# FUNCTIONAL PROPERTIES OF STRETCHABLE CONDUCTIVE INK (SCI) WITH VARYING SUBSTRATE

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# FUNCTIONAL PROPERTIES OF STRETCHABLE CONDUCTIVE INK (SCI) WITH VARYING SUBSTRATE

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**A report submitted**

**in fulfilment of the requirements for the degree of**

**Bachelor of Mechanical Engineering (Hons)**



**Faculty of Mechanical Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2022**

**DECLARATION**

I declare that this project report entitled "Functional Properties Of Stretchable Conductive Ink (SCI) With Varying Substrate" is the result of my own work except as cited in the references

Signature : ............................................................................................

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Date : 15/2/2022

# APPROVAL

I hereby declare that I have read this project report, and in my opinion, this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering

Signature : .........................................................................

Supervisor's Name : .........................................................................

Date : .........................................................................

**DEDICATION**

To my beloved father and mother,

Mohamed Mustafa Bin Samad & Saripah Binti Mahamad Sarip

# ABSTRACT

Stretchable conductive ink (SCI) is a functional material that enables the conductive ink film to have better electronic conductivity after stretching and folding. This project aims to investigate the effect of different polymer substrates on the functional properties of SCI. First, SCI's electrical and mechanical samples with varying GNP filler loading on Polyethylene (PET) and thermoplastic (TPU) substrates were prepared and tested. More specifically, the range of GNP filler loading used in this research is 5 wt.%, 7.5 wt.%, and 10 wt.%. Before the electrical and mechanical testing, the formulated SCI with different GNP filler loading was subjected to viscosity test by using a digital viscometer (MODEL 52DV). Besides, the hydrophobicity of the formulated SCI was investigated on the as-received PET and TPU substrate through a contact angle test using self-fabricated contact angle measuring. Then, the sample was characterised using a four-point probe to determine the SCI's sheet resistance ($R_s$), which refers to ASTM F390 as a guideline; meanwhile, mechanical properties were characterised through a quantitative 180° peel test using a universal testing machine. By formulating SCI using different GNP filler loading, the viscosity increases as the filler loading increases; however, low viscosity is not appropriate with the stencil printing method and affects the electrical properties of the printed SCI on the substrate. The electrical properties of SCI printed on TPU and PET substrate show a decrease in sheet resistance with increasing GNP filler loading, from 5 wt. % to 10 wt.%. However, the SCI printed on the TPU substrate exhibit better conductivity than the SCI printed on the PET substrate. There is a reduction in adhesion strength from the peel test with increasing GNP filler loading. In addition, the results suggest that the SCI exhibited higher adhesion strength when printed onto the PET substrates than on TPU substrates, possibly because of the hydrophilic nature of the polymer material. Such finding is directly correlated with the degree of wetting, based on the contact angle measured on PET, which is low and yield high adhesion strength. Overall, it can be concluded that the SCI printed on different substrates affect the functional properties of the SCI.

# ABSTRAK

*Dakwat konduktif boleh renggang ialah bahan berfungsi yang membolehkan filem dakwat konduktif mempunyai kekonduksian elektronik yang lebih baik selepas regangan dan lipatan Projek ini bertujuan untuk mengkaji kesan substrat polimer yang berbeza pada sifat fungsi SCI. Pertama, sampel SCI dengan muatan pengisi GNP yang berbeza pada substrat Polietilena (PET) dan termoplastik (TPU) telah disediakan dan diuji dari segi sifat elektrik dan mekanikal. Secara lebih khusus, julat muatan pengisi GNP yang digunakan dalam penyelidikan ini ialah 5 wt.%, 7.5 wt.%, dan 10 wt.%. Sebelum ujian elektrik dan mekanikal, SCI yang dirumus dengan pengisi GNP yang berbeza telah dikenakan ujian kelikatan dengan menggunakan viskometer digital (MODEL 52DV). Selain itu, sifat kehidrofobikan SCI telah dikaji pada substrat PET dan TPU dengan kondisi sedia ada melalui ujian sudut sentuhan menggunakan pengukuran sudut sentuhan buatan sendiri. Kemudian, sampel dicirikan menggunakan kuar empat mata untuk menentukan rintangan helaian SCI ($R_s$), dengan merujuk kepada ASTM F390 sebagai garis panduan; sementara itu, sifat mekanikal dicirikan melalui ujian pengupasan 180° kuantitatif menggunakan mesin ujian universal. Dengan formulasi SCI menggunakan muatan pengisi GNP yang berbeza, kelikatan meningkat apabila muatan pengisi meningkat; walau bagaimanapun, kelikatan rendah tidak sesuai dengan kaedah cetakan stensil dan menjejaskan sifat elektrik SCI yang dicetak pada substrat. Sifat elektrik SCI yang dicetak pada substrat TPU dan PET menunjukkan penurunan rintangan helaian dengan peningkatan beban pengisi GNP, daripada 5 wt. % hingga 10 wt.%. Walau bagaimanapun, SCI yang dicetak pada substrat TPU mempamerkan kekonduksian yang lebih baik daripada SCI yang dicetak pada substrat PET. Terdapat pengurangan dalam kekuatan lekatan daripada ujian pengupasan dengan peningkatan beban pengisi GNP. Di samping itu, keputusan menunjukkan bahawa SCI mempamerkan kekuatan lekatan yang lebih tinggi apabila dicetak pada substrat PET berbanding substrat TPU, berkemungkinan disebabkan sifat hidrofilik bahan polimer. Penemuan sedemikian dikaitkan secara langsung dengan tahap pembasahan, berdasarkan sudut sentuhan yang diukur pada PET, yang rendah dan menghasilkan kekuatan lekatan yang tinggi. Secara keseluruhannya, dapat disimpulkan bahawa SCI yang dicetak pada substrat yang berbeza mempengaruhi sifat fungsian SCI.*

**ACKNOWLEDGEMENTS**

Firstly, I would like to take this opportunity to express my sincere gratitude to my supervisor, Dr. Siti Hajar Binti Sheikh Md Fadzullah, whose contribution to stimulating suggestions and encouragement helped me to coordinate my project. I am grateful to her for her understanding, guidance, and insightful support in the development process.

I would also like to acknowledge with much appreciation my family and friends who invested their full support in me to complete this research.

A special thanks to Zuraimi, Andee, and Dani, postgraduate students who constantly share their knowledge and experience, primarily to experiment with this research. Appreciation is also given to all the technicians who contribute their expertise and dedicate their time to help me complete this research.

# TABLE OF CONTENTS

**LIST OF TABLES**

# LIST OF FIGURES

## LIST OF ABBREVIATIONS

| | |
|---|---|
| PCB | Printed Circuit Boards |
| SCI | Stretchable Conductive Ink |
| LED | Light Emitting Diode |
| TCF | Transparent conductive film |
| AgNWs | Silver Nanowires |
| CNT | Carbon Nanotube |
| GNP | Graphene Nanoplatelets |
| TPU | Thermoplastic polyurethane |
| PET | Polyethylene terephthalate |
| SEM | Scanning Electron Microscope |
| 0D | Zero Dimension |
| 1D | One Dimension |
| 3D | Three Dimension |
| UV | Ultra Violet |
| PEDOT:PSS | Poly(3,4-ethylenedioxythiophene) Polystyrene Sulfonate |
| DMSO | Dimethyl Sulfoxide |
| EG | Ethylene Glycol |

## LIST OF SYMBOL

| | | |
|---|---|---|
| °C | = | Degree Celsius |
| Ω | = | Ohm |
| sq. | = | Square |
| $T_g$ | = | Glass temperature |
| m | = | Meter |
| µm | = | Micrometre |
| L | = | length |
| G | = | Correlation factor |
| I | = | Current |
| V | = | Voltage |
| Rs | = | Sheet Resistance |
| MPa | = | Mega Pascal |
| TPa | = | Tera Pascal |
| $\theta_{eq}$ | = | Contact Angle |
| $\gamma_{SV}$ | = | Solid-gas surface tension |
| $\gamma_{SL}$ | = | Solid-liquid surface tension |
| $\gamma_{LV}$ | = | Liquid-gas surface tension |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Nowadays, technology is an essential part of our life. Technology has evolved in various ways, and it is certainly possible that it's getting better. People are always trying to improve everything that can benefit our lives. Without electronic devices, people's lives would be at stand fill, and nothing would get done fast enough.

The development of electronic technology is growing rapidly, especially in printed circuit boards (PCBs). PCB is the main component of the electronic system that plays a vital role to support mechanically and electrically connected electronic components using conductive pathways, tracks, or signal traces etched from copper sheets laminated onto a non-conductive substrate (Hunrath & Forest, 2009). However, PCB is a conventional rigid electronic component limited to the wearable electronic industry to open up various applications, especially healthcare, energy, and military. It is because the rigid PCB cannot be stretched and bent. Therefore, with such a growing development in electronic technology, stretchable electronic devices are the new technology that can replace the use of PCB in the wearable electronic industry and directly leads to economic growth today and has positive effects on various aspects of daily life.

Generally, the stretchable electronic devices primarily consist of stretchable conductive ink (SCI), stretchable substrate, and an electronic circuit (i.e. resistor, LED, and capacitor) (Aziz et al., 2020). According to (Ding et al., 2020), SCI is a functional material that enables the conductive ink film to have better electronic conductivity after stretching and folding. This matter is caused by the effect of this ink that would aid in the automation and refinement of the manufacture of stretchable conductors and have a significant impact on flexible electronics. Other than that, the development of SCI has enabled a broad range of applications, for instance, the production of transparent conductive films (TCFs), flexible energy harvesting and storage, and wearable sensors. Moreover, it is due to SCI attractive features; it can be compressed, twisted, and adapted to complex non-planar surfaces besides the low manufacturing cost with high output (Huang & Zhu, 2019).

The SCI is classified into metal-based (i.e. silver, Copper and AgNws), carbon-based (CNT, Graphite and Carbon black) and hybrids of metal and carbon-based (i.e. Ag-PDMS and rGO-AGNP). (D. C. Kim et al., 2020) states that all of these types' mechanical and electrical performances depend on the size and shape of filler material. The best suitable filler material for the fabrication of SCI is nanomaterials and polymers with 1D long-chain structures (D. C. Kim et al., 2020). The 1D material can form junctions between the adjacent fillers and high conductivity. However, the stretchable substrate also plays a vital role in the fabrication of the SCI. From the literature, it was argued that an unsuitable substrate could affect the behaviour of the SCI (Aziz et al., 2020).



## 1.2 Problem Statement

The stretchable conductive inks (SCI) have received an increasing demand, especially in wearable sensors, due to their great flexibility and expendability while maintaining conductivity at high levels. In addition, stringent performances such as electrical and mechanical required the fillers in SCI to be shifted from metallic to nanocarbon-based materials (Graphene and CNT) due to their remarkable characteristics (Wenting Dang et al., 2017). However, the replacement of metal fillers with nanocarbon-based materials is not fully explored in their functionality, performance, and durability on the various substrates.

Moreover, determining the viscosity of newly formulated SCI is essential because viscosity is the parameter determining the suitable printing method used to print the SCI onto the substrate (Khan et al.,2020). The unsuitable printing method used may affect the evenness of the SCI towards the substrate surface (Onggar et al., 2020). Conversely, there is limited solid data on the relationship between viscosity and printing methods that can affect SCI's electrical and mechanical properties printed on substrates. Thus, the viscosity of the SCI with different filler loading will be discovered by understanding the relationship between the SCI and the printing method.

Other than that, different substrates have different interface energy. The interface energy is related to the wetting and adhesion in which the wetting phenomenon influences the quality of printing and process reliability of the SCI (Yunos et al., 2020). The wetting phenomenon can be studied through the hydrophobicity of the SCI towards the substrate. However, there is still a lack of exploration on the hydrophobicity of the SCI on the polymer substrate, especially towards thermoplastic polyurethane (TPU) and Polyethylene terephthalate (PET).

Subsequently, numerous studies have been analysed and discussed regarding the SCI's performance that used polymer as a binder. Based on the previous study, the polymer binder reduces the conductivity of the SCI due to the high resistance of the polymer binder (Mohammed & Pecht, 2016). However, the replacement of polymer binder with conductive polymer binder like PEDOT: PSS is not fully explored in terms of electrical and mechanical performance. Furthermore, filler content and the amount of polymer binder used in newly formulated SCI is vital to discover because they are the main factors that affect the functionality of the SCI (Merilampi et al., 2010).

Hence, this study aims to perform a comprehensive material characterization that serves as a baseline using newly formulated nanocarbon-based SCI for functionality and durability with varying substrate material.

## 1.3 Objectives

The objectives of this project are as follows:

1. To examine the viscosity of the SCI with different filler loading.
2. To study the hydrophobicity of the SCI with different filler loading towards varying substrates.
3. To evaluate the electrical and mechanical properties of the SCI with different filler loading on varying substrates



## 1.4 Scope of Project

The scopes of this project are:

i. Formulation and fabrication of SCI on TPU and PET substrates.
ii. The viscosity of SCI with different filler loading.
iii. Contact angle test to determine the hydrophobicity of SCI on TPU and PET substrate.
iv. SCI sheet resistance measurement by conducting a four-point probe test on printed SCI.
v. SCI mechanical testing via 180° peel test.

## 1.5 Planning and Execution

Table 1.1 demonstrates the research planning and activities for PSM 1, including the process title selection, literature review for understanding the research related to the project, designing the experiment, report writing and submission, and finally, PSM I presentation. The research activities in PSM II started with the formulation of the samples, viscosity test, contact angle test, and then the material characterisation for electrical and mechanical properties for all samples. Lastly, all the data were analysed, and the results are discussed in this report. Research activities of PSM II are illustrated in Table1.2.

Table 1.1 PSM I Gantt chart

| **Week** / **Activities** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Research Title Selection | | | | | | | | | | | | | | | |
| Literature Review | | | | | | | | | | | | | | | |
| Methodology research study | | | | | | | | | | | | | | | |
| Submission Progress Report | | | | | | | | | | | | | | | |
| Report Writing | | | | | | | | | | | | | | | |
| Report Submission | | | | | | | | | | | | | | | |
| PSM 1 Seminar | | | | | | | | | | | | | | | |

Table 1.2 PSM II Gantt chart

| Week / Activities | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Literature Review | | | | | | | | | | | | | | | |
| Formulation and Fabrication of SCI | | | | | | | | | | | | | | | |
| Characterization of the SCI<br>• Viscosity test<br>• Contact angle test<br>• Sheet resistivity test<br>• 180° peel test | | | | | | | | | | | | | | | |
| Data Analysis | | | | | | | | | | | | | | | |
| Report Writing | | | | | | | | | | | | | | | |
| Report Submission | | | | | | | | | | | | | | | |
| PSM II Seminar | | | | | | | | | | | | | | | |

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

This chapter includes a review of several related research studies based on previous research. The main subtopics discussed in this chapter are the stretchable conductive ink (SCI), polymer binder, a conductive filler, and SCI's electrical and mechanical properties based on the previous study on this chapter.

## 2.2 Stretchable Conductive ink

According to Ding et al. (2020), SCI is a functional material that enables the conductive ink film to have better electronic conductivity after stretching and folding. This matter is caused by the effect of this ink that would aid in the automation and refinement of the manufacture of stretchable conductors and have a significant impact on flexible electronics. Next, the development of SCI has enabled a broad range of applications, for instance, the production of transparent conductive films (TCFs), flexible energy harvesting and storage, and wearable sensors. It is due to SCI attractive features; it can be compressed, twisted, and adapted to complex non-planar surfaces besides the low cost of manufacturing with high output (Huang & Zhu, 2019).



Subsequently, the most critical requirement of SCI is the ability to stretch after the sintering has taken place. It still maintains the electrical conductivity of the conductive filler. Furthermore, a good SCI is an ink that can strain at least 20% of its original length while maintaining electrical and mechanical performances (Mohammed & Pecht, 2016). It is a good starting point for this nascent technology as 20% stretchability can meet many current requirements.

## 2.3 Conductive Filler

Conductive filler is the material used to fabricate conductive ink, which provides electrical conductivity to SCI. Therefore, the electric properties of SCI mainly depend on the type of conductive filler. However, the good conductive filler has superior inherent electrical properties: good charge transport capabilities, excellent electrical properties, inherent softness, and good mechanical properties.

There are two types of conductive used in SCI: metal-based and non-metal based. The non-metal based are divided into two, which are carbon-based and conducting polymer. Figure 2.1 shows the classification of conductive filler with examples.



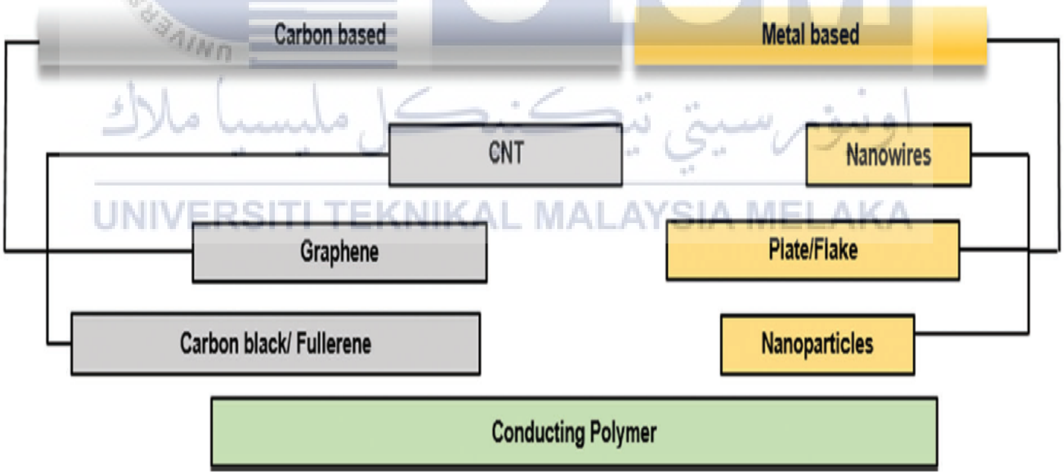


Figure 2.1: Classification of conductive filler with example (Choi et al., 2019)

### 2.3.1 Metal-Based

Metal-based nanomaterial is widely used as a conductive filler for SCI. It is because it has highly conductive and mechanical flexibility, such as Silver, Gold, and Copper. Conversely, it can be classified into three classes which are nanoparticles (0D), nanowires (1D), and nanoflakes (2D). Figure 2.2 shows the SEM images of 0D, 1D and 2D metal-based nanomaterials.

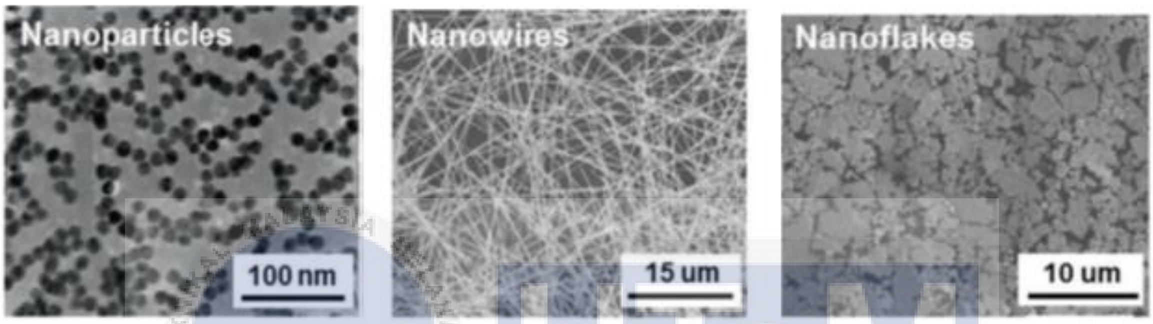


Figure 2.2: SEM images of 0D, 1D and 2D metal-based nanomaterial (D. C. Kim et al., 2020)



Among the three-dimensional metal-based nanomaterials, nanowires (1D) are commonly used as conductive fillers in SCI since they have the highest electrical conductivity compared to 0D and 2D metal-based materials. Examples of metal-based nanowires are silver nanowires (AgNWs), copper nanowires (CuNWs) and gold nanowires (AuNWs). According to (Choi et al., 2019), all the functional nanomaterial and polymers with 1D long chain structures can form a junction between the adjacent filler. Besides, it can provide a high level of conductivity with a small volume of fillers. Therefore, it shows that the 1D shape of the material can prevent the issue of increased loading of fillers in SCI.

The AgNWs and CuNWs are dynamically used to develop stretchable conductive composites such as flexible transparent conductive films, optoelectronic devices and molecular electronics. Due to their high intrinsic electrical conductivities, facile synthesis