



# CONDUCTIVE POLYMERS - A ROUTE FOR SUSTAINABILITY

CONDUCTIVE FIBRES CREATED BY COATING METHOD

MSc Thesis

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By

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IN PARTIAL FULFILMENT OF THE AWARD OF MASTERS OF  
SCIENCE DEGREE IN CHEMICAL ENGINEERING WITH  
SPECIALISATION IN WASTE MANAGEMENT AND RE-  
SOURCE RECOVERY TECHNOLOGY

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**Conductive polymers – A route for sustainability  
(Conductive fibres created by coated method)**

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**Keyword : conductive fibres, coating method, polyaniline, Panipol, surface resistivity, yarn resistivity**

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## **Preface**

This final 20 credit points degree project is the conclusive part of the Master program in Engineering – Waste Management and Resource Recovery Technology at the University college of Borås.

The project was carried at the Polymer Technology Laboratory, University College of Borås, while conductive polymer supplied from Finnish Panipol Company.

This research work has been quite challenging due to it gave me the opportunity to think and carry out all part of the research independently and to be critically minded.

My great appreciation goes to my supervisor and examiner, Professor Michael Skrifvars for his supporting and guidance during the research and his willingness to put me through at all times. My thanks also go to Dr. Dag Henriksson and Dr. Peter Therning co-ordinators of this program during these two years study in the University College of Borås and living in Sweden as a free mover student.

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## SUMMARY

The concept of sustainable use of materials defines as utilizing raw material as less as possible and introducing less toxic substances to the environment as well. Smart materials are one route for sustainability, as they have optimal performance in relation to material composition. New technologies can be developed by using smart materials. One area is the development of smart textiles, meaning the incorporation of electronic functions in textiles. These functions can be used for human protection or monitoring of health. Conductivity is a key factor in smart textiles. The aim of this report is to identify electrically conductivity of textile fibres in conjunction with conductive polymer (polyaniline). By applying conductive polymer (polyaniline ink) on textiles fabric and fibres it is possible to obtain conductive textile products. This project focuses on the development of conductive fibres by coating of an individual fibre or a few different types of fabric with conductive polymer polyaniline dispersion in water and toluene as solvent. Various situations have been taken into consideration and investigated for different concentration to different times of coating and deposit thickness. Performance on resistivity calculation led to find optimum concentration and coating numbers and deposit thickness. Based on the inventory, a qualitative resistivity analysis is carried out for the purpose of identifying which combination of concentration and times of coating in the case of woven types fibre or coating thickness in the case of non woven types of fabrics as well as the types of fabrics would provide the better conductivity properties in the textile fibres and fabrics.

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# 1. INTRODUCTION

## 1.1. BACKGROUND

The major concerns over increasing functionality in textiles objects followed by innovation of intrinsically conductive polymers led to many research in this field. Conductive polymers display a wide range of electrical properties. The goal of using conductive polymers is achieving new conductive materials and new products having properties difficult or impossible to achieve by existing materials. However electrically conducting polymers such as polypyrrolles, polythiophene and polyaniline with complex dynamic structures provided the possibility of creating conducting polymers with a diverse range of properties from chemical to electrical can be manipulated to produce materials with different conductivities and different redox properties. [1]

The first industrially application of conductive polymers was provided by adding conductive additives for plastics and thermosets conductive compounds represented the fastest growing classes of especially thermoplastics and thermosets [2]. These conductive compounds are typically manufactured by the additives such as carbon black, metal powder, metal and carbon fibres to polymer matrix, however several disadvantages associate with this current technology including processing, loadings and the extreme high costs associated with these problem [3].

New intrinsically conductive polymers (ICPs) such as polyaniline or polypyrrolles also known as synthetic metals represent another class of conductive additives. Polyaniline based conductive polymers can be used neat or blends and composed with commodity polymers such as polyethylene, polypropylene, polystyrene, soft PVC, phenol formaldehyde resins and different types of thermoplastic elastomers. Unlike conventional filled materials, mechanical properties of the end products are close to those of the insulating matrix polymers. [3,4,5] Now conductive plastics are broadly applied to meet different industrial need such as packaging industry for electronic devices, fenestration ,automotive industry construction such as antistatic floor and work surface, mining such as conductive pipes for explosives, antistatic packaging and textile industry. [6] There are several advantages of using packaging conductive polymers based for electronic devices to reduce ESD electro static discharge related problems.

The other important part of industrially application of conductive polymer represented the use of polyacetylene to make batteries, but this project did not attract commercially interest. A second generation of plastic batteries was based on polyaniline electroactive conductive

polymer with a high commercial attraction could take more interest in using of intrinsically conductive electroactive polymers for the other part of industrially application of these new materials [7].

The idea of applying conductive polymers in the textile structure comes from military needs to improve the functionality in soldering cloths for particular purposes. To boost the combination of high functionality and compactness as well as comfort, there is a strong need for substantial developments concerning flex technologies. In the field of smart textiles the flexible circuit board technology allows a practical way to integrate smart textiles with electronic systems. The major target of conductive polymer technology development in the field of smart textile has been to combine the electrical properties of these new materials with the mechanical and processability properties of conventional textile polymers which led to developing wide range of research on producing conductive fibres and fabrics [8]. Applications of conductive polymers for smart textile have been limited due to their lack of processability, flexibility and strength. These limitations can be overcome by different methods such as blending conductive polymers with conventional textile polymers. One area of creating conductive fibres and fabrics is coating textiles substrates with conducting polymers to make conductivity, which possess the mechanical properties of textiles whilst retaining the desirable electrical properties of conducting polymers. Providing the basis for smart textiles depends on conductive polymers.

In this investigation the basis of conductive substance utilised for conventional textile fibres and fabrics in order to enhance the electrical conductivity of the textile fibres and fabrics are polyaniline salts dispersed in water and toluene (Polyaniline in solvent). There have been investigations in the area of conductive fibres in various methods. This investigation has been developed for coated textiles in the presence of conductive polymer. As experimental results conductivity property entirely depends on the concentration of the conductive substances, coating numbers and deposit thickness. The combination of appropriate concentration, with a variety of coating numbers or deposit thickness could provide variety electrical properties which have been developed by further inventory analysis to identify the optimum combination for desirable results.

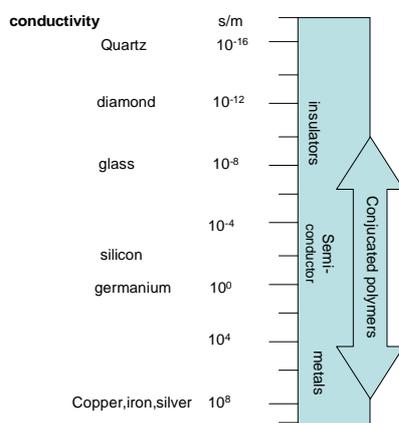
The steps of this research can be divided in three distinct parts:

- Coating textile samples to provide electrical conductive fibre and fabrics samples.
- Measurement of linear resistance and surface resistance for prepared samples.
- Mathematical and inventory analysis required to achieve the desired results.

## **1.2. ELECTRONIC PROPERTIES OF MATERIAL**

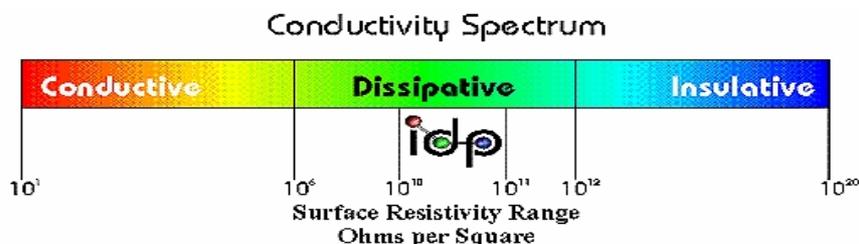
Materials from electrical conductivity point of view are divided in three different types, metals, semiconductors and insulators, which the level of conductivity is given in the Figure (1).

For a long time metals were considered as dominant area of electrical conductivity until the discovery of semiconductors properties which opened a new field for basic scientific and applied science researches. New conductive technologies are emerging; one being a class of polymers intrinsically able to carry a current along their polymer chains, the other is a conventional textile polymer or other type of industrial plastic. Two categories are now available, one is melt-processable and thus highly efficient at creating conductive networks when alloyed with a thermoplastic matrix polymer which is under research and development and the other is coating which is utilizing in some industrial purposes and considered as a useful method in some of industrial application. Inherently Conductive Polymers and Inherently Dissipative Polymers (ICPs and IDPs) differ in the range of conductivity they impart and the mechanism involved.



**Figure 1: Levels of electrical conductivities. [9]**

Based on this figure conjugated polymers from conductivity point of view ranged from  $10^{-8}$  S/m to  $10^8$  s/m theoretically, Based on literature ICP conductivity can reach as high as  $10^4$  (S/cm) or ( $10^{-4} \Omega \text{ cm}$ ). However typical conductivity is in the range of 1-100 S/cm. [10] The other part that we are discussing in this project is connected to surface conductivity which the range of surface resistivity is given schematically in the Figure (2).



**Figure 2: Surface resistivity indicates conductivity spectrum. [11]**

### 1.3. CONDUCTIVE POLYMERS

The history of conductive polymers began in the 1960's when the existence of conductive trans-poly acetylene (TPA) was theoretically proposed. In 1997, Shirakawa a Japanese graduate student succeeded in synthesising the polymer. [12]

Until then polymers had been made conductive by adding electrically conductive components such as metal particles, ions and salts. The polymer, merely acted as a supporting matrix for the conductor [13, 14, 15]. This situation changes completely in the case of inherently conductive polymers, in which it is the polymer chain that provides the conductive path for the electrons. This is possible by the existence of conjugated double bonds in the polymer back-bone. [16]

Conjugation occurs when a molecule contains both single and double bonds, which are alternating within the molecular structure [17-19]. An example of this structure is polyacetylene (Figure1), which consist of a long chain of carbon atoms, each bond to two carbon neighbouring carbons and a single hydrogen atom. The carbon- carbon bonds are not identical, but alternate between single and double bonds. Normally the electrons in the bonds remains localized and can not carry an electron current but when the material is doped with strong electron acceptors such as iodine, the polymer began to conduct nearly as well as a metal, with a conductivity eighteen times higher than pure polyacetylene. It has confirmed that the polymer had become metallic by showing that doping caused it to absorb and reflect far infrared light, whereas the pure polymer is transparent. Photons in that range allow polyacetylene electrons to absorb energy and enter the so-called conduction band.

Polyacetylene and related materials behave quite differently from traditional semiconductors and conductors. For one thing at intermediate doping levels, current is carried not by dislocated nearly free electrons, as in silicon or copper, but by the electrons in the carbon – carbon bonds when a dopant removes an electron from the molecule, it can turn a double bond into a one electron single bond, forcing a carbon atom to make single bonds with both of its neighbouring carbons. That charged “defect”, called a polaron, can travel down the molecule as each successive carbon atom grabs an electron from its neighbour trying to compensate for the change. Since single and double bonds have different lengths, the movement of charge is ultimately connected with stress and strains among the carbon atoms themselves, not just their electrons. Polarons and other polymer chain defects called solitons turned out to have unexpected properties, such as spin in the absence of charge or charge in the absence of spin.

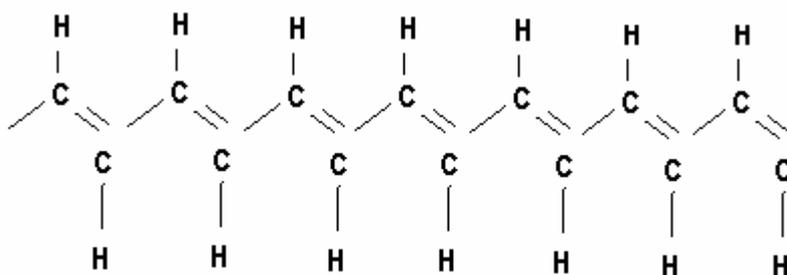


Figure 3: Polyacetylene an example of conjugated polymer. [20]

Conjugated systems are special because the electrons in the P-orbital of the double bonds are free to move throughout the polymer chain. [17, 18]

In order to provide conduction two important factors are required; extra electrons and mobility. One could rightfully be expected due to polymer chain like polyacetylene would conduct electricity throughout its length and the other is free charge like impurities in semiconductors but not exactly the same. Conductive polymers are doped conjugated polymers with oxidizing or reducing chemical agents that remove electrons from or add electrons to the polymer. The oxidation or reduction changes the electronic structure of the polymer so that it can conduct electricity. The degree of conductivity is related to many factors, including the polymeric structure, degree of doping and types of dopant. [21-22]

Practically, the first generation of intrinsically conductive polymers did not achieve great commercial success due to their tendency to be insoluble, unprocessable and sensitivity to the environmental conditions. However several more recent polymers have been developed that exhibit much greater stability and showed promising commercial potential. These include polyaniline, polypyrroles and polythiophene. [1, 2]

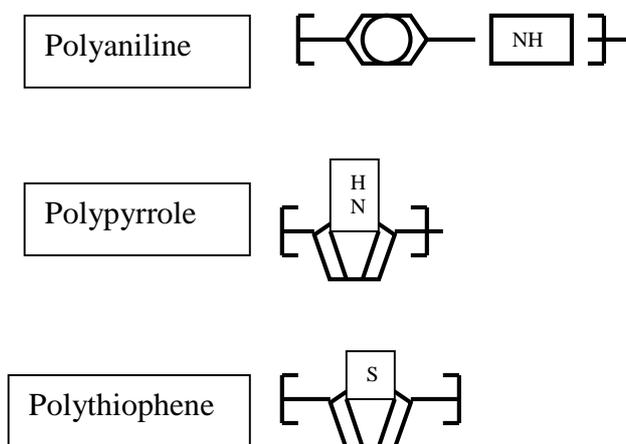


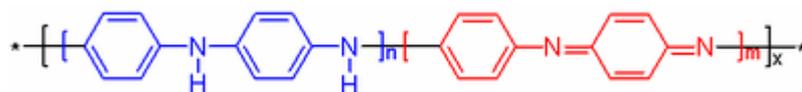
Figure 4: Intrinsically conductive polymers. [2]

#### 1.4. POLYANILINE

Among the different type of ICP polymers we will discuss about polyaniline which is used in its soluble form to obtain conductive fibres and fabrics by coating.

Polyaniline is polymer with semi-flexible structure. It was discovered in 1934 as aniline black. Polyaniline also exists naturally as part of a mixed copolymer with polyacetylene and polypyrroles. [1, 2, 21]

As the Figure 3 shows the aniline monomer in polymerized form can be in five distinct oxidation states from ( $n=1$  &  $m=0$ ) to ( $n=0$  &  $m=1$ ) in which ( $n+m$ ) is always constant and equal to one. Among them Emeraldine ( $n=0,5$  &  $m=0,5$ ), often referred to as Emeraldine base (EB) is the most useful form due to its high stability at room temperature compared to the other form of this polymer.



**Figure 5: Main polyaniline structures ( $n + m=1$ ,  $X$ = degree of polymerization. [23]**

Polyaniline will become conductive by doping, in which the polymer is partially oxidized or reduced. It can be designed to achieve the desired conductivity for a given application even as high as for silicon or germanium. Other advantages of polyaniline is that it is both melt and solution processable, this means that the compound can be easily mixed with conventional polymers and that is easy to fabricate polyaniline products into required shapes. Moreover, products consisting of polyaniline compound can be easily disposed of without environmental risks. [24]

The compositions of polyaniline are soluble in water and selected organic solvents. [21] The melt processable polyaniline exhibits good environmental stability characteristics.

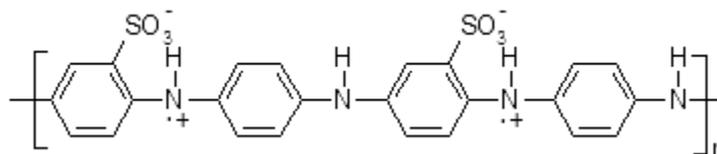
Some polyaniline based materials are solution and melt processable. They provide precisely controlled electrical conductivity over a wide range, improve phase compatibility and thus blendability with bulk polymers, and provide easier means of processing and forming conductive products which could be future development in this area. [21]

Panipol is a trade name of a polyaniline based inherently conductive polymer (ICP) and manufactured by Panipol of Finland, the only manufacturer of melt processable inherent conductive polymer additives in the world. They also manufacture polyaniline (EB) as well as conductive solvent and water based polymer products. Panipol was established by the Finnish company Neste. The Panipol technology is based on the extensive research and development of conductive polymers done by Neste since 1982, the whole technology gathered since 1982, including large portfolio of patents, was transferred to Panipol. The technology includes work done at UniAx joint venture of Neste and Nobel Prize winner Alan Heeger, since the separation from Neste in 1998 Panipol has continued to apply for more patents.

Panipol product lines consist of: [21-22]

1. Melt processable ICP- Panipol DX master batches for dry mixing and Panipol CX for compounding.
2. Panipol coating systems and conductive inks
3. Panipol; polyaniline – non conductive Emeraldine base form as well as conductive polyaniline salt (both dry powders)

In this project two different soluble forms of polyaniline are investigated to produce conductive fibre and fabric, one is sulfonated polyaniline and highly soluble in water and dipolar solvent which is called PANI W, (Figure 4). The other one dissolves in organic solvent, like toluene is called PANI T.



**Figure 6: Sulfonated polyaniline, soluble in water and other dipolar solvents. [25]**

## 1.5. APPLICATIONS USING POLYANILINE BASED CONDUCTIVE POLYMER

Innovation of conductive polymers provided various fields of research in applied science and research development in academic centres and industrial sectors as well.

The interest in electrically conductive fibres and fabrics is growing rapidly in areas such as sensing, electrostatic discharge, corrosion protection, dust and germ free clothing, monitoring, data transfer in clothing and in military applications. The basic element to achieve all these purposes is the modification of the mechanical and electrical properties of fibres and fabrics to obtain the new functionality in the textile applications. [1, 21] Electrically conductive, colored and transparent thin films and coatings, which would otherwise be difficult to achieve with conventional filled materials, can be made using polyaniline based compositions. The stability and solubility of polyaniline can be controlled by the selection of an appropriate method of polymerization. Polyaniline is soluble in several common organic solvents, and can be deposited by different coating methods on the surface of fabrics and yarn as well as many other materials. [21-22]

## 1.6. SMART TEXTILE CONNECTED TO CONDUCTIVE POLYMERS

Mass production of fibres and their weaving into textiles dates back to the early stages of the industrial revolution. The assembly of fibres through weaving and other processes are the basis of the mass production of textiles. Both conductivity and mechanical properties of conducting polymers could be improved by producing fibres. Textile production technologies for the making of conducting polymer fibres are an extremely attractive prospect. [1-2]

It is in the merging field of the electronic textiles and conducting polymer technologies. An electronic textile contains electronic components integrated into a conventional fabric structure. While some examples seem futuristic (computers or mobile phones built into sports jackets) other appears more achievable such as energy storage (batteries, capacitors) or energy conversion (photovoltaic, thermal energy harvesting), as well as application in the area of biomedical monitoring. [26, 27]

## 1.7. RESEARCH OBJECTIVES

In this research project we use a textile yarn and three different types of fabrics. The yarn is conventional polyester and the fabrics are used in air filtration from residential to industrial building. These filters adsorb dust and particles by providing membranes for air ventilation. One effective area of using conductive polymers is in the surface conductivity of air filtration. Theoretically by applying the negative electrostatic charge on one surface of air filter, particles which have the positive charge adsorb on the other side of the filter. There are some advantages at high particle adsorption whenever we provide negative charge in one filter side where particle and dust are in positive charge can adsorb more efficient on the other side of filter compare to non coated and charge free conventional filters' surfaces. In this part of experiment the surface conductivity and the different levels of conducting gained by surface coating take into consideration and the results are being further discussed.

The goal of this research can be divided in two individual parts as follows:

- To compare the conductivity resulted from polyaniline based materials in aqueous state and soluble in a solvent (toluene) coated on yarns.
- To investigate the surface conductivity of three different fabrics which are normally utilising in air filtration for different types of building from residential to industrial in order to provide the cleaner air coming into the buildings.

## 2. MATERIALS AND EXPERIMENT DESCRIPTION

### 2.1. MATERIAL USING IN THE EXPERIMENT

#### 2.1.1 Conductive polymers

(Panipol W) is a dispersion of conductive polyaniline in water consists of: Polyaniline salt (< 10%); Water (> 90%) supplied by Panipol LTD Finland

(Panipol T) Polyaniline in Toluene consists of: Toluene>85%; Alkyl Benzene Sulfonic acid<10%; Polyaniline <5% supplied by Panipol LTD Finland.



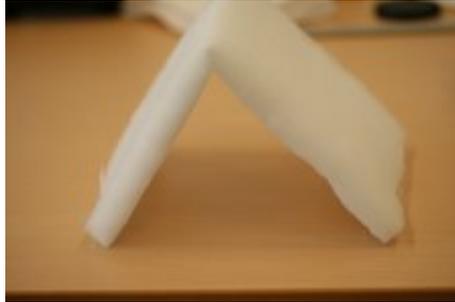
#### 2.1.2 Substrate materials

Diolen high tenacity yarns which are using in textile constructions, tents, light conveyor belts, filtration fabrics and sail cloth and other application. (Provided by Obernburg, the Netherlands)

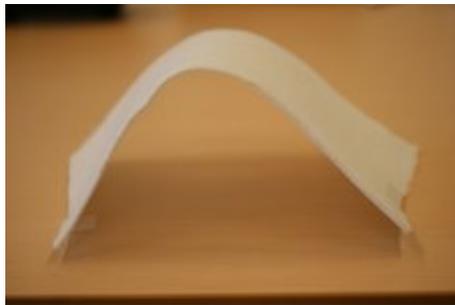
Three different filter media samples have been used for experiment with conducting coating. The material is used in ventilation systems in offices, apartments and industrial building for particle removal.

The three materials are made of the following polymers: (Provided from Scand Filter Company in Sweden)

- A thick (15-20 mm) non woven filter media made of 100% polyester fibre:



- Thin nonwoven material, made of polypropylene and mod acrylic fibre.



- Melt blown material (four different layers made of 100% polypropylene).



## **2.2. INSTRUMENT USING IN THE EXPERIMENT**

### **2.2.1 Resistance meter METRISO 2000**



**Description:** High resistance tester for the measurement of resistance to ground and surface resistance ranged from  $10^3\Omega$  to  $10^{12}\Omega$ . [28]

**Following measurements and tests can be performed with the METRISO<sup>®</sup> 2000:**

- Resistance to ground, surface and volume resistance (with especial measuring probes).
- Insulation resistance (with variable and rising measurement voltage).
- Temperature and relative humidity (with included, special sensor).
- Voltage and frequency.

### 2.2.2 Concentric ring probe



**Description:** The concentric ring probe is an instrument to be used in conjunction with a resistance meter to measure surface resistivity to IEC61340-5. Due to its design it is more accurate than a square probe, especially at the high end of the resistance range. The centre electrode is spring loaded. The product is supplied with carbon-loaded pads. [29]

**Physical and electrical specification**

|                                      |  |
|--------------------------------------|--|
| Dimensions                           | 67*120 mm                              |
| Outer probe diameter                 | 63 mm                                  |
| Inner probe diameter                 | 30 mm                                  |
| Mass                                 | 2.5 Kg                                 |
| Insulation resistance between probes | > $2 \times 10^{13}\Omega$ at 500 Volt |
| Probe resistance-carbon pads         | < $100\Omega$ at low test voltage      |
| Correction factor                    | Multiply by 10                         |

### **2.2.3 Surface coating bars**



This instrument was used for applying known thicknesses of coating PAN W and PAN T on the surfaces of the samples.

### **2.2.4 Microscope NIKON SMZ 800**

This is applied for microscopic structure analysis of the samples.

### **2.2.5 Glass plates**

Used for coating and measuring the resistance of yarn samples provided during experiments and brushes.

## **2.3. METHOD**

Various techniques are available for manually coating fibres such as spraying, brushing and sinking fibres in the bath media of polyaniline salt. The technique used in this experiment to elucidate the electrical conductivity properties in textile fibre and textile fabrics is brushing fibres samples with polyaniline salt.

The procedure is shortly introduced in this part in order to explain the basic features of this experimental technique to interested readers that are not familiar with this method.

The present investigation is related to an inherently conductive polymer (polyaniline) coated on the surface of fabrics as well as yarn kind textile fibre in order to provide conductive fibres and fabrics. Conductive polymer coated on the fibre has superior adhesiveness. In this project electrical resistances of the different samples is measured and their resistivities inves-

tigated from their magnitudes which is a factor of a materials' properties in conducting of electric current to the variations of their mean values. In the case of the yarn kind fibre theoretically when an electrical potential difference is applied across a conductor, its movable charges flow giving rise to a constant electric current. In a linear conducting property resistivity is constant. In order to investigate resistivity of the created conductive fibre resistances measured in four different lengths of the samples. All samples measured in the temperature 20-24 degrees centigrade and RH % in the range of 50-60.

### 2.3.1 Measurement of yarn resistance

In this part yarns have been fixed on the surfaces of glass plates ( $\sim 25 \times 25 \text{cm}^2$ ) in parallel with enough space for coating and measuring the resistance of the fibres. Fibres are coated with Panipol W and T individually and in different concentration (1% to 10% for PAN W and 1% to 5% for PAN T) by brushing. Since this manual coating technique involves with the different types of error, in order to calculate error and uncertainty, for each concentration five or more different samples have been made. The coated samples were dried and then the resistances were measured for each sample in four different lengths (5, 10, 15 and 20) for resistivity calculation. After the first coating and measurement of resistances of the samples each sample was coated for a second time and the resistances was measured. This was done for all concentrations and the same method was used, as for the first coating. This process was repeated for a third time as well. Second and third coatings were done in order to evaluate the effect of the number of applied coatings on conductivity resulted. In fact this part of the experiments which will be described in detail in the results, has been developed to provide the higher conductivity and analyse the effect of several times coating on more homogeneously results in coating technique in practice.



### 2.3.2 Measuring resistances of fabrics

In this part of the project three types of non-woven fabrics, which are normally using as air filtration for buildings, were coated with a conductive polymers (Panipol W and T) in differ-

ent concentration and thickness. The coating was applied by using coating bars (K-Bar) and the surface resistances were measured by a concentric probe and the conductive meter.



## 2.4. MEASUREMENTS AND RESISTIVITY CALCULATIONS

The rule for resistivity calculation is different for linear (yarn) resistivity and surface resistivity. In this part we will explain these two theoretically.

### 2.4.1 Resistivity and resistance in yarns

The conductivity is defined as the ratio of the current density  $J$  to the electrical field strength  $E$ ; as  $J = \sigma E$ , or it can be easily defined as  $U = R I$  (Ohm's law); where  $U$  is the drop in potential (in volts) across the resistor  $R$ , and  $I$  is the current (in amperes) through the resistor.

The reciprocal of  $R$  is called resistance, and the Ohm's law is an empirical law which does not cover all material such as vacuum tubes, gas discharges, semiconductor and what is termed one dimensional conductor (e.g. a linear polyene chain) generally all deviate from Ohm's law.[30] In Ohmic material the resistance is proportional to the length  $l$  of the sample and inversely proportional to the sample cross section  $A$ :  $R = \rho l/A$  where  $\rho$  is the measured resistance in  $\Omega\text{cm}$  (in SI units is  $\Omega\text{m}$ ) Its inverse  $\sigma = \rho^{-1}$  is conductivity.

In this project we determined  $\Omega\text{cm}$ , and the linear correlation for conductive fibres investigated. Since we do not have enough information on how the product exhibits the linear electrical conductive properties after coating and whether it shows metal conductivity or not, we have measured the resistance of each sample in four different lengths (5,10,15 and 20 cm) in order to analyze the dependency of resistivity on concentration and coating techniques used. Based on a literature resistivity definition, resistivity of conductive fibres should be independent of resistances measured and the length of the sample for each sample in the experiment. Linear changes in resistances in correlation with length resulted resistivity in the measuring phase. Based on this rule defines as  $(\rho = \partial R / \partial L)$ , linear correlation when the best line fitted on those four points (appendix B), then the slope of the curve simply defines the resis-

tivity. The other important fact in this investigation is that the conductivity properties for fibres coated with conductive polymer depend on the number of free electrons and how fast they can move in the material (mobility  $\mu$ ):  $\sigma = n \mu e$  where "e" is electronic charge. In this experiment we will have considered on this part when we provide several time coating on fibres. In fact in this part we will analyse whether several times coating on fibres will reduce the conductivity or not, still free charges can be motivated in several times coating in order to provide the higher conductivity in fibres. This rule is the same as thickness of coating layer in different fabrics for achieve the higher conductivity as we will describe in its place. [4, 25]

#### 2.4.2 Surface resistivity and resistance using a concentric ring probe

Surface resistivity in ohm/square is used to evaluate isolative materials where high resistance characteristics are desirable. Surface resistance in ohms is a measurement to evaluate static dissipative packaging as well [31-34]. Here in this experiment the surface resistivity of all samples have been measured and then based on the following calculation the resistivity calculates.

$$\text{Ohm's law} \implies J_s = E/\rho_s \quad (1)$$

where  $J_s$  is surface current density for a concentric ring configuration.

Surface resistance based on literature sources is the ratio of a DC voltage  $U$  to the current,  $I_s$  flowing between two electrodes:

$$R_s = U/I_s \quad (2)$$

On the other hand the electric current density is often expressed by:  $J = I/S$  where ( $I$ ) is the current and  $S$  is the surface area. Surface current density  $J_s$  is defined as  $J_s = I/D$  where  $D$  is the width of the electrode.

For a concentric probe as it is shown in Figure 7.

$$J_s = I_s / 2\pi r^2 \quad (3)$$

where the radius  $r$  varies from  $R_1$  to  $R_2$ . In surface resistance or resistivity we make an assumption as well, we assume that the all the currents flow between electrodes along the surface and do not penetrate into the bulk of the material. The other useful formula is the Ohm's law which describes relationship between a current density  $J$  and the electric field intensity  $E$ , as we describes in the ohm's law  $J_s = E/\rho_s$ ; therefore, it is possible to find electric field between the concentric rings.

By using equation (1) and (3) we get:

$$E = \rho_s I_s / 2\pi r \quad (4)$$

The voltage between electrodes can be found by integrating the electric field from R1 to R2:

$$\begin{aligned}
 U_{R1,R2} &= \int_{R1}^{R2} E \, dr \\
 U_{R1,R2} &= \int_{R1}^{R2} \rho_s I_s / 2\pi r \, dr \\
 U_{R1,R2} &= (\rho_s I_s / 2\pi) \int_{R1}^{R2} 1/r \, dr \\
 &= \rho_s I_s / 2\pi \ln (R2/R1) \quad (5)
 \end{aligned}$$

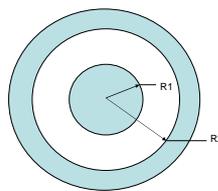
Substituting  $R_s = U / I_s$ :

$$R_s = \rho_s / 2\pi \ln (R2/R1) \quad (6)$$

$$\text{Or: } \rho_s = R_s 2\pi / [\ln (R2/R1)] = R_s \cdot K \quad (7)$$

The geometric dimension of the concentric probe being used during this investigation are  $D1=30.48 \pm 0.64$  mm and  $D2= 57.15 \pm 0.64$  mm. By calculation R1 and R2 and using formula (7);  $K= 2\pi / [\ln (R2/R1)]$

$$K = 10$$



**Figure 7: Schematic configuration for concentric ring electrodes. R1 = Outer radius of the centre electrode, R2 = Inner radius of the outer electrode**



## 3. RESULTS

### 3.1 ANALYSIS OF YARN RESULTS

#### 3.1.1 Yarns coated with PAN W

Yarns were fixed on the two sides of the glass plates with sufficient spaces in order to coat individual fibres and facilitate measuring in different lengths of coated fibres. Fibres were then coated with PAN W in different concentration. For each concentration we have provided different samples to calculate error and uncertainty discussed in ``METHOD``. Results of the measurement is sorted in ``APPENDIX A``. For each length and concentration we have several data. These data from statistical point of view have specific mean values and standard deviation from their mean values. The tables below illustrate the results on these two parameters for the first time coating fibres with PAN W.

**Table 1: Mean values and deviation of resistances at the first time of coating (1%-3%)**

| Concentration   | 1 %    |         |         |         | 2 %    |      |      |      | 3 %    |      |      |      |
|-----------------|--------|---------|---------|---------|--------|------|------|------|--------|------|------|------|
|                 | R(MΩ)  |         |         |         | R(MΩ)  |      |      |      | R(KΩ)  |      |      |      |
| Fibre length    | L (Cm) |         |         |         | L (Cm) |      |      |      | L (Cm) |      |      |      |
|                 | 5      | 10      | 15      | 20      | 5      | 10   | 15   | 20   | 5      | 10   | 15   | 20   |
| Mean Resistance | 39935  | 48143   | 164 652 | 287 508 | 11     | 15,7 | 19,6 | 27,3 | 883    | 1934 | 2522 | 3173 |
| Deviation (±)   | 26333  | 115 343 | 152 243 | 163 401 | 13.7   | 15.6 | 13   | 13.3 | 339    | 597  | 664  | 836  |

**Table 2: Mean values and deviation of resistances at the first time of coating (4%-6%)**

| Concentration       | 4 %            |      |         |         | 5 %            |      |      |      | 6 %            |     |      |      |
|---------------------|----------------|------|---------|---------|----------------|------|------|------|----------------|-----|------|------|
|                     | R(K $\Omega$ ) |      |         |         | R(K $\Omega$ ) |      |      |      | R(K $\Omega$ ) |     |      |      |
| Fibre length        | L (Cm)         |      |         |         | L (Cm)         |      |      |      | L (Cm)         |     |      |      |
|                     | 5              | 10   | 15      | 20      | 5              | 10   | 15   | 20   | 5              | 10  | 15   | 20   |
| Mean Resistance     | 3885           | 5347 | 6 248,4 | 7 875,6 | 863            | 2294 | 2968 | 3935 | 414            | 838 | 1192 | 1629 |
| Deviation ( $\pm$ ) | 2635           | 2292 | 2 180,8 | 2 719,8 | 445            | 1576 | 1761 | 1564 | 220            | 350 | 539  | 794  |

**Table 3: Mean values and deviation of resistances at the first time of coating (7%-10%)**

| Concentration       | 7 %            |        |         |        | 8 %            |     |       |     | 10 %           |     |     |     |
|---------------------|----------------|--------|---------|--------|----------------|-----|-------|-----|----------------|-----|-----|-----|
|                     | R(K $\Omega$ ) |        |         |        | R(K $\Omega$ ) |     |       |     | R(K $\Omega$ ) |     |     |     |
| Fibre length        | L (Cm)         |        |         |        | L (Cm)         |     |       |     | L (Cm)         |     |     |     |
|                     | 5              | 10     | 15      | 20     | 5              | 10  | 15    | 20  | 5              | 10  | 15  | 20  |
| Mean Resistance     | 516            | 952,5  | 1 231,4 | 1469   | 233            | 438 | 608,7 | 851 | 118            | 295 | 384 | 506 |
| Deviation ( $\pm$ ) | 250,3          | 560,33 | 606,93  | 607,12 | 111            | 125 | 181,1 | 276 | 53.6           | 226 | 207 | 198 |

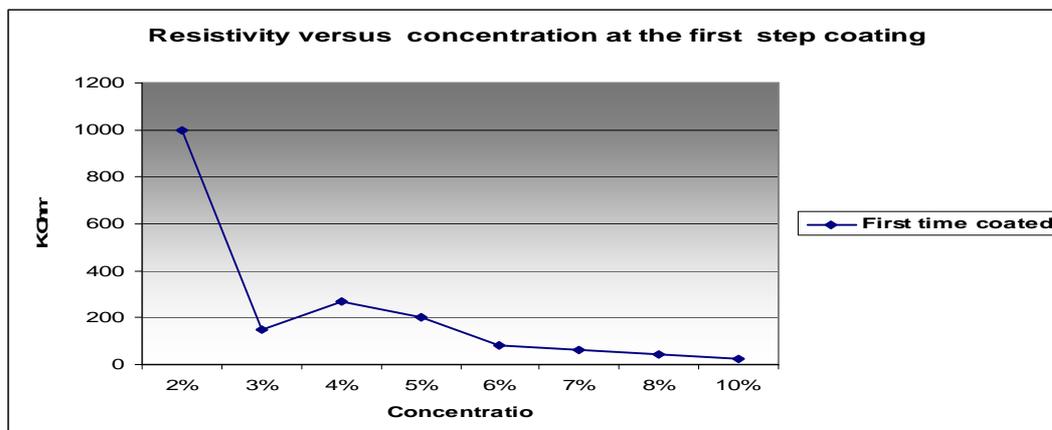
Mean resistances for each concentration in this step used for the further resistivity calculation and analysis, as it has demonstrated in APPENDIX B. As it is described in the method of the research, resistivity ( $\rho$ ) should be independent of the length of the created conductive fibres, due to the rule of linear conductivity. In the determination of resistivity we have applied a graphical method of analysing by constructed the best linear curves fitted the measured four different resistances and their calculated mean resistances values. From definition of the resistivity, the slope of these curves is estimated as resistivity ( $\rho$ ) for each individual created conductive fibre.

**Table 4: Resistivity ( $\rho$ ) for created conductive fibres at the first step of coating and deviation**

| Concentration          | 1%       | 2%    | 3%    | 4%    | 5%    | 6%    | 7%    | 8%    | 10%   |
|------------------------|----------|-------|-------|-------|-------|-------|-------|-------|-------|
| resistivity ( $\rho$ ) | 16 666,7 | 1000  | 150   | 267   | 203   | 81,7  | 61    | 41,4  | 25,5  |
| Deviation ( $\pm$ )    | (*)      | 1900  | 80    | 359   | 137   | 69    | 59    | 26,4  | 16,3  |
| Unit                   | M Ohm    | K Ohm | K Ohm | K Ohm | K Ohm | K Ohm | K Ohm | K Ohm | K Ohm |

(\*); For 1% concentration of PAN W, it has demonstrated a non linear correlation.

**Graph 1: First time coating and resistivity resulted in different concentration**



This graph shows a dramatic change in resistivity for 3% concentration at the first time coating and slightly increasing on resistivity for four and five percent concentration and again decreasing of resistivity for higher concentration. This result is not approved by theory and literature. In order to explain this phenomenon we can construct a few hypotheses which is describing as follow.

### **3.1.1.1 First hypothesis is inhomogeneous coating at the first step**

In order to analyze this result we have repeated this experiment with new samples again and, the result was the same as before.

By recording a live microscopic photography procedure (Fig 10-15) particularly for 3% concentration we observed that polyaniline molecules dispersed around fibre on the surface of glass plate has roughly higher motivation and interest to move toward the polyaniline on the surface of fibre or attach to the fibre to create the larger molecule chain on the surface of the fibre.

In the early few seconds all polyaniline molecules separated from its aqueous phase and adhere to the fibre rapidly. This phenomenon can be observed from the pictures below.



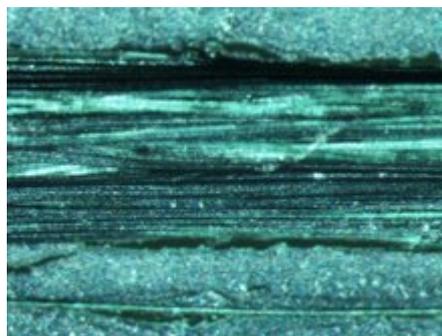
**Figure 8:** PANW 3% conc. Dropping on fibre.



**Figure 9:** 3% conc. after few seconds



**Figure 10:** PANW 3% conc. Two phases separation.



**Figure 11:** A homogeneous conductive fibre creates.

As these photos show a few seconds after dropping polyaniline (3% concentration) on fibres, polyaniline molecules demonstrate a tendency to attach to the fibre. Material dissipated around the fibre (shown as small polyaniline particles) on the surface of the plate through microscopic photos shows the polyaniline molecules' movement toward the fibre surface in order to attach to the fibre or other larger polyaniline polymer chains on the fibre. This means that the mobility of polyaniline molecules in this concentration is higher than in other concentrations, as we can see in figure 11 almost all polyaniline molecules separated from their aqueous phase and provided a homogeneous concentration around the fibre and left a clear aqueous phase on the plate surface. This phenomenon has not been observed for other concentrations during live microscopic photography. In 4 and 5% concentrations the dissipated polyaniline molecules in the aqueous phase do not show the same motivation toward the fibre or the larger polyaniline molecule on the surface of the fibre, and keep drying on the surfaces of the plate. The fact of higher conductivity for higher concentration obviously is due to the material coated on the fibre containing higher conductive molecules than it is supposed to be in lower concentration, which normally leads to higher conductivity, but in 3% concentration, in which we have shown in this experiment is a critical point for starting a reasonable conductive phase for a fibre coated with polyaniline dispersed in water.

### 3.1.1.2 Second hypothesis is connected to the coating technique

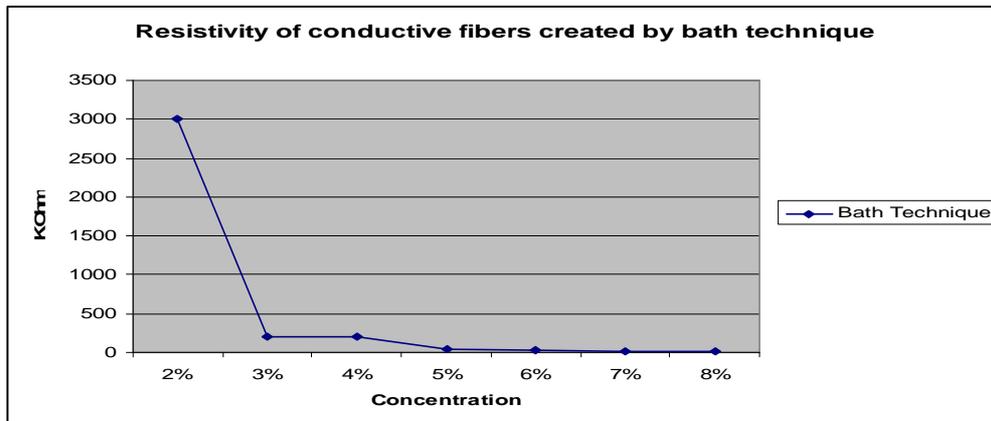
As it is discussed in the “METHOD” there are few techniques on coating fibres, which can effect on homogeneous conductive fibre created. It means that whether we use the other method of coating, perhaps the result would be difference from other in some extend. By using glass plates we provide a better condition for motivation of polyaniline molecules in aquatic phase in a balance with other condition such as optimum concentration.

In order to test this idea the other technique for coating is used. This technique was dipping fibres in a bath of different concentrations of PAN W, then they were dried and fixed on the surface plates for measuring. The result illustrated in the table and graph below.

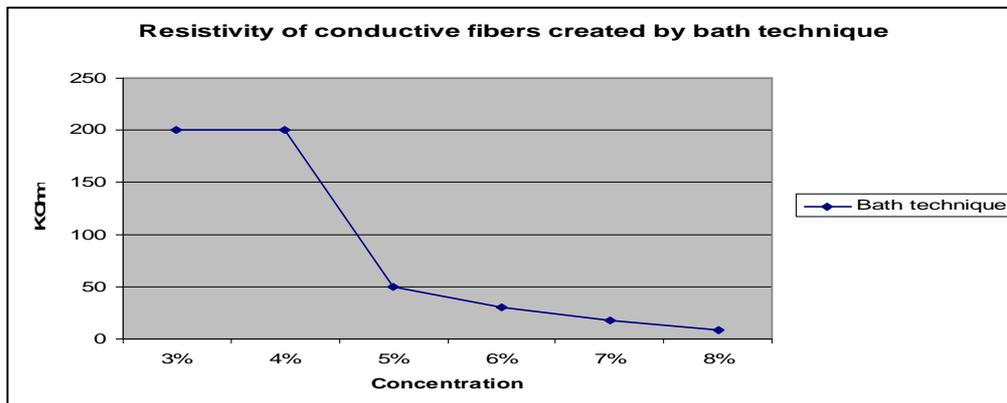
**Table 5: Result of bath technique used for creating conducting fibres.**

| <b>Resistivity(<math>\rho</math>) of conductive fibres created by bath technique</b> |            |            |            |            |            |            |            |
|--|------------|------------|------------|------------|------------|------------|------------|
| <b>Concentration</b>   | <b>2 %</b> | <b>3 %</b> | <b>4 %</b> | <b>5 %</b> | <b>6 %</b> | <b>7 %</b> | <b>8 %</b> |
| <b>Resistivity(<math>\rho</math>)</b>  | 3000       | 200        | 200        | 50         | 30         | 18         | 8          |
| <b>Unit</b>  | K Ohm      |

**Graph 2: Bath technique and resistivities of conductive fibres (1% - 8%)**



**Graph 3: Bath technique and resistivities of conductive fibres (2% - 8%)**



As the graphs show by increasing concentration resistivity decreases, but 3% concentration is still a critical point of all.

Since the conductivity resulted in 1% concentration is so low compare to other concentration, so we have not put in these graphs.

### 3.1.1.3 Third hypothesis is covering inhomogeneous coating by several times coated yarns

In order to develop this hypothesis, fibres which were coated and characterised in the first step, were coated for the second time with the polyaniline salt with the same concentration which were coated before. The measuring of their resistances illustrated in the ``APPENDIX A`` and their calculated resistivities illustrated in the table and graphs below.

**Table 6: Mean values and deviation of resistances at the second time of coating (1%-3%)**

| Concentration       | 1 %            |       |       |      | 2 %            |      |      |      | 3 %            |     |     |      |
|---------------------|----------------|-------|-------|------|----------------|------|------|------|----------------|-----|-----|------|
|                     | R(M $\Omega$ ) |       |       |      | R(K $\Omega$ ) |      |      |      | R(K $\Omega$ ) |     |     |      |
| Fibre length        | L (Cm)         |       |       |      | L (Cm)         |      |      |      | L (Cm)         |     |     |      |
|                     | 5              | 10    | 15    | 20   | 5              | 10   | 15   | 20   | 5              | 10  | 15  | 20   |
| Mean Resistance     | 47,5           | 103,7 | 214,5 | 1272 | 773            | 1305 | 1703 | 2133 | 288            | 651 | 925 | 1262 |
| Deviation ( $\pm$ ) | 24,22          | 69,67 | 118,5 | 1247 | 326            | 456  | 632  | 665  | 66,4           | 135 | 182 | 328  |

**Table 7: Mean values and deviation of resistances at the second of coating (4%-6%)**

| Concentration       | 4 %            |     |     |     | 5 %            |     |     |     | 6 %            |     |     |     |
|---------------------|----------------|-----|-----|-----|----------------|-----|-----|-----|----------------|-----|-----|-----|
|                     | R(K $\Omega$ ) |     |     |     | R(K $\Omega$ ) |     |     |     | R(K $\Omega$ ) |     |     |     |
| Fibre length        | L (Cm)         |     |     |     | L (Cm)         |     |     |     | L (Cm)         |     |     |     |
|                     | 5              | 10  | 15  | 20  | 5              | 10  | 15  | 20  | 5              | 10  | 15  | 20  |
| Mean Resistance     | 261            | 472 | 685 | 873 | 147            | 298 | 449 | 593 | 103            | 201 | 293 | 404 |
| Deviation ( $\pm$ ) | 79             | 97  | 103 | 103 | 35             | 68  | 100 | 123 | 11             | 30  | 34  | 75  |

**Table 8: Mean values and deviation of resistances at the second time of coating (7%-10%)**

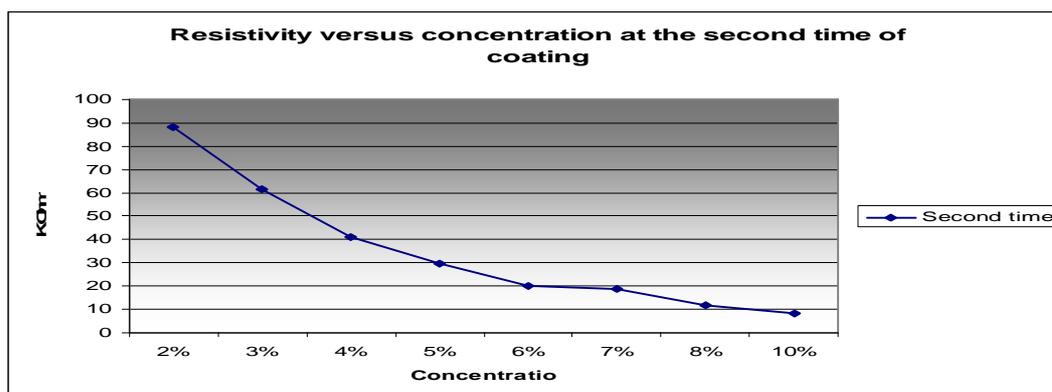
| Concentration   | 7 %    |      |       |      | 8 %    |      |     |     | 10 %   |     |     |     |
|-----------------|--------|------|-------|------|--------|------|-----|-----|--------|-----|-----|-----|
|                 | R(KΩ)  |      |       |      | R(KΩ)  |      |     |     | R(KΩ)  |     |     |     |
| Fibre length    | L (Cm) |      |       |      | L (Cm) |      |     |     | L (Cm) |     |     |     |
|                 | 5      | 10   | 15    | 20   | 5      | 10   | 15  | 20  | 5      | 10  | 15  | 20  |
| Mean Resistance | 94,3   | 179  | 270,7 | 375  | 47     | 101  | 157 | 227 | 56     | 106 | 146 | 183 |
| Deviation (±)   | 8      | 17,5 | 44,2  | 74,2 | 17,2   | 25,4 | 44  | 64  | 42     | 69  | 68  | 66  |

**Table 9: Resistivity (ρ) for created conductive fibres at the second step of coating and deviation**

| Concentration   | 1%    | 2%    | 3%    | 4%    | 5%    | 6%    | 7%    | 8%    | 10%   |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| resistivity (ρ) | 57,1  | 88,2  | 61,7  | 40,9  | 29,7  | 20,2  | 18,6  | 11,9  | 8,5   |
| Deviation (±)   | (*)   | 68,8  | 29,2  | 12,2  | 10,3  | 5,8   | 5,6   | 5,5   | 7,3   |
| Unit            | M Ohm | K Ohm |

(\*); For 1% concentration of PAN W, it has demonstrated a non linear correlation.

**Graph 4: Second time coating and resistivity resulted in different concentration**



As this graph shows after the second time coating resistivities follows the concentration reversely. This result is supported theoretically.

In order to analyze the effect of the steps of coating on homogeneous conductive fibres created, we have proceeded coating of the fibres with the third time coating with PAN W. The results are in the tables and graphs below:

**Table 10: Mean values and deviation of resistances at the third time of coating (1%-3%)**

| Concentration       | 1 %            |     |      |      | 2 %            |       |       |      | 3 %            |     |     |     |
|---------------------|----------------|-----|------|------|----------------|-------|-------|------|----------------|-----|-----|-----|
|                     | R(M $\Omega$ ) |     |      |      | R(K $\Omega$ ) |       |       |      | R(K $\Omega$ ) |     |     |     |
| Fibre length        | L (Cm)         |     |      |      | L (Cm)         |       |       |      | L (Cm)         |     |     |     |
|                     | 5              | 10  | 15   | 20   | 5              | 10    | 15    | 20   | 5              | 10  | 15  | 20  |
| Mean Resistance     | 37,4           | 8,2 | 13,4 | 18,6 | 285,2          | 579,3 | 839,8 | 1083 | 120            | 235 | 347 | 447 |
| Deviation ( $\pm$ ) | 3,2            | 6,6 | 10,5 | 15,2 | 60             | 116   | 159   | 188  | 25             | 42  | 55  | 61  |

**Table 11: Mean values and deviation of resistances at the third of coating (4%-6%)**

| Concentration       | 4 %            |      |      |     | 5 %            |      |      |      | 6 %            |     |     |      |
|---------------------|----------------|------|------|-----|----------------|------|------|------|----------------|-----|-----|------|
|                     | R(K $\Omega$ ) |      |      |     | R(K $\Omega$ ) |      |      |      | R(K $\Omega$ ) |     |     |      |
| Fibre length        | L (Cm)         |      |      |     | L (Cm)         |      |      |      | L (Cm)         |     |     |      |
|                     | 5              | 10   | 15   | 20  | 5              | 10   | 15   | 20   | 5              | 10  | 15  | 20   |
| Mean Resistance     | 115,4          | 234  | 348  | 447 | 61             | 128  | 194  | 263  | 46             | 97  | 145 | 195  |
| Deviation ( $\pm$ ) | 10,4           | 20,2 | 29,2 | 32  | 11,2           | 15,3 | 17,9 | 26,3 | 4,8            | 6,1 | 6,6 | 14,8 |

**Table 12: Mean values and deviation of resistances at the third time of coating (7%-10%)**

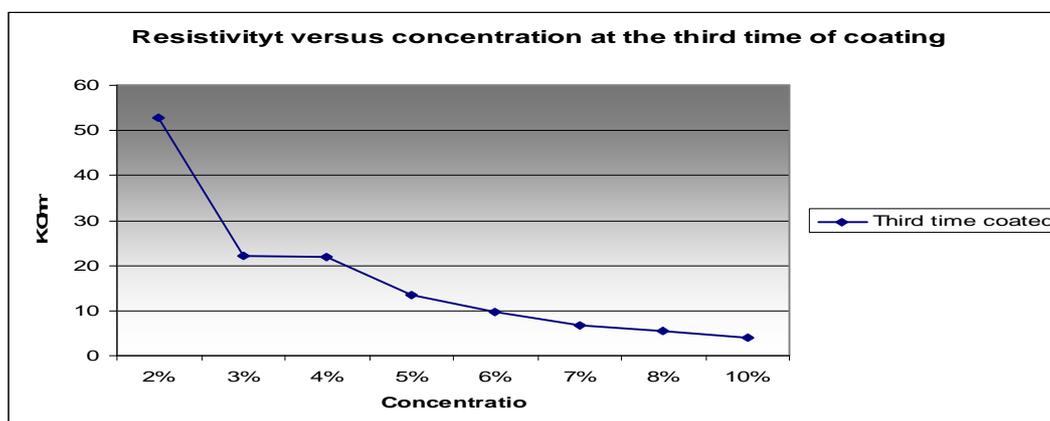
| Concentration       | 7 %            |      |       |       | 8 %            |      |      |       | 10 %           |    |      |      |
|---------------------|----------------|------|-------|-------|----------------|------|------|-------|----------------|----|------|------|
|                     | R(K $\Omega$ ) |      |       |       | R(K $\Omega$ ) |      |      |       | R(K $\Omega$ ) |    |      |      |
| Fibre length        | L (Cm)         |      |       |       | L (Cm)         |      |      |       | L (Cm)         |    |      |      |
|                     | 5              | 10   | 15    | 20    | 5              | 10   | 15   | 20    | 5              | 10 | 15   | 20   |
| Mean Resistance     | 39,4           | 73,2 | 106,8 | 140,6 | 18,6           | 48,3 | 70,9 | 102,3 | 18,6           | 39 | 63,5 | 79   |
| Deviation ( $\pm$ ) | 6,6            | 10   | 13,5  | 15    | 6              | 10,2 | 13,8 | 13,9  | 8,8            | 17 | 18   | 15,5 |

**Table13: Resistivity ( $\rho$ ) for created conductive fibres at the third step of coating and deviation**

| Concentration          | 1%    | 2%    | 3%    | 4%    | 5%    | 6%    | 7%    | 8%    | 10%   |
|------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| resistivity ( $\rho$ ) | 1     | 52,9  | 22,2  | 22    | 13,5  | 9,76  | 6,8   | 5,58  | 4     |
| Deviation ( $\pm$ )    | (*)   | 17,1  | 6,2   | 3     | 2,5   | 1,6   | 1,5   | 1,3   | 1,65  |
| Unit                   | M Ohm | K Ohm |

(\*); For 1% concentration of PAN W, it has demonstrated a non linear correlation.

**Graph 5: Third time coating and resistivity resulted in different concentration**



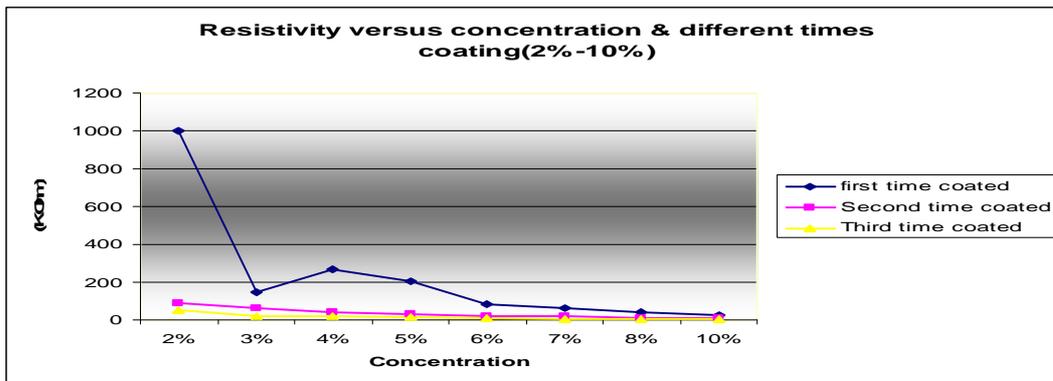
As this graph shows 3% concentration is still in the critical concentration for creating conductive fibres.

By putting all the values of resistivities in these three steps of coating together, we can demonstrate the better visual conclusion of the results. Data in three different times of coating and different concentration are in the table 14. This table and graphs below illustrate a comparison between these three different steps and concentration.

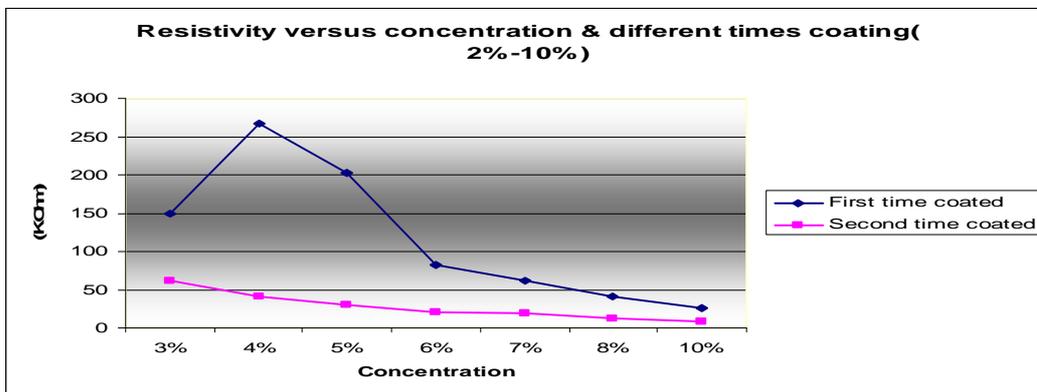
**Table 14: Resistivity ( $\rho$ ) for created conductive fibres at three steps of coating and deviation**

| Concentration | 1%       | 2%    | 3%    | 4%    | 5%    | 6%    | 7%    | 8%    | 10%   |
|---------------|----------|-------|-------|-------|-------|-------|-------|-------|-------|
| Coating #     |          |       |       |       |       |       |       |       |       |
| 1             | 16 666,7 | 1000  | 150   | 267   | 203   | 81,7  | 61,22 | 41,44 | 25,5  |
| 2             | 57,1     | 88,2  | 61,7  | 40,9  | 29,7  | 20,2  | 18,6  | 11,9  | 8,5   |
| 3             | 1        | 52,9  | 22,2  | 22    | 13,5  | 9,76  | 6,81  | 5,58  | 4     |
| Unit          | M Ohm    | K Ohm | K Ohm | K Ohm | K Ohm | K Ohm | K Ohm | K Ohm | K Ohm |

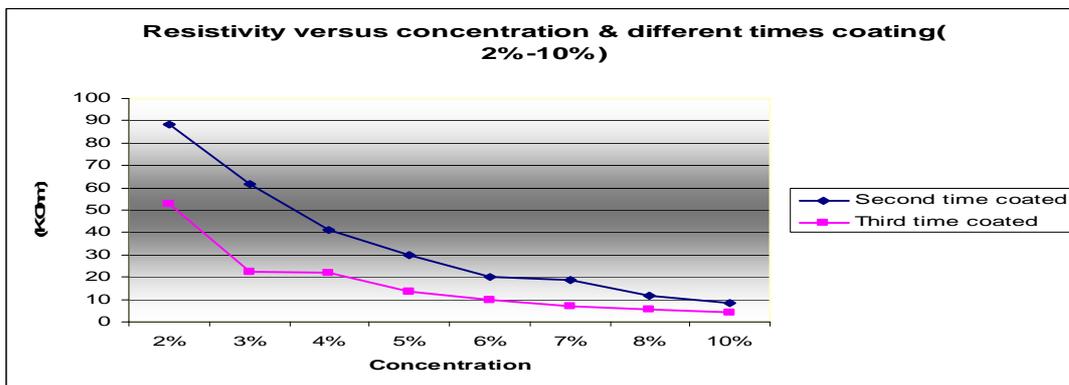
**Graph 6: Resistivity resulted of different times of coating and different concentration**



**Graph 7: Resistivity resulted of different times of coating and different concentration**



**Graph 8: Resistivity resulted of different times of coating and different concentration**



From table 14 and graphs results in this part of experiment summarized in bellows:

- At the first step of coating 3% w/w concentration is a critical point for creating conductive fibres in spite of the coating methods.

- One step more coating could be substituted with higher concentration. As the table 14 shows; two times coating with 3% concentration can create conductive fibre with lower resistivity than 6% concentration at the first step of coating. The result for the first step coating with 8% concentration is roughly the same as it has determined in 4% concentration with two times coating and 10% with 5%.
- For third time coating except for the 3% concentration which the resistivity are almost the same, other concentrations show the lower rate of resistivity decreasing compare to the second step of coating and higher concentration with one step lower coating number means that coating number has also an optimal range for decreasing resistivities as concentration, but still the resistivity decreases with one step more coating.
- In general two times coating can provide more homogeneous conductive fibres with a compromising resistivity level.
- Analysis of the deviations of calculated mean resistivities values demonstrated in the table 15.

**Table 15: Analysis of deviation % compared to the mean values**

| Concentration               | 1%       | 2%   | 3%   | 4%    | 5%   | 6%   | 7%    | 8%    | 10%  |
|-----------------------------|----------|------|------|-------|------|------|-------|-------|------|
| <b>Coating #</b>            |          |      |      |       |      |      |       |       |      |
| <b>First (Mean)</b>         | 16 666,7 | 1000 | 150  | 267   | 203  | 81,7 | 61,22 | 41,44 | 25,5 |
| <b>First (Deviation)</b>    | *        | 1900 | 150  | 266,6 | 203  | 81,7 | 61,2  | 41,4  | 22,5 |
| <b>First (Deviation %)</b>  | *        | 190  | 56,7 | 134,6 | 67,5 | 84   | 96    | 63,7  | 63,9 |
| <b>Second (Mean)</b>        | 57,1     | 88,2 | 61,7 | 40,9  | 29,7 | 20,2 | 18,6  | 11,9  | 8,5  |
| <b>Second (Deviation)</b>   | *        | 68,8 | 29,3 | 12,2  | 10,3 | 5,76 | 5,6   | 5,5   | 7,3  |
| <b>Second (Deviation %)</b> | *        | 78   | 47,5 | 29,8  | 34,7 | 28,6 | 30    | 46,2  | 85,8 |
| <b>Third (Mean)</b>         | 1        | 52,9 | 22,2 | 22    | 13,5 | 9,76 | 6,81  | 5,58  | 4    |
| <b>Third (Deviation)</b>    | *        | 17,1 | 6,2  | 3     | 2,5  | 1,6  | 1,5   | 1,3   | 1,65 |
| <b>Third (Deviation %)</b>  | *        | 32,3 | 27,9 | 13,6  | 18,5 | 16,4 | 22    | 23,3  | 41,3 |

(\*); For 1% concentration of PAN W, it has demonstrated a non linear correlation.

As this table shows coating fibres at the first time involves more than 50% deviation from their mean values for each concentration, but for fibres coated with Panipol 3% concentration this is still lower than others. At the second step of coating fibres, it is in more acceptable ranges than the previous step from the deviation point of view, and for 4% to 7% we can get the better results as well. At the third step of coating percentage deviation is even lower.

### 3.1.2 Fibre coated with PAN T

The other substance which is used in this project is PAN T (Panipol T, polyaniline in toluene as a solvent). The goal of this part of research is comparing the effect of conductive polymer (polyaniline) dispersed in water with the solvent type in creating conductive fibres and fabrics. Using a solvent for coating as it shows in figure 5 transfer a thin film on the fibre but in polyaniline dispersed in water, after coating on the fibre and occurring evaporation of water content we will get a deposit conductive polymer in the structure of fibres. The procedure of this part of experiment is the same as it was for the fibres coated with PAN W. PAN T consists of polyaniline in maximum 5% w/w in the solvent, so it has diluted from 1% to 4% in toluene. Fibres which were fixed on the glass plate coated with each concentration for at least five individual samples. After drying fibres, resistance for each sample measured in four different lengths (5, 10, 15 and 20). The results arranged in APPENDIX A.

In this part we used two different method of analysis, one is the same as the fibre coated with PAN W and the other is by statistic software such as “SPSS” and “MEANTAB”.

#### 3.1.2.1 Analysis by determining the resistivity and deviation

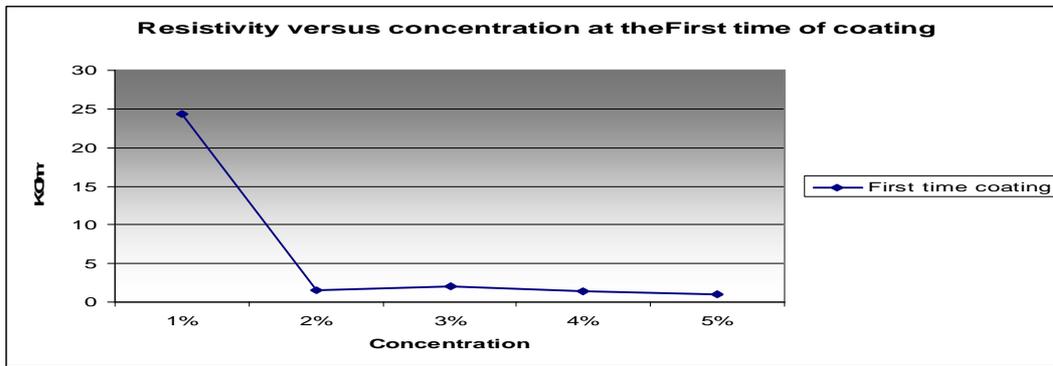
Based on the mean values of the resistances measured, the slope of the best fitted linear curve on those four resistances for each concentration, defines the resistivity of the created conductive fibre. Resistivities and their deviation at the first step of coating shows in table 16.

**Table 16: Resistivities and deviations at the first time of coating fibres with PAN T**

| Concentration(w/w)                 | 1%   | 2%   | 3%  | 4%    | 5%  |
|------------------------------------|------|------|-----|-------|-----|
| Resistivity(K $\Omega$ )<br>(Mean) | 24.2 | 1.5  | 2   | 1.477 | 1   |
| Deviation( $\pm$ )                 | 81.8 | 0.55 | 1.3 | 1.23  | 0.4 |
| Deviation (%)                      | *    | 36,6 | 65  | 83    | 40  |

(\*); For 1% concentration of PAN T, it has demonstrated a non linear correlation.

**Graph 9: Resistivity resulted in different concentration of PAN T**



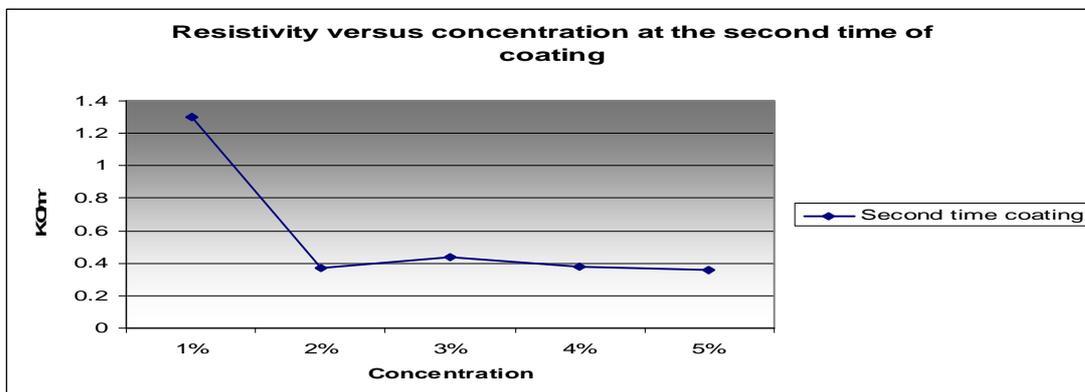
As the table 16 and the graph 9 show at the first time of coating, for 1% concentration we can not achieve the standard level of resistivity and deviation.

In order to analyse the effect of coating steps in providing more homogeneous conductive fibres, samples are coated for the second time after the first step of coating and measured. Data organized in appendix A and based on the data the mean values and deviation for each sample calculated for four (5, 10,15 and 20) different lengths. The slope of the best linear curve fitted on the four resistances results the resistivity for each concentration based on the theory. Resistivities and their deviations show in the table 17. The graph 17 provides a visual figure of the table 17.

**Table 17: Resistivities and deviations at the second time of coating fibres with PAN T**

| Concentration(w/w)        | 1%   | 2%   | 3%   | 4%   | 5%   |
|---------------------------|------|------|------|------|------|
| Resistivity(KΩ)<br>(Mean) | 1.32 | 0.37 | 0.44 | 0.38 | 0.36 |
| Deviation(±)              | 0.44 | 0.09 | 0.21 | 0.26 | 0.19 |
| Deviation (%)             | 33   | 24   | 48   | 68   | 53   |

**Graph 10: Resistivity resulted in different concentration of PAN T for the second time coating**

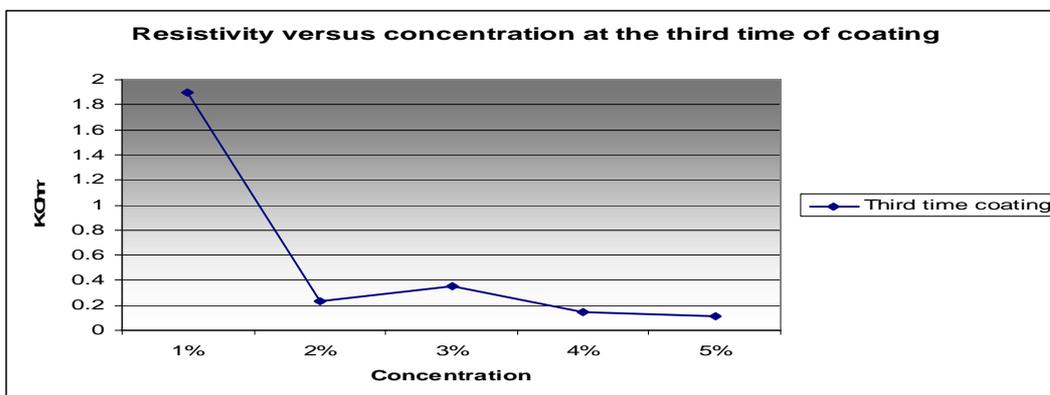


Coating fibres developed for the third time and the results are showed in table 18.

**Table 18: Resistivities and deviations at the third time of coating fibres with PAN T**

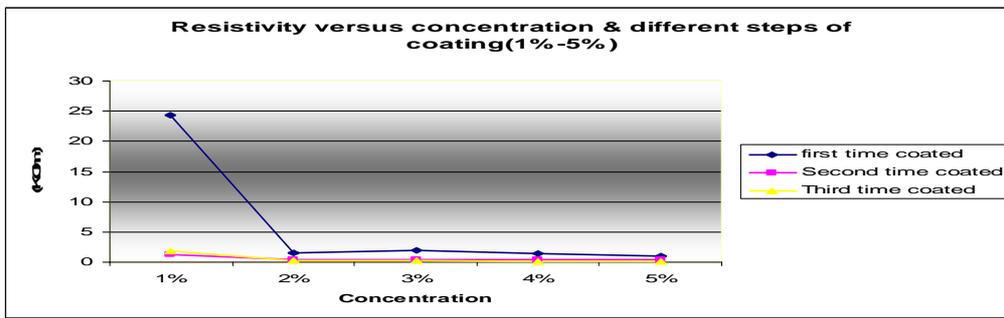
| Concentration(w/w)        | 1%   | 2%   | 3%    | 4%    | 5%    |
|---------------------------|------|------|-------|-------|-------|
| Resistivity(KΩ)<br>(Mean) | 1.94 | 0.23 | 0.35  | 0.15  | 0.11  |
| Deviation(±) (KΩ)         | 0.93 | 0.02 | 0.132 | 0.072 | 0.043 |
| Deviation (%)             | 48   | 8,6  | 38    | 48    | 39    |

**Graph 11: Resistivity resulted in different concentration of PAN T for the third time coating**



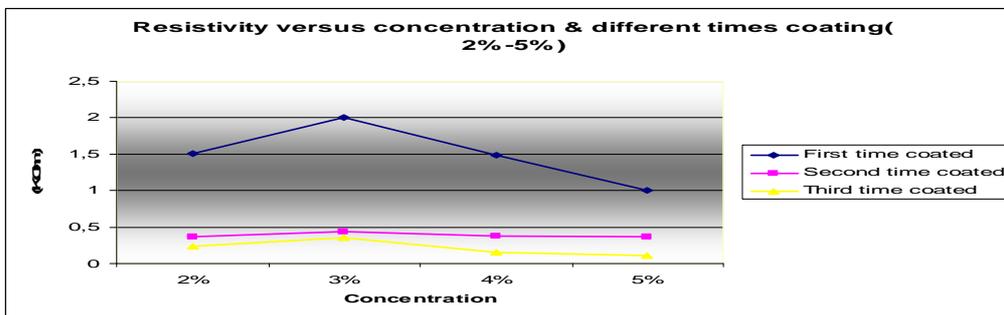
Putting all these data together demonstrate a better visual conclusion of this part of the research. Three graphs below figure out the resistivities resulted on three different steps of coating in one scale to compare the results. These graphs are on the mean values of the resistivities calculated basis. As these graphs show higher concentration as well as coating times creates the lower resistivity in average, but still we have to consider deviation as other important factor.

**Graph 12: Resistivities of conductive fibres in different steps of coating (1%-5%)**

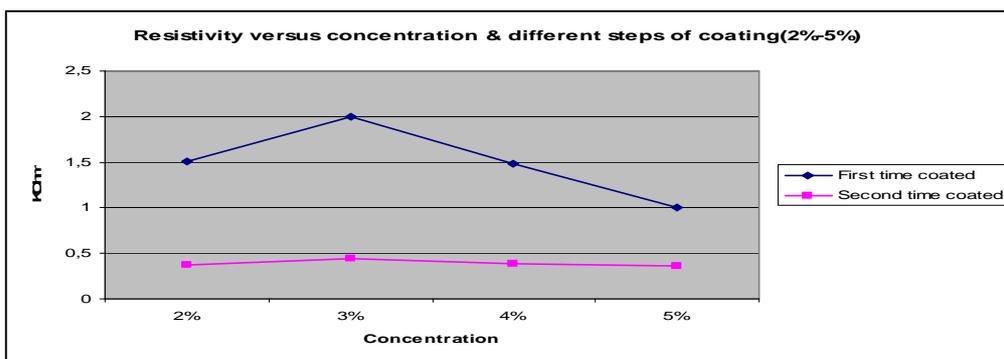


Resistivity of conductive fibres in 1% concentration and first step of coating is considerably high compare to other concentration. Graph 13, 14 and 15 show the effect of other concentrations in different steps of coating.

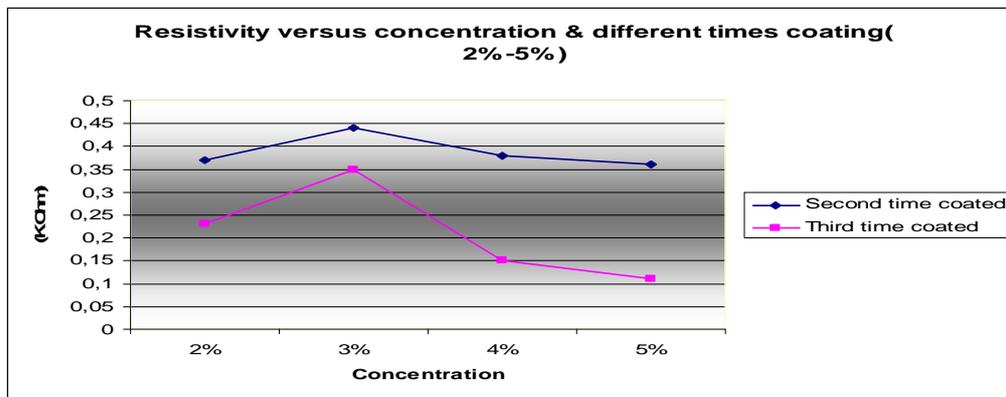
**Graph 13: Resistivities of conductive fibres in different steps of coating (2%-5%)**



**Graph 14: Resistivities of conductive fibres at first and second step of coating (2%-5%)**



**Graph 15: Resistivities of conductive fibres at second and third step of coating (2%-5%)**



The other important factor have to be analyzed is deviation of resistivities from their mean values. In order to normalize these values and compare with each other, we normalize them on percentage expression based on their mean values.

**Table 19: Mean values of resistivities and deviation percentages for different coating times**

| Concentration               | 1%   | 2%   | 3%    | 4%    | 5%    |
|-----------------------------|------|------|-------|-------|-------|
| <b>Coating #</b>            |      |      |       |       |       |
| <b>First (Mean)</b>         | 24.2 | 1.5  | 2     | 1.477 | 1     |
| <b>First (Deviation)</b>    | 81.8 | 0.55 | 1.3   | 1.23  | 0.4   |
| <b>First (Deviation %)</b>  | *    | 36,6 | 65    | 83    | 40    |
| <b>Second (Mean)</b>        | 1.32 | 0.37 | 0.44  | 0.38  | 0.36  |
| <b>Second (Deviation)</b>   | 0.44 | 0.09 | 0.21  | 0.26  | 0.19  |
| <b>Second (Deviation %)</b> | 33   | 24   | 48    | 68    | 53    |
| <b>Third (Mean)</b>         | 1.94 | 0.23 | 0.35  | 0.15  | 0.11  |
| <b>Third (Deviation)</b>    | 0.93 | 0.02 | 0.132 | 0.072 | 0.043 |
| <b>Third (Deviation %)</b>  | 48   | 8,6  | 38    | 48    | 39    |

(\*); For 1% concentration of PANT, it has demonstrated a non linear correlation.

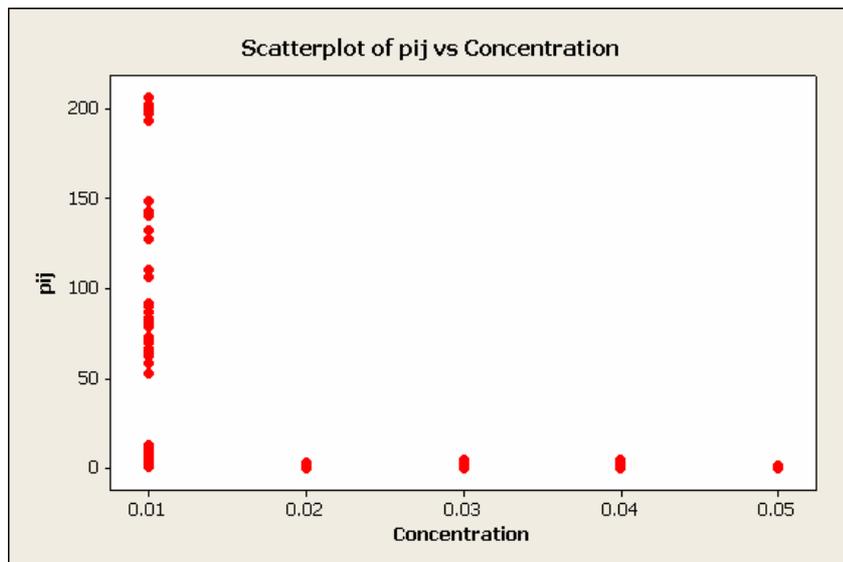
Table 19 figures out an integrated summary of this part of experiment. As this table shows higher concentration along with higher coating step can create the better conductivity.

- Resistivity decreases dramatically for 2% concentration and a homogeneous conductive fibre resulted. Both resistivity and its standard deviation are considerably lower than those have been resulted for other concentration.
- After s the second step of coating, 2% concentration still provides the better result, whereas 1% concentration after second time coating demonstrates dramatically changes on both resistivity and its deviation. The results in other concentration demonstrated slightly changes.

- At the first step of coating at 2% concentration created conductive fibre shows the lower resistivity and better deviation which can be considered as an inhomogeneous coating at the first step but the result for second and third time coating provided a reasonable resistivity at 2% concentration and the better deviation percentage. This result concerns that 2% concentration as a critical concentration in creating conductive fibres.
- Totally we can consider 2% concentration as a compromising point for both mean resistivity value and deviation compare to other concentration at all steps of coating as well as two times of coating fibre.

### 3.1.2.2 Analysis by statistic software (MEANTAB)

One other method of analysing data is by using statistic software such as SPSS. In this part all data putted in the SPSS data inventory and the result could not be shown in the form of graphs. These graphs below analysed by MEANTAB. The following graphs can give interesting results which support the results given by the previous method. The goal is analysing the effect of concentration and coating number on conductivity and how the conductivity varies with these two factors.



*Figure 12: The scatterplot of pij versus concentration*

This graph shows that in 1% concentration the resistivity is much higher than for 2 and higher percent concentration. This is the result that we have already discussed about it means that 1% concentration is not in the acceptable range of resistivity while the variation of the resistivity from the mean value is high as well. So we have omitted the data for the 1% concentration from the inventory and analysis proceeds for the higher concentration.

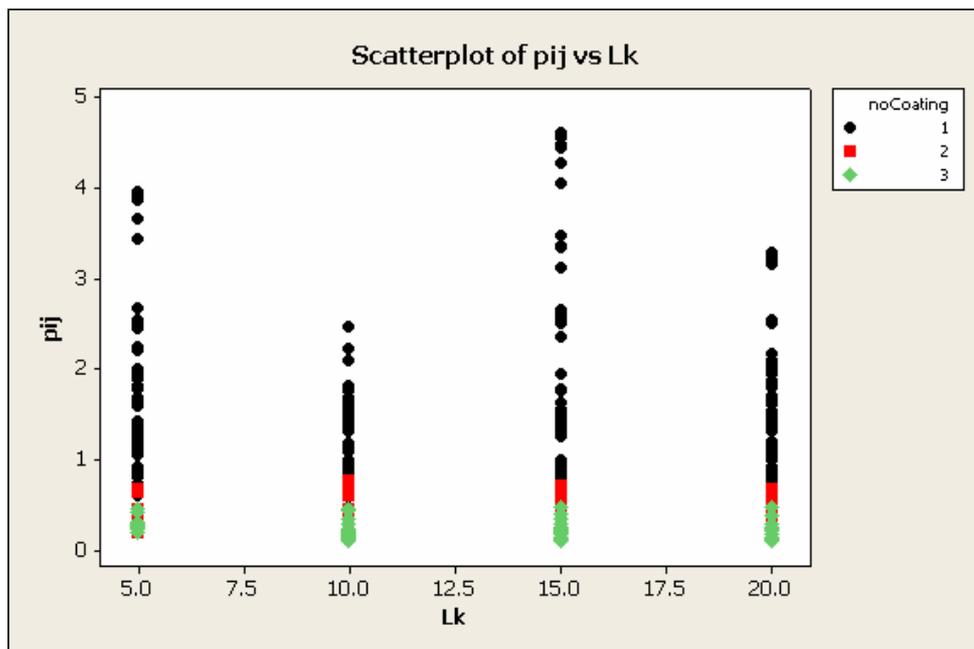


Figure 13: The scatterplot of  $\rho_{ij}$  versus the length

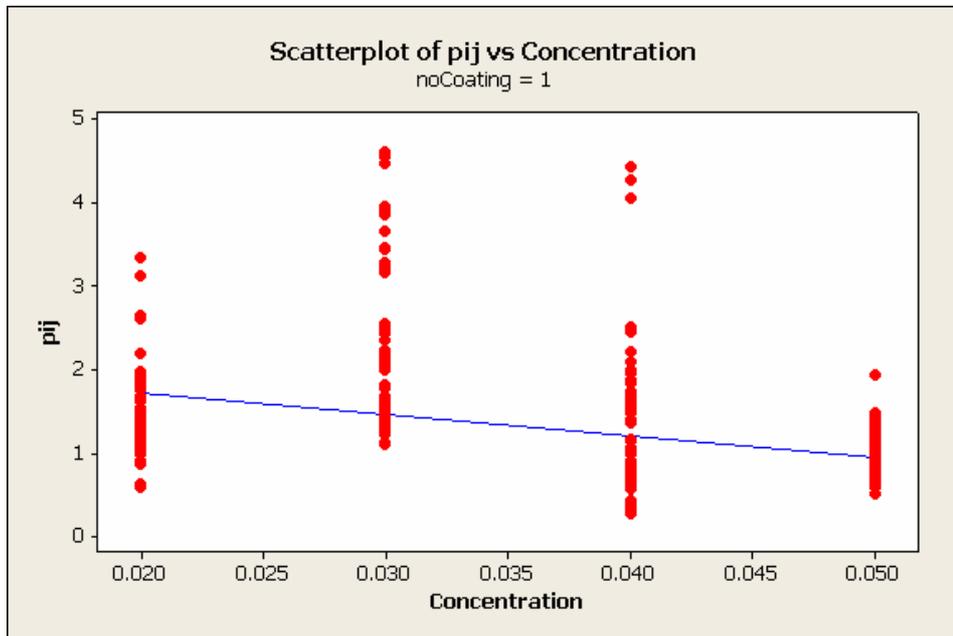


Figure 14: First time coating and the scatterplot of  $p_{ij}$  versus concentration

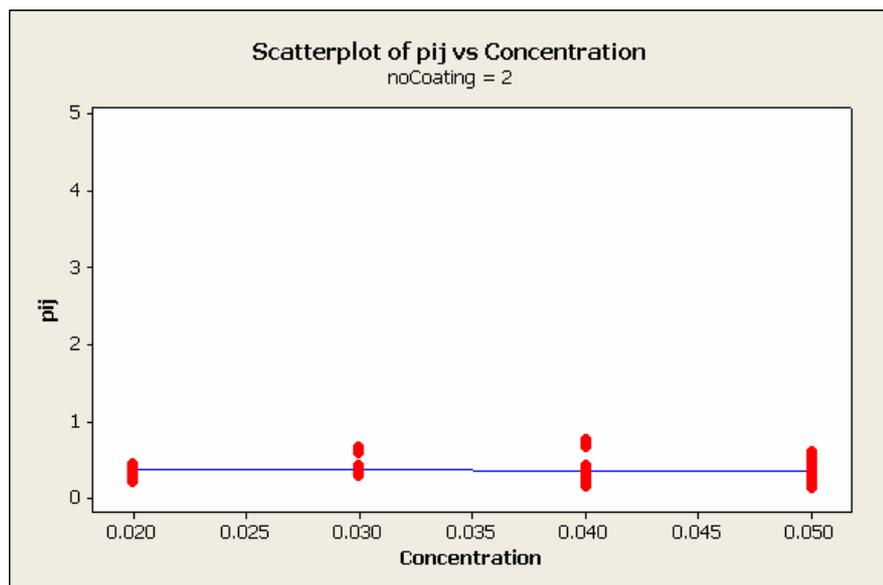
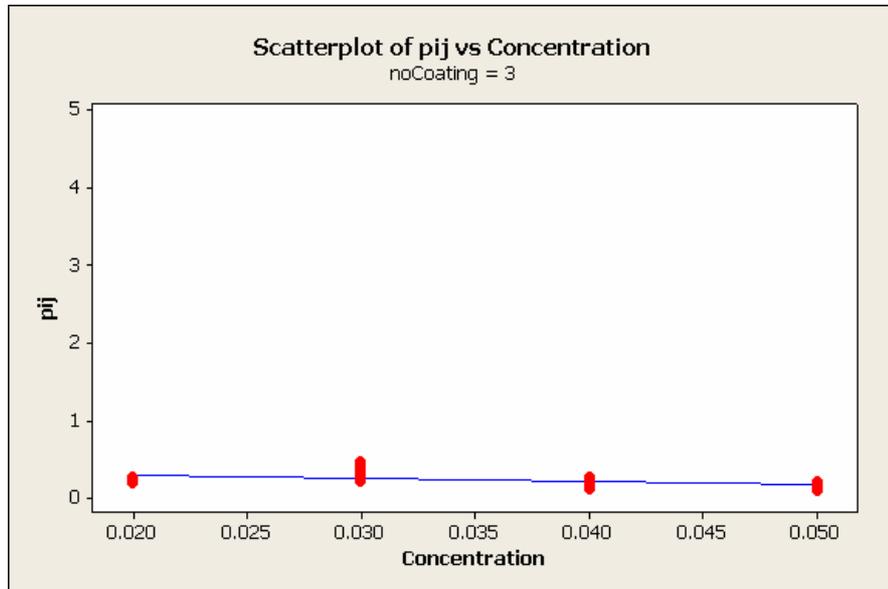


Figure 15: Second time coating and the scatterplot of  $p_{ij}$  versus concentration



**Figure 16: Third time coating and the scatterplot of pij versus concentration**

Theoretically resistivity is independent coefficient of the length of the conductive filament. Graph 13 demonstrates that at the first time of coating the resistivity is not constant as well as high variation for each measuring length. This result differs from the second and third time of coating. The results of the graph 14, 15, 16 are as below.

- The optimum coating times in creating homogeneous conductive fibres is two times coating. This result can be showed in the graphs 14, 15 and 16.
- Moreover besides creating homogeneous conductive fibres at the second time coating the effect of higher concentration to produce conductive fibre will be decreased from the first time coating. At the second time coating resistivity would be roughly constant for all concentration means that with the concentration as low as two percent we will get a reasonable level of resistivity with conductive fibres. At the third step of coating resistivity getting slightly decrease in increasing concentration.

This method of analyzing can be developed for created conductive fibres with PAN W. Since the large inventory size and supporting the result with the previous method of analyzing, we have only explained it with the created conductive fibres with PAN T.

### 3.2 FABRICS CONDUCTIVITY ANALYSIS

The other part of this project is investigation of conductive polymer on creating conductive fabrics by surface coating. Fabrics which are being used in this part are using as air filtration for building in three different types which are described in section.

As it has been explained one important purpose of using conductive fabrics is electrostatic charge adsorbs ion. Dust and particles in air have positive charges, if we provide negative charge on surfaces of air filters, particles adsorptions will enhance and cleaner air let get in the building. Two different polyaniline dispersed in water and in toluene coated on three different types of fibres in different concentration and coated on the surfaces with different thickness by using k bar. The standard KBars which are used in this investigation are in two different types as are shown in table below:

**Table 20: Closed wound standard K Bars**

| Bar No. | Colour Code | Wire Diameter(mm) | Wet film Deposit( $\mu\text{m}$ ) |
|---------|-------------|-------------------|-----------------------------------|
| 0       | White       | 0,05              | 4                                 |
| 2       | Red         | 0,15              | 12                                |
| 5       | Horn        | 0,64              | 50                                |
| 8       | Blue        | 1,27              | 100                               |

**Table 21: Open wound standard K Bars**

| Bar No. | Colour Code | Wire Diameter(mm) | Wet film Deposit( $\mu\text{m}$ ) |
|---------|-------------|-------------------|-----------------------------------|
| 150     | -----       | 0,25              | 150                               |
| 200     | -----       | 0,36              | 200                               |
| 300     | -----       | 0,51              | 300                               |
| 500     | -----       | 1,00              | 500                               |

#### 3.2.1 Fabrics Coated with PAN W

In this part three different types fabrics coated with PAN W. In order to optimise the number of samples we used a selective K Bar for each concentration, means that for higher concentration we used K Bar with lowest wet film deposit thickness and for lower concentration used of highest wet film deposit thickness, otherwise we had to provide  $8*8*3=192$  different samples and for each sample five times measurements which was out of the standard range of data processing.

Data are given in APPENDIX A part three. Resistivity of each sample calculated and the results are given in tables and graphs below. Since the data in this part are three dimensional

data we can consider and discuss in different aspects. First we discuss about the effect of concentrations on surface resistivity of different fabrics for each individual deposit thickness.

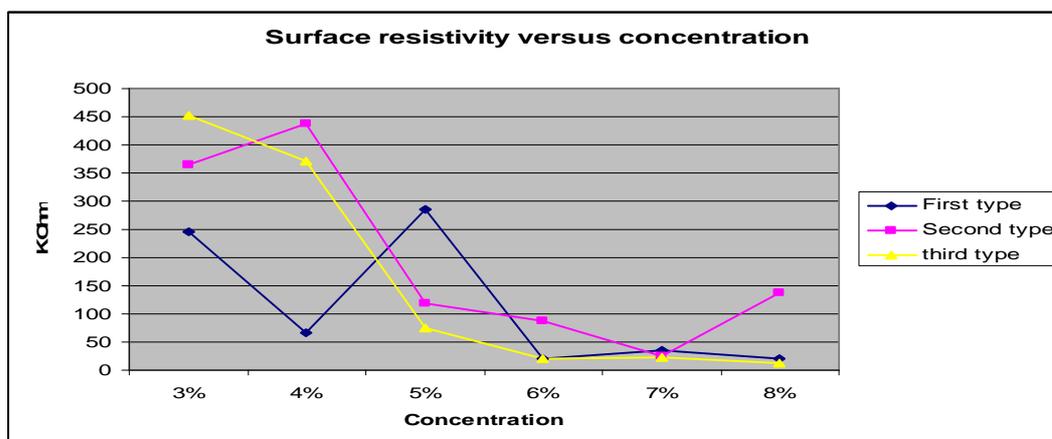
### 3.2.1.1 Surface resistivity of different types of fabrics on basis of film deposit thicknesses

PAN W which are coated with standard K Bar on surface of three different types fabrics and deposit thickness are given in tables and the following graph:

**Table 22 : Surface resistivity versus concentration in 4 $\mu$ m deposit thickness**

| Concentration |             | 3 % | 4 % | 5 % | 6 % | 7 % | 8 %  |
|---------------|-------------|-----|-----|-----|-----|-----|------|
| 4 $\mu$ m     | First type  | 245 | 67  | 286 | 21  | 36  | 21   |
|               | Second type | 365 | 438 | 118 | 88  | 24  | 137  |
|               | third type  | 452 | 371 | 76  | 21  | 22  | 13.5 |

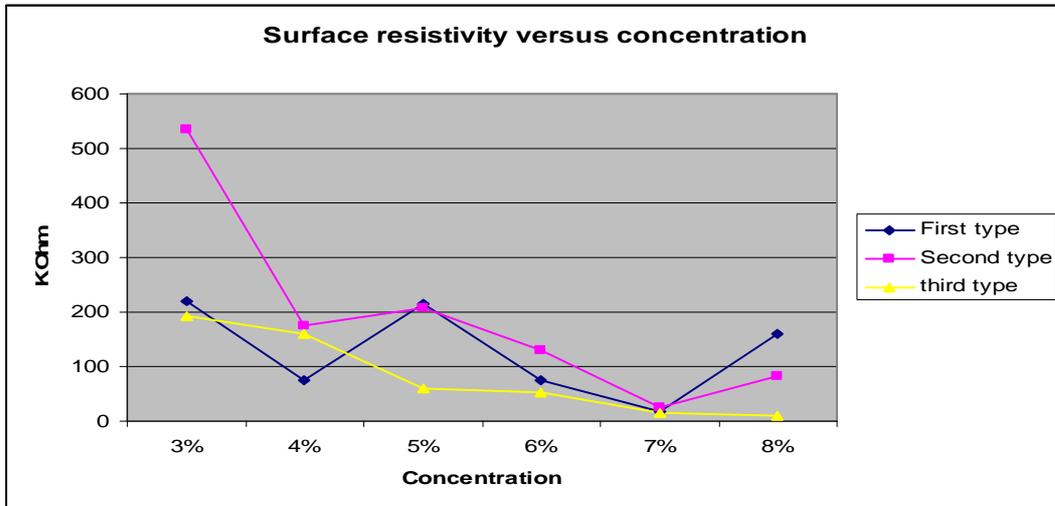
**Graph 16: Surface resistivity versus concentration in 4 $\mu$ m deposit thickness**



**Table 23: Surface resistivity versus concentration in 12 $\mu$ m deposit thickness**

| Concentration |             | 3 % | 4 % | 5 % | 6 % | 7 % | 8 % |
|---------------|-------------|-----|-----|-----|-----|-----|-----|
| 12 $\mu$ m    | First type  | 219 | 76  | 215 | 74  | 18  | 159 |
|               | Second type | 536 | 174 | 207 | 130 | 26  | 82  |
|               | third type  | 193 | 161 | 59  | 52  | 15  | 10  |

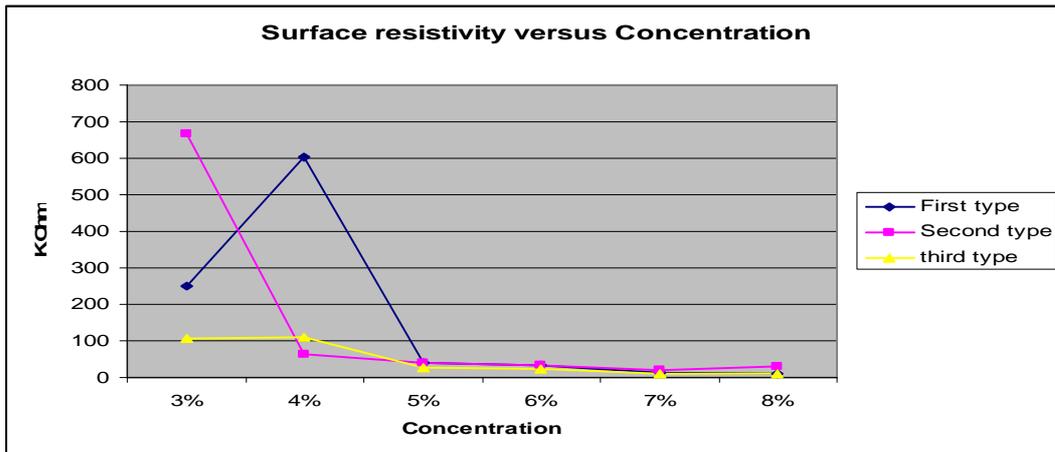
**Graph 17: Surface resistivity versus concentration in 12µm deposit thickness**



**Table 24: Surface resistivity versus concentration in 50µm deposit thickness**

| Concentration |             | 3 % | 4 % | 5 % | 6 % | 7 % | 8 % |
|---------------|-------------|-----|-----|-----|-----|-----|-----|
| 50µm          | First type  | 251 | 605 | 41  | 32  | 14  | 11  |
|               | Second type | 668 | 65  | 41  | 35  | 20  | 30  |
|               | third type  | 107 | 109 | 27  | 23  | 10  | 10  |

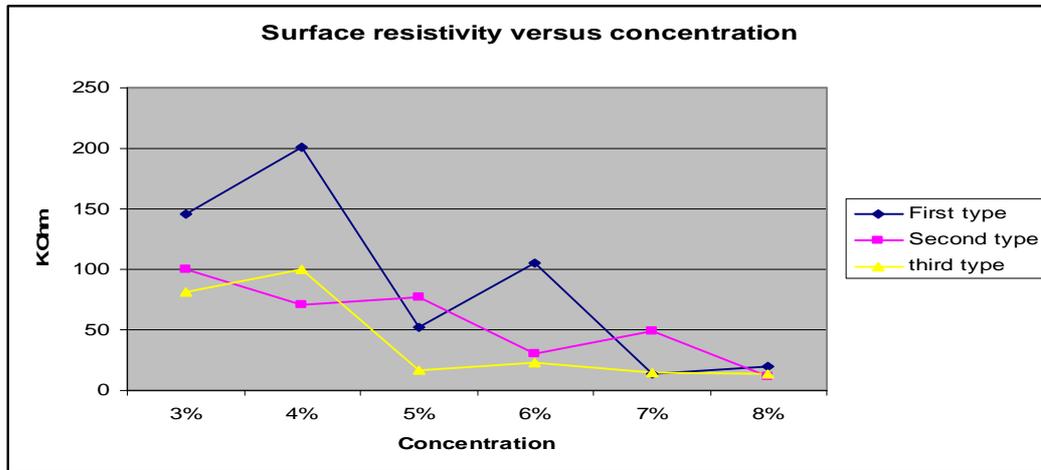
**Graph 18: Surface resistivity versus concentration in 50µm deposit thickness**



**Table 25: Surface resistivity versus concentration in 100µm deposit thickness**

| Concentration |             | 3 % | 4 % | 5 %  | 6 % | 7 % | 8 % |
|---------------|-------------|-----|-----|------|-----|-----|-----|
| 100µm         | First type  | 146 | 201 | 52   | 105 | 14  | 20  |
|               | Second type | 100 | 71  | 77   | 30  | 49  | 11  |
|               | third type  | 81  | 100 | 16.5 | 23  | 15  | 14  |

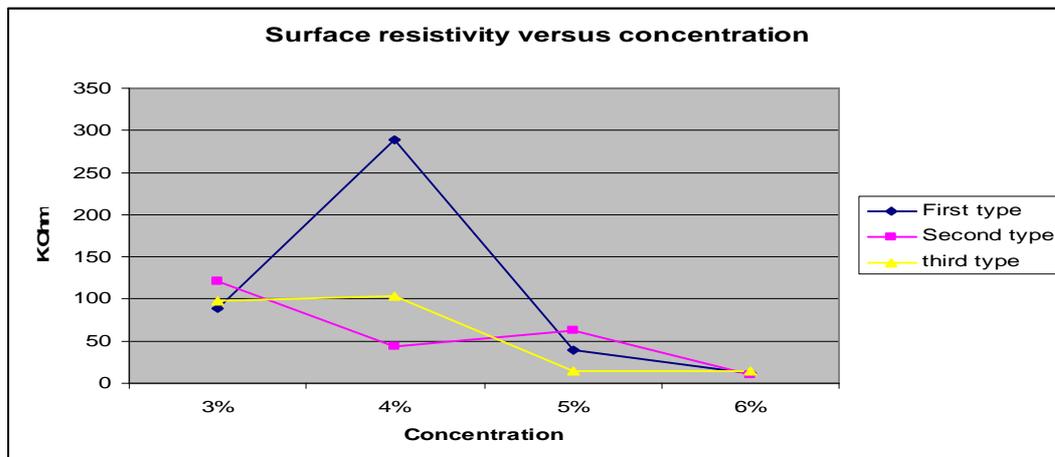
**Graph 19: Surface resistivity versus concentration in 100µm deposit thickness**



**Table 26: Surface resistivity versus concentration in 200µm deposit thickness**

| Concentration |             | 3 % | 4 % | 5 % | 6 % |
|---------------|-------------|-----|-----|-----|-----|
| 200µm         | First type  | 89  | 289 | 40  | 12  |
|               | Second type | 121 | 44  | 63  | 10  |
|               | third type  | 97  | 104 | 14  | 14  |

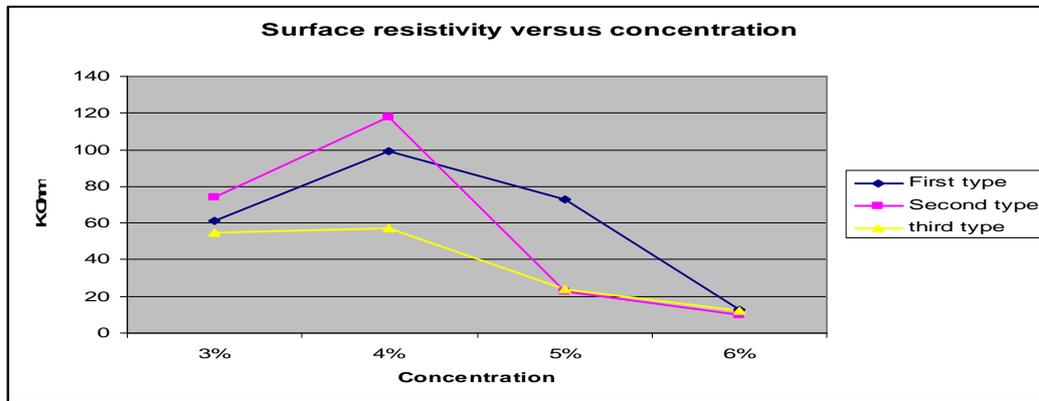
**Graph 20: Surface resistivity versus concentration in 200µm deposit thickness**



**Table 27: Surface resistivity versus concentration in 300µm deposit thickness**

| Concentration |             | 3 % | 4 % | 5 % | 6 % |
|---------------|-------------|-----|-----|-----|-----|
| 300µm         | First type  | 61  | 99  | 73  | 13  |
|               | Second type | 74  | 118 | 23  | 10  |
|               | third type  | 55  | 57  | 24  | 12  |

**Graph 21: Surface resistivity versus concentration in 300µm deposit thickness**



As these graph shows the third kind fabric (thin and three layer) exhibit better homogeneous resistivity and the first kind (thick and one layer) is the worst for almost all deposit thickness. It is due to the first fabric has more porosity of all, and after evaporating water in PAN W especially in lower concentration leave inhomogeneous coating. The problem as the graphs shows cover in higher concentration for the first type of fabric. The other important result is gaining a pleasure level of surface resistivity for the third and second type fabrics in low concentration of PAN W particularly 50 µm film deposit with 3 - 4% concentration.

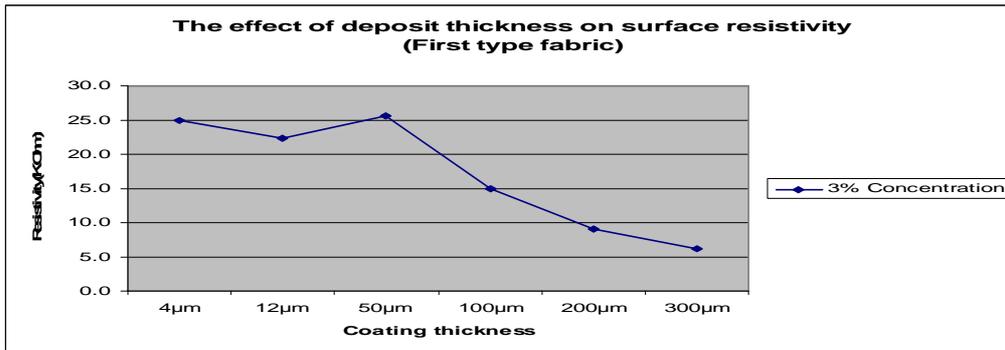
### 3.2.1.2 Surface resistivity of different types of fabrics and film deposit thicknesses on basis of concentration

**Table 28: Surface resistivity versus deposit thickness for different concentration**

|               |                        | First type fabric |      |      |      |      |      |
|---------------|------------------------|-------------------|------|------|------|------|------|
| Concentration | Deposits thickness(µm) | 4                 | 12   | 50   | 100  | 200  | 300  |
| 3 %           | Resistivity KΩ(mean)   | 245               | 219  | 251  | 146  | 89   | 61   |
|               | Deviation              | 56                | 20   | 18   | 27   | 32   | 9    |
|               | Diviation %            | 22.9              | 9.1  | 7.2  | 18.5 | 36.0 | 14.8 |
| 4 %           | Resistivity KΩ(mean)   | 67                | 76   | 605  | 201  | 289  | 99   |
|               | Deviation              | 5                 | 4    | 207  | 81   | 131  | 3    |
|               | Diviation %            | 7.5               | 5.3  | 34.2 | 40.3 | 45.3 | 3.0  |
| 5 %           | Resistivity KΩ(mean)   | 286               | 215  | 41   | 52   | 40   | 73   |
|               | Deviation              | 10                | 84   | 5    | 10   | 9    | 8    |
|               | Diviation %            | 3.5               | 39.1 | 12.2 | 19.2 | 22.5 | 11.0 |
| 6 %           | Resistivity KΩ(mean)   | 21                | 74   | 32   | 105  | 12   | 13   |
|               | Deviation              | 4                 | 15   | 5    | 9    | 1    | 1    |
|               | Diviation %            | 19.0              | 20.3 | 15.6 | 8.6  | 8.3  | 7.7  |
| 7 %           | Resistivity KΩ(mean)   | 36                | 18   | 14   | 14   |      |      |

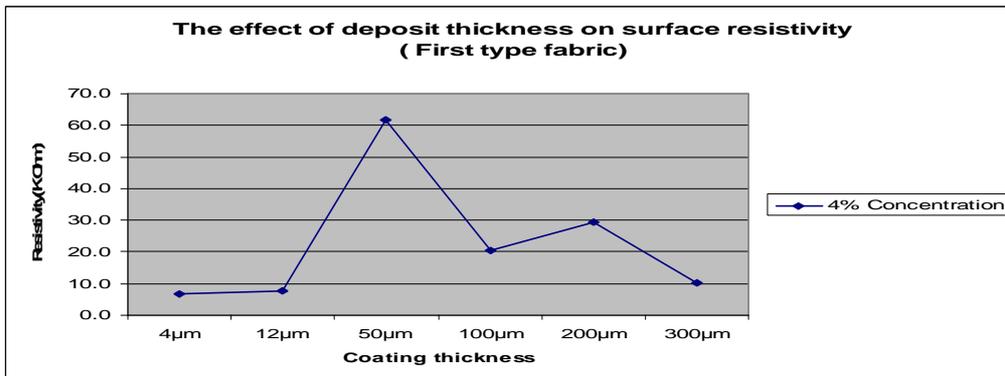
|     |                         |      |      |     |      |  |  |
|-----|-------------------------|------|------|-----|------|--|--|
|     | Deviation               | 6    | 2    | 1   | 1    |  |  |
|     | Deviation %             | 16.7 | 11.1 | 7.1 | 7.1  |  |  |
| 8 % | Resistivity<br>KΩ(mean) | 21   | 159  | 11  | 20   |  |  |
|     | Deviation               | 4    | 64   | 1   | 3    |  |  |
|     | Deviation %             | 19.0 | 40.3 | 9.1 | 15.0 |  |  |

**Graph 22: Surface resistivity versus deposit thickness for 3% concentration**

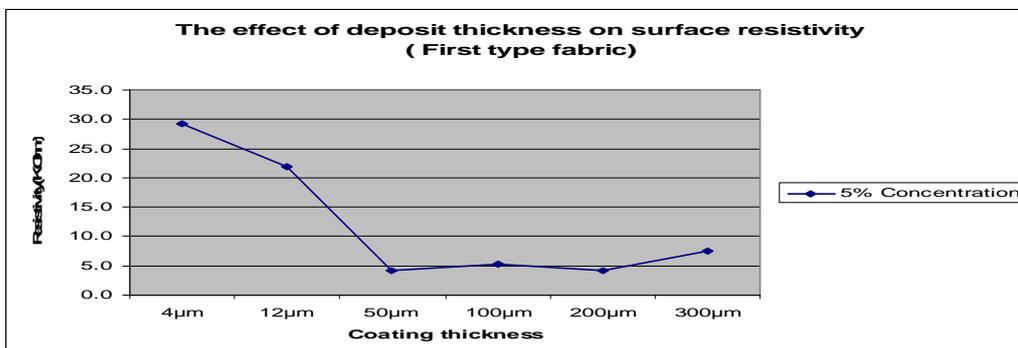


This graph illustrates the higher resistivity for lower deposit thickness.

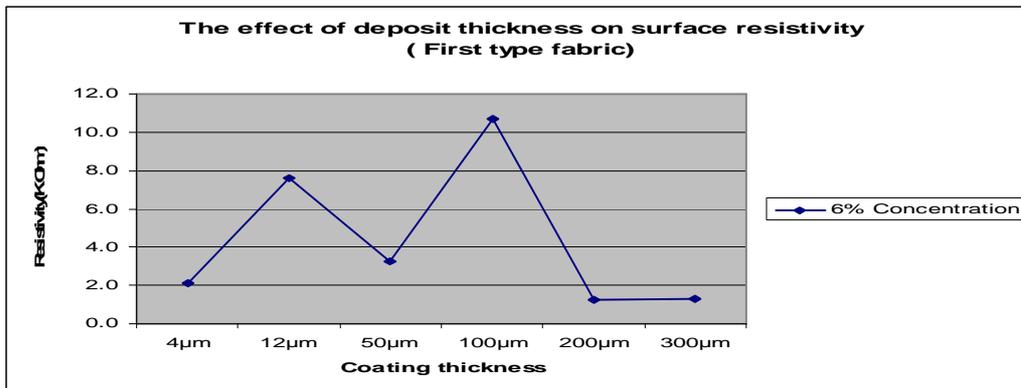
**Graph 23: Surface resistivity versus deposit thickness for 4% concentration**



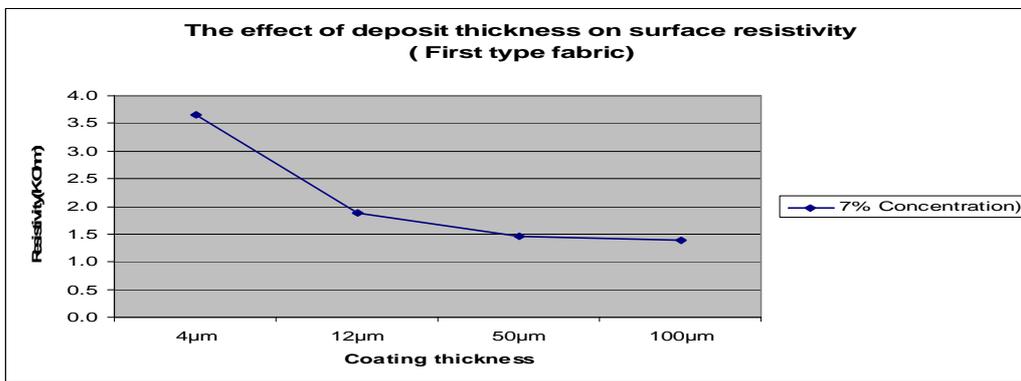
**Graph 24: Surface resistivity versus deposit thickness for 5% concentration**



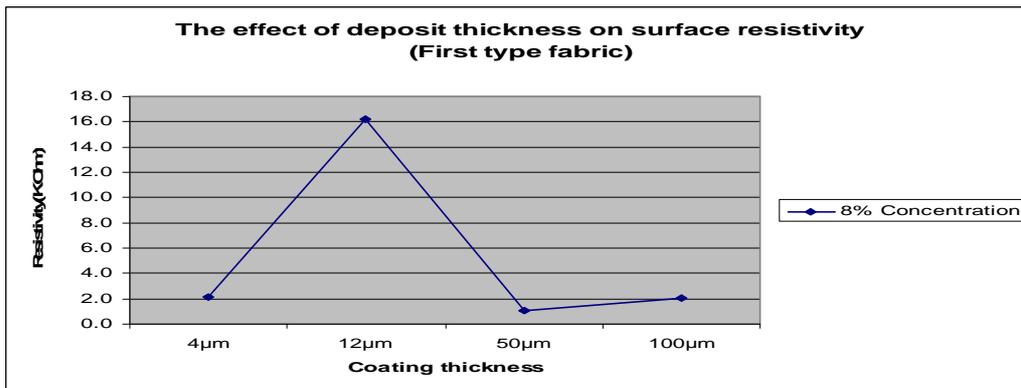
**Graph 25: Surface resistivity versus deposit thickness for 6% concentration**



**Graph 26: Surface resistivity versus deposit thickness for 7% concentration**



**Graph 27: Surface resistivity versus deposit thickness for 8% concentration**

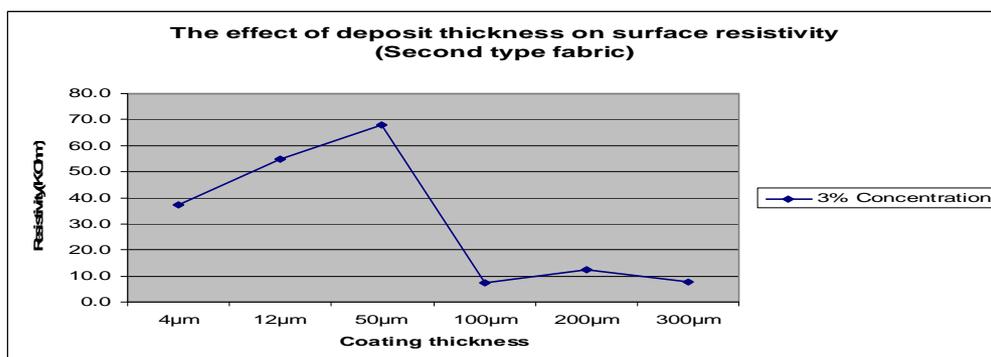


For the first type fabric as it is given in table 28 and shown in the graphs 22 to 27, for 3% concentration resistivity has roughly linear correlation with surface deposit thickness. 5% concentration demonstrates an optimal deposit thickness on 50 µm and for deposit thickness higher than this slightly changes on resistivity occurs. For concentration higher than 5% this deposit thickness remains an optimal point and increasing deposit thickness over this gives slight changes on resistivity and increasing concentration is more effective on surface resistivity lessening than that could achieve by increasing deposit thickness. As the table 28 shows deviation percentage in almost all experimental results are in an acceptable ranges.

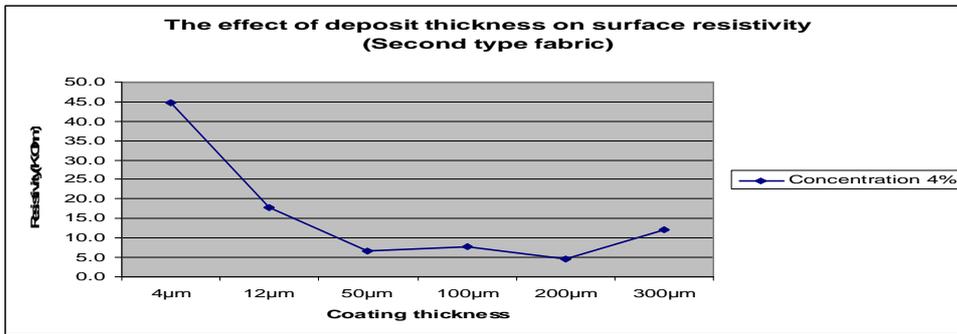
**Table 29: Surface resistivity versus deposit thickness for different concentration**

|               |                                      | Second type |      |      |      |      |      |
|---------------|--------------------------------------|-------------|------|------|------|------|------|
| Concentration | Deposits thick-ness( $\mu\text{m}$ ) | 4           | 12   | 50   | 100  | 200  | 300  |
| 3 %           | Resistivity K $\Omega$ (mean)        | 365         | 536  | 668  | 71   | 121  | 74   |
|               | Deviation                            | 186         | 130  | 160  | 12   | 50   | 13   |
|               | Deviation%                           | 51.0        | 24.3 | 24.0 | 16.9 | 41.3 | 17.6 |
| 4 %           | Resistivity K $\Omega$ (mean)        | 438         | 174  | 65   | 77   | 44   | 118  |
|               | Deviation                            | 45          | 38   | 10   | 31   | 7    | 24   |
|               | Deviation%                           | 10.3        | 21.8 | 15.4 | 40.3 | 15.9 | 20.3 |
| 5 %           | Resistivity K $\Omega$ (mean)        | 118         | 207  | 41   | 30   | 63   | 23   |
|               | Deviation                            | 45          | 25   | 9    | 7    | 8    | 5    |
|               | Deviation%                           | 38.1        | 12.1 | 22.0 | 23.3 | 12.7 | 21.7 |
| 6 %           | Resistivity K $\Omega$ (mean)        | 88          | 130  | 35   | 49   | 10   | 10   |
|               | Deviation                            | 12          | 105  | 4    | 11   | 0.5  | 0    |
|               | Deviation%                           | 13.6        | 80.8 | 11.4 | 22.4 | 5.0  | 0.0  |
| 7 %           | Resistivity K $\Omega$ (mean)        | 24          | 26   | 20   | 11   |      |      |
|               | Deviation                            | 5           | 6    | 2    | 2    |      |      |
|               | Deviation%                           | 20.8        | 23.1 | 10.0 | 18.2 |      |      |
| 8 %           | Resistivity K $\Omega$ (mean)        | 137         | 82   | 30   | 28   |      |      |
|               | Deviation                            | 31          | 60   | 0.8  | 13.8 |      |      |
|               | Deviation%                           | 22.6        | 73.2 | 2.7  | 49.3 |      |      |

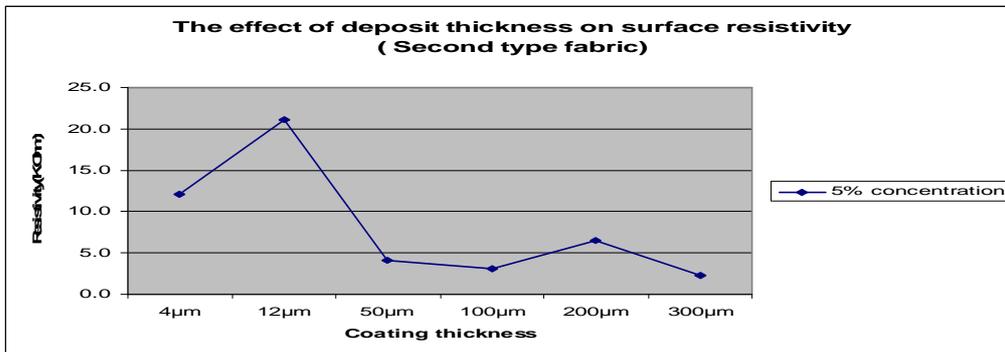
**Graph 28: Surface resistivity versus deposit thickness for 3% concentration**



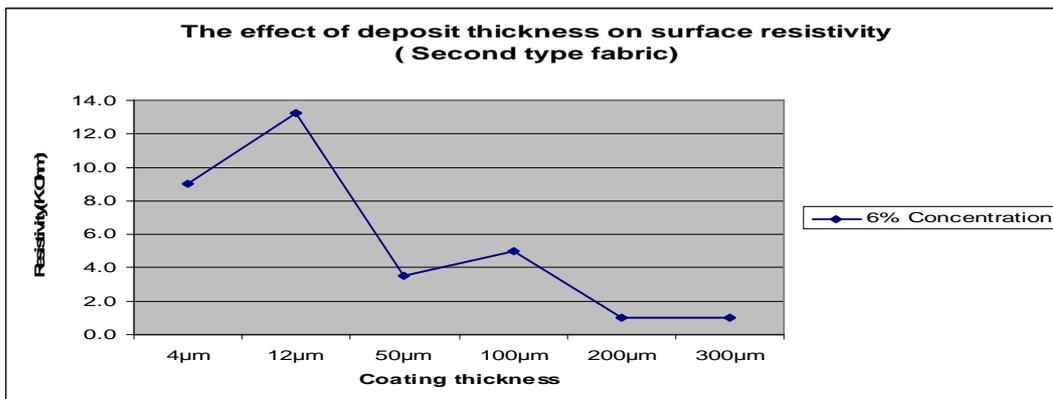
**Graph 29: Surface resistivity versus deposit thickness for 4% concentration**



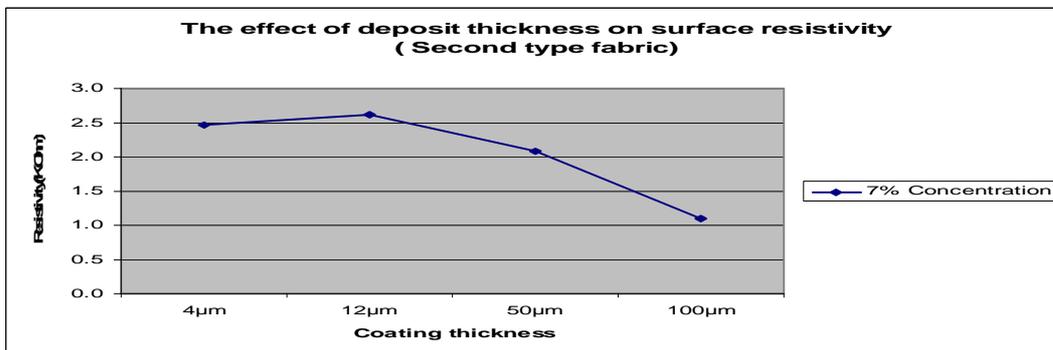
**Graph 30: Surface resistivity versus deposit thickness for 5% concentration**



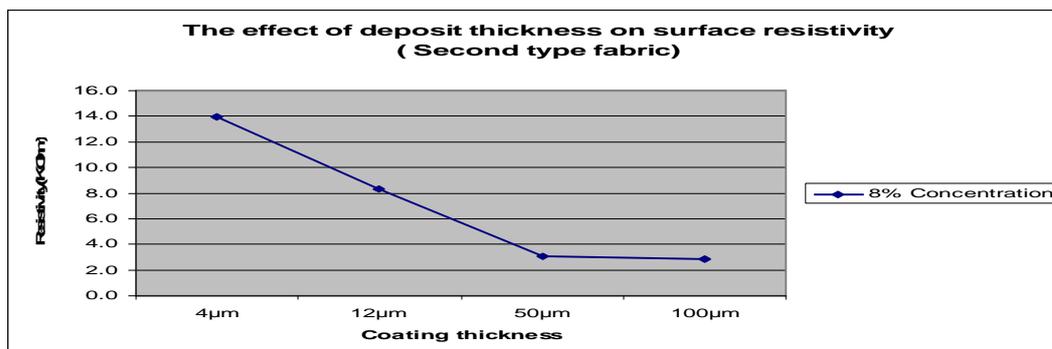
**Graph 31: Surface resistivity versus deposit thickness for 6% concentration**



**Graph 32: Surface resistivity versus deposit thickness for 7% concentration**



**Graph 33: Surface resistivity versus deposit thickness for 8% concentration**



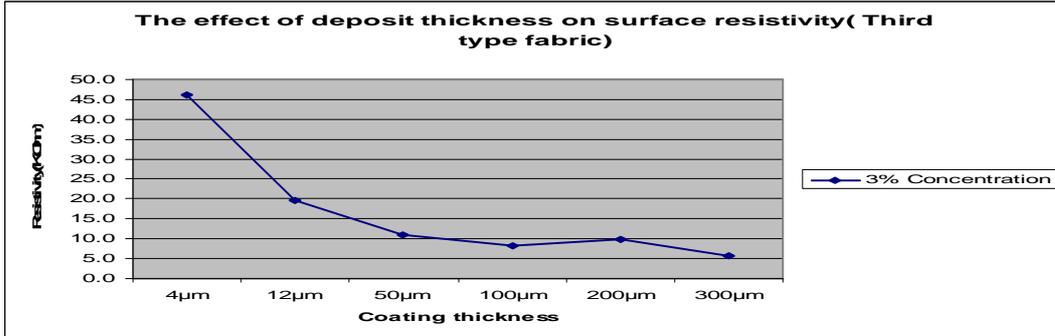
For second type fabric as it is given in table 29 and shown in the graphs 28 to 33, 50 μm can be considered as an optimal deposit thickness for creating surface conductivity for the second type fabric in this experiment except for 3% concentration. Deposit thickness effect on conductivity slightly changes over 50 μm and small changes on resistivity occur. Concentration higher than 5% is more effective on decreasing resistivity than that could be by increasing deposit thickness over 50 μm. Deviation percentage in 50 μm deposit thickness is also in an acceptable range. Based on these graphs we can practically define resistivity desired for specific purposes.

**Table 30: Surface resistivity versus deposit thickness for different concentration**

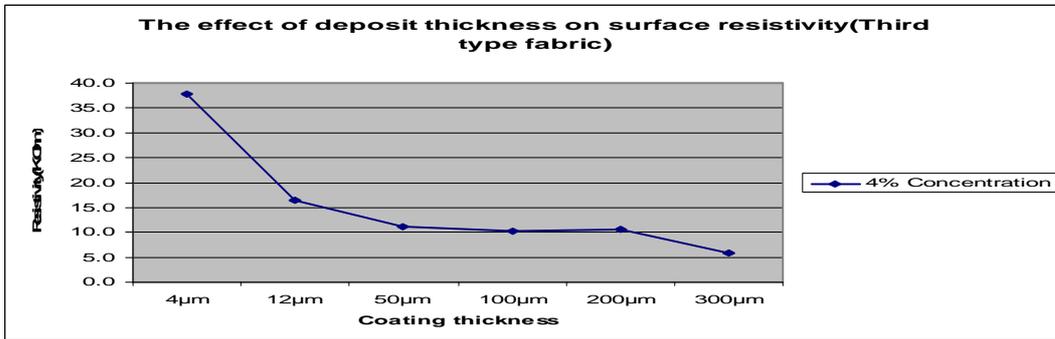
|               |                         | third type fabric |      |      |      |      |      |
|---------------|-------------------------|-------------------|------|------|------|------|------|
| Concentration | Deposits thick-ness(μm) | 4                 | 12   | 50   | 100  | 200  | 300  |
| 3 %           | Resistivity KΩ(mean)    | 452               | 193  | 107  | 81   | 97   | 55   |
|               | Deviation               | 207               | 84   | 44   | 27   | 54   | 7    |
|               | Deviation%              | 45.8              | 43.5 | 41.1 | 33.3 | 55.7 | 12.7 |
| 4 %           | Resistivity KΩ(mean)    | 371               | 161  | 109  | 100  | 104  | 57   |
|               | Deviation               | 32                | 26   | 13   | 23   | 36   | 7    |
|               | Deviation%              | 8.6               | 16.1 | 11.9 | 23.0 | 34.6 | 12.3 |
| 5 %           | Resistivity KΩ(mean)    | 76                | 59   | 27   | 16.5 | 14   | 24   |
|               | Deviation               | 26                | 12   | 5    | 3.6  | 1.6  | 14   |
|               | Deviation%              | 34.2              | 20.3 | 18.5 | 21.8 | 11.4 | 58.3 |
| 6 %           | Resistivity KΩ(mean)    | 21                | 52   | 23   | 23   | 14   | 12   |
|               | Deviation               | 3                 | 4.5  | 10   | 10   | 2.4  | 2.2  |
|               | Deviation%              | 14.3              | 8.7  | 43.5 | 43.5 | 17.1 | 18.3 |
| 7 %           | Resistivity KΩ(mean)    | 22                | 15   | 10   | 15   |      |      |
|               | Deviation               | 8.4               | 4    | 0.4  | 3.3  |      |      |
|               | Deviation%              | 38.2              | 26.7 | 4.0  | 22.0 |      |      |
| 8 %           | Resistivity KΩ(mean)    | 13.5              | 10   | 10   | 14   |      |      |

|  |            |      |     |     |      |  |  |
|--|------------|------|-----|-----|------|--|--|
|  | Deviation  | 2    | 0   | 0.8 | 2.3  |  |  |
|  | Deviation% | 14.8 | 0.0 | 8.0 | 16.4 |  |  |

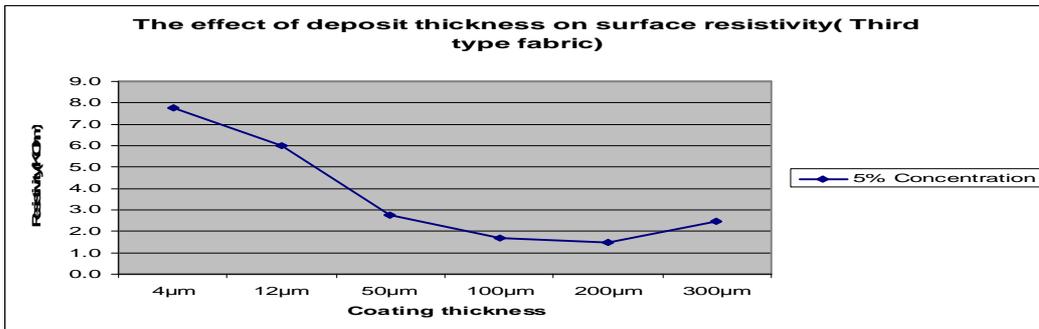
**Graph 34: Surface resistivity versus deposit thickness for 3% concentration**



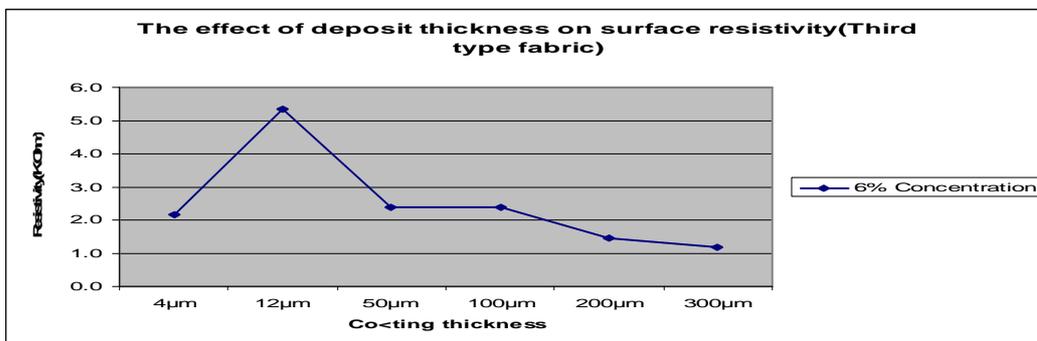
**Graph 35: Surface resistivity versus deposit thickness for 4% concentration**



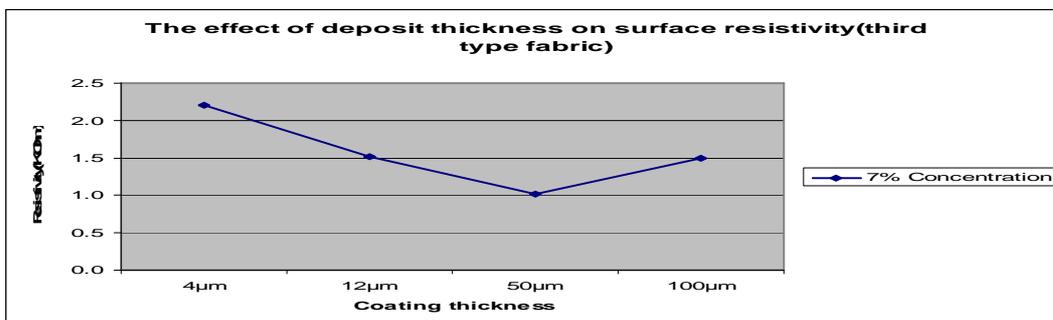
**Graph 36: Surface resistivity versus deposit thickness for 5% concentration**



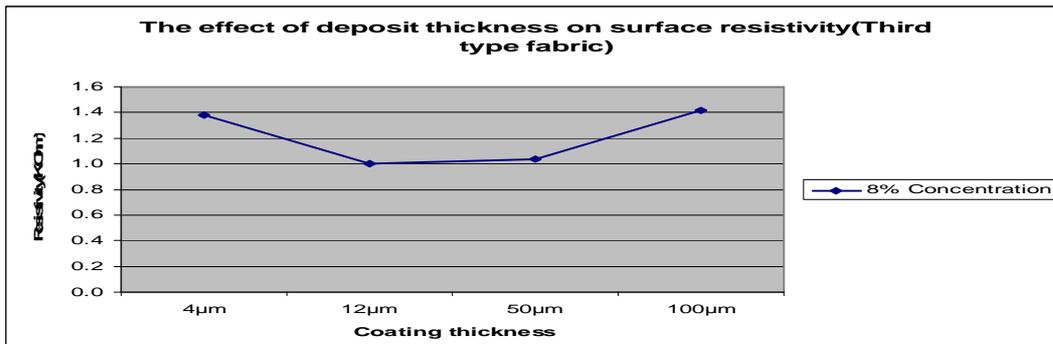
**Graph 37: Surface resistivity versus deposit thickness for 6% concentration**



**Graph 38: Surface resistivity versus deposit thickness for 7% concentration**



**Graph 39: Surface resistivity versus deposit thickness for 8% concentration**



For third type fabric as it is given in table 30 and shown in the graphs 34 to 39, 50 µm can be considered as an optimal deposit thickness for creating surface conductivity for the third type fabric in this experiment as well. Deposit thickness effect on conductivity slightly changes over 50 µm and small changes on resistivity occur. The effect of concentration over 5% exhibits slightly changes on resistivity as well. Concentration higher than 5% is more effective on decreasing resistivity than that could be by increasing deposit thickness over 50 µm. Deviation percentage in 50 µm deposit thickness is also in an acceptable range. Based on these graphs we can practically define resistivity desired for specific purposes.

### 3.2.2 Fabrics coated with PAN T

In this part three different types fabrics coated with PANT. In order to optimise the number of samples, we used a selective K Bar for each concentration, means that for higher concentration we used K Bar with lowest wet film deposit thickness and for lower concentration used of highest wet film deposit thickness. Practically due to the property of polyaniline in a solvent, thin film formations create conductive fibres and fabric, simply with a thin film deposit resistivity would be resulted. For 4% concentration the thinnest deposit film (4 $\mu$ m) created conductivity. The results are the same for all types of fabrics as they are given in tables 31 to 33. Resistivity of each sample calculated and the results are given in tables below as well. Due to the resolution of resistance meter we can not measure resistance lower than 1 K $\Omega$ . Based on the data the lowest resistivity calculated, is ~10 K $\Omega$ .

**Table 31: Surface resistivity versus deposit thickness for different concentration of PANT**

| <b>(First kind fabric)</b> |                  |   |      |      |      |      |                |            |                    |
|----------------------------|------------------|---|------|------|------|------|----------------|------------|--------------------|
| <b>Concentration</b>       | <b>Thickness</b> | <b>Surface resistance(K<math>\Omega</math>)</b> |      |      |      |      | <b>Average</b> | <b>Dev</b> | <b>Resistivity</b> |
| 4 %                        | 4 $\mu$ m        | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00           | 0.00       | 9.8                |
| 3 %                        | 4 $\mu$ m        | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00           | 0.00       | 9.8                |
| 2 %                        | 12 $\mu$ m       | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00           | 0.00       | 9.8                |
| 1 %                        | 50 $\mu$ m       | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00           | 0.00       | 9.8                |

**Table 32: Surface resistivity versus deposit thickness for different concentration of PANT**

| <b>(Second kind fabric)</b> |                  |   |      |      |      |      |                |            |                    |
|-----------------------------|------------------|---|------|------|------|------|----------------|------------|--------------------|
| <b>Concentration</b>        | <b>Thickness</b> | <b>Surface resistance(K<math>\Omega</math>)</b> |      |      |      |      | <b>Average</b> | <b>Dev</b> | <b>Resistivity</b> |
| 4 %                         | 4 $\mu$ m        | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00           | 0.00       | 9.8                |
| 3 %                         | 4 $\mu$ m        | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00           | 0.00       | 9.8                |
| 2 %                         | 12 $\mu$ m       | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00           | 0.00       | 9.8                |
| 1 %                         | 50 $\mu$ m       | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00           | 0.00       | 9.8                |

**Table 33: Surface resistivity versus deposit thickness for different concentration of PANT**

| <b>(Third kind fabric)</b> |                  |   |      |      |      |      |                |            |                    |
|----------------------------|------------------|---|------|------|------|------|----------------|------------|--------------------|
| <b>Concentration</b>       | <b>Thickness</b> | <b>Surface resistance(K<math>\Omega</math>)</b> |      |      |      |      | <b>Average</b> | <b>Dev</b> | <b>Resistivity</b> |
| 4 %                        | 4 $\mu$ m        | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00           | 0.00       | 9.8                |
| 3 %                        | 4 $\mu$ m        | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00           | 0.00       | 9.8                |
| 2 %                        | 12 $\mu$ m       | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00           | 0.00       | 9.8                |
| 1 %                        | 50 $\mu$ m       | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00           | 0.00       | 9.8                |

### 3. DISCUSSION

A wide variety of synthesis and processing methods exist that can be manipulated to produce materials in forms that can be integrated into truly smart structures. Polyester yarn and three different fabrics objected for preparing conductive textile fibres based on PANI. Two different type of PANI dispersed in water and dissolved in a solvent used to carry out this experiment and analysis the effect of them in creating conductive fibres. Discussion on each part are brought in results, in this part we provide a general view of whole of this investigation. Theoretically higher concentration defines as a better conductivity in creating conductive fibres but the experimental results does not support this idea for all aspects. Structural merging conductive polymers with textile polymer to provide a new fibre is the same as a rule for other combination of polymers even the process is as a conventional method like coating. Creating conductive fibre by PANT exhibits higher and more homogeneous result than PAN W. Since using PANT involves risk hazardous exposure in the workplaces, still PAN W is unknown in its acute and corona effect which cause to think about routine precautionary decisions making in the workplaces as well. Using PANT due to the existence of a solvent lead film formation whereas in PAN W by evaporating water content in material, polyaniline deposits on fibres. For fibre coated with PAN W a good range of conductivity occurs at 3% concentration and for PANT at 2% concentration.

Conductive fibre at the first step of coating with PAN W is in a low homogeneous level which this weakness can be covered by extra coating step, which leads to decrease resistivity as well. Extra coating is estimated as an effective method in substitution with higher concentration, which definitely has influence on energy saving due to the use of energy for continuous stirring or shaking material during coating fibres in order to provide uniform concentration. This can be concluded in the case of fabrics by substituting deposit thickness with concentration that we have analyzed in detail in the results.

## 4. CONCLUSION

The concept of conductive fibres utilizing for smart objects production offers effective method to enhance the functionality of textile objects compare to the conventional and a promising way to resource development solutions with positive measures for economic booster. Blending, a promising method on creating conductive fibre for using in the structure of textile is still under research, but using coating can meet some industrial needs, which is needed more research in this part as well. In this investigation we have provided an intensive experiment to identify the resistivities gained in coating yarn and fabrics with polyaniline composition, The fact for further experiments straight connected to this field, is to focus on various aspects of conducting polymer coated on fibre and fabric textile, including temperature, humidity and (UV) radiation, ageing, and washing or thermal effects on the electrical properties of the created conductive yarn and fabrics.

Yarn coated with conductive polymer especially in higher concentration and coating step exhibits sort of rigid fibres which can be caused the possible difficulty for weaving and knitting.

Due to the surface coating is an empirical method to define the resistivity, developing experiment in this part to determine resistivities in a matrix with different parameters such as concentration and deposit thickness can provide an empirical instruction for individual industrial purposes.

Creating conductive yarn can be alternated with new enhanced conductive fibre with melt processing which is under research but surface coating can be used for some specific purposes now and so future research on coating method can focus more on surface coating than the yarn kind conductive fibres.

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## 6. BIBLIOGRAPHY

[1] Gordon G. Wallace.; Geoffrey M. Spinks.; Leon A.P.Kane-Maguire.; Peter R. Teasdale. *Conductive Electroactive Polymers, Intelligent Materials Systems*. 2003.

[2] Larry Rupprecht, Editor. *Conductive Polymers and Plastics, In Industrial Applications*, 1999.

[3] Elsevier Limited, *Modifying Conductivity in Plastics: Meeting needs in Electrical and Electronics*. Jan. 2004

[4] Yang, C.Y., Cao, Y. Smith, P. and Heeger, A.J., *Morphology of Conductive, Solution Processed blends of Polyaniline and Poly( Methyl Methacrylate); Synthetic Metals*. 1993

[5] Kul Karni, V.G., Campbell, J.C. and Mathew, W.R., *Transparent Conductive Coatings, Synthetic Metals* .1993

[6] D.J.Small, P. Biocca, " *Lead Free Solder Vs. Conductive Adhesive*", *Advanced Packaging*. Oct.2000

[7] *Packaging Material Standards for ESD-Sensitive Items*, Electronic Industries Assn., EIA STD IS-5-A (now EIA-541; 2.2.2, 4.2.3).

[8] A.Mazzoldi, D.Derossi, F.Lorussi, E.P.Scilingo, R.Paradiso; *Smart Textile for Wearable Motion Capture Systems*; AUTEX Research Journal, Vol.2, No.4 (Dec. 2002)

[9] [http://en.wikipedia.org/wiki/Electrical\\_resistance](http://en.wikipedia.org/wiki/Electrical_resistance)

[10] D.S. Park, Y.B.Shin, S.M. Park, *J.Electrochem.Soc.*, 1993

- [11] <http://images.google.com/imgres?imgurl=http://idptech.com/images/conduct.gif&imgrefurl=http://www.idptech.com/static.htm&h=179&w=513&sz=13&hl=en&start=112&tbnid=1CP5FbDaTjCQ3M:&tbnh=46&tbnw=131&prev=/images%3Fq%3Dsurface%2Bresistivity%26start%3D100%26gbv%3D2%26svnum%3D10%26hl%3Den%26sa%3DG>
- [12] A. j. Heeger, J.R. Schrieffer, and W. P. Su, *Rev. Mod. Phys.* (1988)
- [13] De Rossi D., Della Santa A., Mazzoldi A. *Dressware: Wearable hardware, Material science & Eng. C*,7:31-35. 1999.
- [14] W.Lu, A.G.Fadeev,B.Qi,B.R. Mattes, *Synthetic Metals*, (2003)
- [15] De Rossi D.,Ghelarducci B., Paradiso R., et al, *Sensing threads and Fabrics for Monitoring Body Kinematic and Vital signs, Proceedings of Fibres and Textiles for the future*, Tampere, Finland. 2001
- [16] Mohammad, F. *In Handbook of Organic Conduvtive Molecules and Polymers, Conductive Polymers:Spectroscopy and Physical Properties*; Nalwa, H.S. (Ed.) Wley: New York, 1997;Vol.3, PP. 795-861.
- [17] A.J.Epstein, J. Joo, C.-Y. Wu,A. Benatar, C.F. Faisst, Jr.,J.Zegarski, and A.G.MacDiarmid, *in Intrinsically Conducting Pölymers: An Emerging Technology*, M. Aldissi, ed. (Kluwer Academic Pubs.,Netherlands, 1993
- [18] D. Baeriswyl, D.K. Campbell, and S. Mazumdar, *In Conjugated Conducting Polymers*, edited by H.G. Keiss(Springer-Verlag, Berlin, 1992), p.7.
- [19] W.J. Feast et al , *Synthesis, Processing and material properties of conjugated polymers*, Vol. 37 Number 22 PP. 5017- 5047, 1996.
- [20] <http://en.wikipedia.org/wiki/Polyacetylene>
- [21] Liao et al., *Polymers for Advanced Technologies, Doping of Polyaniline with Polymeric Dopants in Solid State, Gel state and Solutions*. 1995
- [22] Chen et al., *Macromolecules, Structure and properties of Poly(acrylic acid)—Doped Polyaniline*. 1995
- [23] <http://en.wikipedia.org/wiki/Polyaniline>
- [24] L.F.O. Martins, R. M. Q. Mello, M.L. Sartorelli, I.A. *Surface Roughness of electropolymerized Polyaniline and Sulfonated Polyaniline Layers*. 2004
- [25] <http://www.panipol.fi/index.php?option=content&task=view&id=3&Itemid=26>
- [26] <http://images.google.com/imgres?imgurl=http://www.adsdyes.com/products/images/structures/650wp.png&imgrefurl=http://www.adsdyes.com/polyaniline.html&h=86&w=367&sz=3&hl=en&start=18&tbnid=C7nt5kWsrnAOgM:&tbnh=29&tbnw=122&prev=/images%3Fq%3Dpolyaniline%26gbv%3D2%26svnum%3D10%26hl%3Den%26sa%3DG>

- [27] Jolly,R.;Petrescu,C.;Thieblemont, J.C.; Marechal, J.C.;Menneteau, F.D.J *coated Fabrics* 1994,23,228.
- [28] MetrISO 2000 Winprofi- *General Description*
- [29] *Concentric Ring Probe & Kit*, Code H 107 C & H108C
- [30] G.Grem, G. Leditzky, B. Ullrich, G. Leising, *Synthetic metals*, 51(1992)
- [31] ASTM Standard D257-99. *Standard test methods for D-C resistance or conductance of insulating materials*, 1999.
- [32] ESD STM 11.11-2001 Standard. *Surface resistance measurement of static dissipative planar materials*, 2001.
- [33] Michael B. Heaney. *The measurement, Instrumentation and sensors Handbook, chapter Electrical Conductivity and Resistivity*. CRC Press, 1999.
- [34] IEC 61340-5-1 Standard. *Electrostatics – part 5-1: Protection of electronic devices from electrostatic phenomena – general requirements*, 1998.