Properties of Polypropylene Conductive Fiber from Sheath-Core Bicomponent Fiber

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Abstract

This is the study of a conductive sheath-core bicomponent fibers. The intentions of the experiments were to investigate feasibility of conductive sheath-core bicomponent fiber forming, using selected materials, and the fibers' properties. The trails were to extrude the bicomponent fibers with conductive materials in sheath section and supporting materials in core section. The conductive carbon black was selected as conductive material to compound with polypropylene. The virgin polypropylene was chosen as core material in the fibers. It was problematic to form fibers using the conductive carbon black polypropylene compound alone, therefore, the virgin polypropylene was used as the core section in the fibers to promote production stability. The sheath-core carbon black compound bicomponent fibers were steadily produced with designated machine settings. The produced fibers were tested for their physical and mechanical properties and electrical conductivity. The results shows that the fibers with the carbon black polypropylene compound as the fibers' sheath section and the virgin polypropylene as the fibers' core section, have conductive property. The conductivity of the fibers increased when their sheath sections were thicker as the ratio of the carbon black compound become higher. Even though, thicker sheath section of the fibers (40% and over) have higher conductivity, the physical properties of the fibers become weaken and less applicable as textile fibers.

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1. Introduction

Fiber is a fundamental material for yarns, fabrics, clothing, and functional textiles. The advancement of on-going textile science and technology demands new materials to accomplish new needs and developments. The conductive textiles as flexile materials have been explored for the possibilities of improvement [1]-[3]. Conductive textiles are generally needed for both of their antistatic and conductive properties. A common measurement of the conductive property of textile materials is surface resistance (SR). The surface resistance of textile fibers justified as antistatic materials oblige to be between 10-108 ohm-sq [4]. A fundamental principle of forming conductive fibers is their capability of dispersing and transferring electric charge [5]. There are alternative approaches to make conductive fibers, for example impregnating with conductive particles, surface coating with conductive materials, etc [6], [7]. To make fibers with adequate conductivity using common impregnated conductive materials such as metal powder, conductive carbon black powder, and carbon nanotube, considerable amount of them are required, which consequently make the fiber forming problematic as well as curtail their physical properties [8]-[10]. To overcome such obstacle, sheath-core bicomponent fiber forming is an alternative positive method that has been proved to generate smoother production [11], [12]. The attempt to produce the conductive fibers with the conductive materials as the fibers' sheath and a strong supporting material such as their core is a promising alternative. The aims of this study were finding applicable proportions of the sheath and core in the fibers and their properties. The experiments used carbon black powder impregnated in sheath section of the fibers for build up their conductive properties.

2. Research Methodology

The materials in this study were polypropylene polymer of Moplen HP61R from HMC Polymer Co.,Ltd. as a core side of the extruded fibers and 18% carbon black conductive (Timcal Ensaco 250G) mix-melted with 82% ExxonMobil™ PP7555KNE2 compound, produced at Salee Colour PLC, as a sheath side of the extruded fibers.

Fig. 1 Lab scale bicomponent extruder fed spinning machine model LBS-100, Hills, Inc.

The bicomponent fibers were formed with Lab Scale Bicomponent Extruder Fed Spinning Machine - Model LBS-100 by Hills, Inc., as shown in **Fig. 1**. The type of the bicomponent fiber

extrusions was the spin pack type 24-extrusion-sheath-core spinnerets with 0.5 mm. diameter. The extruded fibers were wound up using Leesona winding machine with 300 m/min winding speed. The setting conditions for the fibers are shown in **Table 1**.

Table 1 The bicomponent fiber extrusion machine conditions and fiber winding speeds

| S/C | Melt Pump (A+B=12 rpm) | Temperature (°C) | | | | Spin head | Spinning speed (m/min) |
| | | Extruder A | | Extruder B | | | |
		A1	A2	B1	B2		
100/0	12 / 0						
90/10	10.8 / 1.2						
80/20	9.6 / 2.4						
70/30	8.4 / 3.6						
60/40	7.2 / 4.8						
50/50	6.0 / 6.0	210	220	210	220	230	300
40/60	4.8 / 7.2						
30/70	3.6 / 8.4						
20/80	2.4 / 9.6						
10/90	1.2 / 10.8						
0/100	0 / 12						

Remark: S/C = sheath-core, A1 and A2 = barrel temperature zone 1 and 2 of extruder A, B1 and B2 = barrel temperature zone 1 and 2 of extruder B

Ash Content: The ash content of the samples were tested following ASTM D 3173-73 testing standard using burning crucible at 780 ºC for 45 minutes.

Optical Microscope (OM): The optical microscopic examination, using Olympus CX41 microscope with 4X magnifying power was performed and recorded with connected CCD.

Scanning Electron Microscopy (SEM): The surface of the bicomponent fiber specimens was inspected using scanning electron microscope: JEOL JSM-5410LV with gold sputtering coating at 20 kV, 500 and 2,000 magnifications. The SEM image of the sheath (CB-PP compound)/Core (PP) of the bicomponent fibers at S/C 40/60 ratio (scale bar: 50 and 40 micrometer) were taken with thermos scientific Prisma E – low vacuum mode.

Fiber strength test: The sheath-core bicomponent fibers (CB-PP compound /PP) with winding speed at 300 m/min were tested to evaluate their strengths using tensile strength tester (INSTRON 5569), following the ASTM D3822 Standard Test Method for Tensile Properties of Single Textile Fibers, with gauge lengths of 25 mm [1.0 in.], load cell of 10 N, and crosshead speed at 20 mm/min.

Fiber Shrinkage test: The fibers were tested for measuring their shrinkages following the ASTM D5104-02 Standard Test Method for Shrinkage of Textile Fibers (Single-Fiber Test), where the individual fibers were cut and attached on the upper and lower sides of the specimen template under standard testing condition at 88°C for 5 min., the 10 random specimens were tested. The shrinkage percentages of their values were calculated using the following equation (equation 1).

$$\% \text{ Shrinkage } = \frac{L_0 - L_1}{L_0} \times 100 \qquad (1)$$

where
L_0 = fiber length before test (mm)
L_1 = fiber length after test (mm)

Moisture content test: The fibers were tested to measure their capability to contain moisture using common procedure by putting them into oven at 105°C for 30 min. The fibers were conditioned in standard testing environment of controlled relative

humidity and temperature for 6 hours before the tests. The percentage of the moisture content of each fiber was calculated using the following equation (2).

$$\% \text{ Moisture content} = \frac{W_0 - W_1}{W_0} \times 100 \quad (2)$$

where
W_0 = Conditioned weight of the specimen (g)
W_1 = Oven dry weight of the specimen (g)

Differential Scanning Calorimeter (DSC): The thermal properties of the fibers were tested using the DSC 200 F3: NETZSCH system with heating and cooling mechanism at 10°C/min started from 30 °C to 200 °C and vice versa. The thermal history of the tests were diminished at 200 °C for 5 min. Crystallinity of studied samples was also calculated using the following equation. (equation 3)

$$x = \left(\frac{\Delta H}{(1 - W_f)\Delta H^*} \right) \times 100 \quad\quad (3)$$

where W_f is the weight fractions of nanocomposite filler, ΔH refers to the measured melting enthalpy and ΔH^* denotes 100 % crystalline polypropylene that equals 209 J/g. [13]

Electrical surface resistivity: The electrical surface resistivity (SR) of the compound fibers were conducted using the Surface resistivity detector: OHM-STAT® RT-1000, Hudson (USA).

3. Results and Discussion

The ash contents of the carbon black polypropylene conductive compound are presented in **Table 2**.

Table 2 Ash contents of the polypropylene conductive compound

Number of Sample	Crucible (g)	PP Compound+ crucible (g)	Carbon Black powder (after burning) (g)	% Ash Content
1	39.44	41.22	1.78	17.80
2	45.53	47.33	1.80	18.00
3	35.87	37.68	1.81	18.10
		average	1.79	17.97

It has been successfully proved that mixing carbon black with polypropylene to produce conductive fibers using single screw melt spinning system was achievable. The amount of the carbon black particles and its dispersing pattern are primary considering factors because the unbroken conductive network will be formed only when the matrix has enough conductive particles. The carbon black content used in their experiments were varied but when it reached 8 wt% the single screw fiber spinning become unattainable. [14] The spinning of immiscible polymer blends in single screw system would face difficulties because of weak interactions of the two phases which made their mechanical properties too weak to be stretched out. The bicomponent fiber spinning would strengthen the fibers with strong pure polymer as its core and desirable property polymer on its sheath. [15] The melt spinning into sheath-core bicomponent fibers with low take-up mechanism induced crystallization during the fibers being stretched with made them stronger comparing to the single screw spinning.

[16] Therefore, in this experiment, the ash content of the conductive carbon powder-polypropylene compound chips was approximately 18 wt%. The eleven lots of sheath-core bicomponent fibers with the different material ratios between sheath sections and core sections were successfully produced with the assigned machine setting using the melt pump speed at 12 rpm and winding speed at 300 m/min. The fiber drawing mechanism will distance the carbon black particles apart which lesser their conductive property. [14]

The extruded bicomponent fibers were examined using optical microscope for cross-section configuration to analyze the correlation of the pressure at the screw ends before spinpack (A=core, B=sheath) as shown in **Table 3**. The designated eleven experimental bicomponent fiber productions were conducted using the Hills' spinning machine. The produced fibers were examined on their cross-sections with an optical microscope to study characteristic and the proportion of sheath and core sections in the fibers. When the compound materials were melted in their extruder barrels on each side of the machine - the sheath section (conductive carbon black polypropylene compound) in extruder barrel B, and the core section (virgin polypropylene) in extruder barrel A – the pressures, measured at the end of the screws before enter the melt pumps, were considerably different. The pressure in the extruder barrel B was higher than the pressure in the extruder A, indicating that carbon black particles in the compound affected the extrusion pressures. The pressure at the end of the screws become higher when the compound contain higher percentage of the carbon black, as an example of the pressures in each side of the screws from one of the experiments showed that the pressure of the screw contain virgin polypropylene was 810 psi while the pressure of the screw contain carbon black polypropylene compound was 1,455 psi.

Table 3 Monitoring pressures at screw ends before the spinpacks

No.	Ratio (S/C)	Pressure extruder A (psi)	Pressure extruder B (psi)
1	100/0	0	1455
2	90/10	442	1397
3	80/20	499	1335
4	70/30	534	1156
5	60/40	603	1190
6	50/50	651	1124
7	40/60	688	1030
8	30/70	720	937
9	20/80	756	826
10	10/90	783	650
11	0/100	810	0

Remark: extruder A=core side, extruder B=sheath side

The images in **Fig. 2** show the cross-section of the sheath-core bicomponent extruded fibers with free-fall finishing up mechanism. The microtome cutting technique was used for the specimen preparations. The cross-section images of the sheath-core bicomponent fiber of conductive carbon black/polypropylene in which the fibers' cores are polypropylene and the fibers' sheaths are conductive carbon-black polypropylene compounds. The images clearly reveal the boundaries of the sheath and core of the fibers, except the image a. which is carbon black polypropylene compound and the image k which is sole polypropylene. The

specimens were prepared according to their ratios of the sheath and core polymers in the melt pump settings. The cross-section images of the fibers with the free-fall mechanism show deviation diameters, as a result of the stretching by its own weight. However, the melt pump setting would be able to efficiently appoint the core and sheath ratios of the fibers.
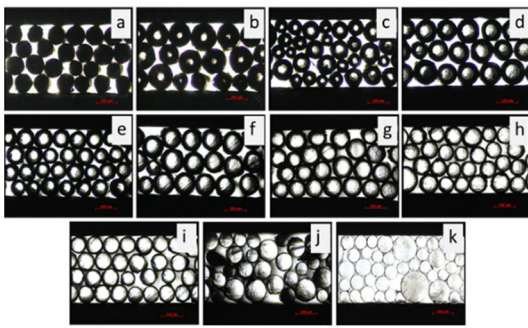

Fig. 2 The 4X magnification cross-section images of Sheath (CB-PP compound)/Core (PP) bicomponent fibers: a) 100/0 b) 90/10, c) 80/20, d) 70/30, e) 60/40, f) 50/50, g) 40/60, h) 30/70, i) 20/80, j) 10/90, k) 0/100
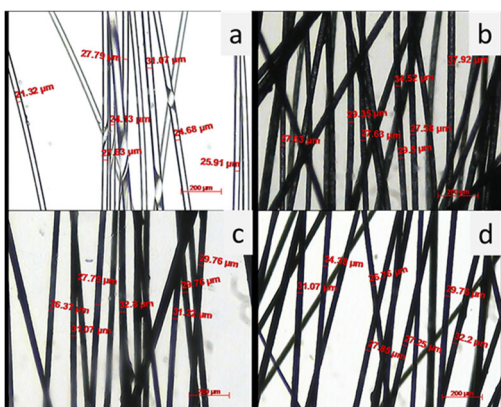
Fig. 3 The 4X magnification longitudinal images of Sheath (CB-PP compound)/Core (PP) bicomponent fibers: a) 0/100, b) 20/80, c) 50/50, d) 80/20

The longitudinal view of the selected fibers is illustrated in **Fig. 3** in which, a) is the microscopic image of sheath-core 0/100 bicomponent fibers, b) is the microscopic image of sheath-core 20/80 bicomponent fibers, c) is the microscopic image of sheath-core 50/50 bicomponent fibers, and d) is the microscopic image of sheath-core 80/20 bicomponent fibers.

The images reveal that the average diameter of the fibers is approximately 30 micrometers. They also show that the bicomponent fibers without conductive carbon black in the sheath section (image k in **Fig. 2**) have markedly higher light transmittance than the fibers with conductive carbon black. The fibers in images b), c) and d) in **Fig. 3** appear as black fibers with very low degree of light transmittance and the surfaces of the fibers are not as smooth as the fibers without the conductive carbon black, some particle of the conductive carbon black randomly emerges on the outer surface of the fibers.

The SEM images in **Fig. 4** and **Fig. 5**, clearly show the smooth surfaces of the fiber which no conductive carbon black powder added. On the other hand, the images b), c), and d), taken from the fibers with conductive carbon black additive, have rough and uneven surfaces which affirm that the conductive carbon black powder particles appear on the fiber surfaces. The surfaces with higher ratio of sheath appear to have denser particles on the surfaces.

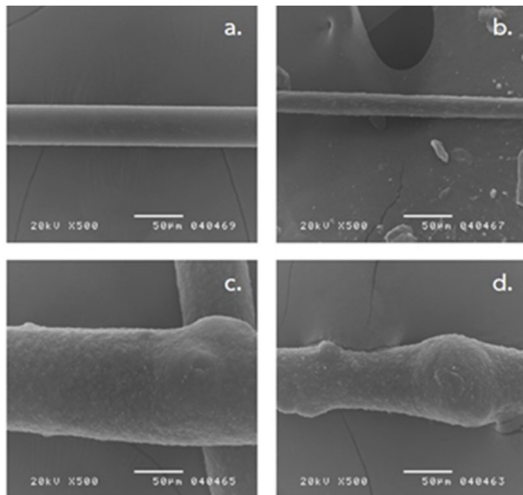The test results of the fiber strength display in **Fig. 7** which clearly indicate the

Fig. 4 SEM magnification (500X) images of Sheath (CB-PP compound)/Core (PP) bicomponent fibers at four different S/C ratios: a. 0/100, b. 20/80, c. 50/50, d.80/20
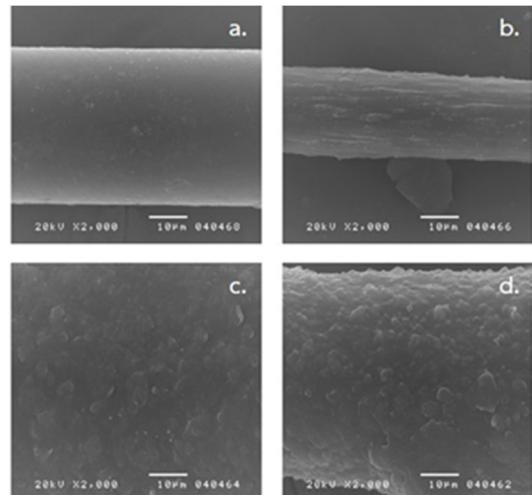

Fig. 5 SEM magnification (2000X) of Sheath (CB-PP compound)/Core (PP) bicomponent fibers at four different S/C ratios: a. 0/100, b. 20/80, c. 50/50, d.80/20

descending tendency of the fibers' strengths as the sheath ratio of the conductive polypropylene compound increase. The fiber strength become higher when the sheath ratio were increased until it reach sheath ratio at 20 then the fiber strength become lesser. This affirmed by Bosak's experiments which indicated that the thinner sheath resulted higher fiber spinnability. [15] The specimen with highest stress scale is the sheath-core component fiber with ratio of 20/80 between the carbon black polypropylene compound and polypropylene virgin. The elongation at break of the fibers had also taken into the consideration. The fibers' elongations increase as the core section of polypropylene virgin increase, which the highest value when the core section reach ratio of 20/80 between the carbon black polypropylene compound and polypropylene virgin. The fiber elongation become higher when the sheath ratio were increased until it reach sheath ratio at 20 then the fiber elongation

become lesser. The elongations at break of the sheath-core bicomponent fibers are illustrated in **Fig. 8**. The results correspond to I. Islam et al. [17] that the tensile properties of the compound materials become higher when adding carbon black in the matrix, until it reach 15 wt% and their strength and elongation would drop as soon as the content of carbon black exceeded 15 wt%. The depreciated strengths were correlated with the crystalline region in the fibers as shown in **Table 5**.
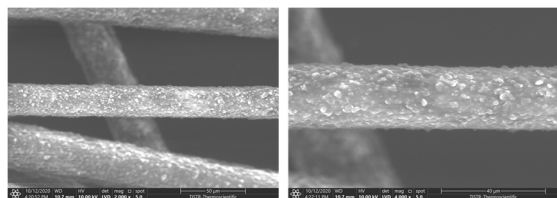

Fig. 6 SEM image of Sheath (CB-PP compound)/Core (PP) bicomponent fibers at S/C ratios: 40/60 (scale bar: 50 and 40 micron from Thermo scientific Prisma E – low vacuum mode)
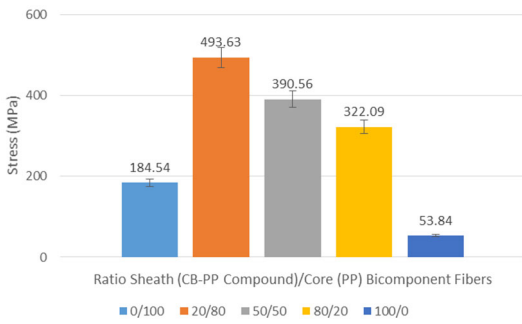
Fig. 7 Tensile strengths of the Sheath (CB-PP compound)/Core (PP) bicomponent fibers
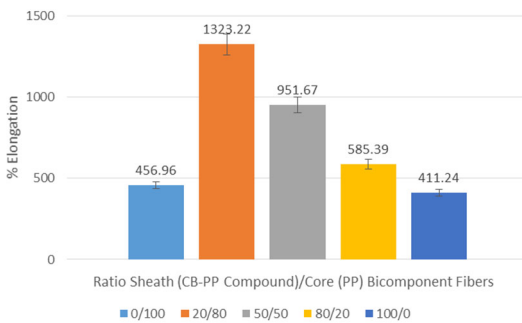

Fig. 8 Elongation at break of the Sheath (CB-PP compound)/Core (PP) bicomponent fibers
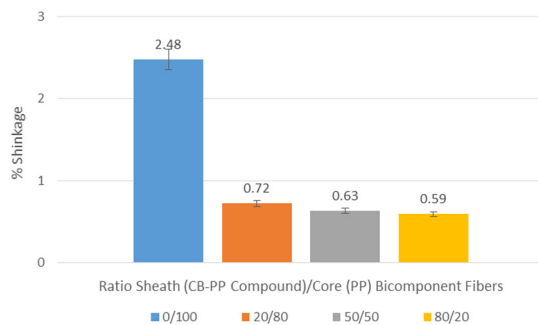

Fig. 9 Fiber shrinkages of the Sheath (CB-PP compound)/Core (PP) bicomponent fibers

The averages of shrinkage percentages of the tested samples display in **Fig. 9**. The fiber shrinkage test results indicate that the

ratios between the conductive polypropylene compound as sheath material and virgin polypropylene as core material influence their shrinkage values. The highest degree of fiber shrinkage is the 0/100 S/C which the domination of the material is polypropylene virgin. On the other hand, the lowest degree of fiber shrinkage is the 80/20 S/C which the conductive polypropylene compound as fiber sheath thickening its outer layer made it more rigid and stable, the higher ratio of sheath section of conductive polypropylene compound the lower degree of the fiber shrinkages.

Table 4 Moisture content of the Sheath (CB - PP compound) / Core (PP) bicomponent fibers

Ratio S/C	Moisture content (%)
0/100	1.05
10/90	0.47
20/80	0.38
30/70	0.31
40/60	0.27
50/50	1.09
60/40	0.97
70/30	0.56
80/20	0.38
90/10	0.56
100/0	0.62

Table 5 Thermal properties of the Sheath (CB-PP compound)/Core (PP) bicomponent fibers

Ratio S/C	T_m (°C)	T_c (°C)	% Crystallinity
0/100	170.2	117.1	35.57
20/80	168.3	118.0	31.80
50/50	166.9	118.2	28.00
80/20	168.3	120.0	26.60

The results of moisture contents (**Table 4**) the sheath-core conductive bicomponent fibers at different S/C ratio

indicate that each fiber contain moisture less than 1.0 wt%. The moisture contents of the fibers show insignificant differences because the conductive carbon black and polypropylene are considered as hydrophobic materials.
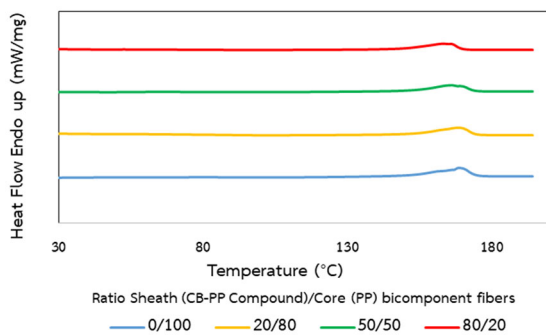

Fig. 10 Thermal properties of the Sheath (CB-PP compound)/Core (PP) bicomponent fibers

By adding carbon black particles into the polypropylene matrix to form fibers, the crystallization were deterred which altered their thermal properties such as melting temperature and supramolecular crystalline structure, so the mechanical and electrical properties were also shifted. [18] The DSC test results, shown in **Table 5** and **Fig. 10**, indicate that melting temperature (Tm) of the bicomponent samples with different compound ratios are between 168.3 - 170.2 °C. The higher conductive carbon black powder in the compounds is the lesser percentage of their crystallinities, this is because the carbon black powder absorbed energy from the core section, (Polypropylene Virgin), which activates the crystallization of the compound earlier, comparing with the crystallization of the pure polypropylene. The crystallization temperatures (T_c) of the compounds also developed the similar outcomes. These outcomes of isothermal and non-isothermal crystallization occur while the molten polymer matrix was cooling down and carbon black particles become nucleation centers which generate crystal growth. The nucleation modify polymer morphology which lead to collapse of polymer spherulitic structure. Besides, the nucleation increases polymer crystallization temperature yet heighten the crystals' melting temperature. [19] It is also found that by lessening surface free energy of nucleating additives, the crystallization temperature will be increased. [20]

To make polypropylene compound matrix become conductive, there must have enough carbon black particles dispersed throughout that it reach the percolation threshold. [14] The percolation threshold is the point that conductive particles in the materials congregate and touch one another or be close enough for electrons to tunneling hop and become conductive path or network. [21] The surface resistivity meter is the device to measure the leakage of current along an insulating material surface which can be applied to rate their conductive properties. The experimental results showed that the surface resistance of the sheath-core conductive bicomponent fibers increased if the fiber samples had higher ratio of conductive sheath section comparing with the ones with lesser ratio of the section. The surface resistivity of the samples at 2×10^{12} ohm/sq, the material is considered as

insulative material. The results of surface resistance are shown in **Table 6**. The results conform to Y. Li et al. [21] that the percolation threshold was reach when there were enough carbon black particles in the composite that sharply lowered the volume resistivity when the insulting materials become conductive materials. Despite the percolation threshold, the over excessive amount of carbon black in the matrix would not further decrease the volume resistivity because the conductive network has already exist.

Table 6 Surface resistance of the Sheath (CB-PP compound)/Core (PP) bicomponent fibers

Ratio S/C	Surface resistance (ohm/sq)
100/0	8.14×10^5
90/10	3.65×10^5
80/20	2.70×10^5
70/30	3.09×10^6
60/40	1.66×10^6
50/50	1.72×10^6
40/60	5.80×10^7
30/70	9.47×10^{12}
20/80	1.50×10^{11}
10/90	2.00×10^{12}
0/100	2.00×10^{12}

The surface resistivity test results, in **Table 6**, show that when the sheath section of the bicomponent fibers becomes thicker, the conductive property of the fiber becomes higher accordingly. Therefore, when the sheath section of the fibers reach 40%, the fibers turned into dissipative material according to the conductive in **Table 6**. This is because the compound materials has denser conductive carbon black particles on their surfaces which correlated with microscopic images and SEM images of the fibers as show in **Fig. 6**.

4. Conclusion

The conductive property of the fibers was gained by adding conductive carbon black powder in the sheath section of the experimented bicomponent fibers and the fiber forming processes were eased with the virgin polypropylene as their core section. The different proportions of the sheath and core sections in the bicomponent fibers presented different amount of conductivity. The proportions that produced adequate conductive property when sheath section were 40% and above. However, when the conductive sheath sections become higher the strength of the fibers were diminished.

Though, there are many alternative methods to produce conductive fibers, the fibers with carbon black compound as conductive material is considered longer-lasting than other methods. The fibers with conductive property require substantial amount of carbon black particles, therefore, sheath-core bicomponent technique allows the fibers to be steadily formed with adequate strength. These fibers have high potential to be further formed into nonwoven fabric with spunbond and meltblown techniques. There are several potential applications of the conducting fibres such as occupational work wears (e.g. antistatic mechanic working dress and glove), industrial uses (e.g. antistatic place mat for fuel-combustion machine and equipment), weather shields (e.g. weather shield glove), and packaging (e.g. antistatic bag for storing electronic components).

5. Acknowledgement

6. References

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