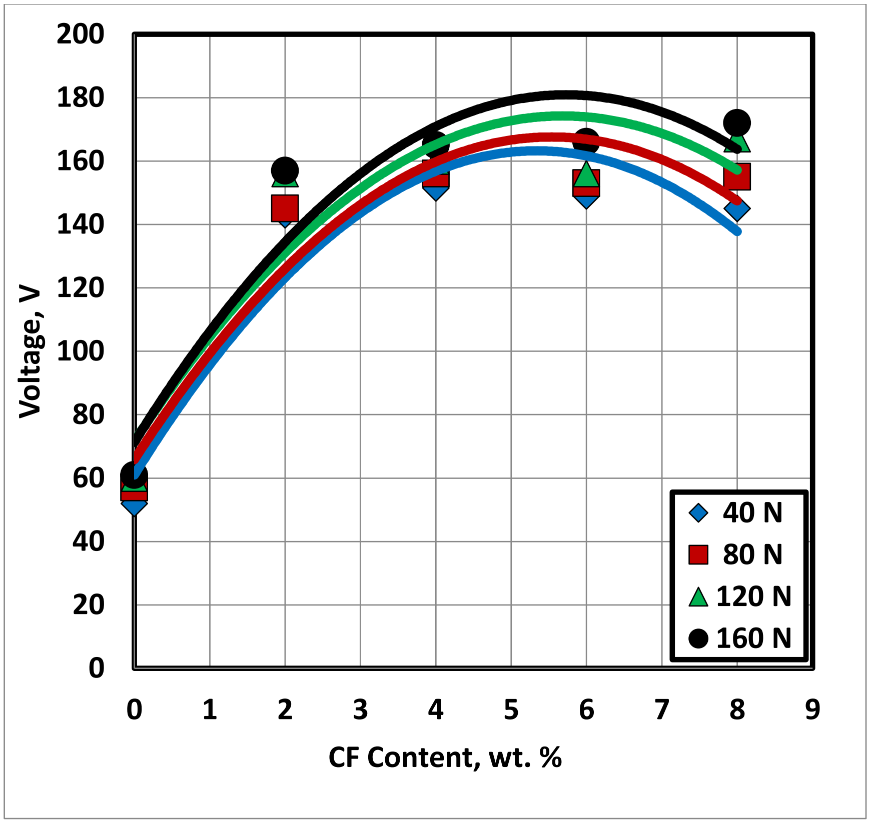


Fig. 7 ESC generated from sliding of bare foot and test specimens at 1 mm close to the surface.

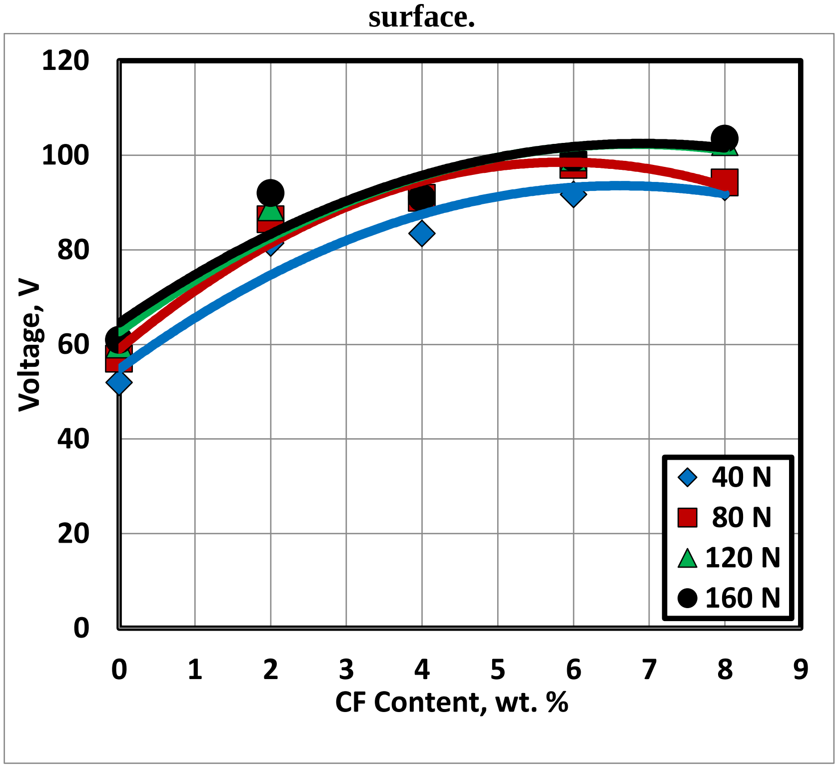


Fig. 8 ESC generated from sliding of bare foot and test specimens at 5 mm close to the surface.

The effect of the distance of CF from the surface on the ESC generated from sliding of bare foot and test specimens is shown in Fig. 9 for composites reinforced by 8 wt. % CF. As the distance of CF from friction surface increased ESC drastically decreased. This observation confirmed the effect of the distance of CF from the sliding surface on the generated voltage. It seems that when CF were closer to the surface, its ability to generate relatively extra higher voltage increased, while voltage decreased with increasing the distance of CF location from the surface. Voltages were 175 and 105 volts in epoxy reinforced by wires at 1 and 5 mm far from the surface respectively at 160 N load.

Friction coefficient is considered as the main factor in evaluating the safety of walking against floor materials. The measure of the safety is the friction coefficient displayed between bare foot and footwear against floor. As the friction coefficient increases, the safety of walking increases. Effect of the distance of CF from the surface on friction coefficient displayed by sliding bare foot against epoxy composites is shown in Fig. 10, where friction coefficient drastically decreased with increasing the distance of CF from the sliding surface. It seems that when CF were closer to the surface, they were strongly influenced by ESC formed on the surface and consequently the adhesion of the sliding surfaces increased. This observation confirmed the influence of the electric field on friction coefficient, where the values of friction can be controlled by varying the distance of CF from the epoxy surface. Based on that observation, it can be concluded that friction coefficient critically depends on the value of the generated voltage. This behavior can be explained on the basis that, generation of equal electric static charges on the sliding surfaces of different signs would increase the attractive force between the two surfaces and consequently the adhesion increased leading to friction increase.

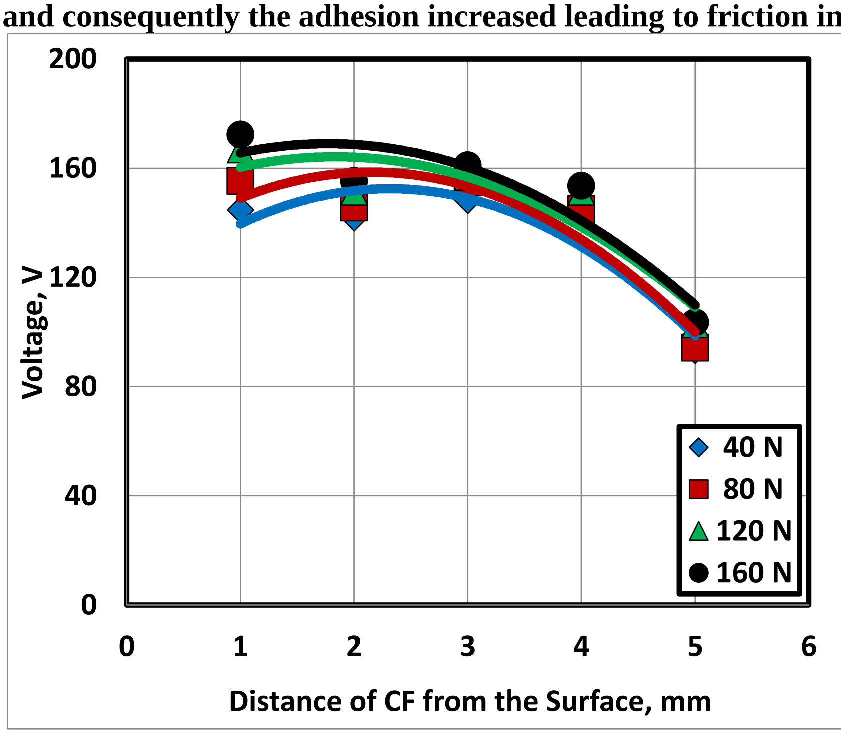


Fig. 9 Effect of the distance of CF from the surface on ESC generated from sliding of bare foot against the test specimens.

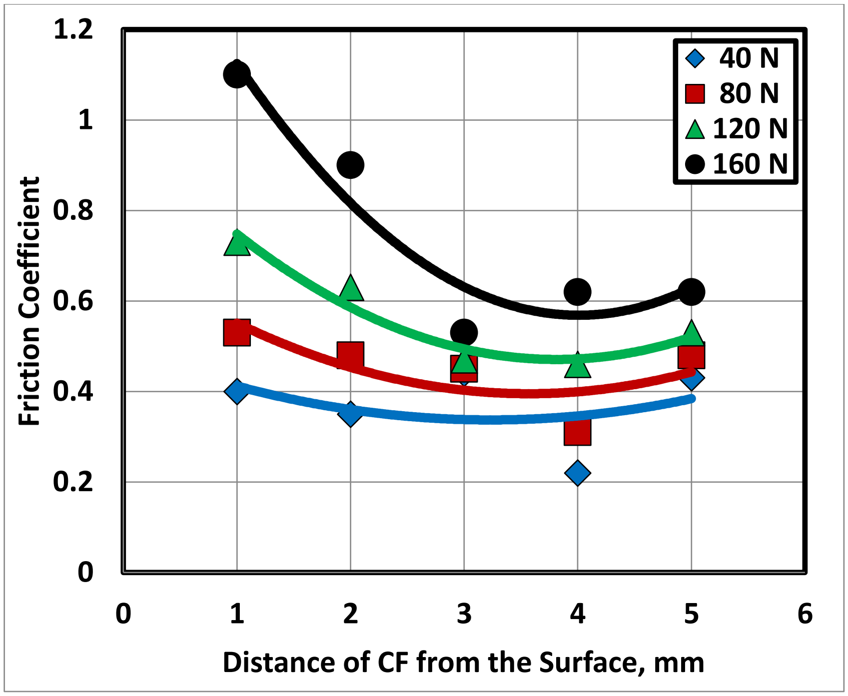


Fig. 10 Effect of the distance of CF from the surface on friction coefficient displayed by sliding between bare foot and epoxy.

The results of contact and separation as well as sliding of rubber footwear on the tested epoxy floor are illustrated in Figs. 11 – 17. The effect of contact and separation for epoxy reinforced by CF and rubber on ESC is shown in Figs 11 -13. Increasing CF content leads to significant ESC increase. Besides, as the normal load increases ESC increases. As the distance of the CF from the friction surface increases voltage decreased. ESC generated on the sliding surfaces due to generating electric field inside the matrix of epoxy. Presence of CF inside epoxy matrix would generate extra electric static charge on the sliding surface. It is observed that ESC values were much higher than that recorded for bare foot/epoxy condition. The highest voltage value was 255 volts for rubber, while it recorded 47 volts for epoxy. This behavior is attributed to the fact that bare foot conducted the electric static charge generated in the contact surface. It is known that epoxy is ranked as negative charged material, while skin of the bare foot is positive charged one and the gap is relatively short in the triboelectric series which decreases the voltage difference, while the gap between epoxy and rubber is higher. It is therefore necessary to select the materials based on their triboelectric charging. Figure 13 illustrates the effect of CF location on ESC. It can be noticed that when CF were closer to the surface, their ability to be affected by ESC increased. Significant decrease in ESC was observed as the distance of CF from friction surface increased. ESC generated from sliding of epoxy filled with CF and rubber is shown in Figs. 14 - 16. It is shown that, increasing CF causes significant ESC increase. Increasing normal load increases ESC due to increasing contact area caused by the increase of the rubber deformation that has significant effect on increasing ESC. The most interesting experimental fact was the very high voltage values observed for sliding, where the highest value reached 1080 volts for composites reinforced by 8 wt. % CF at 160 N load.

Dry sliding of rubber against epoxy generated much higher voltage measured on the epoxy surface. This observation can confirm the necessity to develop new materials to be applied as floor of low ESC. As the load increased, the voltage remarkably increased.

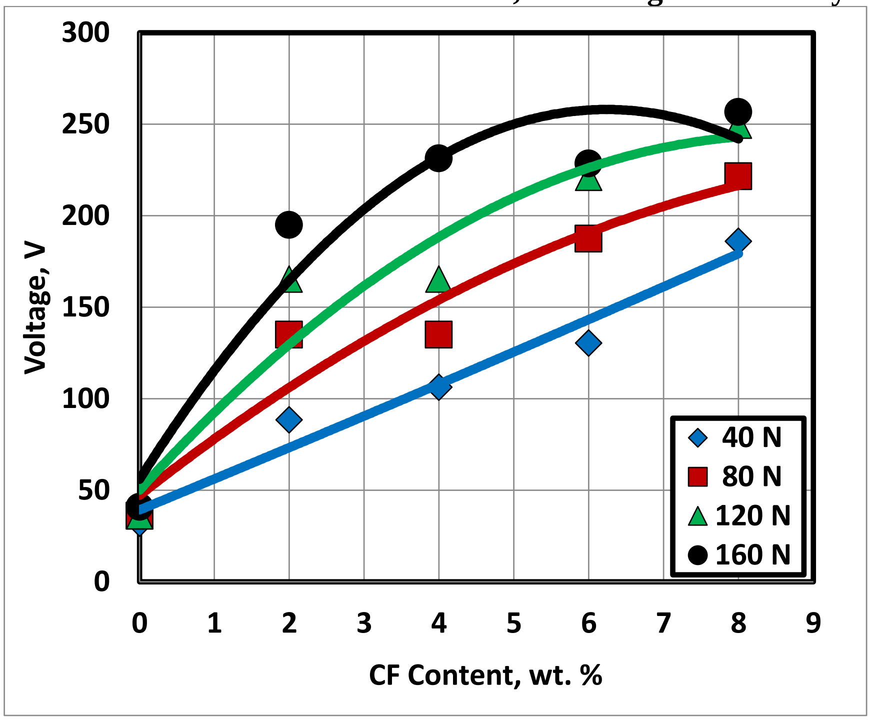


Fig. 11 ESC generated from contact and separation of rubber and epoxy at 1 mm close to the surface.

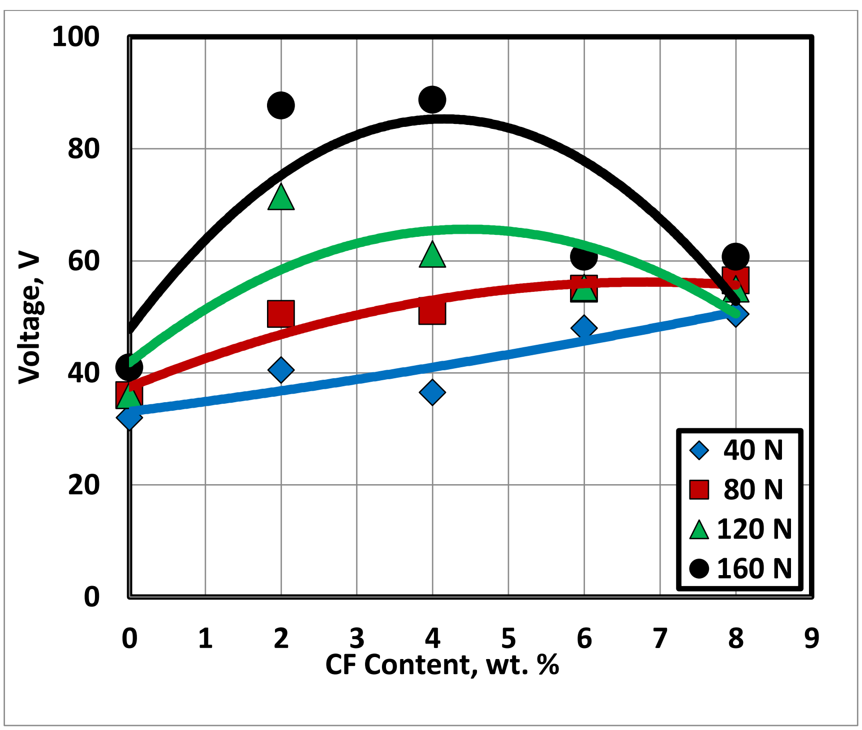


Fig. 12 ESC generated from contact and separation of rubber and epoxy at 5 mm close to the surface.

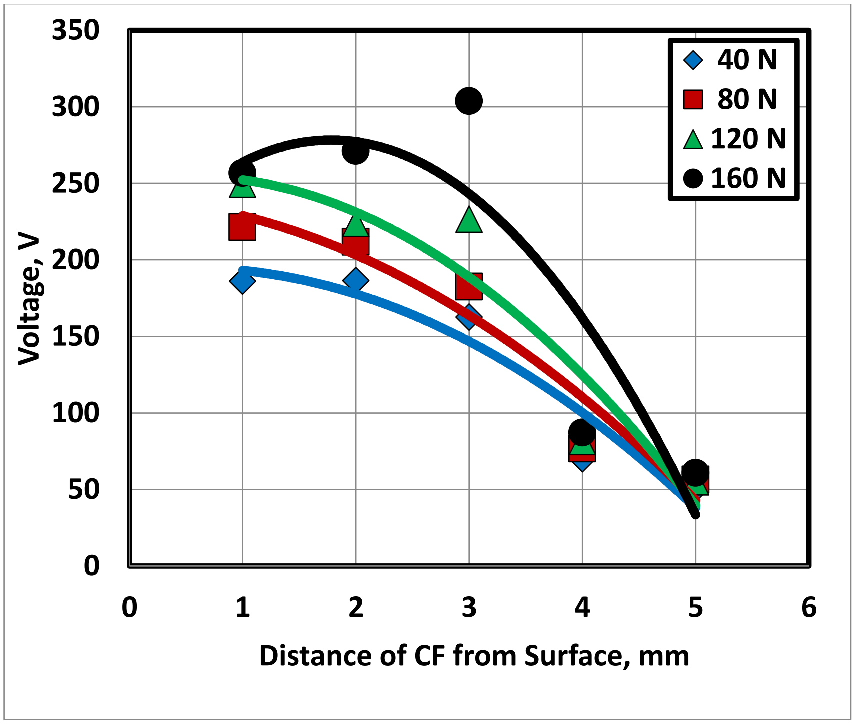


Fig. 13 Effect of the distance of CF from the surface on ESC generated from contact and separation of rubber and epoxy.

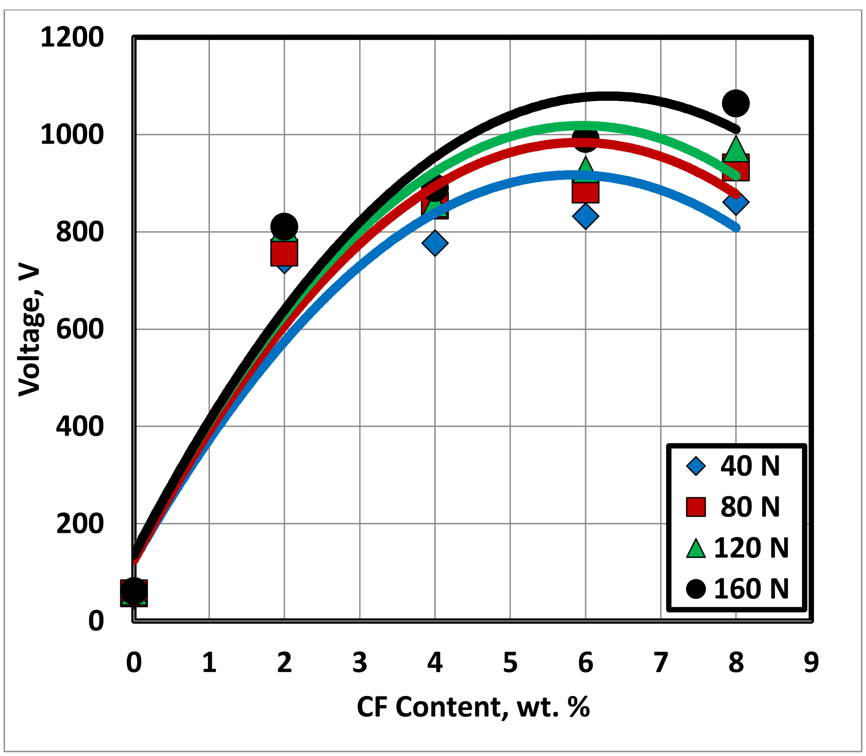


Fig. 14 ESC generated from sliding of rubber against epoxy at 1 mm close to the surface.

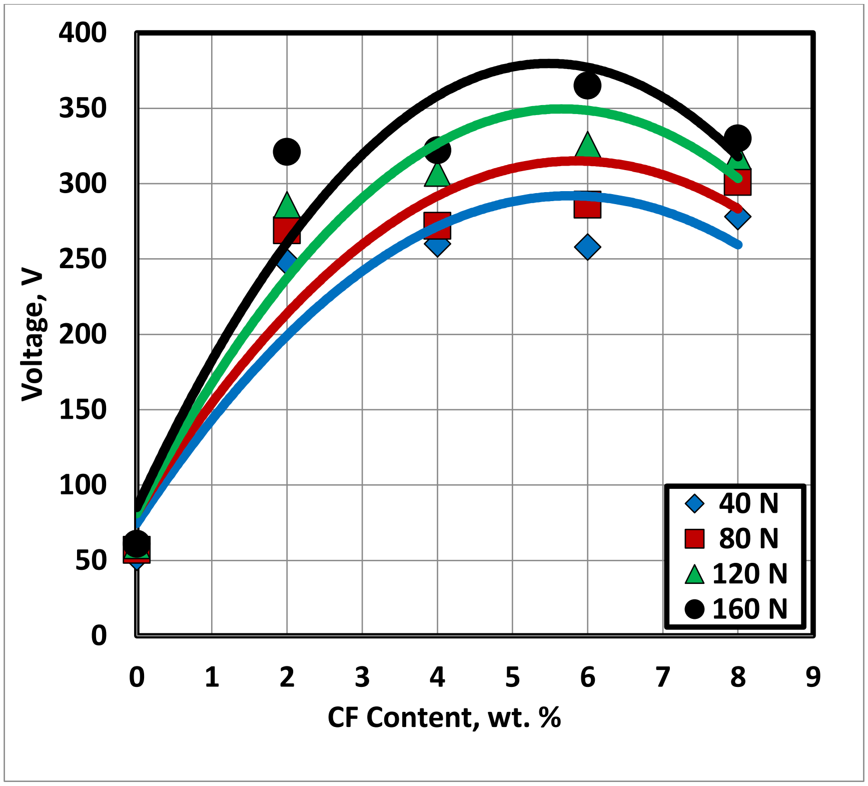


Fig. 15 ESC generated from sliding of rubber against epoxy at 5 mm close to the surface.

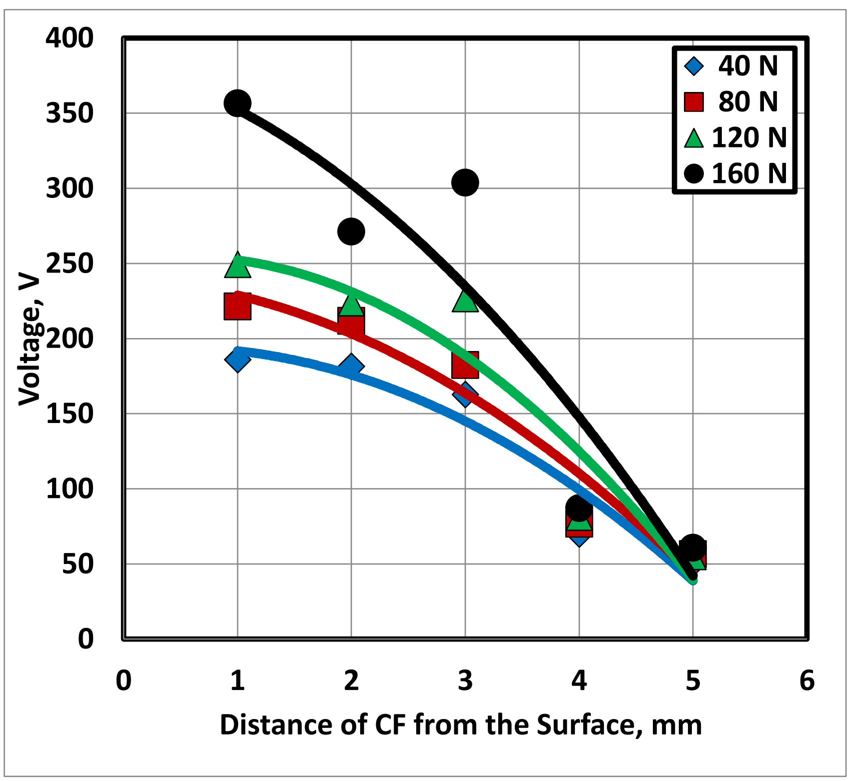


Fig. 16 Effect of the distance of CF from the surface on the electrostatic charge generated from contact and separation of rubber and test specimens.

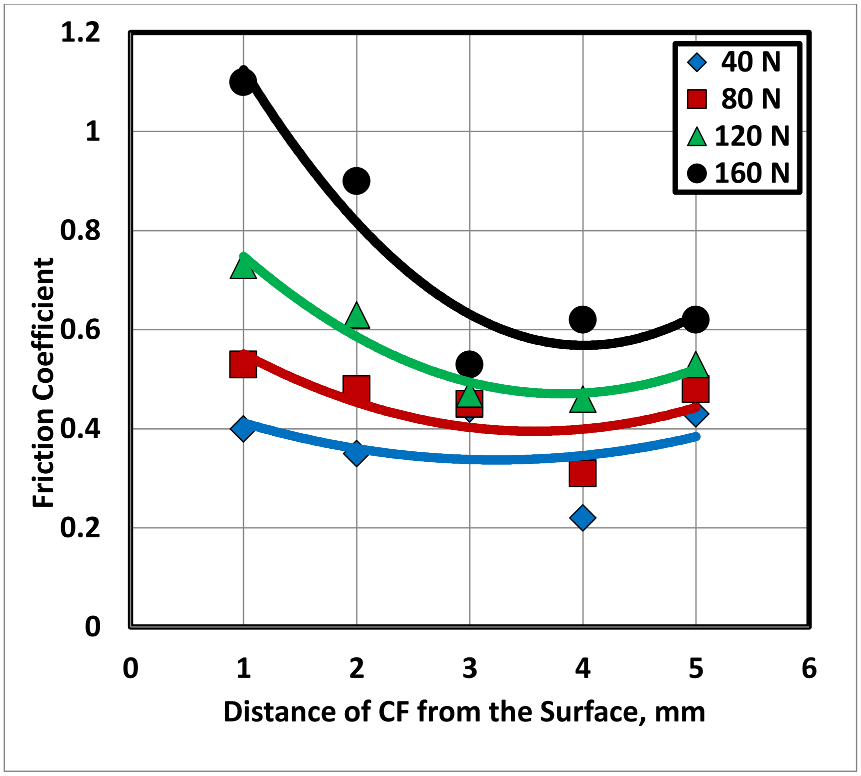


Fig. 17 Effect of the distance of CF from the surface on the friction coefficient for sliding condition generated between rubber and test specimens.

The effect of the distance of CF from the sliding surface on friction coefficient displayed by sliding of rubber against epoxy composites is shown in Fig. 16. It seems that adhesion between epoxy and rubber increased with increasing CF content. From experiments carried out in the present work, it was observed that ESC increases with increasing CF content. Besides, as the CF are close to the sliding surface ESC increases. To explain that behavior, it is demanded to understand the relationship between tribology and electrification, i. e., triboelectrification. Sliding of materials as well contact and separation cause the charge transfer to build up, Fig. 18. Sometimes, the charge continues to increase, and sometimes it gradually decreases. The charge variations versus sliding distance suggest that, the charge does not always build up uniformly as sliding proceeds. These variations could be due to random contamination of the surface transfer of previously charged surface. Material transfer and surface distortion plays significant role in charge transfer, Figs. 19 – 21. The deformation which occurs during sliding must surely disturb the positions of the surface molecules by large amounts.

Based on Faraday's law when an electric field moves past different materials, the magnet will produce a larger current when moving past conductors than insulators. Presence of CF will increase the current flowing in the fibres. According to Faraday, electric fields are created in any region of space where a magnetic field is changing with time, while according to Maxwell, magnetic field is created in any region of space where an electric field is changing with time.

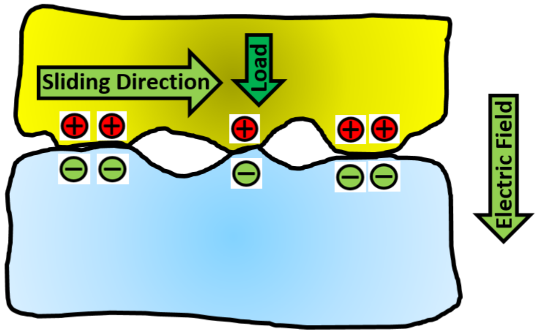


Fig. 18 Generation of ESC on the sliding surface. An electric field will be generated as a result of the ESC.

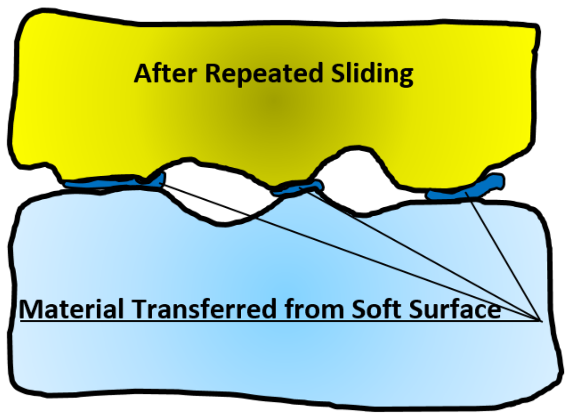


Fig. 19After repeated sliding the material is removed from the relatively softer material to the harder one.

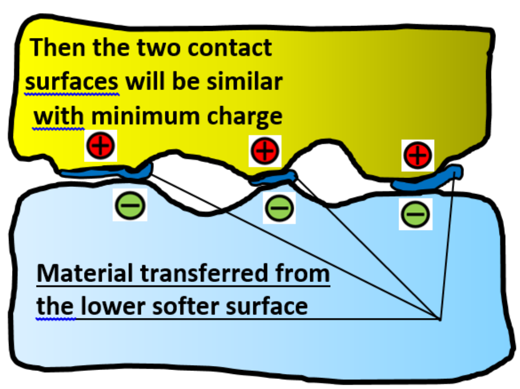


Fig. 20 Further sliding after material transfer causes lower amount of ESC because the two contact surfaces are similar.

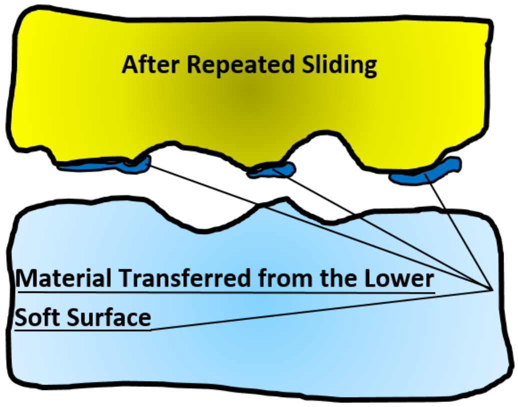


Fig. 21 The same trend of material transfer will occur in contact and separation.

The strength of the electric field inside the epoxy matrix is proportional to how much charge is generated on the friction surface. Faraday indicated that the change of the flux over time may induce a current in a conductor and thus create a source of EMF (voltage, potential difference). The Faraday principle states that if an electric conductor is moved through a magnetic field, or a magnetic field moves through the conductor, electric current will be induced and flow into the conductor. The induced current creates an induced magnetic field. The Magnetic field around a straight conductor is directly proportional to the current value and inversely proportional to the distance from the conductor. Voltage is induced in the wire loop whether the magnetic field moves past the wire or the wire moves through the magnetic field. Voltage can be induced by the relative motion between a conductor and magnetic lines of force.

The significant ESC increase when the CF were close to the surface confirmed the presence of a magnetic field around the CF that is directly proportional to the current value and inversely proportional to the distance from the conductor, Fig. 22. Based on Faraday principle that states if an electric conductor is moved through a magnetic field, or a magnetic field moves through the conductor, electric current will be induced and flow into the conductor. The induced current creates an induced magnetic field.

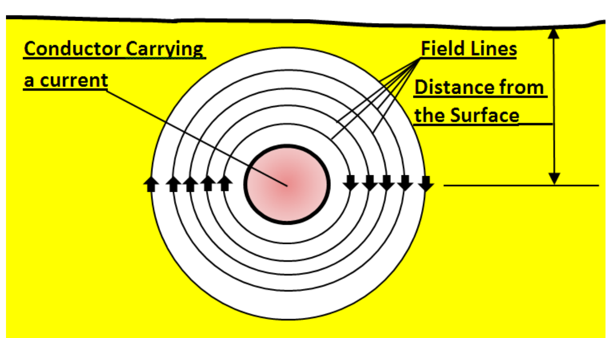


Fig. 22 Generation of magnetic field around the CF.

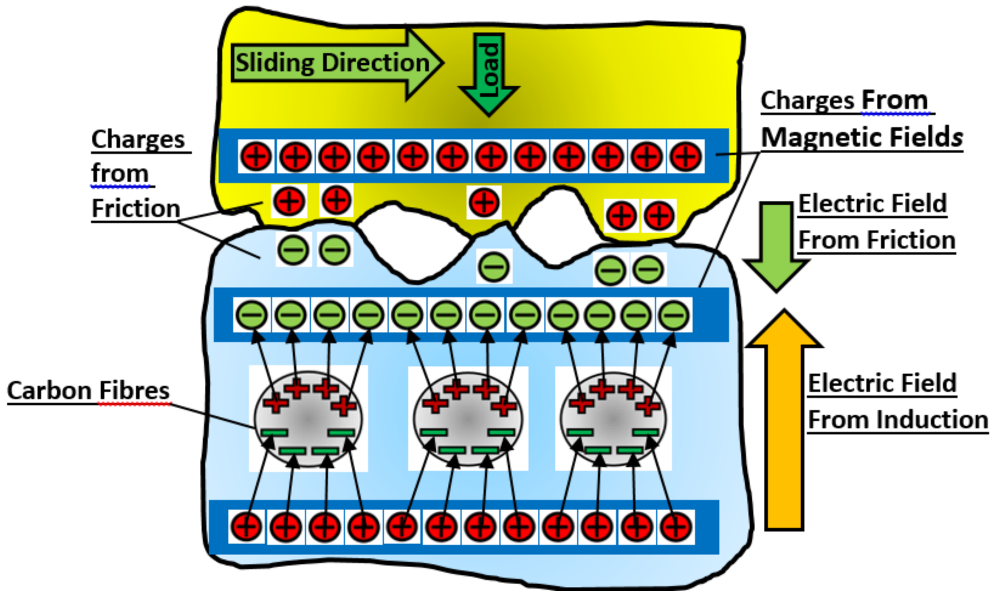


Fig. 23 Generation of electric field from friction and inuction from the CF.

It is well known that when an electric field and a wire move relative to each other, a voltage is induced. Besides, strong electric field produces high voltages. In the present work, CF reinforcing epoxy represents the wire, and the electric field is generated from ESC generated from friction. It is expected that high voltage will be generated on the sliding surface, Fig. 23. Secondly, it is known that by changing the magnetic field around a conductor a voltage will be induced by electromagnetic induction.

CONCLUSIONS

1. ESC generated from contact and separation of epoxy and bare foot slightly increases with increasing CF content and normal load, where epoxy of 8 wt. % CF content displayed the highest value of ESC. Significant decrease in ESC was observed as the distance of CF from friction surface increased.
2. ESC generated from sliding of bare foot and bare foot was higher than that recorded for contact and and separation. Besides, ESC significantly increased with increasing CF content. As the distance of CF from friction surface increased ESC drastically decreased. This observation confirmed the effect of the distance of CF from the sliding surface on the generated voltage.
3. Friction coefficient drastically decreased with increasing the distance of CF from the sliding surface. It seems that generation of equal ESC on the sliding surfaces of different signs would increase the attractive force between the two surfaces and consequently the adhesion increases leading to friction increase.
4. ESC generated from contact and separation as well as sliding of rubber/epoxy was much higher than that recorded for bare foot/epoxy. Friction coefficient remarkably increases as CF get closer to the sliding surface.
5. Friction coefficient depends on the amount of ESC generated from triboelectrification.

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