Study of Structure and Properties of Polyester/ Carbon Blends for Technical Applications

Manisha A. Hira, Arup Rakshit

Abstract**—**Textile substrates are endowed with flexibility and ease of making–up, but are non-conductors of electricity. Conductive materials like carbon can be incorporated into textile structures to make flexible conductive materials. Such conductive textiles find applications as electrostatic discharge materials, electromagnetic shielding materials and flexible materials to carry current or signals. This work focuses on use of carbon fiber as conductor of electricity. Carbon fibers in staple or tow form can be incorporated in textile yarn structure to conduct electricity. The paper highlights the process for development of these conductive yarns of polyester/carbon using Friction spinning (DREF) as well as ring spinning. The optimized process parameters for processing hybrid structure of polyester with carbon tow on DREF spinning and polyester with carbon staple fiber using ring spinning have been presented. The studies have been linked to highlight the electrical conductivity of the developed yarns. Further, the developed yarns have been incorporated as weft in fabric and their electrical conductivity has been evaluated. The paper demonstrates the structure and properties of fabrics developed from such polyester/carbon blend yarns and their suitability as electrically dissipative fabrics.

Keywords**—**Carbon fiber, hybrid yarns, electrostatic dissipative fabrics.

I. Introduction

CARBON, at an atomic level, has the potential to be a good conductor, due to its availability of valence electrons, which can transfer to other materials to create an unequal proton to electron ratio and therefore charges. However, not all allotropes of carbon are conductive; it depends upon the molecular structure. If all valence electrons are taken up in the bonding, there are none available to be transferred in the creating an electrical current [1]. For example in a diamond structure all 4 of the carbon atoms valence electrons are covalently bonded to other carbon atoms, therefore none are available to transfer.

Carbon fibers are graphitic forms, derived from different precursors viz., polyacrylonitrile and pitch. The fibers have high strength and are fine about 10 micron in diameter. These fibers may be in tow form, nomenclature as 1K, 2K or 12K, implying the number of filaments in the tow. Similarly, the fibers from PAN based precursor are ranging from 1.5 D to 3 D and are available in varying staple lengths of 38 to 76 mm. The pitch based fibers have higher electrical conductivity as compared to PAN based precursors. This difference is due to the stretch given the fiber during manufacture and its carbonization temperature. At higher temperature and stretch, there is greater alignment of graphitic planes to the fiber axis, leading to higher tensile strength and electrical conductivity [1], [2].

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II. Background of the Study

Textile materials traditionally are nonconductors of electricity. The era of growing electronics and smart materials demands the development of flexible conductive materials. These can be developed by imparting electrical conductivity to textile substrates. Conductive materials can be incorporated into textile structures using various techniques. Metallic filaments could be plied to form a conductive yarn or embroidered onto the fabric substrates. Coating of textile substrates with metallic pigments is yet another method of making conductive substrates. Even coating with organic polymers like polyaniline or polypyrole can be used or coating with carbon nanomaterials can be tried for making conductive textiles [3], [4]. The present focus is making of conductive yarns; few of the approaches have been incorporating a core of a conductive metal like copper into yarn structure. Several studies have been reported on making conductive yarns using varying gauges of copper core with varying sheath materials like cotton, polyester or polypropylene. Most of the development has been on DREF spinning only [5]-[8]. Similarly, regarding the development of conductive yarns using conventional technique, several fibers have been blended. The conductive fibers in the form of very fine stainless steel have been used. [9]

Electrical resistance of a material indicates how strongly the material opposes the flow of electric current through it. Based on the electrical resistance of the materials, conductive textiles can be classified as Insulators (resistance greater than $10^{11}\Omega$), Dissipaters (resistance range 10^4 to 10^{11} Ω) and Conductors (resistance less than 10^4 Ω). Depending upon the level of conductivity, the textile materials find applications as substrate to dissipate static electricity, to carry electrical current or data signals or as materials to shield electromagnetic radiation. [4]

The present study has explored the possibility of incorporating two forms of carbon fiber into textile yarn structures. The methods of incorporation for both have been different owing to the structure and available form of the fibers.

The tow form of fiber has been incorporated into the yarn structure to form a hybrid core sheath yarn, with carbon tow at the core and polyester staple forming the sheath using DREF II spinning technique. Friction (DREF II) spinning system is an Open-end or core sheath spinning system. It is one of the promising spinning methods to produce yarns for technical textile applications. The core is positioned exactly center and the spinning tension is less as compared to the other systems like ring and rotor spinning systems. The DREF spinning system can produce yarns with high delivery rate, about 200 m/min. Due to complete cover of the core filaments, yarns can be produced with required tensile properties by altering core proportion. Various core materials have been used by researchers [10]-[14] in DREF spinning technique, these range from filament of synthetic fibres or yarn of rigid fibres like carbon, basofil or metal strands. The present work focuses on development of electrically conductive core/sheath yarns comprising of carbon filament as core and polyester staple fibres as sheath. Polyester fibre is traditionally an insulator and is susceptible to generation of electric charges. Carbon roving has high electrical conductivity. The combination of these as hybrid yarns for making electrically conductive yarns has been depicted. The work of development of the optimized structure of the hybrid yarn using DREF II spinning has been described in the subsequent sections.

In the second part of the work, staple form of the carbon fiber has been blended with polyester staple fiber of similar physical characteristics using conventional ring spinning technique. In order to obtain a homogenous blend of polyester and carbon fibers, blowroom blending has been preferred. Similar studies have been reported on blending of metal fibers to develop conductive yarns. The aim of the work was to optimize the proportion of carbon fiber content in the yarn so as to obtain electrical conductivity without sacrificing other yarn characteristics.

The subsequent sections highlight the process of development of electrically conductive yarns and their properties. These yarns have been further incorporated as weft in fabric. The fabrics developed have been further characterized for their physical and functional properties.

III. Experimental Work

A. DREF Spinning Parameters-Process and Raw Materials

DREF spinning technology, an experimental plan to develop conductive yarns with carbon core and polyester sheath was made. In this study, the development of hybrid yarn with carbon roving core and polyester staple fibers as sheath was undertaken on DREF II spinning system. Details of the materials used for development of yarns are given in Table I.

TABLE I
PROPERTIES OF CORE & SHEATH FIBERS USED FOR DREF SPINNING

Property	Carbon Tow	Polyester sliver
Linear density, Tex	200	4542
Fiber specification	3K	38 mm, 1.4 D
Electrical resistance, Ohm	150	$>10^{20}$

Process variable of DREF spinning like opening roller speed and air suction pressure were varied to develop a hybrid yarn of polyester with carbon core. Keeping in view the aim of development, it was felt that the conductivity of the hybrid yarn can be improved by reducing its resistivity. The key parameter available for controlling it is the hybrid yarn diameter. Opening roller speeds were varied as 3,400 rpm, 3,800 rpm and 4,200 rpm. The diameter of yarn was found to be lower for higher opening roller speeds and core sheath feed ratio of 1:1. This was further assisted with increasing suction pressure for the compaction of the yarn.

The suction pressure was further varied for opening roller speed of 4,200 rpm with 1:1 carbon polyester feed ratio to study the effect of suction pressure on yarn diameter and yarn resistivity. The results of the same have been summarized in Table II. It can be seen that as the suction pressure increases the yarn diameter reduces; only upto 26 hPa, beyond which compaction is not possible and there is variability of yarn diameter too. The variability in yarn diameter also increases as the suction pressure increases beyond 26 hPa. Accordingly, the mechanical and electrical properties of developed yarns have been shown in Figs. 1 & 2 respectively. It can be seen that as suction pressure increases the yarn strength increase and then decrease beyond 26 hPa. The trend is similar to that seen in case of yarn diameter. The probable factors influencing this could be the increase variability in the yarn diameter at increased suction pressure and the deterioration in yarn core properties with increased compaction.

TABLE II
INFLUENCE OF AIR SUCTION PRESSURE ON YARN DIAMETER OF DREF YARN

Yarn sample	Suction pressure (hPa)	Yarn diameter (mm)	Diameter Variability %
Y1	13	0.470	2.7
Y2	26	0.452	1.9
Y3	39	0.462	3.1

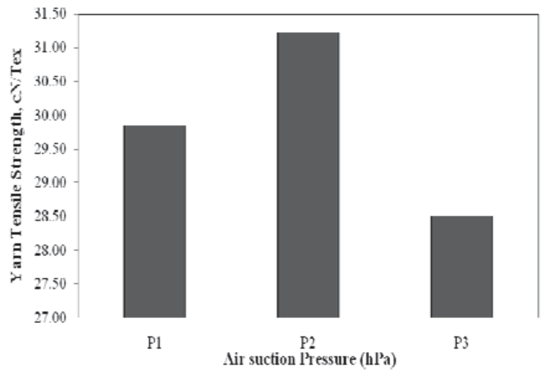

Fig.1 Influence of air suction pressure on tensile strength of polyester/carbon DREF spun yarn

Fig. 2 depicts the influence of air suction pressure on electrical resistivity of hybrid DREF yarns of Polyester sheath with Carbon core. It can be seen that for suction pressure of 26 hPa, the electrical resistivity is the lowest. The yarn diameter reduces as the air suction pressure increases till 26 hPa, beyond this pressure there is increase in distortion and variability in the diameter. Consequently, the yarn electrical resistivity is lowest at pressure of 26 hPa.

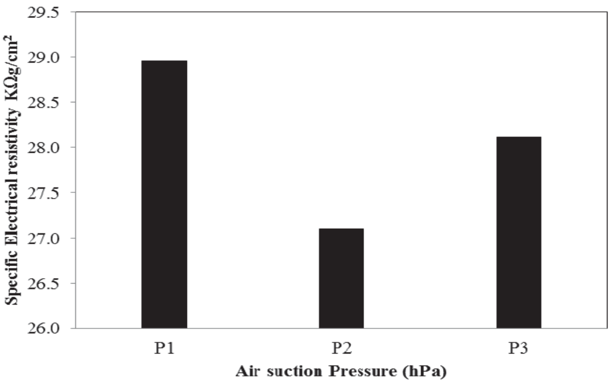

Fig. 2 Influence of air suction pressure on electrical resistivity of Polyester/Carbon DREF spun yarn

Accordingly, yarn processing was carried out on DREF II spinning with following machine parameters:

- 1:1 ratio for core roving sliver feed
- Suction pressure 26 hPa
- Opening roller speed 4,200 rpm
- Yarn delivery speed 200 mpm
- Spinning drum speed 5,000 rpm

The resultant yarn was evaluated for its physical, mechanical and electrical properties.

B. Ring Spinning – Process and Raw Materials

The staple form of carbon fiber was used for developing electrically conductive yarns by blending it with polyester and spun using ring spinning technique. The fiber details used in formation of ring spun conductive yarns are depicted in Table III.

TABLE III
PROPERTIES OF FIBERS USED FOR RING SPINNING

Properties	Carbon fiber	Polyester fiber
Length, mm	38 mm	38 mm
Fineness, Denier	1.5	1.4
Electrical resistance, ohm	$2x\ 10^6$	$>10^{20}$

The polyester/carbon staple fibers were subjected to blowroom blending in varying proportions with 90/10, 95/5 & 98/2 percentage by weight. The fibers were spun to a ring spun count of 30’s Ne. During the spinning trials of yarns, it was envisaged that as the carbon content in the yarn would increase, electrical resistance of the yarn would reduce. However, the spun yarns showed as different trend. As the carbon fiber content increases in yarn, electrical resistivity reduces, but the tensile strength of the yarn reduced as the carbon fiber content increases from 2% to 10%. From the trials, it was found that, for 30’s Ne yarn, the electrical resistivity is lower as compared to 45’s Ne and 60’s Ne yarns, irrespective of the proportion of carbon fiber content.

The yarns were processed on ringframe with the following parameters:

- Feed roving hank 2’s Ne
- Ring yarn count 30’s Ne (19.86 Tex)
- Twist Multiplier 3.4

The resultant yarns, like the DREF spun yarns, were evaluated for their properties.

C. Fabric Formation Using Developed Conductive Yarn

The yarns thus spun were used to formation of fabric. The fabric weaving was carried out using polyester warp and polyester/carbon yarn as weft. In each of the case depending upon the yarn count spun, the warp was chosen appropriately. The details of the fabrics are as shown in Table IV.

TABLE IV
FABRIC CONSTRUCTION PARAMETERS

Fabric construction parameters	DREF yarn	Ring spun yarn
Warp count, Tex	Textured Polyester filament, 133	Polyester 19.86
Weft count, Tex	Polyester/Carbon DREF yarn, 347	Polyester/carbon 19.86
Ends/cm	7	28
Picks/cm	7	28

IV. RESULTS & DISCUSSION

A. Yarn Parameters

The yarns spun on DREF had been tested for their physical properties like linear density and diameter. Also, the tensile strength and elongation were checked on a universal tensile tester. The electrical resistivity of the yarn was measured with help of a megaohmeter. The results of the same are depicted in Table V.

TABLE V
PROPERTIES OF DREF SPUN HYBRID POLYESTER/CARBON YARN

Yarn Properties	
Yarn linear density, Tex	347
Observed yarn diameter, mm	0.452
Tensile strength, cN/Tex	31.72
Elongation %	1.73
Specific Electrical Resistivity, kΩ.g/cm^2	27.1

The ring spun yarns were also evaluated for their performance; the details of the same are reported in Table VI.

TABLE VI
PROPERTIES OF RING SPUN POLYESTER/CARBON BLEND YARN

Yarn Properties	
Blend percentage	98/2
Yarn linear density, Tex	19.68
Observed yarn diameter, mm	0.166
Tensile strength, cN/Tex	20.8
Elongation %	13.2
Specific Electrical Resistivity, KΩ.g/cm^2	154

It can be seen that the yarn spun on DREF spinning with carbon core is coarser in denier and has higher strength. It has about 40 % of polyester sheath wrapped around it. It has strength of about 31.72 cN/Tex. It is rigid with low elongation of 1.73% only. Its specific resistance is 27.1 kΩ.g/cm^2.

The ring spun yarn has staple fibers of carbon blended with polyester. Various blends had been tried out ranging from 2%, 5% to 10% of carbon fiber. It was found that the increase in carbon fiber content in the blend caused irregularity and lower strength of the yarn. The resultant yarn with higher carbon fiber did not show any significant improvement in electrical resistivity. Hence, 2% blend of polyester/carbon was found to be optimum. These fibers are homogenously spread into the matrix of yarn. The yarn is finer, less bulky in diameter. It has relatively lower strength and electrical conductivity. It is composed of discontinuous strands of conductive carbon staple fibers. The yarn has strength of 20.8 cN/tex and elongation of 13.2%. It is relatively more pliable as compared to DREF spun yarn and has specific electrical resistivity lower than DREF yarn, about 154 kΩ.g/cm^2.

The yarns with incorporated carbon fibers in different form have shown electrical resistance in dissipative current range. Hence depending upon their physical characteristics could find application as various static dissipative fabrics.

B. Fabric Parameters

The fabrics had been developed using conductive yarns, both ring spun as well as DREF spun. The fabric construction in each case used warp of a 100% polyester filament, with count compatible with the conductive weft being used. Hence, in fabrics made out of DREF spun conductive weft, 1200 D Textured Polyester had been used as warp with sett of 7 x 7 per cm. The fabric construction using ring spun conductive yarn as weft has used 19.86 Tex textured warp with a set of 28 x 28 threads per cm. the fabrics had been tested for their physical and functional properties, the summary of the observations are shown in Table VII.

TABLE VII
PROPERTIES OF FABRICS WITH CARBON BLENDED CONDUCTIVE WEFT

Fabric construction	Polyester textured warp & Polyester/Carbon DREF spun weft	Polyester warp & Polyester/Carbon Ring spun weft
Fabric grammage, g/sq.m	370	150
Fabric thickness, mm	1.03	0.38
Surface resistivity kΩ/□	29.3	103
Static Decay time, t_{50}, s	0.16	2.29

The results of surface resistivity of fabrics demonstrate that the fabrics with DREF conductive weft has lower surface resistivity of 29.3 kΩ/□, or greater electrical conductivity. However, the fabric with ring spun conductive yarn has higher surface resistivity of 103 kΩ/□. This can be attributed to the conductive core of DREF spun yarns that contributes about 60% of the yarns. There are several factors responsible towards this behavior. The staple fibers are inherently lower in conductivity than carbon core. The core in DREF yarns can be conveniently wrapped with Polyester fiber sheath, but ring spinning of polyester/carbon blends makes it difficult to handle the rigid carbon fiber at carding and drawing stage. Hence increasing the percentage of carbon fiber in the blend has shown loss in strength and irregularity of the yarns. The yarn spun out of these discontinuous strands has higher resistance and consequently the fabrics using 2% carbon fiber give resistance of order 103 kΩ/□. Also, the Static Decay test conducted for the developed fabrics has shown that the fabric with DREF spun Polyester/Carbon yarn in weft would serve as an excellent static dissipative fabric with static half time decay (t_{50}) of 0.16 seconds. However, the fabric with ring spun polyester/carbon blend has static half time decay (t_{50}) of 2.29 seconds. This difference can be attributed to the available continuous core of carbon filament in core of DREF spun yarns. Nevertheless, according to Standard EN 1149–5:2008, dissipative electrostatic material is that in which the half decay time is $t_{50} < 4$ s or the surface resistance $\leq 2.5 \times 10^9$ Ω on one surface at least [15]. Both the developed fabrics fulfill this condition for electrostatic dissipation. Hence, it may be observed that the fabrics developed out of both the yarn structures can be used as electrostatic dissipative textiles. The application would differ from apparel to upholstery, depending upon the construction of the material.

V. CONCLUSION

Carbon fiber in staple as well as tow form can be successfully incorporated in textile yarns as hybrid yarn using DREF technique and blend yarn using ring spinning technique to make electrically conductive yarns. The Hybrid yarns of Polyester/Carbon spun using DREF technique have shown lower specific resistivity 27.7 kΩg/cm^2. Also by virtue of its continuous core, these yarns have higher strength of 31.72 cN/Tex and lower elongation. The DREF spun yarns are rigid and are thicker. The fabric derived out of polyester warp and this hybrid yarn as weft has shown excellent static dissipative properties.

The ring spun yarns with carbon blends have shown higher specific resistance as compared to DREF spun yarns. The resultant fabric made using this ring spun yarn as weft has surface resistivity 103 kΩ/□ and static decay time is beyond 2 seconds. Although, the half decay time for static charge is higher for fabrics with ring spun polyester/carbon blend, it is with the said limit of 4 s for electrostatic dissipative fabrics. Thus, it may be concluded that carbon fiber can be incorporated in textile yarns and fabrics in these forms to dissipate static charges. Fabrics with DREF spun Polyester Carbon weft can be used as furnishing and carpets in clean room application. The ring spun polyester carbon blended yarns need to be used in both warp as well as weft to improve upon the static dissipative performance of the fabric. Due to inherent flexibility in the structure, it can be then used to develop clean room garments.

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