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Electrostatic charge generation and buildup during contact and frictional electrification of woven textile fabrics

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Woven textile fabrics of cotton, polyester, nylon and polypropylene have been tested for contact and frictional electrification under similar experimental conditions. These fabrics are contacted and rubbed with steel and polytetrafluoroethylene (PTFE) for investigating electrostatic charge generation and dissipation properties between polymer-metal and polymer-polymer materials. Measurements have been made for the charge buildup after first initial contact/rubbing; the charge buildup during 50 contact/rubbing cycles; and the half-life discharge time. It is observed that the charge generation during rubbing and contact with steel is less than that with PTFE. It is also observed that the samples charged by rubbing decay quickly as compared to the contact charged samples. The findings indicate that with a few exceptions, the charge magnitude and polarity follow the triboelectric series.

Keywords: Charge decay, Contact charging, Cotton, Nylon, Polyester, Polypropylene, Rub charging, Static electricity, Triboelectric charging, Woven fabric

1 Introduction

When any two neutrally charged materials are brought into contact and then separated, one material acquires positive charge and the other negative charge. If these materials are conductors, such as metals, the generated charge dissipates quickly. However, if the materials are insulators, the generated charge may stay on the surface for a significant time. Lower resistance fibres, such as cotton and rayon, do not create many troubles due to static charging because the generated charge decays quickly. Synthetic textile fibres, such as polyester and polypropylene, are insulators with more than 10^{16} ohms-cm volume resistance, and tend to generate and retain significant amounts of static charge on the surface during processing. This creates major quality and performance issues in synthetic fibres. In order to reduce the detrimental effects of static charge generation on such textile materials, it is important to understand the charge generation and dissipation mechanism.

Significant research has been performed and several careful reviews have been published explaining the electrostatic charging mechanism on textile materials [1-4]. However static charge mechanism is still not completely understood. The particular importance of the current study is to explain the differences in the contact and the rubbing charge generation mechanisms, and the differences between the polymer-insulator and insulator-insulator charging mechanism.

According to Arridge[5], the generation of static electric charge is an interfacial phenomenon and the charge lies about a few nanometers near the surface. The surface of polymeric materials is different from the bulk with surface thickness limited to few nanometers. The maximum surface charge that can be generated on any solid insulated surface is 26.4 $\mu C/m^2$. Even at this maximum charge level, only eight out of a million atoms are charged. Surface charges involving a few parts per million could significantly influence the static electric properties of the textile materials.

Triboelectric series have been proposed by several authors [1-9], in which materials are listed in an order according to the static charge generated on their surface when they are rubbed with another material. In this series, materials that are placed in the top of the series are charged positive when rubbed with materials placed lower in the table. The first triboelectric series including textile materials, was established in 1757 by Wilcke[6] and subsequently several other researchers came up with slightly different triboelectric series. However, the order of

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materials in the triboelectric series is not universally agreed. Triboelectric series from two authorities in which it is clear that the positions of cotton and steel are reversed are given below:

According to Adams[7]:
nylon > cotton > steel > polyester > polypropylene > PTFE

According to Tsuji et al.[8]:
nylon > steel > cotton > polyester > polypropylene > PTFE

Since textile materials have a very sensitive surface, the anomalies found in the series could be attributed to differences in sample preparation and surface cleanliness of the testing materials, plus the data may also be influenced by the measuring technique and its probe sensitivity.

Triboelectric charging on polymers (insulators) is a complex phenomenon and research on textile materials is difficult with reproducibility remaining a major challenge. Electrostatic charging of metals and semiconductors seems to be well explained in the literature, whereas the same is not true for textiles and the universally agreed conclusions are elusive. In this research, widely used woven textile fabrics from cotton, polyester, nylon and polypropylene are tested to understand the differences in contact and frictional charging (rubbing). All these fabrics are tested with PTFE and steel for insulator-insulator and insulator-conductor charging effects. A triboelectric series has been established based on the magnitude of charge generated on their surface determined from rubbing and contact charging measurements and the influence of test method is discussed.

2 Materials and Methods

2.1 Sample Preparation

Woven fabrics of cotton, polyester, nylon and polypropylene (purchased from Testfabrics Inc., USA) were cut into rectangles of 110 × 80 mm for the rubbing electrification tests and circles of 6 mm diameter for contact charging tests. Rubbing and contact heads of steel and polytetrafluoroethylene) (PTFE) of 10 mm × 20 mm × 3 mm (for rubbing) and a circular sample of 6 mm diameter (contact) size were used to study the polymer-metal and polymer-polymer rubbing effects. The edges of the rubbing head were polished in order to avoid any abrasive damage to the fabric specimens during the rubbing. These fabrics were cleaned by deionized water bath at 60°C for 20 min.

Two types of cleaning procedure were adopted for these fabrics. For cotton, polyester and polypropylene fabrics, a simple cleaning procedure was followed as adopted by previous workers[9,10]. These samples were cleaned with isopropyl alcohol ($(CH_3)_2CHOH$, FW = 60, Sigma-Aldrich) at 21°C for 20 min. The samples were then dried in the oven at 120°C. The fabrics were then conditioned in a walk-in environmental room at 21° C and 43% RH for 24 h before testing. The surface of nylon fabric is very sensitive and more thorough cleaning is required for these fabrics. For nylon fabrics, 1g/L Alkon MRV and 1 g/L TSPP were added to water and heated to 71° C and then nylon fabric was added and treated for 20 min. Then these fabrics were again cleaned with the procedure adopted for cotton, polyester, and polypropylene fabrics. All of these experiments were conducted at 21° C and 43% RH as suggested by AATCC test method 76. Before each test, the initial surface potential of the fabric was measured and any residual charges were removed by using an ionized air gun. Before each test, the contact/rubbing heads were also cleaned with 2-propanol (Sigma-Aldrich) and deionizer gas.

2.2 Materials and Experimental Design

Finish free fabrics of cotton, polyester, nylon and polypropylene were used in this work. Basic fabric specifications are given in the Table 1.

2.3 Equipment and Test Protocols

To investigate the effect of rubbing on static charge generation, a customized rubbing charge measurement equipment[11] was used in a controlled environment. Rubbing apparatus consists of a movable rubbing head with an insulated stationary platform to place the fabric sample. A probe is placed at a constant distance next to the moving rubbing head. When the rubbing head moves along the fabric, the charge generated on the fabric is continuously monitored by the probe. The following parameters were maintained constant for the rubbing test measurements: rubbing force 1N; rubbing frequency 25 cycles/ min; rubbing speed

Table 1 — Fabric details

Fabric	Thread density inch^{-1} (Warp × Weft)	Yarn number, Ne (Warp × Weft)
Cotton I	128 × 67	41 × 43
Cotton II	63 × 57	42 × 37
Filament nylon	112 × 86	71 × 69
Spun nylon	52 × 43	12 × 22
Filament polyester	85 × 82	62 × 61
Spun polyester	48 × 58	15 × 28
Spun polypropylene	31 × 22	25 × 38

47mm/s; acceleration/deceleration 400 mm/ s^2; rubbing stroke length 52 mm (46.48 mm at constant speed; + 2.76 mm acceleration; + 2.76 mm deceleration); number of rubbings 50; and data collection rate: 100 points/s. The responses measured for the rubbing are surface potential after first cycle of rubbing; after 50 cycles of rubbing; and half life time day in seconds. Typical charge data after every rubbing cycle is shown in Fig. 1.

The effect of contact and separation on the electrostatic properties of the textile fabrics was also measured. For the contact charging measurements, fabric sample of 6 mm diameter was placed on a contact head using a double-sided tape, and the fabric sample was brought into contact and separated from the stainless steel/ PTFE surface. After every contact, the fabric sample was moved inside a Faraday cage and the charge was detected and the data was recorded. The following test conditions were kept unchanged for all the contact tests: contact force 16 N; contact frequency 50 contacts/min; number of contacts for the test 50; and data collection rate 300 points/min. The responses measured for this research were: the charge after the first contact; charge accumulated after 50 contacts; and half-life time in seconds. Typical static charge data after every contact is shown in the Fig. 2.

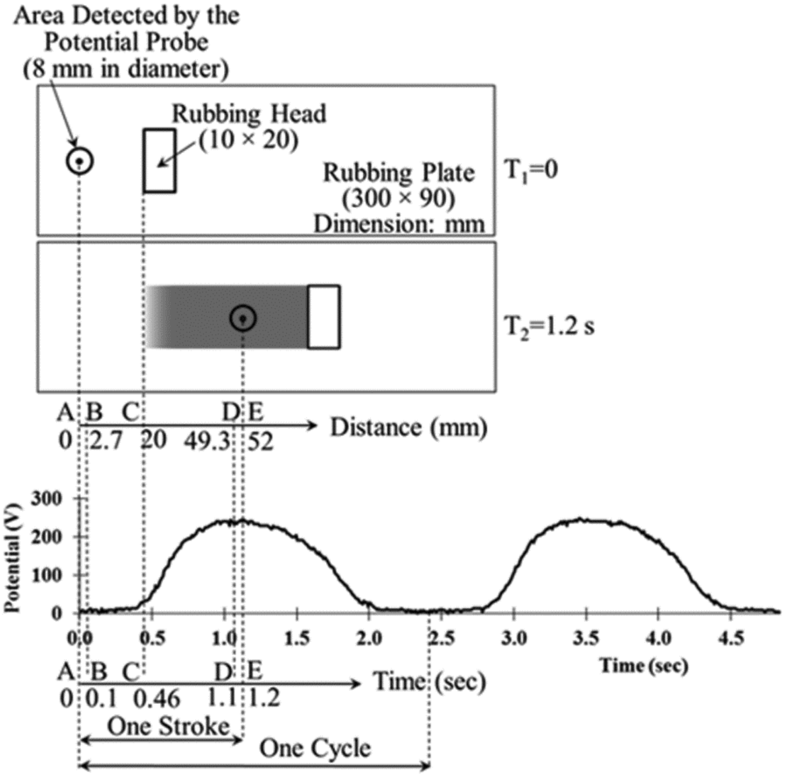

Fig. 1 — Charge measurement and signal analysis during the during rubbing[10]

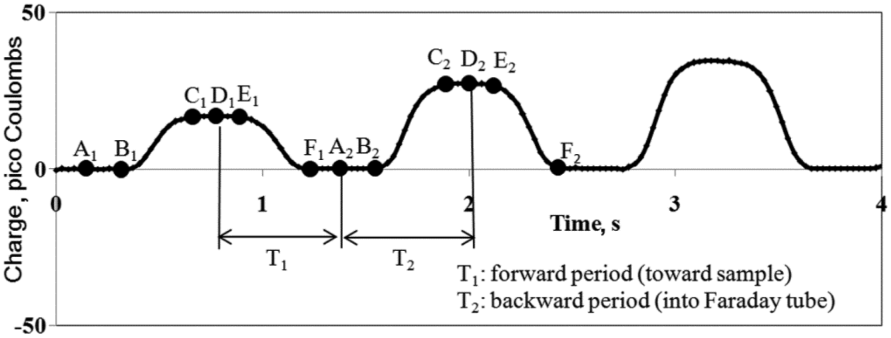

Fig. 2 — Typical static charge data of repeated contact test[12]

2.4 Signal Analysis for Rubbing Electrification

Surface potential measured during several repeats of rubbing testing is shown in Fig. 1. Before the test specimen has been rubbed, the surface potential measured on the specimen is zero. As shown in Fig. 1, rubbing has been started when the probe is at point A and the rubbing cycle has been ended when the probe is at point E.

In Fig. 1 the whole rubbing measurement cylce has been portrayed. The rubbing equipment consists of a surface potential probe, and a rubbing head which rubs the fabric specimen placed on a rubbing plate. The rubbing head and the probe are fixed parallel to each other horizontally at a distance of 20 mm. The voltmeter probe has a resolution of 8 mm in both x, y and z directions. The dimensions of rubbing head is 10×20 mm and the rubbing plate is 300×90 mm. Dimensions of the rubbing head, the rubbing plate and the probe are shown in Fig. 1. The total length covered during the rubbing (one stroke) is 52 mm and time required for one stroke is 1.2 s.

When considering the voltage measured, the probe is accelerated from point A to point B for a time period of 0.1 s. At point B the stepper motor reaches the constant speed, from where the motor moves the rubbing head to positon D for a time period of 1 s and then decelerates for 0.1 s and finally stops at position E. Since, the probe is placed behind the rubbing head, the area that is rubbed and meaured is from C to E, which is about 32 mm. The stepper motor moves the probe back until it reaches the position A. The surface potential measured is shown in the curve. As shown, from point A to C, the surface potential is measured on an unrubbed area, which is nearing about zero. From point C to E, the surface potential is increasing as rubbing takes place. At point E, the rubbing stroke is finished and the rubbing head moves backwards.

2.5 Signal Analysis for Contact Electrification

The device developed to establish the contact electrification is described elsewhere[12]. Typical signal measured during contact electrification is shown in the Fig. 2. At point B_1, the fabric specimen enters the Faraday cage and at point D_1 the fabric is completely inside the Faraday cage and the charge is measured after the first contact. Similarly at point F_1, the fabric specimen is completely out of the Faraday cage and at point D_2 the specimen is placed inside the Faraday cage and charge is measured after a second contact. This process is repeated until charge is measured for 50 contacts.

3 Results and Discussion

3.1 Rubbing Charging

3.1.1 Charge Generation

The charge (surface potential in Volts) measured after the initial cycle of rubbing when cleaned untreated fabrics are rubbed with steel and PTFE is shown in Fig. 3. Three specimens have been tested for every experiment and averages are calculated. It may be observed that rubbing with steel generates much less charge (about 29 - 374 V) on all the fabrics as compared to rubbing with PTFE (278 - 1300 V).

Rubbing with steel generates less charge on cotton (about 29 V on cotton II and 65 V on cotton I) as compared to other fabrics. In the published Triboelectric series[13], steel is placed at middle of the table next to cotton, polyester, nylon and polypropylene. However, PTFE is placed at the bottom of the table, which suggests that any material contacted/rubbed with PTFE would be charged positively and the amount of charge generated would be more. The results support the placement of these materials in the triboelectric series. The charge measured on all fabrics rubbed with PTFE is found to be higher, as expected. When these fabrics are rubbed with PTFE, all the materials are charged positively. These results again follow the triboelectric series and nylon, which is placed at the top of the triboelectric series, generates more charge than other materials used in this research.

Polypropylene and spun polyester fabrics are charged negatively when rubbed with steel. In the published triboelectric series, these tested materials were placed in following order from positive to negative side: nylon, cotton, steel, polyester, polypropylene and PTFE. From the above triboelectric series, it is expected that when rubbed with steel, nylon and cotton exhibit positive charge, while polyester and polypropylene exhibit negative charge. These observations are found to be true in these experiments except in the case of polyester filament

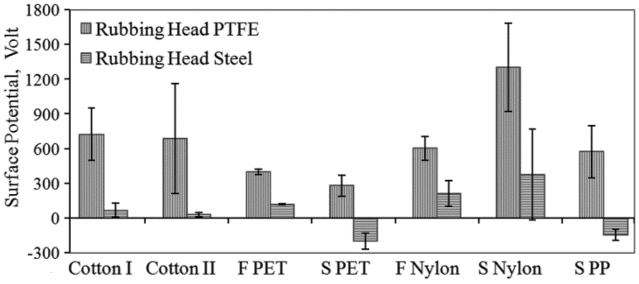

Fig. 3 — Surface potential measured on the fabrics after the first cycle of rubbing

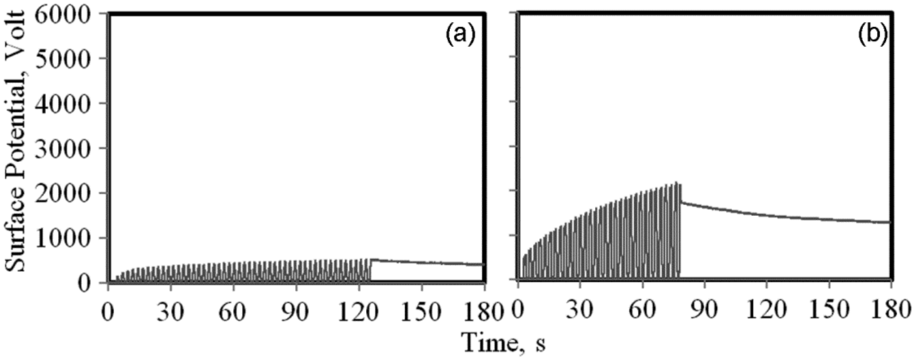

Fig. 4 — Charge generation and accumulation on filament polyester rubbed with (a) steel and (b) PTFE

which is charged positively. The charge reversal could be due to the reason that some finishes, which are applied on filament polyester surface during the processing, may have not been completely removed. Even a very small contamination would highly influence the static electric properties of the textile and polymeric materials. However, different observations are found when the similar experiments are performed for contact charging.

3.1.2 Charge Buildup

The charge was measured for 50 cycles of rubbing for all samples[14]. Although the behavior of various fabrics is found different in the magnitude of charge generated, they followed the pattern as shown in Fig. 4. It can be observed that the charge generated is significantly higher for samples rubbed with the PTFE rubbing head, as compared to the steel rubbing head. This can be attribute to the placement of these materials in the triboelectric series and insulator-insulator charge effects.

The important findings observed during the charge buildup measurements are:

(i) Cotton is placed next to steel in the triboelectric series[7,15], suggesting that the charge generated on cotton is less when contacted/rubbed with steel, as compared with to materials.

(ii) Repeated rubbings increase the amount of charge generated on the fabric surface due to the increase in the real contact area during rubbing as a result of deformation of the surface and smoothing the asperities on the surface. This phenomenon is more evident for the PTFE rubbed samples. For steel rubbed samples, the saturation potential is reached quickly because steel is a conductive material, and there is a possibility that charge can back flow to steel.

(iii) The charge dissipates quickly on cotton because cotton is a low resistant material (resistivity 10^9 ohms/ square) compared to the other manmade fibers, such as polyester, nylon and polypropylene which are highly resistant (more than 10^{14} ohms/ square).

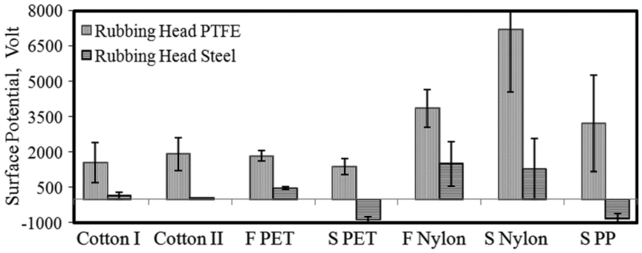

Fig. 5 — Surface accumulated after 50 rubbings on textile fabrics

3.1.3 Charge Accumulation

Figure 5 shows the charge accumulated after 50 rubbings on the tested textile fabrics. Similar to the charge measured after the initial contact, the charge measured after 50 rubbings is much higher for nylon (about 3810-7210 V) as compared to other samples (1378-3235 V). Also higher charge is generated on spun nylon fabric (7210 V) as compared to filament nylon (3810 V).

The triboelectric series of the materials from the literature and the observed triboelectric series when rubbed with steel and PTFE are shown in the Table 2. For clarity the fabrics which were manufactured from filament and staple yarns have been identified. For the steel rubbed samples the observed triboelectric series was perfectly matched with the triboelectric series published in the literature in both charge magnitude and charge polarity (except for filament polyester). For the samples which are rubbed with PTFE, observed series is in match with the triboelectric series found in the literature in terms of polarity; however there is slight mismatch in terms of magnitude. In this work, polypropylene fabric shows higher charge than the cotton and the polyester fabrics.

3.2 Contact Charge Measurements

3.2.1 Charge Generation

Charge measured on the surface of the fabric after first contact with steel and PTFE are shown in Fig. 6. The charge is measured inside a Faraday cage in micro Coulombs/square meters.

All the samples when contacted with PTFE are charged positively and those which are contacted with steel are charged negatively. Contacting with PTFE generates a higher positive charge on these fabrics (1.2 - 2.9 μC/ m^2), while contacting with steel generates a lower negative charge (- 0.07 to -1.2 μc/ m^2). According to published triboelectric series, when contacted with steel, nylon should be charged positively, polypropylene and polyester should be charge negatively. However, in the case of cotton there are some discrepancies in the published literature. In some published series[7], cotton is placed above the steel and in some series[8] steel is placed above cotton. In this research, for the rubbing charge experiments, nylon charged positive when rubbed with steel, and for the contact charge measurements the charge observed is negative. However, the contact charge generated on nylon when contacted with steel is less (-1.2 μC/ m^2) as compared to contact charge measurement with PTFE (-2.9 μC/m^2).

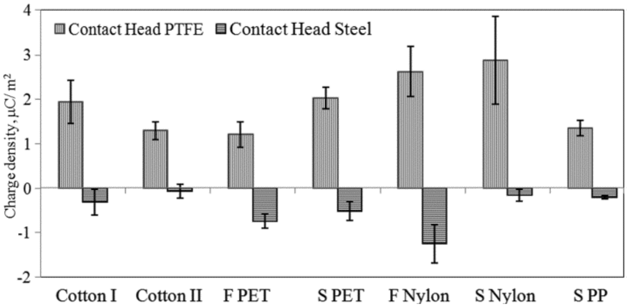

Fig. 6 — Charge measured after first cycle of contact on textile fabrics

3.2.2 Charge Buildup

The surface charge buildup on the seven textile fabrics, when contacted with PTFE and steel for 50 contacts has been measured and the results are shown in Fig. 7 (for polyester filament fabric). Other fabrics exhibit different magnitude of charge but the trends are found similar.

3.2.3 Charge Accumulation

Charge accumulated on various textile fabrics after 50 contacts with PTFE and steel are shown in Fig. 8. As in the case of the rubbing charge results, contacting with PTFE generates more charge than contacting with steel. After 50 cycles, samples contacted with steel are found negatively charged, and samples contacted with PTFE are found positively charged. Comparative studies on the charge polarity and magnitude measured for these samples with published triboelectric series are shown in the Table 3.

Table 2 — Triboelectric series as per the literature[3] and this study when rubbed with steel and PTFE

Literature		This study	
Steel	PTFE	Steel	PTFE
Nylon +	Nylon +	Filament nylon +	Spun nylon +
PP-	Cotton +	Spun nylon +	Filament nylon +
PET-	PET +	Filament PET +	PP +
Cotton+	PP +	Cotton +	Spun polyester +
		Spun PP -	Cotton +
		Spun PET -	Spun polyester +

Table 3 — Triboelectric series found in the literature[3] and in this research when contacted with steel and PTFE

Literature		This study	
Steel	PTFE	Steel	PTFE
Nylon +	Nylon +	Nylon -	Nylon +
PP-	Cotton +	PET –	Cotton +
PET-	PET +	Cotton –	PET +
Cotton+	PP +	PP -	PP +

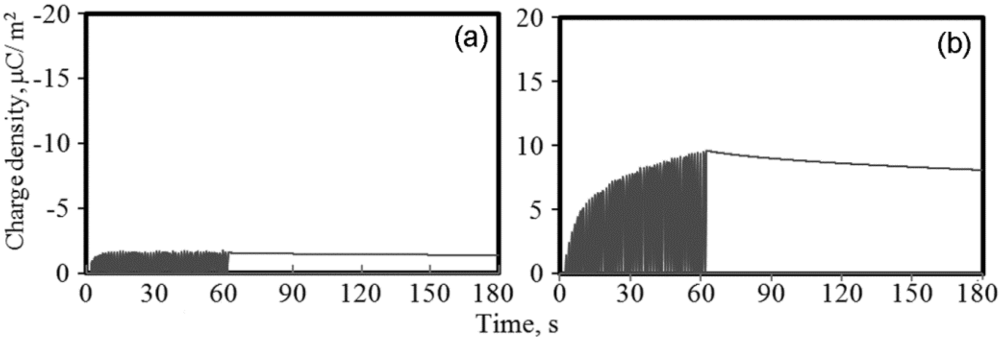

Fig. 7 — Charge generation and accumulation on filament polyester contacted with (a) steel and (b) PTFE

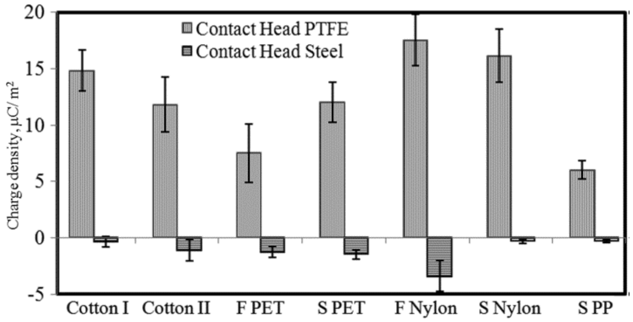

Fig. 8 — Surface charge accumulated after 50 contacts on textile fabrics

Samples which are contacted with PTFE have followed the triboelectric series in the literature with respect to both magnitude and polarity of the charge measured. It can be seen from Table 3 that there is discrepancy between the previously published triboelectric series and current results. Nylon is placed on the top with a much higher generated charge (spun nylon 16.13 and filament nylon 17.54 μc/m^2) and PP is on the bottom with a lower charge (6.01 μc/m^2). Interestingly, some discrepancies are found even in this research when compared with the triboelectric series. Nylon and cotton, which are placed above steel in the published triboelectric series, are charged negatively when they contact with steel. However for both cotton samples and spun nylon samples even after 50 contacts with steel, the generated charge is very low (-1.46μc/m^2), but for filament nylon higher charge (-3.42 μc/m^2) is generated . When these samples are tested for rubbing with steel they show positive charge.

The difference in findings observed for the nylon and polyester after contact charging as compared to rubbing, can be attributed to the interaction between the air and the fabric sample during the test. Rubbing testing has been carried out open in atmosphere, where the sample has more chance to interact with ions available in the air. During contact charging measurements, the fabric sample, after contacting with contact head, is placed in the Faraday cage where the charge on the sample is less affected by the ions available in the air.

3.2.4 Charge Break Down

Charge break down occurs when the materials are charged with substantial static electric charge, which according to Gauss law, creates an electric field. If the electric field created is large in a smaller area, then the charge will be discharged due to the dielectric breakdown of the air molecules. Theoretically, the maximum charge that can be generated on any solid surface at normal atmospheric conditions is 26.4 μc/m^2. The charge buildup measured on the nylon fabric is shown in the Fig. 9. As the number of contacts increases, the charge accumulated on the sample increases and attains saturation level. Once the charge attains the maximum value or saturation, it breaks down and the sparks will be produced. As seen in Fig. 9, after 20 contacts the charge has increased to 18.14 μC/m^2 and some charge has decayed due to air break down. The observed air breakdown charge on nylon is lower than the theoretical breakdown limits. From these measurements it can be found that breakdown charge of the insulating surfaces can be varied. This could be attributed to the surface anomalies of these structures, such as non-uniform surface, impurities on the surface, etc.

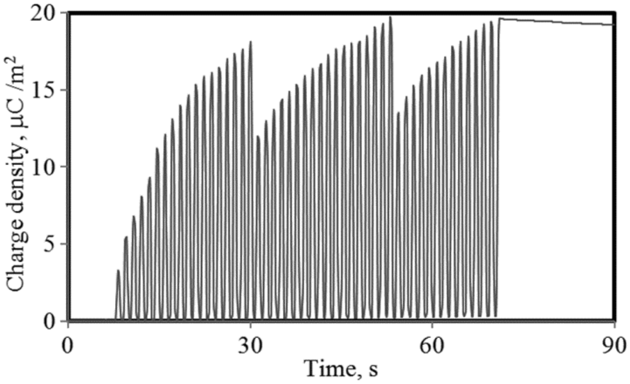

Fig. 9 — Charge build up on PTFE contacted spun nylon fabric

3.3 Charge Decay of Rubbed and Contacted Fabrics

Figure 10 shows the half life time decay for fabrics which are rubbed with PTFE and steel for 50 cycles. The charge decay is independent of rubbing material, and for both steel and PTFE rubbed materials the half life time appears to be similar. Samples which are rubbed with PTFE show higher charges as compared to steel rubbed samples, but their charge decay times are the same. This means that the charge decay seems to be independent of the magnitude of the charge measured on the samples. The “cross over mechanism”, as observed by Ieda *et al.*[15], explains that materials, which have higher charge, decay quicker as compared to materials having lower charge.

Fabrics made from spun yarns appear to decay quicker as compared to filament fabric samples. This could be because of the protruding yarn hairiness on the spun fabrics interacting with air, which helps the charge to decay quickly.

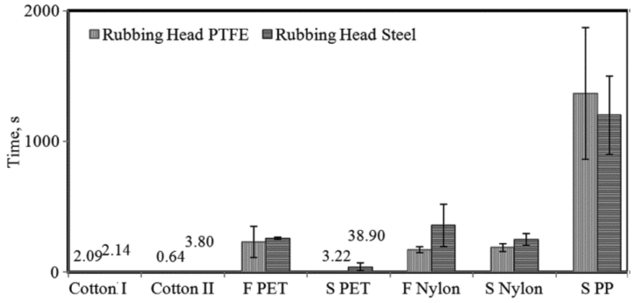

Fig. 10 — Half-life measured on textile fabrics after rubbing with steel and PTFE

Table 4 — Comparative study on resistivity and half-life time

Fibre	Resistivity ohm m	Half life time, s	
		Steel	PTFE
Cotton	10 ^{9}	2.09 ± 0.61	2.14 ± 2.09
		0.64 ± 0.24	3.8 ± 2.09
Filament polyester	10 ^{14}	230 ± 120	258 ± 8
Spun polyester		3.2 ± 0.1	39 ± 30
Filament nylon	10 ^{15}	169 ± 23	356 ± 162
Spun nylon		187 ± 30	250 ± 46
PP	10 ^{16}	1366 ± 503	1200 ±300

In Table 4, the volume resistivity measured on the textile fabrics and the half-life time measure on these textile fabrics are compared. It can be understood that cotton, which has lower resistivity, shows very quick (0.6-3.8 s) charge decay, irrespective of the charge generated on its surface. In case of polyester, which has a higher resistivity, the half-life time decay is greater. Similarly for nylon and polypropylene, which are highly resistive materials, the charge decays slowly. Half-life decay time is correlated to the measured resistivity. The charge decay on the rubbed samples is mainly attributed to the emission into the atmosphere, breakdown of the voltage (charge), surface and volume conductivity of the material and ion desorption.

Charge decay measured on the PTFE contacted samples is shown in Fig. 11. Since charge measured when contacted with steel is low, and all these measurements were carried out inside the Faraday cage, it is very difficult to measure the charge decay on samples which have a small amount of charge.

No systematic differences are displayed in the half life time decay of the various samples after contact charging. The half-life time decay on cotton samples and polypropylene are almost the same, despite a big difference in the conductivity of these samples. Also the charge decay time of the rubbed samples is not found the same as those of the contact charged samples. When the material is placed inside the Faraday cage, it shields the sample from the external effects, such as ions.

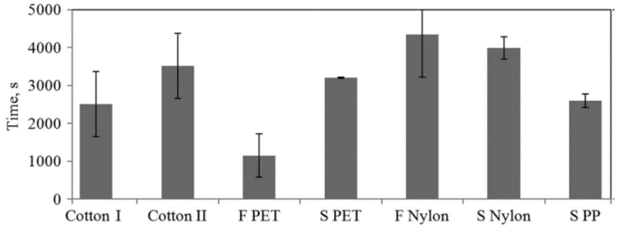

Fig. 11 — Half-life decay measured on textile fabrics after contact with PTFE

4 Conclusion

The results presented are for woven textile fabrics which are charged with steel and PTFE for the contact and frictional electrification. Rubbing and contact charging cotton with steel generates a lot less charge on cotton and similar testing with PTFE generated much higher charge on cotton. The mechanism of metal-polymer charge is different from polymer-polymer charging. The implication is that since cotton is placed next to steel in the triboelectric series, charge transfer between cotton and steel will be less.

After every cycle of rubbing/contact charging the charge has been built gradually and the charge measured after 50 cycles is found higher. Repeated rubbings/ contacts increase the charge on the fabric surface because increase in contact area due to the deformation of the surface destroy the asperities on the surface after every cycle of rubbing/contact. The magnitude and amount of charge generated on the samples followed the triboelectric series, except for the following:

- Filament polyester is positively charged when rubbed with steel. Spun polyester is charged positive when rubbed with steel.
- Nylon and cotton are supposed to charge positive when contacted with steel. However the same samples are negatively charged when rubbed with steel. From these observations it is found that there is difference between contact and frictional charging mechanism. Contact charging mechanism is very simple as compared to frictional charging mechanism.

During contact charging, higher charge is accumulated on nylon with a charge density of 20 $\mu c/m^2$. Theoretically, a charge breakdown occurs at a charge density of 26 $\mu c/m^2$ but in the current study the breakdown for nylon occurs at 18.1 $\mu c/ m^2$.

The charge decay measurements show different results depending on how the samples are charged. Rubbing charged samples decay quickly as compared to contact charged samples. This could be due to the greater exposure to the air during rubbing, as opposed to more limited exposure when the contact charged samples were placed in a shielded Faraday cage. These observations indicate the ions in the air play a major role in charge decay properties. Additionally, the charge decay properties of the rubbed samples are in relation with the conductivity of the fabrics. For cotton, which is relatively more conductive as compared to the other fabrics, the charge disappears very quickly; in contrast, polypropylene, a more insulating material stores the charge on its surface for a longer time.

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