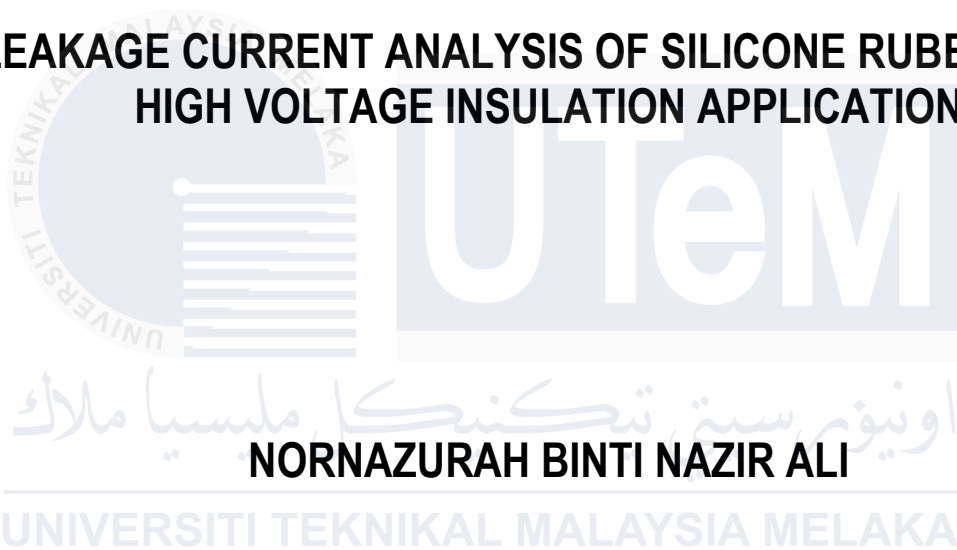




LEAKAGE CURRENT ANALYSIS OF SILICONE RUBBER FOR HIGH VOLTAGE INSULATION APPLICATION



NORNAZURAH BINTI NAZIR ALI

DOCTOR OF PHILOSOPHY

2025



Faculty of Electrical Technology and Engineering

LEAKAGE CURRENT ANALYSIS OF SILICONE RUBBER FOR HIGH VOLTAGE INSULATION APPLICATION

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

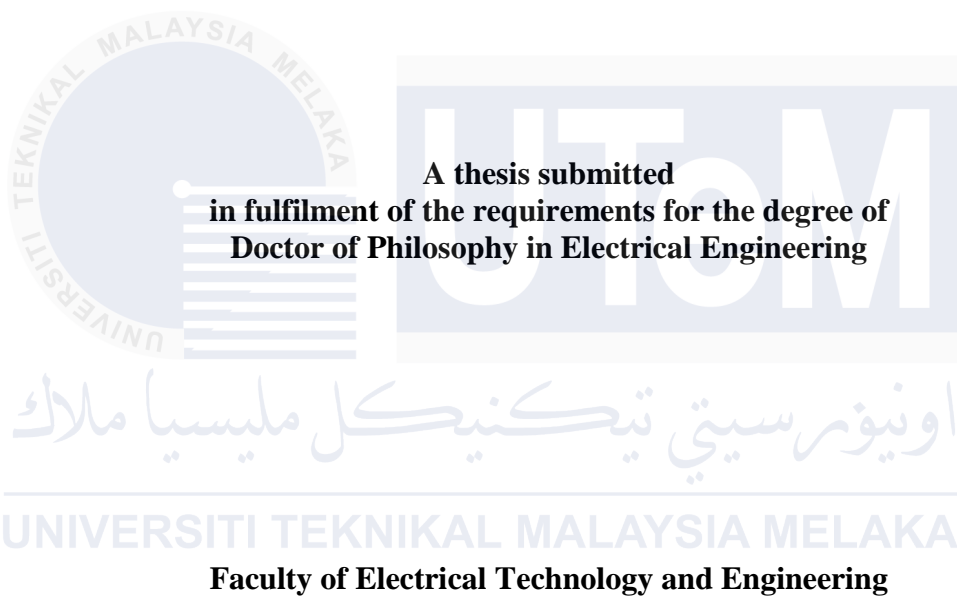
Nornazurah Binti Nazir Ali

Doctor of Philosophy in Electrical Engineering

2025

**LEAKAGE CURRENT ANALYSIS OF SILICONE RUBBER FOR HIGH
VOLTAGE INSULATION APPLICATION**

NORNAZURAH BINTI NAZIR ALI



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2025

DECLARATION

I declare that this thesis entitled “Leakage Current Analysis of Silicone Rubber for High Voltage Insulation Application” Is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree



Signature :

Name :

Nornazurah Binti Nazir Ali

Date :

6/8/2025

اونيورسيتي تيكنيكل مليسيا ملاك

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

APPROVAL

I hereby declare that I have read this thesis and, in my opinion, this thesis is sufficient in terms of scope and quality for the award of Doctor of Philosophy in Electrical Engineering.



Signature :

Supervisor Name : PM Dr Hidayat Bin Zainuddin

Date : 6/8/2025

اونيورسيتي تيكنيكل مليسيا ملاك

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DEDICATION

To my beloved late father, *Nazir Ali Bin Shangkotti*. Though you are no longer with me in this life, your presence is still deeply felt in everything I do. Your strength, guidance, and wisdom continue to be my greatest inspiration. To my dearest mother, *Noor Begam Binti Mohd Said*. Thank you for always believing in me, even when the journey was uncertain. Your unconditional love, sacrifices, and steadfast encouragement have been the foundation of my perseverance. I am forever grateful.



ABSTRACT

The study of Silicone Rubber (SiR) polymeric outdoor insulating materials primarily focuses on enhancing their performance against ageing, allowing these materials to achieve a longer lifespan. To develop an optimised outdoor insulating material, both the material composition and processing parameters are investigated using the Design of Experiment (DOE) approach via *Design Expert Software* of two-level full factorial analysis. This study consists of two stages: the first to identify the best SiR mix based on selected parameters, and the second to test it under different operating conditions. The first stage evaluates four factors affecting SiR performance : A) Alumina Trihydrate (ATH) filler loading, B) Dicumyl peroxide (DCP) concentration, C) mixing speed, and D) mixing time, using leakage current (LC) as the performance indicator, based on Inclined Plane Tracking (IPT) test at 60 and 360 minutes as per BS EN IEC 60587:2022 standards. The data was collected using DAQ equipment and LabVIEW software, filtered in Python, and imported into *Design Expert Software* to analyse the influence of factors and their interrelations on LC values. Initially, at 60 minutes, the interrelation factor of AB had the most significant impact on LC, but by the end of the test at 360 minutes, factor A was deduced as the dominant factor. Next, the optimised SiR blend with the lowest LC (0.690588 mA) at 360 minutes was found, which is Sample 5, consisting of 50 pphr of ATH, 0.5 pphr of DCP, a mixing speed of 70 rpm, and a mixing time of 10 minutes, with desirability of 1 and a good Capability Process Index (Cpk) of 2.14, ensuring the quality and consistency of the samples' reproducibility in manufacturing. To support these findings, additional analyses were conducted, including weight loss evaluation, mechanical testing of tensile strength, morphological examination via Scanning Electron Microscopy (SEM), and chemical characterization through Fourier Transform Infrared Spectroscopy (FTIR). The optimised sample showed the lowest LC, high tensile strength, and smaller FTIR peak changes after the IPT test compared to other samples. The surface image analysis using SEM revealed a distinct impact of ageing, which was particularly severe for samples with the lowest ATH and highest LC values. The optimised blend was then replicated for further analysis in the second stage, and the focus now shifts to identifying the endurance and performance of the optimised sample under several critical factors during SiR degradation, again under the IPT test. This time, the factors were set to A) voltage, B) contaminant flow rate, and C) contaminant concentration. The interrelations between the factors and their influence on SiR's LC values and the maximum withstandable LC of optimised SiR sample were discovered. In both periods of 60 and 360 minutes, factor C emerged as the most significant, followed by B and A. The maximum LC values that the optimised samples could withstand under various circumstances were also determined, and it was found that even when all factors were set to their maximum, the LC remained below 60 mA, in line with the standard requirements. In conclusion, the statistical analysis demonstrates that it is possible to optimise SiR to achieve excellent electrical, physical, mechanical, and chemical properties by adjusting material composition and processing parameters. The findings also revealed the interrelation between various factors and their impact on SiR performance, allowing for future adjustments to achieve a desired SiR with a specific LC output.

ANALISIS ARUS BOCOR GETAH SILIKONE UNTUK APLIKASI PENEBATAN VOLTAN TINGGI

ABSTRAK

Kajian terhadap bahan penebat luar Getah Silikone (SiR) polimer tertumpu kepada usaha meningkatkan prestasinya terhadap penuaan bagi membolehkan bahan ini mencapai jangka hayat yang lebih panjang. Bagi membangunkan bahan penebat luar yang optimum, kedua-dua komposisi bahan dan parameter pemprosesan telah dikaji menggunakan pendekatan Reka Bentuk Eksperimen (DOE) melalui perisian Design Expert dengan analisis faktorial penuh dua tahap. Kajian ini terdiri daripada dua peringkat: peringkat pertama bertujuan mengenal pasti campuran SiR terbaik berdasarkan parameter yang dipilih, manakala peringkat kedua menguji campuran tersebut di bawah pelbagai keadaan operasi. Peringkat pertama menilai empat faktor yang mempengaruhi prestasi SiR, iaitu: A) kandungan pengisi Alumina Trihydrate (ATH), B) kepekatan Dicumyl Peroxide (DCP), C) kelajuan pengadunan, dan D) masa pengadunan, dengan menggunakan arus bocor (LC) sebagai penunjuk prestasi berdasarkan ujian Penjejakan Satah Condong (IPT) selama 60 dan 360 minit mengikut piawaian BS EN IEC 60587:2022. Data dikumpul menggunakan peralatan DAQ dan perisian LabVIEW, ditapis menggunakan Python, dan dianalisis menggunakan perisian Design Expert bagi menilai pengaruh faktor dan interaksinya terhadap nilai LC. Pada awal ujian (60 minit), faktor interaksi AB memberikan kesan paling ketara terhadap LC, namun pada akhir ujian (360 minit), faktor A dikenalpasti sebagai faktor dominan. Seterusnya, campuran SiR optimum dengan nilai LC paling rendah (0.690588 mA) pada 360 minit telah dikenal pasti, iaitu Sampel 5 yang mengandungi 50 pphr ATH, 0.5 pphr DCP, kelajuan pengadunan 70 rpm, dan masa pengadunan 10 minit, dengan kebolehinginan bernilai 1 dan Indeks Proses Keupayaan (Cpk) yang baik sebanyak 2.14, yang memastikan kualiti dan kebolehulangan penghasilan sampel dalam proses pembuatan. Bagi menyokong penemuan ini, beberapa analisis tambahan telah dijalankan termasuk penilaian kehilangan berat, ujian mekanikal (kekuatan tegangan), pemeriksaan morfologi menggunakan Imbasan Mikroskop Elektron (SEM), dan pencirian kimia menggunakan Spektroskopi Transformasian Fourier Inframerah (FTIR). Sampel optimum menunjukkan LC paling rendah, kekuatan tegangan yang tinggi dan perubahan puncak FTIR yang lebih kecil selepas ujian IPT berbanding sampel lain. Analisis permukaan menggunakan SEM menunjukkan kesan penuaan yang ketara, khususnya pada sampel yang mempunyai kandungan ATH paling rendah dan nilai LC tertinggi. Campuran optimum ini kemudiannya dihasilkan semula untuk analisis lanjut dalam peringkat kedua yang menumpukan kepada penilaian ketahanan dan prestasi di bawah beberapa faktor kritikal semasa degradasi SiR, sekali lagi menggunakan ujian IPT. Kali ini, faktor yang dikaji ialah A) voltan, B) kadar aliran bahan kontaminasi, dan C) kepekatan bahan kontaminasi. Hubungan antara faktor dan pengaruhnya terhadap nilai LC serta nilai maksimum LC yang boleh ditahan oleh sampel optimum telah dikenal pasti. Dalam kedua-dua tempoh ujian 60 dan 360 minit, faktor C didapati paling signifikan, diikuti oleh B dan A. Nilai maksimum LC yang dapat ditahan oleh sampel optimum di bawah pelbagai keadaan turut ditentukan, dan didapati bahawa walaupun semua faktor berada pada tahap maksimum, nilai LC kekal di bawah 60 mA, selaras dengan keperluan piawaian. Sebagai kesimpulan, analisis statistik membuktikan bahawa bahan SiR boleh dioptimumkan untuk mencapai sifat elektrik, fizikal, mekanikal dan kimia yang sangat baik dengan pengubahan komposisi bahan dan parameter pemprosesan.

Penemuan ini turut mendedahkan hubungan antara pelbagai faktor dan kesannya terhadap prestasi SiR, membolehkan pengubahan pada masa hadapan untuk mencapai bahan SiR dengan keluaran LC yang dikehendaki..



ACKNOWLEDGEMENTS

First and foremost, I would like to express my gratitude to my main supervisor, *Assoc. Prof. Dr. Hidayat bin Zainuddin*, and my co-supervisor, *Assoc. Prof. Ir. Ts. Dr. Jeefferie bin Abd Razak*, for their invaluable supervision, support, and encouragement throughout the completion of this research and thesis. Their expertise and guidance have been instrumental in my progress. I would also like to extend my gratitude to my late supervisor, *Ir. Dr. Aminuddin bin Aman*, for his insightful ideas and knowledge during the early stages of my Ph.D. journey. His guidance laid the foundation for this research, and his influence has continued to inspire me throughout this endeavour.

Next, my heartfelt thanks and deepest love go to my beloved parents, my late father *Nazir Ali bin Shangkotti* and my mother *Noor Begam binti Mohd Said*, whose love, guidance and encouragement have been the foundation of my journey. I carry my father's memory with pride and affection. His enduring spirit and unwavering belief in me continue to inspire and strengthen my resolve to persevere. To my mother, whose constant prayers, gentle strength, and unconditional support have been my anchor through every challenge, I am forever grateful. Her resilience and quiet sacrifices have shaped the person I am today.

I am also immensely grateful to my family members, especially my brother, *Mohd Rasyidi bin Nazir Ali*, for his generous financial assistance, and to my sister, *Nornazirah binti Nazir Ali*, for her steadfast emotional support during challenging times. Their encouragement and belief in my journey have been a constant source of strength, helping me persevere through the most difficult moments. I also wish to extend my heartfelt appreciation to my brother, *Mohamad Nazmeer bin Nazir Ali*, whose sharp sarcasm, dark humour and

brutally honest words, although not always gentle, somehow served as an unexpected source of motivation, helping me stay focused and determined to complete my Ph.D. studies.

A special thank you goes to *En. Mohd Wayudi bin Md Hussain* for his invaluable technical guidance as the High Voltage Engineering Laboratory Technician. I am also deeply grateful to *Universiti Teknikal Malaysia Melaka (UTeM)* for providing the space, environment, equipment, and laboratory facilities essential for completing my Ph.D. studies. Thank you to *Immortal Green Industrial Sdn Bhd* for supplying the materials needed for my studies. I am very grateful for their support. Additionally, my heartfelt thanks go to my friends, whose companionship and support have been invaluable throughout this journey. Their encouragement and kindness have helped make this experience fulfilling and memorable.

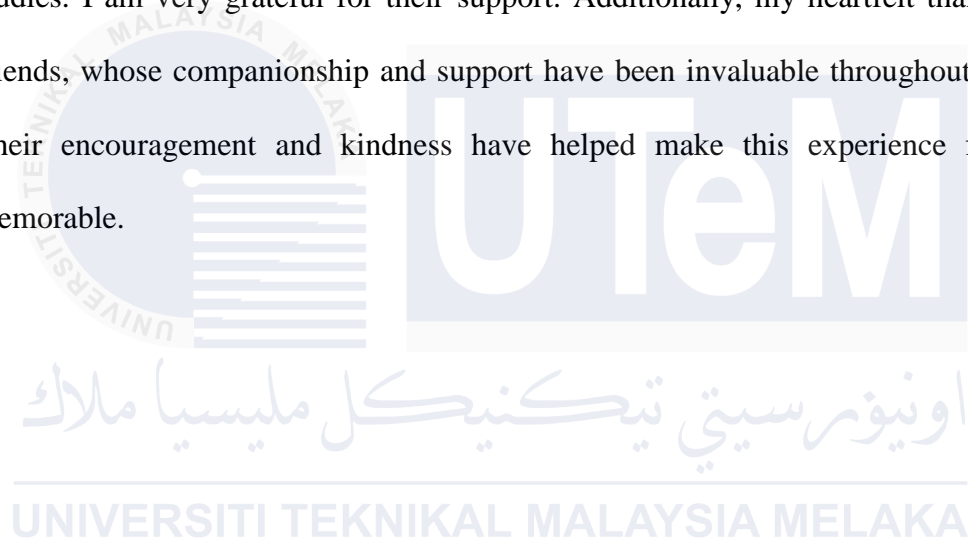


TABLE OF CONTENTS

	PAGES
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	vi
LIST OF TABLES	ix
LIST OF FIGURES	xi
LIST OF APPENDICES	xvi
LIST OF ABBREVIATIONS	xvii
LIST OF SYMBOLS	xviii
LIST OF PUBLICATIONS	xix
 CHAPTER	 1
1. INTRODUCTION	1
1.1 Introduction	1
1.2 Problem Statement	6
1.3 Objectives	13
1.4 Scope of Research	14
1.5 Significance of Research	15
1.6 Thesis Outline	17
 2. LITERATURE REVIEW	 19
2.1 Introduction to Solid High Voltage (HV) Insulator	19
2.2 Benefits, Uses, and Structure of Silicone Rubber in High Voltage (HV) Insulators	20
2.3 Degradation Factors of Polymeric Insulators	23
2.3.1 Environmental Stress of Outdoor Polymeric Insulators	24
2.3.2 Electrical Stress	26
2.3.3 Mechanical Stress	28
2.4 Key Factors in the Development of Silicone Rubber (SiR) Insulators: Material Formulations and Processing Parameters (The First Stage)	29
2.4.1 Material Formulations: Selection and Composition	29
2.4.2 Processing Parameters	41
2.5 High Voltage (HV) Insulation Testing for Outdoor Applications	46
2.5.1 Electrical Properties Testing via Inclined Plane Tracking (IPT) Test (BS EN IEC 60587:2022)	48
2.5.2 Physical Properties Testing (Scanning Electron Microscope (SEM))	52
2.5.3 Mechanical Properties Testing (Tensile Strength)	54
2.5.4 Chemical and Environmental Testing (Fourier-Transform Infrared Spectroscopy (FTIR))	59
2.6 Leakage Current (LC)	61

2.6.1	Development of Leakage Current (LC) and Flashover Mechanism	63
2.6.2	Leakage Current (LC) Measurement	66
2.7	Key Factors Affecting Leakage Current (LC) in Silicone Rubber	72
2.7.1	Pollutants, Moisture, and Applied Voltage Effect on Leakage Current (LC) (Related to the Endurance and Performance of Sample in the Second Stage)	73
2.7.2	Sample Ageing and Surface Degradation Effect on Leakage Current (LC)	76
2.7.3	Effect of Filler Type on Leakage Current (LC) (Micro, Nano and Hybrid Fillers)	77
2.8	Design of Experiment (DOE)	80
2.8.1	Design of Experiment (DOE) in Electrical Power System Field	82
2.8.2	DOE Technique in <i>Design Expert Software</i>	83
3.	RESEARCH METHODOLOGY	92
3.1	Introduction	92
3.2	The First Stage	97
3.2.1	Configuration of <i>Design Expert Software</i>	97
3.2.2	Development and Preparation of SiR Material Composite: Samples Weighting, Mixing and Moulding	101
3.2.3	Tests Conducted on Prepared Materials	107
3.2.4	Data Analysis Procedures	121
3.3	The Second Stage	123
3.3.1	Configuration of Design Expert Software	123
3.3.2	Development and Preparation of SiR Material Composite: Samples Weighting, Mixing and Moulding	124
3.3.3	Tests Conducted on Prepared Materials	125
3.3.4	Data Analysis Procedures	126
3.4	Experimental Hardware, Software Configurations, and Verification Procedures of Leakage Current (LC)	127
3.4.1	Experimental Hardware and Software Configuration (LabVIEW and DAQ):	128
3.4.2	Configuration of Python Software for the Pre-processing of LC Data	135
3.4.3	Verification of the IPT Measurement System (LabVIEW Verification)	138
3.4.4	Verification of Power Supply Harmonics	141
4.	RESULT AND DISCUSSION	146
4.1	Introduction	146
4.2	The First Stage	148
4.2.1	Statistical Analysis of LC	150
4.2.2	Statistical Analysis Summary of the First Stage	195
4.2.3	Analysis of Samples' Weight Loss, Tracking Length and Depth via Multiple Linear Regression Plot	197
4.2.4	Supporting Test	202
4.2.4	Overall Conclusion of the First Stage	219
4.3	The Second Stage	221
4.3.1	Statistical Analysis of LC	223

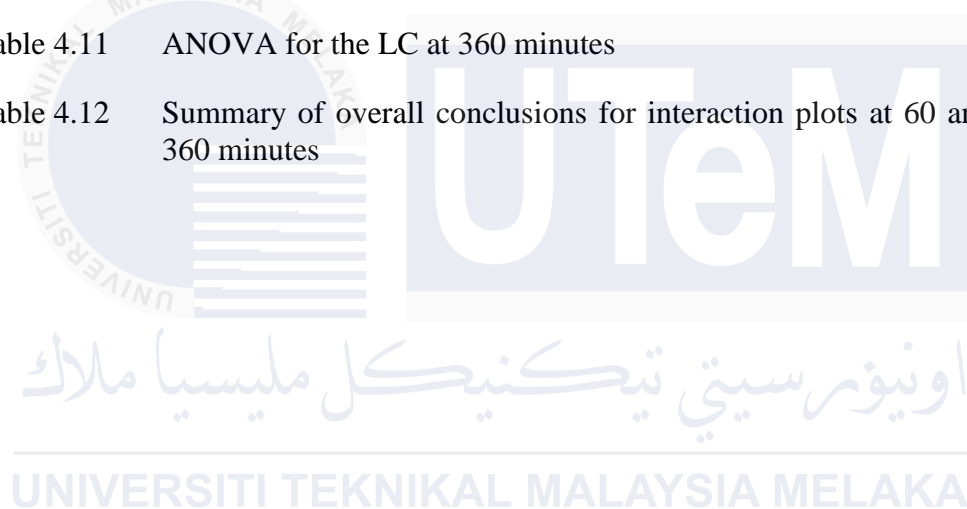
4.3.2 Overall Conclusion of the Second Stage	243
5. CONCLUSION AND FUTURE RECOMMENDATION	245
5.1 Introduction	245
5.2 Conclusions	245
5.3 Recommendations for Future Research	249
REFERENCES	251
APPENDICES	298



LIST OF TABLES

TABLE	TITLE	PAGE
Table 1.1	Mapping of research objectives to the corresponding stages of the study	13
Table 2.1	Types of Peroxides and Curing Temperature Ranges (Ali, 2017)	40
Table 2.2	Summary of previous findings related to processing parameters	45
Table 2.3	Various types of tests are available according to their categories (Aman, 2014), (Horňáková and Lehner, 2020)	47
Table 2.4	Summary of research on the tensile strength and strain of SiR with different types of fillers and various concentrations, used as insulating materials in other studies	57
Table 2.5	Table A summary of the time intervals used to represent leakage current (LC) in different research papers	68
Table 2.6	Leakage current (LC) for hybrid filler studies	79
Table 3.1	Experimental factors and their ranges for SiR composites	96
Table 3.2	The level of concentration used in SiR Blends	98
Table 3.3	Formulations of the 19 samples used in the first stage	100
Table 3.4	Mixing formulations for SiR blends	102
Table 3.5	The test parameters of IPT test (British Standard Institution., 2022)	111
Table 3.6	Comparison between methods 1 and 2 in the IPT test (British Standard Institution., 2022)	115
Table 3.7	The testing conditions decided for the 11 samples in the second stage	124
Table 3.8	The examples of data obtained after FFT	138
Table 3.9	The crest factor of the supply voltage	142
Table 4.1	LC values for all samples in the first stage of analysis	149
Table 4.2	The percentage of contribution values for all factors and their interactions	152
Table 4.3	ANOVA for the LC at 60 minutes	155

Table 4.4	ANOVA for the LC at 360 minutes	156
Table 4.5	Summary of overall conclusions for interaction plots at 60 and 360 minutes	185
Table 4.6	The samples chosen to be tested	202
Table 4.7	The important peaks in the SiR materials	207
Table 4.8	The experimental conditions for the 11 runs with varying voltage, flow rate and contaminant concentrations	222
Table 4.9	The percentage of contribution values for all factors and their interactions	225
Table 4.10	ANOVA for the LC at 60 minutes	226
Table 4.11	ANOVA for the LC at 360 minutes	226
Table 4.12	Summary of overall conclusions for interaction plots at 60 and 360 minutes	237



LIST OF FIGURES

FIGURE	TITLE	PAGE
Figure 1.1	The advantages of polymeric insulators make them favourable compared to ceramic and glass insulators	1
Figure 1.2	Simplified flowchart illustrating the process of identifying the problem statement in this study	12
Figure 1.3	The critical stages in the study are explained briefly for further understanding	18
Figure 2.1	A unit of poly-siloxane with R functional group	21
Figure 2.2	Functional group variations in SiR	22
Figure 2.3	Solid high-temperature vulcanising (HTV) silicone rubber	22
Figure 2.4	The chemical reaction occurring in SiR during dry band arching	27
Figure 2.5	Close-up on the specimen configuration in IPT test set-up (British Standard Institution., 2022)	51
Figure 2.6	Formation process of Leakage Current (LC)	64
Figure 2.7	Visual representation of a time-frequency domain signal (Candy, 2024)	67
Figure 2.8	Example of 3D plot model graph (Nazir Ali et al., 2024)	91
Figure 3.1	Summary of the methodological approach adopted in this study	94
Figure 3.2	Overview of the research flow	95
Figure 3.3	The regular two-level factorial design	99
Figure 3.4	Input details of each factor in the first stage	99
Figure 3.5	Weighting scale used in weighing all materials accurately	103
Figure 3.6	The internal mixer used to produce SiR blends	104
Figure 3.7	The prepared SiR blends	105
Figure 3.8	Hot press machine used in curing the SiR samples	106
Figure 3.9	Sample size used for IPT test	106
Figure 3.10	The sample size of 200 mm x 200 mm x 3 mm	107

Figure 3.11	Dimensions of test samples featuring perforations for electrode attachment (British Standard Institution., 2022)	109
Figure 3.12	The dimension of the filter paper used in IPT test	110
Figure 3.13	Ammonium chloride salt (NH_4Cl)	112
Figure 3.14	The wetting agent of Isooctylphenoxypolyethoxyethanol	112
Figure 3.15	The equipment used to check the resistivity of the contaminants	113
Figure 3.16	The close-up of specimens mounted to the IPT machine	114
Figure 3.17	Sample to be tested under SEM	117
Figure 3.18	SEM machine of Zeiss EVO 50	117
Figure 3.19	The chamber for specimens during the FTIR testing	119
Figure 3.20	The Jasco FTIR-6100 machine	119
Figure 3.21	The Shimadzu Universal Testing Machine 20 kN	120
Figure 3.22	SiR dumbbell specimens for tensile strength testing and their specifications	121
Figure 3.23	Summary of material preparation process for the IPT test	125
Figure 3.24	Electrical circuit configuration for the IPT test, amended from (Aman, 2014)	130
Figure 3.25	Physical arrangement of equipment for the IPT test	131
Figure 3.26	The measuring and protection circuit	132
Figure 3.27	LabVIEW interface used to obtain LC values during the IPT test	134
Figure 3.28	Example of LC data collected and stored in an Excel file	136
Figure 3.29	The flowchart for pre-processing of LC data	137
Figure 3.30	The frequency generator used for input verification	139
Figure 3.31	Vrms displayed by the LabVIEW	140
Figure 3.32	Irms of LC displayed in the LabVIEW	140
Figure 3.33	The image captured by the LabVIEW program is similar to those displayed by the frequency generator	141
Figure 3.34	The setup to check the harmonics of the power supply	142

Figure 3.35	Percentage of voltage input harmonics (VTHD) during the IPT test at 3.5 kV over a duration of 6 hours	143
Figure 3.36	Percentage of voltage input harmonics (VTHD) during the IPT test at 4.5 kV over a duration of 6 hours	144
Figure 3.37	Percentage of voltage input harmonics (VTHD) during the IPT test at 5.5 kV over a duration of 6 hours	145
Figure 4.1	Flow chart emphasizing the flow of analysis for the research	147
Figure 4.2	Superimposed image of the half-normal plots for the 60 and 360 minute IPT tests in the first stage	151
Figure 4.3	The AB interaction plot at 60 minutes a) C: 40 rpm, D: 5 minutes, b) C: 70 rpm, D: 5 minutes, c) C: 40 rpm, D: 10 minutes and d) C: 70 rpm, D: 10 minutes	161
Figure 4.4	The AC interaction plot at 60 minutes a) B: 0.5 pphr, D: 5 minutes, b) B: 1.5 pphr, D: 5 minutes, c) B: 0.5 pphr, D: 10 minutes and d) B: 1.5 pphr, D: 10 minutes	164
Figure 4.5	The BC interaction plot at 60 minutes a) A: 10 pphr, D: 5 minutes, b) A: 50 pphr, D: 5 minutes, c) A: 10 pphr, D: 10 minutes and d) A: 50 pphr, D: 10 minutes	166
Figure 4.6	The BD interaction plot at 60 minutes a) A: 10 pphr, C: 40 rpm, b) A: 50 pphr, C: 40 rpm, c) A: 10 pphr, C: 70 rpm and d) A: 50 pphr, C: 70 rpm	169
Figure 4.7	The AB interaction plot at 360 minutes a) C: 40 rpm, D: 5 minutes, b) C: 70 rpm, D: 5 minutes, c) C: 40 rpm, D: 10 minutes and d) C: 70 rpm, D: 10 minutes	172
Figure 4.8	The AC interaction plot at 360 minutes a) B: 0.5 pphr, D: 5 minutes, b) B: 1.5 pphr, D: 5 minutes, c) B: 0.5 pphr, D: 10 minutes and d) B: 1.5 pphr, D: 10 minutes	175
Figure 4.9	The AD interaction plot at 360 minutes a) B: 0.5 pphr, C: 40 rpm, b) B: 1.5 pphr, C: 40 rpm, c) B: 0.5 pphr, C: 70 rpm and d) B: 1.5 pphr, C: 70 rpm	178
Figure 4.10	The BC interaction plot at 360 minutes a) A: 10 pphr, D: 5 minutes, b) A: 50 pphr, D: 5 minutes, c) A: 10 pphr, D: 10 minutes and d) A: 50 pphr, D: 10 minutes	181
Figure 4.11	The BD interaction plot at 360 minutes a) A: 10 pphr, C: 40 rpm, b) A: 50 pphr, C: 40 rpm, c) A: 10 pphr, C: 70 rpm and d) A: 50 pphr, C: 70 rpm	184

Figure 4.12	The interrelations between AB at a) 60 minutes and b) 360 minutes	188
Figure 4.13	The interrelations between AC at a) 60 minutes and b) 360 minutes	189
Figure 4.14	The interrelations between AC at a) 60 minutes and b) 360 minutes	190
Figure 4.15	The interrelations between BD at a) 60 minutes and b) 360 minutes	191
Figure 4.16	The optimised combination of SiR for the lowest LC at 60 minutes	193
Figure 4.17	The optimised combination of SiR for the lowest LC at 360 minutes	193
Figure 4.18	The Cpk for the optimised combination of SiR for the lowest LC at 360 minutes	195
Figure 4.19	Weight loss, tracking length, and depth against filler concentration	199
Figure 4.20	Weight loss, tracking length, and depth against DCP curing agent concentration	199
Figure 4.21	Weight loss, tracking length, and depth against mixing speed	200
Figure 4.22	Weight loss, tracking length, and depth against mixing time	200
Figure 4.23	The plot representing the true average tensile strength for the SiR samples	204
Figure 4.24	Stress-strain graph of the SiR materials	204
Figure 4.25	FTIR of the samples before IPT test	206
Figure 4.26	FTIR of samples after IPT test	207
Figure 4.27	Silicone oxygen stretching plots for all samples	208
Figure 4.28	Siloxane stretching plots for all samples	209
Figure 4.29	Silicone methyl stretching plots for all samples	210
Figure 4.30	Carbon-hydrogen stretching plots for all samples	210
Figure 4.31	OH, hydrophilic plots for all samples	211
Figure 4.32	SEM images of sample 2 before the IPT test at a) 100× magnification and b) 500× magnification	213

Figure 4.33	SEM images of sample 2 after the IPT test at a)100× magnification and b) 500× magnification	214
Figure 4.34	SEM image of sample 7 before the IPT test at a) 100× magnification and b) 500× magnification	215
Figure 4.35	SEM image of sample 7 after the IPT test at a) 100× magnification and b) 500× magnification	216
Figure 4.36	SEM image of sample 5 before the IPT test at a) 100× magnification and b) 500× magnification	217
Figure 4.37	SEM image of sample 5 after the IPT test at a) 100× magnification and b) 500× magnification	218
Figure 4.38	Superimposed image of the half-normal plots for the 60 and 360 minute IPT tests in the second stage	224
Figure 4.39	AB interaction plot at 60 minutes for a) C: 500 μ S/cm and b) C: 4500 μ S/cm	229
Figure 4.40	BC interaction plot at 60 minutes for a) A: 3.5 kV and b) A: 5.5 kV	231
Figure 4.41	AB interaction plot at 360 minutes at a) C: 500 μ S/cm and b) C: 4500 μ S/cm	234
Figure 4.42	BC interaction plot at 360 minutes when a) A: 3.5 kV and b) A: 5.5 kV	236
Figure 4.43	The interrelations between AB at a) 60 minutes and b) 360 minutes	240
Figure 4.44	The interrelations between BC at a) 60 minutes and b) 360 minutes	240
Figure 4.45	Optimisation of factor values to achieve the best value of LC while maintaining proper Cpk values with (a) maximum A, minimum B and C, b) maximum B, minimum C and A, c) maximum C, minimum A and B, and d) maximum A, B and C	243

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
Appendix A	SiR Datasheet	298
Appendix B	Python coding for FFT	300
Appendix C	Images for all 19 samples used in analysis in the first stage	301



LIST OF ABBREVIATIONS

ASTM	-	American Society for Testing and Materials
ATH	-	Aluminium Trihydrate
DAQ	-	Data Acquisition
DCP	-	Dicumyl Peroxide
DOE	-	Design of Experiments
EPDM	-	Ethylene-Propylene-Diene Rubber
FFT	-	Fast Fourier Transform
FTIR	-	Fourier Transform Infrared Spectroscopy
IPT	-	Inclined Plane Tracking
LC	-	Leakage Current
NR	-	Natural Rubber
OVAT	-	One Variable At a Time
Pphr	-	Parts Per Hundred Rubber
Rpm	-	Revolutions Per Minute
SEM	-	Scanning Electron Microscope
SiR	-	Silicone Rubber
THD	-	Total Harmonic Distortion

LIST OF SYMBOLS

%	-	Percentage
A	-	Ampere
Al ₂ O ₃	-	Aluminium Oxide
cm	-	centimetre
g	-	gram
g/cm ³	-	gram per cubic centimetre
Hz	-	Hertz
I _{rms}	-	root mean square current
kN	-	kilonewton
kV	-	kilovolt
kΩ	-	kiloohm
mA	-	miliampere
ml/min	-	millilitres per minute
mm	-	millimetre
MPa	-	megapascal
μA	-	microampere
μS/cm	-	microsiemens per centimetre
SiO ₂	-	Silica/ Silicone Dioxide
V	-	Volt
V _{pp}	-	peak to peak voltage
V _{rms}	-	root mean square voltage
Ω	-	Ohm