NON-CERAMIC INSULATORS IN COASTAL TROPICAL CLIMATES

The Case Study of Tanzania Field Performance of Polymeric Insulators and Dielectric Characteristics of Silicone Rubber and Epoxy Resin Formulations

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M.Sc. (Electrical Power Engineering) Thesis

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Aviti Thadei

A Thesis Submitted in Fulfilment of the Requirements for the Degree of Master of Science (Electrical Power Engineering) of the University of Dar es Salaam

University of Dar es Salaam

August 2010

CERTIFICATION

The undersigned certify that he has read and hereby recommend for acceptance by the University of Dar es Salaam a thesis entitled: "***Non-Ceramic Insulators in Coastal Tropical Climates:*** *The Case Study of Tanzania Field Performance of Polymeric Insulators and Dielectric Characteristics of Silicone Rubber and Epoxy Resin Formulations*" in fulfilment of the requirements for the degree of Master of Science (Electrical Power Engineering) of the University of Dar es Salaam.

_____

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DEDICATION

To ***Getrude*** *and* ***Furaha***

…Knowledge is a stepping-stone for societal development…

ABSTRACT

Since use of non-ceramic insulators (NCIs) began worldwide in 1970s, researchers have been busy perfecting these products, monitoring them in service and analysing their failure modes. In Tanzania, there is need to monitor and evaluate NCIs for use in its tropical climates. This tropical climate is characterised by heavy rains, high insolation resulting to high temperatures and high humidity. One aim is to investigate and evaluate aging and performance of NCIs in these climates regarding their hydrophobicity (HC), layer conductivity, quantifying oxidation and chalking indices. Another aim is investigation in order to characterise the dielectric properties of polymeric formulations.

Achieving those objectives necessitated adopting methods such as field visits, Swedish Transmission Research Institute (STRI) guide for HC measurements, guide for visual observations of damage and deterioration (STRI, 2005) and Fourier Transform Infrared Spectroscopy (FTIR) spectra. In addition, characterising the polymeric formulations used surface and volume resistivity methods and dielectric frequency spectroscopy. Fit of the resistivity data to curves used robust regression methods, which are resistant to outliers.

Results indicated excellent performance of NCIs in Tanzania regardless of poor HC, higher layer conductivity caused by high contamination, deterioration and damage. Contamination caused failure of one insulator from Masaki substation with its surfaces showing presence of oxidation and chalking products. In addition, High Voltage yard insulators showed varying degrees of material deterioration and layer conductivity with

varying degrees of HC. Dielectric characterisation of polymeric formulations showed higher surface and volume resistivities. Furthermore, there were higher dielectric losses in silicone rubber (SIR) than in epoxy resin. SIR displayed both low and higher frequency relaxations whereas epoxy resin displayed higher frequency relaxations. There was low and higher frequency relaxation exacerbated by electrode polarisation in series combined SIR and epoxy resin. The dielectric losses contained dc conductivity, hopping conductivity and electrode polarisations.

With these findings, the Tanzania utility is urged to speed up upgrading insulation for distribution and transmission lines. In addition, it could set up a R&D department to deal with NCIs.

TABLE OF CONTENTS

Page

Certification ..... **i**
Declaration and Copyright ..... **ii**
Acknowledgement ..... **iii**
Dedication ..... **iv**
Abstract ..... **v**
Table of Contents ..... **vii**
List of Publications ..... **xiii**
List of Acronyms ..... **xiv**
List of Figures ..... **xvii**
List of Tables ..... **xx**

CHAPTER ONE: INTRODUCTION **1**
1.1 General Introduction ***1***
1.1.1 Background Information on Outdoor Polymeric Insulation *1*
1.1.2 Construction of Non-Ceramic Insulators *3*
1.1.3 Polymer Materials used for Manufacturing Outer Sheaths of Non–Ceramic Insulators *4*
1.1.4 Brittle Fractures of the Central Rod *4*
1.1.5 Worldwide Applicability of Non-Ceramic Insulators *5*
1.1.5.1 Comparison between Polymeric, Porcelain and Glass Insulators 5
1.1.5.2 Extent of Usage of Non-Ceramic Insulators 7
1.1.6 Tanzania Climatic Conditions *9*
1.1.7 Advantages and Disadvantages of Polymeric Insulation *11*
1.2 Problem Statement ***13***
1.3 Research Objectives ***16***
1.3.1 Main Objectives *16*
1.3.2 Specific Objectives *16*
1.4 Study Significance ***16***

1.5 Scope of the Research ***17***
1.6 Study Contribution ***17***
1.7 Organization of the Thesis ***17***

CHAPTER TWO: LITERATURE REVIEW **20**
2.1 Surface Characteristics of Non–ceramic Insulators in Field ***20***
2.1.1 Hydrophobicity *20*
2.1.2 Hydrophobicity Measurements *21*
2.1.3 Environmental Stress Effects on Hydrophobicity and Performance of Polymeric Insulators *22*
2.1.3.1 Hydrophobicity Loss and Recovery 22
2.1.3.2 Biofilms and Contamination Effects on Hydrophobicity 23
2.1.3.3 Oxidation and Depolymerization 26
2.2 Nucleophilic/Electrophylic Attacks, Vandalism and Discharges due to Electric Field ***28***
2.3 Other Damages on Non–ceramic Insulators ***29***
2.4 Summarising Effects of Stresses on Polymeric Insulators ***30***
2.5 Quantifying Pollution on Insulator Surface ***33***
2.6 Quantification of Oxidation, Degradation, Deterioration and Aging of Non–ceramic Insulators ***34***
2.6.1 Preamble *34*
2.6.2 Using Gas Chromatography/ Mass Spectroscopy (GC/MS) *35*
2.6.2.1 Procedure 35
2.6.2.2 Usefulness of GC/MS 35
2.6.3 Using Fourier Transform Infrared Spectroscopy *38*
2.6.3.1 Procedure 38
2.6.3.2 Important Bonds and their Characteristics Absorption Bands 38
2.6.3.3 Usefulness of FTIR Spectra 39
2.7 Leakage Currents on Polymeric Insulators ***43***
2.8 Flash-over Voltage on Polluted Polymeric Insulators ***46***
2.8.1 The Obenaus Polluted Insulator Model *46*

2.8.2 Factors Affecting Flashover Voltages *47*
2.8.3 Economic Effects of Flashover Occurrences *48*
2.8.4 Methods to Reduce or Overcome Flashover *49*
2.9 Biofouling on Polymeric Insulators ***50***
2.9.1 Biofilms on Insulators In Tanzania *51*
2.9.2 Identification of Biofilms on Insulator Surfaces *52*
2.9.3 Effect of Biofouling on Polymeric Insulators *54*
2.10 Dielectric Characteristics of Polymeric Formulations ***56***
2.10.1 Resistivity of Solid Insulation Systems *56*
2.10.2 Measuring Volume Resistivity *58*
2.10.3 Measuring Surface Resistivity *59*
2.10.4 Frequency Spectroscopy of Solid Insulation Systems *60*
2.10.4.1 Dielectric Properties of Solid Insulation Systems 61
2.10.4.2 Dielectric Polarization 62
2.10.4.3 Tools for Measuring Dielectric Properties 63
2.10.4.4 Dielectric Properties of a Polymer under the Action of an Electric Field 65
2.10.4.5 Simple Series and Parallel Dielectric Networks 68
2.10.5 Conductance of Polymer Networks *70*
2.11 Review of Past Work on Insulation Systems in Tanzania ***72***
2.11.1 Review of Undergraduate Research Works *72*
2.11.2 Postgraduate Research Works *74*
2.11.3 Pollution Severity of Insulators in Tanzania and their Electrical Performance up to 1999 ..... *75*
2.11.5 Pollution Severity of Insulators in Tanzania and their Performance from 1999 Todate *77*

CHAPTER THREE: METHODOLOGIES AND EQUIPMENTS 81
3.1 Field and Laboratory Investigation of Installed Non–ceramic Insulators in Tanzania ***81***
3.1.1 Hydrophobicity Measurements *81*
3.1.2 Determination of Pollution and Damage *81*

3.2 Determination of Soluble/Salt Deposit Density and Layer Conductivity..... 82
3.2.1 Surface Conductivity (κ)..... 82
3.3 Determination of Aging, Oxidation, Degradation and Depolymerization of Polymeric Insulators..... 82
3.3.1 Method of Gas Chromatography/Mass Spectrometry..... 82
3.3.2 Method of Fourier Transform Infrared Spectrometry..... 83
3.3.3 Calculating Oxidation Index and Chalking Index..... 84
3.4 Polymeric Material Characterisation..... 84
3.4.1 Polymeric Sample Manufacturing..... 85
3.4.2 Resistivity Testing Methods..... 87
3.4.3 Analysis of Resistivity Data..... 88
3.4.4 Dielectric Loss Factor Measurements..... 89

CHAPTER FOUR: RESULTS OF FIELD INVESTIGATIONS 91
4.1 Performance of Polymeric Insulators in Tanzania..... 91
4.1.1 Polymeric Insulators Installed by Local Utility..... 91
4.1.2 Performance of Test Polymeric Insulators..... 94
4.2 Results from Field Test Sites..... 94
4.2.1 Kimara Feeder..... 94
4.2.1.1 Observations at Kimara Feeder Insulators..... 96
4.2.2 Tazara Feeder..... 99
4.2.3 Ohio Street Distribution Line..... 100
4.2.4 Masaki Substation..... 101
4.2.4.1 Installation Work and Early Performance..... 101
4.2.4.2 Visual Observations..... 103
4.2.4.2 FTIR Results..... 105
4.2.4.3 Leakage Currents..... 107
4.2.5 Wazo Hill Substation..... 107
4.2.6 Ruvu Chini Water Pump Station in Coast Region..... 108
4.2.7 Kunduchi and Ras Kiromoni Marine Cable Link to Zanzibar..... 111
4.2.8 High Voltage Yard at University of Dar es Salaam..... 112

4.2.8.1 Visual Observation 112
4.2.8.2 FTIR Results 114
4.3 Oxidation and Chalking Indices 120
4.4 Conductivity of Insulators' Surfaces 121

CHAPTER FIVE: DIELECTRIC CHARACTERISATION OF POLYMERIC FORMULATIONS 122
5.1 Surface Characteristics of Polymeric Formulations 122
5.1.1 Surface Resistivity 122
5.1.1.1 Repeating and Prolonging Resistivity Measurements 124
5.1.2 Reflections on the Surface Resistivity Results 128
5.2 Volume Resistivity Results 128
5.2.1 Summary of Epoxy Resin Results 128
5.2.1 Summary of Silicone Rubber Results 129
5.2.1 Repeated Volume Resistivity Measurements 130
5.2.3 Volume Resistivity of Series Joined Silicone Rubber and Epoxy Resin 131
5.3 Summary of Resistivity Results 132
5.4 Dielectric Loss Results 133
5.4.1 Single Polymer Results 133
5.3.2 Losses of Series Joined Silicone Rubber and Epoxy Resin 135

CHAPTER SIX: EVALUATION OF THE THESIS 138
6.1 Instrumentation Challenges 138
6.2 Logistical Challenges 139
6.3 Data and Sample Challenges 140
6.4 Achievements 141
6.4.1 Field Investigation of Polymeric Insulators 141
6.4.2 Dielectric Characterisation of Polymeric Formulations 142

CHAPTER SEVEN: CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK **143**

7.1 Field Activities in Tanzania ***143***

7.1.1 Conclusions *143*

7.1.2 Recommendations and Future Work *145*

7.2 Resistivity Measurements ***146***

7.2.1 Conclusions *146*

7.2.2 Recommendations and Future Work *147*

7.3 Dielectric Measurements ***148***

7.3.1 Conclusions *148*

7.3.2 Recommendations and Future Work *149*

REFERENCES 150

APPENDIX A 168

APPENDIX B 179

LIST OF PUBLICATIONS

PAPER A Surface Resistivity of Silicone Rubber Formulations Tested in Room Ambient Conditions – *The Case of Silicone Rubber Formulations with and Without Filler Materials*, in *Proceedings of International Conference on Research and Development*, *Vol. 1, No. 12*, pp. 52 – 56, 2008.

PAPER B Dielectric Properties of Series Joined Silicone Rubber and Epoxy Resin Formulations, Unpublished.

LIST OF ACRONYMS

ACRONYM	MEANING
A	Ampere
Á	Parameter related to temperature
ALTH	Alumina trihydrate
β	Shape factor
C	Capacitance
CH_n	Hydrocarbons
CoET	College of Engineering and Technology
COO	Carbonyl compounds
CTH	Chalmers University of Technology
EE	Electrical Engineering Department
ELF	Extreme low frequency
EPDM	Ethylene propylene di-ene monomer
EPS	Extracellular polymeric substances
ESDD	Equivalent soluble/salt deposit density
f	Frequency in hertz
FO	Flash over voltage
FTIR	Fourier transform infrared spectroscopy
G	Conductance
GCLA	Government Chemist Laboratory Agency
GC/MS	Gas chromatography mass/spectrometry
GFR/FRP	Glass fibre reinforced plastic rod
He	Helium gas
Hz	Hertz
HC	Hydrophobicity
HTV	High temperature vulcanised
HV	High voltage
HVL	High voltage laboratory
I	Electric current
ICIEA	International Conference on Industrial

	Electronics
IR	Infra-red rays
K	Kimara insulator
κ	Layer surface conductivity
KIPTS	Koosloo Insulator Pollution Testing Station
kV	Kilo volts
LC	Leakage current
LF	Low frequency range
LFD	Low frequency dispersion
LLW	Live line washing
LSR	Liquid silicone rubber
mA	milliampere
M	Masaki polymer insulator
MC	Masaki ceramic insulator
mm	millimetre
NCI	Non-ceramic insulator
NSDD	Non-soluble deposit density
n.d	No publication date on a paper or a book
PC	Personal computer
PDMS	Polydimethylsiloxanes
R	Resistance
RAF	Relative aging factor
RoW	Right of way
RTV	Room temperature vulcanised rubber
S	Surface area
SDD	Salt deposit density
SIR	Silicone rubber
$Si\text{-}CH_n$	Silicon-alkyl functional group
STRI	Swedish Transmission Research Institute
T	Temperature
t	Thickness
TANESCO	Tanzania Electric Supply Company

TAZARA	Tanzania and Zambia Railway Authority
TU	Upper part of a shed
UDSM	University of Dar Es Salaam
UV	Ultra-violet rays
V	Volts or voltage
VI	Virtual instrument
w	Angular frequency in radians
XLPE	Cross-linked polyethylene
Υ	Admittance
Z	Impedance
μA	microampere
σ	Ionic conductivity within a material
δ	Dielectric loss factor or delta
ε	Dielectric permittivity
Ω	Ohm
τ	Dielectric relaxation time
ρ	Resistivity

LIST OF FIGURES

Page

Figure 1.1 NCIs (a) older designs, and (b) newer designs.....3
Figure 2.1 Ageing stress, effects and results on NCIs 31
Figure 2.2 Obenaus model of insulator flashover 46
Figure 2.3 An insulator with biofilms from Tanzania Ruvu Chini 51
Figure 2.4 Microscopic view of (a) algae and (b) fungal hyphae..... 53
Figure 2.5 Volume resistivity measurement technique 58
Figure 2.6 Surface resistivity measurement technique 59
Figure 2.7 Dielectric frequency analyzer 68
Figure 2.8 Simple: (a) parallel; and (b) series RC networks representing dielectric materials. 69
Figure 2.9 Circuit analogue of electrical insulation with a single relaxation time. 69
Figure 2.10 Simple dielectric characteristics for low frequency regions..... 71
Figure 2.11 Time variation of LCs on Silicone Rubber Insulators from Ruvu Chini Tanzania 79
Figure 4.1 Polymeric insulators installed in Tanzania along TAZARA industrial area in Dar es Salaam 93
Figure 4.2 Kimara polymeric insulators. 96
Figure 4.3 Kimara polymeric insulators showing biofouling, dust and soot on sheds, shank and end fittings of insulators 97
Figure 4.4 HC of Kimara insulators..... 97
Figure 4.5 Polymeric insulators at TAZARA 100
Figure 4.6 Polymeric insulators at Ohio street 101
Figure 4.7 Masaki insulator one year after installation in 1996.....102
Figure 4.8 Masaki substation insulators 103
Figure 4.9 Damaged insulator (M1) from Masaki substation 104
Figure 4.10 FTIR results of insulator M1 showing transmittance of dark surface and the white surface.....105
Figure 4.11 Comparison of content of dark and white surface of insulator M1. .106
Figure 4.12 Wazo hill polymeric insulators covered in cement dust.....108

Figure 4.13 Ruvu Chini insulators showing hydrophobicity, contamination and damages.....110
Figure 4.14 HVL insulators with two years dust contamination 114
Figure 4.15 FTIR of HVL-1 displaying the top surface, bottom surface and bulk transmittance peaks 115
Figure 4.16 Reduction of functional groups with respect to the bulk available material of HVL-1.....116
Figure 4.17 Excess functional groups displayed by insulator NCI-1 117
Figure 4.18 FTIR of NCI-2 depicting bottom and top surfaces' peaks 118
Figure 4.19 Relative presence of functional groups in top and bottom surfaces of NCI-2.....119
Figure 4.20 Scatter plots of oxidation and chalking indices of polymeric insulators 120
Figure 4.21 Conductivity of HVL and Masaki insulators.....121
Figure 5.1 Surface resistivity of silicone rubber formulations at room ambient conditions.....123
Figure 5.2 Surface resistivity of epoxy resins formulations in room ambient conditions.....123
Figure 5.3 Surface resistivity of silicone rubber formulations obtained from consecutive tests 125
Figure 5.4 Surface resistivity of silicone rubbers when tested continuously for 19 hours in dry conditions.....126
Figure 5.5 Surface resistivity of epoxy resin formulations obtained from repeating measurements.....127
Figure 5.6 Surface resistivity of epoxy resin sample for a prolonged application of dc voltage.....127
Figure 5.7 Volume resistivity of epoxy resin formulations 129
Figure 5.8 Volume resistivity of silicone rubber formulations 129
Figure 5.9 Volume resistivity of silicone rubber formulations in repeated measurements.....130
Figure 5.10 Plots of volume resistivity of series combination of silicone rubber and epoxy resin 131
Figure 5.11 Tan delta of silicone rubber formulations.....134
Figure 5.12 Experimental results of tan delta for epoxy resin formulations 134

Figure 5.13 Tan delta of series joined silicone rubber and epoxy resin formulations.....136
Figure 5.14 Dielectric loss (tan delta) of single and series combined polymer formulations.....137

LIST OF TABLES

Page

Table 1.1 Comparison of polymer, porcelain and glass insulators.....6
Table 1.2 Average monthly rainfall in Dar es Salaam and Coast Region between 1995 and 1997..... 10
Table 2.1 Criteria for STRI HC Classification 21
Table 2.2 Transmission lines insulator contaminants and their sources 32
Table 2.3 Characteristic Infra Red absorption bands of functional groups..... 39
Table 2.4 Concentration of cations and anions on seawater and insulator dust in High Voltage Yard 73
Table 2.5 Dimensions of test NCIs installed in Dar es Salaam and Coast Region .. 74
Table 2.6 ESDD of installed insulators 75
Table 2.7 Hydrophobicity of installed insulators..... 75
Table 2.8 Visual observation of insulators as of July 1998 76
Table 2.9 HC and flashover of biologically contaminated and uncontaminated insulators from Ruvu Chini 77
Table 3.1 Sample manufacturing parameters 87
Table 4.1 IEC 60815 pollution severity and the creepage distances recommended for insulators 92
Table 4.2 Tanzania's transmission line and system/maximum design voltages ... 92
Table 4.3 IEC 60815 pollution levels and maximum electric field strength..... 93
Table 4.4 Test insulator specifications 95
Table 4.5 Observations at Kimara feeder test site with light pollution level..... 98
Table 4.6 Observations at Ruvu Chini substation site with light pollution level..111
Table 5.1 Resistivity values of polymeric formulations 132

CHAPTER ONE
INTRODUCTION

1.1 General Introduction

1.1.1 Background Information on Outdoor Polymeric Insulation

In high voltage power lines, achieving the prevention of current flow to the ground is by securing them to the supporting structures through insulators. These insulators have two functions; to support the high voltage parts mechanically and to insulate them from ground (Dernfalk, 2002; Gorur *et al.*, 2005; Wallström, 2005; Theraja *et al.*, 2002).

The history of insulators in transmission lines goes as far as the earliest construction of telegraphic lines, which used porcelain insulators. These insulators served the electrical power industry successfully for more than 120 years (Dernfalk, 2002, 2004; Fernando, 1997, 1999; Wallström, 2005). But due to some failures of ceramic insulators, an alternative material was introduced in the 1970s (Amin & Salman, 2006; Dernfalk, 2002, 2004; Fernando, 1997, 1999; Giriantari *et al.*, 2006; Gubanski *et al.*, 2000; Papailiou, 1999; Wallström, 2005); these materials are polymers. The first idea of using polymer insulators was introduced in USA in 1948; however, it was not taken seriously (Papailiou, 1999). Due to this it took over ten years to manufacture an epoxy insulator in 1959 (Gustavsson, 2000; Phillips, 2002). Epoxy materials suffered from tracking and erosion, which necessitated further developments culminating to NCIs in mature form of apparatus, line and post insulators (Gubanski *et al.*, 2007; Gutman *et al.*, 2004; Kobayashi *et al.*, 2000). Also, the Swiss manufactured their first polymer insulator in

1970, which was hollow–core used for housing cable terminations, and soon after other designs followed (Gorur *et al.*, 2005; Papailiou, 1999) and China followed suit in early 1970's (Xidong *et al.*, 1999).

Raychem researchers (Thornley & Shocket, 1994) presented a test protocol to evaluate polymeric insulation systems returned from various places of the world. In that paper one narration about the damage observed say:

"*The worst damage seems to be on the upper surface of the sheds where one would expect the most combination of Ultraviolet (UV) plus any chemical 'soup' that is flowing down the termination. The whitening is exposed aluminium-trihydrate fillers (ALTH). Although it is known that stable arcing can occur on the upper shed surface, it appears that the erosion mechanisms are removing polymers and red fillers faster than the ALTH.*" (Thornley & Shocket, 1994)

These words hint that the degradation and aging of polymeric insulation systems is but a complex phenomenon. These current times have seen improvement of production technologies of non–ceramic insulators (NCIs) from simple manufacturing techniques in the late 1948s to these days' sophisticated ones. These also make NCIs very young compared to their counterparts' glass and porcelain insulators. Instead of the preferred old technology of traditional mechanical bonding, nowadays technology allows stronger chemical bonding between the epoxy rod and the housing rubber. Prompt for several research interests of NCIs is due to their young age.

1.1.2 Construction of Non-Ceramic Insulators

The initial designs of polymeric insulators which came into being over three decades ago had a central rod coated with polymer material, and a shed that were separately mounted (Amin & Salman, 2006). These designs proved failure due to slippage of the sheds from rod or opening and damage of the rod–shed interface. The following insulators were design improved by directly mounting the shed onto the rod and then encapsulating the mount by polymer materials. However, these designs failed soon. Therefore, Material Scientists, Engineers, Moulders and Fabricators for over the last 15 years worked to introduce newer designs, which are in use to–date. These designs have a glass fibre reinforced (GFR) epoxy or fibre reinforced plastic (FRP) rod covered with polymer sheath and having polymer sheds into the same mould.

Figure 1.1 shows older and newer NCIs. The work of the outer shed apart from protecting the central rod is to provide sufficient pollution withstand by a sufficient creepage distance. The central rod provides the required mechanical strength against bending and tension of the transmission lines.

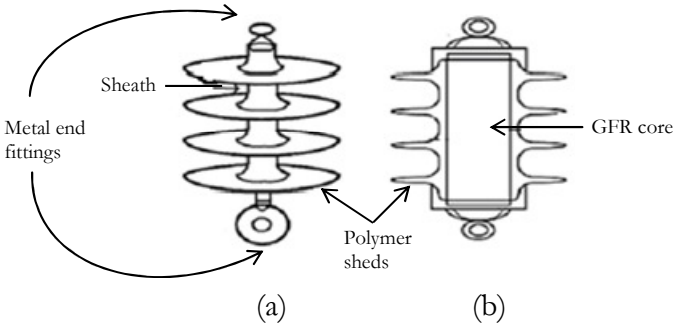


Figure 1.1 NCIs (a) older designs, and (b) newer designs

Source: Amin & Salman (2006)

1.1.3 Polymer Materials used for Manufacturing Outer Sheaths of Non–Ceramic Insulators

There are three different polymer materials used for manufacturing outer sheaths, which include high temperature vulcanised (HTV) rubber, room temperature vulcanised (RTV) rubber and liquid silicone rubber (LSR). However, the rubber on itself lacks some characteristics such as stiffness, mechanical stability, flame retardancy and resistance to tracking. To achieve such characteristics requires addition of filler materials (Akram *et al.*, 2005). Filler materials include aluminium trihydrate (ALTH), boron and fumed silica sand. Bernstorf *et al.* (2006) documented a lot of information regarding polymer composition. Amin & Salman (2006) writes about functioning of filler materials. Suksri & Tonmitr (2005) argue that adding fillers may as well improve mechanical strength only sacrificing electrical properties.

Currently, the most important HTV or RTV polymers for manufacturing outer sheds and sheath for outdoor high voltage insulation systems are silicone rubbers (SIR) as pointed out by the work of Bernstorf *et al.* (2006). Material used to manufacture central rods of those insulators are epoxy resin and glass, which are characteristic improved by fillers. Then, since nothing is perfect, despite reinforcements they undergo some mechanical failures like brittle fracturing of the central rod.

1.1.4 Brittle Fractures of the Central Rod

Deterioration of the outer sheath will automatically lead to the exposure of the internal central rod, which might crack and immediately break thus dropping the line. These damages on the rod are due for it becoming brittle fractured and finally stress corroded

(Liang & Dai, 2006; Montesinos *et al.*, 2002). Test results showed that the chemical functional groups NO_3^-, NO_2^-, together with SO_4^{2-}, were formed both on the brittle fracture (BF) surface of FRP rod and in the rust on end fitting near BF crack (Liang & Dai, 2006). The field-failed insulator revealed that the BF is influenced not only by nitric acid, which may be formed by electrical discharge, but also by sulphuric acid, which may come from acid rain (Liang & Dai, 2006; Montesinos *et al.*, 2002). Earlier results suggested that chemical reactions other than acid production can promote stress corrosion cracking of the rod and these may play a significant role in the failure process (Montesinos *et al.*, 2002). Nevertheless, these insulators are worldwide becoming a preferred choice.

1.1.5 Worldwide Applicability of Non-Ceramic Insulators

Today, worldwide it seems NCIs are becoming cheaper (Dernfalk, 2002). In North America, Switzerland, Australia and Czech Republic the cost of buying, transporting, installing and maintaining NCIs is cheaper than ceramic insulators. Following wide acceptance of NCIs, it is imperative to discuss the differences between them, porcelain and glass insulators.

1.1.5.1 Comparison between Polymeric, Porcelain and Glass Insulators

Table 1.1 from (Phillips, 2002) gives comparisons between polymeric, porcelain and glass insulators. The differences covered are wide regarding outdoor high voltage applications.

Table 1.1 Comparison of polymer, porcelain and glass insulators

Porcelain vs. Glass vs. Polymer			
Type	Properties	Constraints	Issues
Polymeric	- Lightweight & easier to handle - Reduced installed cost - Improved contamination performance - Smaller profile	- Reduced dry arcing distance - Susceptible to arcing damage due to flashovers - Lack of standard dimensions - Relatively "limited" experience - Difficult to inspect - Damaged by corona activity, e.t.c.	- Susceptible to aging - Prone to handling damage - Need grading rings - Contamination performance changes with time - Brittle Fracture
Porcelain	- Porcelain inert surface - Performance well quantified - Puncture of a single unit does not take out a string - Long history of use - Damaged units easier to identify - Flexible in length (No. of units/discs)	- Heavy and cumbersome - Hidden defects - Fun to shoot :– attracts vandalism	- Pin corrosion - Cement growth - Post cascade failures
Glass	- Performance well quantified - Long history of use - Easy visual identification of damaged unit - Flexible in length (# of units/discs)	- Heavy and cumbersome - Real fun to shoot :– attracts vandalism	- Surface defects - failure

Source: Phillips (2002)

From early on, the NCIs exhibited better performance in polluted environments than glass and porcelain insulators (Fernando, 1997; 1999; Mbwana, 1995; Phillips, 2002), and considered as a special product for use in the most severely contaminated areas (Macetech, 2004; Macey & Vosloo, n.d; Mbwana, 1996, 1997; Vosloo & Holtzhausen, 2003a, 2003b; Jiang *et al.*, 2004; Xidong *et al.*, 1999). For example, in South Africa, large-scale re–insulation of transmission lines greatly improved system reliability and eliminated costly washing procedures (Macetech, 2004; Fierro–Chavez *et al.*, 1999). The same observed in USA (Gorur *et al.,* 2005); Israel (Kaidanov *et al.*, 1996); and Saudi

Arabia (Al-Hamoudi & Al-Hamouz, 2003). These serve as explanations of better electrical performance of NCIs. Extent of NCIs usage worldwide highlighting profits derived is the next discussion.

1.1.5.2 Extent of Usage of Non-Ceramic Insulators

These polymeric insulation systems are a mature product with all ranges of products types such as line insulator types, hollow–core insulators, and apparatus insulators for applications in distribution to extra–high voltage systems (Giriantari *et al.*, 2006; Gubanski *et al.*, 2007).

Nowadays growing usage of NCIs for electric power transmission lines is evident in USA (Amin & Salman, 2006; Gorur *et al.*, 2005; Liang *et al.*, 2007). Amin & Salman (2006) had a statistic that the polymer insulator usage is about 60% but faced with problems of road salts (Gorur & Venkataraman, 2005). The growing usage of polymeric insulators in Europe is reported in (Dernfalk, 2002; Gustavsson, 2002; Papailiou, 2005).

China has extensively applied polymeric insulators in transmission, distribution, high voltage ac (HVAC) and high voltage dc (HVDC) lines (Shaouwu *et al.*, 2001a; Wang *et al.*, 2002; Xidong *et al.*, 1999; Zhicheng *et al.*, 2005; Zixia *et al.*, 2002). About 90% of those NCIs serve in polluted areas (Jiang *et al., 2004*; Liang *et al.*, 2007; Shaowu *et al.*, 2001). The failure rate of polymeric insulators is very small reported as 4 out of 100 000 pieces (Su & Jia, 1999). By 1999 the total NCIs installed in China was 600 000 (Xidong *et al.*, 1999).

South Africa has applied NCIs in some polluted climates (Vosloo *et al.*, 1996a, 2001b) which led to first tests on natural aged NCIs in 1999 (Gutman *et al.*, 1999). These tests

helped in selection of a test site at Koeberg Insulator Pollution Testing Station (KIPTS) further setting down their own aging and pollution test standards (Vosloo *et al.*, 2001b). In Sri Lanka, they are thinking of stressing NCIs higher than ordinary porcelain insulators following a study by Fernando *et al.* (2006). Those insulators had good electrical performance after 10 years of applications in Ceylon Electricity Board (CEB).

Other countries to adopt usage of NCIs are Oman and Israel (Gutman *et al.*, 2004; Kaidanov *et al.*, 1996); Tanzania (Magige, 2002); Mexico (Fierro–Chavez *et al.*, 1999); Middle East (Al-Hamoudi & Al-Hamouz, 2003; Kaidanov *et al.*, 1996; Khan *et al.*, 2006); and Sri Lanka (Fernando *et al.*, 2006).

Tanzania is a country with electrical power installed capacity of 700 MW, which include hydro–electricity and thermal–electricity. Its electrical power systems insulators before year 2001, were largely porcelain and glass for the transmission and distribution lines, except for six insulators found installed in Ruvu Chini water pumping station since 1974 in Bagamoyo (Fernando, 1997, 1999; Gubanski, 1998; Gubanski *et al.*, 2001; Kyaruzi & Gubanski, 1999; Mbwana, 1995, 1997). From 2001, the local utility, Tanzania Electric Supply Company Limited with the acronym TANESCO started buying NCIs and began installations in power lines. Some of the NCIs bought were about 10 000 pieces of 11 kV from USA; and 10 000 pieces of 33 kV from Italy (Magige, 2002; Notes, 2008). The 11 kV insulators were made of silicone alloy rubber, and the 33 kV insulators were made of pure silicone rubber. These insulators were horizontal type.

1.1.6 Tanzania Climatic Conditions

Tanzania with a total area of about 945 087 square kilometres, a land area of 886 037 square kilometres and a population of over 36 million people is essentially a tropical country since geographically it lies between latitudes 1° and 12° South and longitudes 29° and 41° East (Nzali & Mushi, 2003). It has a hot arid central plateau, has temperate highlands in the north and south and has coastal plains to the east facing the Indian Ocean. The area of interest in this research is Dar es Salaam and Coast Region (where Bagamoyo is located).

Dar es Salaam has a tropical climate characterized by high temperatures (average 31 °C), and high humidity as shown in Table 1.2 for years 1995 – 1997. The main wind directions are from NE to SW thus bringing marine moisture. The insolation is high with the average of 4.8 $kWhm^{-2}$. Heavy rain seasons are usually from March to May and November to December shown in Table 1.2.

So as it would appear with its position in tropics, Tanzanian climate becomes important in applications of polymeric insulators. These climates is characterized by high humidity which could reach 80 – 90% (higher than what Table 1.2 shows), high temperatures over 29 °C (Fernando, 1997; 1999; Kihwele & Kyaruzi, 2005; Mbwana, 1995, 1996, 1997) and heavy rains causing high humidity (Kadete & Strojny, 1993: pp. 37; Kihwele & Kyaruzi, 2005; Kyaruzi & Gubanski, 1999; Magige, 2002; Magige *et al.*, 2003) throughout the year.

Table 1.2 Average monthly rainfall in Dar es Salaam and Coast Region between 1995 and 1997

Month	Rainfall (mm)	Temperature (°C)	Humidity (%)	Wind speed (m/s)	Prevailing wind direction	Insolation ($kWhm^{-2}$/day)
January	58.4	31.5	71.0	3.1	NE	6.5
February	89.7	32.5	71.7	3.2	NE	5.3
March	124.8	32.0	73.5	1.8	SW	4.0
April	245.5	30.5	77.5	2.1	SW	4.0
May	247.7	29.5	78.7	2.4	SW	4.3
June	15.8	29.4	78.8	2.4	SW	4.4
July	27.6	28.9	71.9	2.7	SW	4.8
August	26.5	29.0	68.2	2.5	SE	5.5
September	13.5	30.3	67.5	3.0	SE	6.2
October	66.8	30.7	65.2	2.4	SE	5.7
November	177.3	31.1	69.2	2.4	NE	6.2
December	123.4	31.3	72.2	3.3	NE	5.7
Average	101.4	30.6	72.1	2.6	SW & NE	4.8

Source: Mbwana (1996, 1997)

Due to high insolation, the Ultra Violet (UV) radiation is higher in this climate causing accelerated aging of the polymeric housing material (Fernando, 1997; Gustavsson, 2000; Mbwana, 1995) for outdoor applications. In addition, pollution build-up on NCI surface provides an electrolytic layer for leakage currents (LCs) when wetted especially during rainy season and fog as observed in Tanzania (Fernando, 1997, 1999; Kihwele & Kyaruzi, 2005; Magige & Kyaruzi, 2003; Mbwana, 1995, 1997). These LCs may lead to dry-band arcing causing surface degradation (Fernando, 1997, 1999; Gustavsson, 2000; Mbwana, 1997).

1.1.7 Advantages and Disadvantages of Polymeric Insulation

The advantages of polymer insulation systems over the traditional porcelain or glass are that they are very strong, they do not shatter when struck by bullets or due to falling, they are lightweight, they are hydrophobic and have low dielectric loss (refer Table 1.1).

However, being organic materials they are prone to aging resulting into deterioration (Amin, 2007). They have relatively weak chemical bonds which are easily broken for example by high-energy photons, and they may thus degrade by UV radiation and heat; their surfaces become contaminated (by biofilms, marine salts and other pollutants); and these lead to induced LCs (Fernando, 1997; 1999; Gustavsson, 2000; 2002). Gubanski (1995) and Gustavsson (2002) points out the difficulties of establishing long–term hydrophobicity (HC) and mechanisms of flashover voltage suppression by the hydrophobic surfaces. These problems are coupled with the aging of interfaces present within and out the insulating material (Andersson, 2006; Tuncer, 2001) and change of dielectric and surface properties for insulators in field (Ehsani *et al.*, 2007).

The most severe failure of an insulator carrying a power line is when it breaks mechanically and drops the line causing disconnection of the line and putting people's life at risk. The second unwanted failure is when the insulator breaks electrically, due to flashover voltages (FOs) or damage causing the power system to be short or long time disconnected (Andersson, 2006; Dernfalk, 2002; Gustavsson, 2000, 2002). These stresses cause aging of the polymeric insulators.

Amin & Salman (2006) defined aging as the degradation of the polymer insulator by different environmental and electrical stresses. Environmental stresses include UV radiation, moisture, heat, light, atmospheric pressure, and biological degradation caused by biofilms. Electrical stresses include corona, formation of dry bands, arcing over surface of an insulator, roughness and erosion of the surface. These factors also affect ceramic insulators, but the biological degradation is evident on NCIs only.

Nevertheless, polymeric materials are now widely used (Hackam, 1998; Phillips, 2002) because of their overall advantages over porcelain or glass (Gustavsson, 2000, 2002; Phillips, 2002; Tuncer, 2001). They are now in wide use for transformer bushings, arresters, line, and hollow–core insulators (Giriantari *et al.*, 2006; Gubanski *et al.*, 2007 citing from (Pargamin, 2003; Xidong *et al.*, 2003); Zhicheng *et al.*, 2005). Many users are afraid to use polymer insulators because of lack of service experience resulting in not utilising the full potential offered (Gorur *et al.*, 2005; Gubanski *et al.*, 2007; Gustavsson, 2002).

Consequently, research on polymeric insulator performance is a very important field in high voltage engineering evidenced on the number of researches undertaken to address outdoor performance of insulations and cable terminations (*refer to the reference list provided at the end*). Wallström (2005) remarks that biofouling seriously influence the function of an insulator but are not capable of degrading polymer insulators. Biofouling is the contamination/colonization by microorganisms such as fungi, algae, bacteria and the like.

Around the power transmission lines of Tanzania, the evidence of biofouling, soot and dust contamination (collectively called as pollutants) on polymer insulator surfaces is abundant. This research work elucidate the present conditions of those insulators covered with pollutants but are still in operation and some have been damaged while others have so far been functioning properly.

One researcher (Giriantari *et al.*, 2006) commented that there always is a need to monitor the condition of polymeric insulators installed in site closely. This will enable assessment of their condition at a specific time to avoid unforeseen problems and to add information to the research of diagnostics of these NCIs as put forward by (Gubanski *et al.*, 2007).

1.2 Problem Statement

Due to the relatively short history, i.e. slightly over 35 years of extensive use of NCIs (Gubanski *et al.*, 2007; Phillips, 2002) in outdoor high voltage applications, then their degradation and dielectric properties are not well known. Being organic materials and applied on hostile environmental stresses like those of Tanzania, polymer insulators will degrade more quickly than porcelain or glass leading to having higher dielectric losses and deterioration of surface properties. In South Africa, Macey & Vosloo (n.d) observed birds scoring and tearing polymeric insulators relative easily. In Tanzania that happened whereby 'mice' and 'rodents' ate some newly bought and stored ethyl-propyl-diene-monomer (EPDM) insulators in a storage house (Notes, 2008).

Mbwana (1995, 1997) reported installation works and evaluation of NCIs and room temperature vulcanised (RTV) coatings. The researcher reported that SIRs performed better than EPDM and RTV coatings under the tropical conditions of Tanzania. Fernando (1997, 1999) reported of the effects of tropical climates on outdoor polymeric and ceramic insulators, studying the LCs and reported high harmonic content in them. Gubanski (1998) proposed continuation of work of Mbwana on polymer insulators in Tanzania. Kyaruzi & Gubanski (1999) reported successful functioning of NCIs in Tanzania. Gubanski *et al.*, (2000) identified green algae on NCIs surface from Tanzania, and that the effect of these algae on NCIs was not too strong which later Wallström (2005) confirmed. Magige *et al.*, (2003) reported that those growths degraded the HC of the NCIs for short periods before washing. Moreover, Kihwele & Kyaruzi (2005) reported superior artificial contamination performances of NCIs compared to ceramics. These works never touched the subject of quantifying the aging and oxidation of the polymeric insulators of Tanzania, which this thesis is going to do. Further, Phillips (2002) spells out the issues with polymer insulators being aging of polymer materials, limited experience, large variation in designs, materials and manufacturing techniques, and handling concerns in**:** storing, transporting and installing. The aim of this thesis is to look into some of these issues as already said.

Also, the Material Science, Insulation, Physics, Electrical Engineering, Chemistry, and High Voltage Communities are currently researching dielectric (Tuncer *et al.*, 2007), surface and material bulk characteristics of silicone rubber and epoxy resin; materials which are used for manufacturing high voltage outdoor insulation. Jonscher (1999) reviewed dielectric relaxation in solids concluding that despite the complexity of relaxation process, they are guided by simple relations of which Zong *et al.* (2005)

reported that the dielectric properties of epoxy resin (a polymer) decrease with extent of cure and increase with temperature. Riande & Díaz–Calleja (2004) did a great job at discussing electrical properties of polymers in their book. Tuncer & Gubanski (2000) reported on electrical properties of filled SIR saying that the fillers acted as charge traps. Further, by researching the nano– and sub–micron sized fillers in epoxy resin Tuncer *et al.* (2007) showed that the filled resins had more electrical strength than unfilled ones.

Tuncer (2001) discussed the dielectric relaxation in dielectric mixtures, developing a formula for these mixtures in Tuncer *et al.* (2002). Nguyen *et al.* (2004) studied dielectric properties of silica filled silicone rubber and identified two polarization mechanisms, characterised the loss factor (ε) with Havriliaki–Negami model, and discovered that the dominance of hopping charge transport is at moderate higher fields. Tuncer (2006) further discussed the microstructural effects in dielectric mixtures and reported that the filler materials behave as charge traps as before in (Tuncer & Gubanski, 2000). Dakin (2006) discussed the conduction and polarization mechanisms and trends in dielectrics, stressing the importance of dielectric data to interpret molecular behaviour and structure of dielectrics. Zhang *et al.* (2006) examined polymer nanocomposites one polar and another non–polar, whereby it was established a presence of significant interfacial polarizations in polyethylene nanocomposites and none in epoxy nanocomposites.

These works have not characterised SIR and epoxy resin in room ambient conditions by joining them in series in an electrometer using only the pressure exerted by the electrodes. This thesis is going to characterise the surface, volume (bulk) resistivities, and dielectric loss factor of SIR and epoxy resin formulations in room ambient conditions.

1.3 Research Objectives

1.3.1 Main Objectives

This study addresses the following issues: (1) to evaluate the aging of polymeric insulators in Tanzania, and (2) to characterise polymeric formulations in laboratory.

1.3.2 Specific Objectives

Specifically the study concentrated on the following activities:

(1) To evaluate the aging of NCIs in Dar es Salaam and Coast Region of Tanzania;

(2) To evaluate the oxidation and chalking indices of NCIs; and

(3) To characterise surface resistivity, volume resistivity and dielectric loss factor of polymeric formulations namely SIR and epoxy.

1.4 Study Significance

This study is a continuation of several earlier studies done in Tanzania in a research project aimed to study usefulness of NCIs in Coastal Tropical Climates of Tanzania. The study addresses long time evaluation of NCIs in Tanzania not done by previous researchers. Findings presented here, insulators tested, which have been in Tanzania power lines, will provide basis for selection of the same. Field data provide important references for research on aging, pollution property, and to those researching relevant test methods of aged NCIs.

In addition, the study gives out the dielectric characteristics of SIR and epoxy resin, which are important for manufacturers and utilities.

1.5 Scope of the Research

This research work covers field investigation of Tanzania polymeric insulators, evaluating the extent of aging by FTIR, surface layer conductivity, HC measurements and visual observations.

In addition, the same work covers dielectric characterisation of polymeric formulations. The measurements performed are surface and volume resistivity, and frequency spectroscopy.

1.6 Study Contribution

In its entirety, the study contributes the following:

(1) Addition of new knowledge about aging characteristics of NCIs in coastal tropical climates of Tanzania; and

(2) Giving out dielectric characteristics of mechanically joined polymeric formulations.

1.7 Organization of the Thesis

CHAPTER ONE is an introduction that discusses history, growing applicability, advantages and construction of polymeric insulators. It goes on to give the problem statement, research objectives, contribution of the study to both the academy and the industry.

CHAPTER TWO is a literature review, which discusses several aspects of polymer insulators' performance ranging from field applications, electric and dielectric behaviour, to diagnostics methods. It also shed the light on the status of polymeric insulator research in Tanzania.

CHAPTER THREE is methodologies and equipments used for the study. The discussion centres on evaluation procedures and equipments used for field and laboratory investigations of NCIs and the polymeric formulations.

CHAPTER FOUR is a presentation of the field investigation results. Results are provided with discussions.

CHAPTER FIVE is a presentation of dielectric characterisation results obtained for the polymeric formulations prepared in laboratory and industry..

CHAPTER SIX is a part that evaluates the researching process, pointing out challenges faced. In addition, the chapter explains and concludes about the degree of accomplishment achieved.

CHAPTER SEVEN is a conclusion of the thesis, giving recommendations and outlining possible future continuation of the study.

REFERENCES given at the end of the thesis show few selected readings cited in this work, which were instrumental in understanding, arguing and presenting data and results from this study.

APPENDICES attached at the end of the thesis contain papers published during the course of pursuing this study in International Journals as a part of research results dissemination. Note that, successfully published paper is one; the second was unsuccessfully due to financial constraints although accepted by the organizers. The plan is to send the paper to one of international referred journal for publication.

CHAPTER TWO
LITERATURE REVIEW

2.1 Surface Characteristics of Non–ceramic Insulators in Field

2.1.1 Hydrophobicity

One of the novelty advantages of using a polymer insulator, especially SIR is its ability to resist water to form a continuous film on its surface (Dernfalk, 2002). This ability is hydrophobicity (HC). As a result, it improves the performance under heavy and wet pollution conditions (Fernando, 1997, 1999; Mbwana, 1997). The Hydrophobicity of SIRs hinders the formation of a continuous electrolytic layer on the insulator's surface (Gustavsson, 2000; Gubanski *et al.*, 2000; Hackam, 1998; Kyaruzi & Gubanski, 1999; Zhang & Hackam, 1998) which would have led to flowing of leakage currents (LCs).

Operational and environmental stresses cause loss of HC, but one type of polymer is able to recover this property after this loss. This type of polymer is poly-dimethyl-siloxanes (PDMS) which make SIRs. This recovery of HC by SIR is one of the main advantages of using them for high voltage insulation (Chang & Gorur, 1994; Gubanski *et al.*, 2007; Hackam, 1998; Mbwana, 1997). This important parameter deserves a discussion of its measurements in the simplest way.

2.1.2 Hydrophobicity Measurements

In Gutman *et al.*, (2004); Magige *et al.*, (2003); Mbwana (1995, 1996, 1997); and Sundararajan *et al.*, (2003); HC is measured by using Swedish Transmission Research Institute (STRI) HC classification method. In this method, distilled–deionised water sprays the insulator surface from a distance of 25 ± 10 cm for 20 – 30 seconds. Based on the resulting droplets size and pattern, assessment of the nature of the wetting of the surface is either hydrophobic (HC1, 2) or hydrophilic (HC6, 7) and in between (HC3 – 5) as shown in Table 2.1. The judgment is 10 seconds after finishing spraying. In determining pollution performance of NCIs, this work uses the same method. If there were available a goniometer, then measurements of receding and advancing angles of water droplets would give HC. Table 2.1 shows the relationship between the receding angle and formation of droplets.

Table 2.1 Criteria for STRI HC Classification

HC	Description
1	Only discrete circular droplets are formed with receding angle (θ_R) ≈ 80° or larger for the majority of droplets.
2	Only discrete circular droplets are formed with 50° < θ_R < 80° for the majority of droplets.
3	Only discrete droplets are formed which are not circular with 20° < θ_R < 50° for the majority of droplets.
4	Both discrete droplets and wetted traces from water runnels are observed (i.e. θ_R = 80°). Completely wetted areas are < 2 cm^2, together they cover < 90% of the tested area.
5	Some completely wetted areas > 2 cm^2, together they cover < 90% of the tested area.
6	Wetted areas cover > 90%, i.e. small-unwetted traces (spots) seen.
7	Continuous water film covers completely the tested area.

Source: Sundararajan *et al.* (2003); Gutman *et al.* (2004); Mbwana, (1995, 1996, 1997); and Magige *et al.* (2003) all quoting the STRI HC guide

2.1.3 Environmental Stress Effects on Hydrophobicity and Performance of Polymeric Insulators

2.1.3.1 Hydrophobicity Loss and Recovery

Environmental and operational stresses which are electric discharges, deposition of pollutants, growth of biofilms (biological films), influence of water, rain, temperature, insolation, and wind can lead to temporary (in case of PDMS) or permanent (in case of epoxy, EPDM and other non silicone rubber polymers) loss of hydrophobicity. PDMS exhibit an ability to recover repeatedly this property after its temporary loss by an action of one or more stress. Some important findings about HC recovery of SIR are:

(1) hydrophobicity recovery is predominantly due to diffusion of low molecular weight (LMW) silicone polymer chains which occurs with only a fraction (< 20%) of the total LMW polymer content initially available in an unaged material surface (Chang & Gorur, 1994);

(2) this recovery is an adsorption of LMW to the pollution layer (Wang *et al.*, 2002);

(3) LMW chain regeneration and hence surface hydrophobicity recovery occurs even after the initial supply of LMW polymer is depleted (Chang & Gorur, 1994);

(4) HC recovery is significantly affected by ambient temperature (Chang & Gorur, 1994);

HC recovery involves chain regeneration, this causes weakening of the polymer bonds resulting in reduced tensile strength, which could cause aging and damaging of the insulator (Amin & Salman, 2006; Gubanski *et al.*, 2007; Liu *et al.*, 2004; Sundararajan *et al.*, 2003) as shown in Figure 2.1.

SIR can recover hydrophobicity by a number of processes, namely: reorientation of methyl and oxidized groups, condensation of silanol groups and diffusion of oligomeric PDMS (Chang & Gorur, 1994; Gustavsson, 2000). Pollution build up jeopardizes the HC when it is very fast or too dense (Fernando, 1997, 1999; Gustavsson, 2002; Mbwana, 1997; Vosloo *et al.*, 1996). The consequences of HC transfer is the encapsulation of the pollution layer by the oligomeric PDMS resulting in making rain washing less effective and this causes SIR to capture more pollution than ceramic or EPDM. Zhu *et al.* (2006) demonstrated that instead of hydrophobic CH_3 groups formation on the surface; hydrophilic *OH* groups that are by–products of aging might be formed on the surface of aged SIR. Material analysis shows cracking and oxidation of the surface (Xiong *et al.*, 2006). Ageing effects are far from uniform over each shed, the greatest oxidation being on the top surfaces of the sheds where UV irradiation is dominant.

2.1.3.2 Biofilms and Contamination Effects on Hydrophobicity

Biofilms on the surface of a polymeric insulator can seriously reduce the HC (Magige *et al.*, 2003; Wallström, 2005). The news is that those biofilms do not degrade the polymer directly but through secondary mechanisms (Wallström, 2005). In laboratory investigations, Dernfalk (2004) found out that, areas of the insulators covered by growth showed HC6–7 and parts clean to the naked eye had HC3–4 and some very few regions showed HC1. On a coastal field aged EPDM insulator, Sundararajan *et al.*, (2004) reported HC2–3 for surface areas not deteriorated and HC5–6 for the deteriorated surface areas, which in field were in the sun direction. The deteriorated surfaces were readily wettable indicating that the chalking and discolouration affects the surface

properties, HC being one of them. At severe marine sites, the HC recovery is problematic due to densely packed wet salt depositions (Gustavsson, 2000). But, for a shorter time of seven months, with electrical aging, all polymer samples showed HC1 even on eroded spots suggesting that the combination of the stresses is important than a single stress acting solo.

Chang & Gorur (1994) reported that, the decomposition of the *ALTH* filler to generate water and aluminium oxide results in cooling the surface during dry band arcing. The arcing cause temporary loss of HC due to the formation of *hydroxyl* groups because of interaction of the moisture generated from *ALTH* and polymer material with high heat generated necessitating the reaction. Gutman *et al.* (1999) reported of insulators which, after one year installation the NCIs showed deterioration with remarkable decrease in HC. In addition, some 400 kV insulators, which had been in operation for 15 years in UK showed that the sides facing the sun had discoloured (Xiong *et al.*, 2006). White rings at edge of the bottom surfaces of sheds were present on some insulators. The bottom surfaces of sheds showed varied degrees of contamination accumulation and some sheds had a larger degree of contamination accumulation and were dark in colour. The insulator core did not show discoloration, but there were signs of white residue being present.

Shaowu *et al.* (2001a) continued their earlier work on HC evaluation (Shaowu *et al.*, 2001b) in which presented detailed description of the HC status of sample insulators. The characteristics of the HC distribution on SIR insulators showed the following (Shaowu *et al*; 2001a):

(1) After about ten years' service in polluted areas, the insulators still exhibited good HC and maintained satisfactory electric performance same as that shown in (Fernando, 1997, 1999; Gubanski, 1998; Gubanski & Kyaruzi, 1999; Gubanski *et al.*, 2000; Magige *et al.*, 2003; Kihwele, 2001);

(2) HC distribution on the insulator surface is not uniform, for which the upper surface of sheds always presents superior HC than the lower surface. The side facing the prevailing winds has HC a little worse than that on the lee side;

(3) Due to higher electric fields around end fittings, sheds close to the ends, especially the high voltage ones, are always less hydrophobic;

(4) HC status did not show obvious correlation with the years in service. It actually only corresponds to the specific environment investigated;

(5) Surface of the sheath, especially the junction areas between the sheath and the lower surface of sheds, is vulnerable to HC loss; and

(6) Sensitive place to lose HC is the margin zone of sheds or the shed fringes.

Obviously with these observations it can be argued that electric field distribution plays an essential role on the initiation of hydrophobicity loss as suggested by Shaowu *et al.* (2001a) citing from Shaowu *et al.* (2001b). In normal electric field level of NCIs, low–energy discharges would develop between neighbouring water droplets. This kind of low–energy discharge is a very important reason for the deterioration of hydrophobicity in service (Wang *et al.*, 2002).

2.1.3.3 Oxidation and Depolymerization

For a very good polymer for use in outdoor insulation, its intermolecular forces are low due to symmetric non–polar end and side groups attached to the backbone of the polymer. This low intermolecular force is what causes the polymer to have low surface energy, since to create a surface you need energy. The low surface energy causes weak adhesion forces between the polymer and pollution or water so that the surface is less prone to be wetted. However, the hostile environment with its stresses lead to oxidation, crosslink densification, and depolymerization of the polymer surface; hence loss of good insulation characteristics. Using Fourier Transform (FT) to simulate the effects of short time tropical climate stress, Suwarno *et al.*, (1998) noted that short time tropical climate stress cannot degrade polymer insulators, but long time exposure to this environmental stress will lead to oxidation.

Oxidation is the primary degradation mechanism of polymers such as EPDM in outdoor applications (Blackmore *et al.*, 1997, 1998; Sundararajan *et al.*, 2003). Oxidation by exposure, in the presence of oxygen, to one or more of UV light wavelengths, heat or chemically active species produced by electrical discharges, all of which are likely to be present in high voltage (HV) insulation applications. Photo oxidative attacks on the PDMS happen either as by direct bond cleavage by radiation or bond cleavage of atmospheric oxygen initiated only by UV light with a wavelength shorter than 290 nm. Oxidation can lead to polymer chain scission or cross–linking reactions, which progressively bring about changes in the mechanical and surface properties of the polymer.

Gustavsson (2000) studied surface degradation of polymer housing material and found that with no consumption of antioxidants, the PDMS are very stable against oxidative degradation but rapid deterioration occurs when consumption has occurred.

Thermal degradation of polymeric housings bases on local heating on the surface due to standing discharges on the same. Gustavsson (2002) and Xiong *et al.* (2006) reported of thermal energy from short–pulsed discharges being most probable origin of surface degradation. Thermal decomposition in a non–oxidizing atmosphere leads to depolymerization. When thermal aging takes place in oxygen containing atmosphere, the removal of *methyl* groups followed by *siloxane* cross-links will dominate over the depolymerization process and may lead to the formation of a silica–like layer.

Results of degradation for aging organic materials when exposed to UV radiation is the rate of aging doubling for every 10 °C increase in temperature (Chaipanit *et al.*, 2001). This aging manifest in the following (2.1) (cited by Chaipanit *et al.*, 2001 from Schneider *et al.*, 1993) and called relative aging factor (RAF):

$$\text{Relative Aging Factor (RAF)} = -2^{\left(\frac{T_{\max} - T_{avg\,\min}}{10}\right)}. \qquad (2.1)$$

Where T_{max} is the maximum temperature of each month, and T_{avgmin} is the minimum temperature of all average temperature both expressed in degrees Centigrade taken from 30 years averages of San Francisco weather. It was thought at the beginning to use (2.1) in approximating the RAF of insulators in tropical climate of Tanzania, but due to the unavailability of the 30 years averages of Tanzania this won't be possible.

2.2 Nucleophilic/Electrophylic Attacks, Vandalism and Discharges due to Electric Field

PDMS are very sensitive to nucleophilic/electrophilic attacks especially in humid soils where ions involving alkali earth metals act as catalysts for depolymerization, the evidence of this is presence of clay soil on insulator surfaces in service (Mbwana, 1997). The soil had effects on electrical performance of insulators and in some cases thought to induce degradation.

In vandalism prone areas when NCIs are subject to gunshot, the wound formed often leads to rapid deterioration of the GFR rod (Gustavsson, 2000). This leads to mechanical damage of an insulator.

Another degrading mechanism is the electric field (E–field) distribution and enhancements close to water droplets, which causes discharges on the surface and mostly damages the sheath. Such observation is the chemical soup put forward by Raychem researchers (Thornley & Shocket, 1994). E–field enhancements close to the ends are the culprits to cause the soup.

To curb this problem of E–field distribution special corona rings are used. Another mechanism is to use special selected cable terminations, which suppressed the highest electric field strength due to water droplet corona at the insulator surface to the value of 0.54 kV/mm (Gustavsson, 2002).

2.3 Other Damages on Non–ceramic Insulators

Other damages on polymeric insulators are due to rough handling, FO due to bird droppings, birds pecking and chewing on the housing material thereby exposing the FRP/GFR rod. Nevertheless, one paper found that the reduction of FO due to bird pecking was negligible noted in (Gubanski *et al.*, 2007). The same paper (Gubanski *et al.*, 2007) gave a crosscutting review of damages by rodents and birds, which showed significant deterioration of the insulation sheds thereby exposing the GFR rods. Earlier on rodents showed tendency to eat stored polymeric insulators (Dernfalk, 2002). There is damage by rodents reported from Tanzania in this current work. These rodents ate stored EPDM insulators.

In some very severe marine test stations where the contamination severity and humidity levels are very high that the surface is not capable to recover HC fast enough, there are problems with erosion of SIR (Gustavsson, 2000; Houlgate *et al.*, 1990; Vosloo *et al.*, 1996). To safe guard against these extraordinary pollution events necessitated development and use of safe in–field procedures for washing polymeric insulators (Burnham *et al.*, 1995; Fierro–Chavez *et al.*, 1999).

Aging of polymers used for outdoor insulation depends on the material formulations used (Gustavsson, 2002) since the fact is that in outdoor environment EPDM will age rapidly than SIR, and the epoxy insulators are prone to chemical and arcing attacks more than SIR and EPDM and so forth depending on the environment.

Fernando (1997) presented results of polymer insulators tested in laboratory after artificially polluting them. The evaluated parameters of performance were FO, salt deposit density (SDD), surface conductivity, HC and surface resistance. Among the important findings are that the rest time has big impact on surface properties of NCIs, and this was noted by Mbwana (1997).

In 1995, Kyaruzi and Gubanski initiated a study of performance of outdoor polymeric insulation in Tanzania with the collaboration of the power utility (TANESCO) (Kyaruzi & Gubanski, 1999). The study used a set of six polymeric insulators installed in 1974 at Ruvu Chini water pumping station in Bagamoyo, and installation of new insulators in three different sites in Dar es Salaam (Mbwana, 1995) in horizontal position. The old insulators and the ones installed in 1995 all performed well since no failures recorded on them. Up to the time of writing this thesis, one of the insulators installed by Mbwana (1995) failed in service and its removal effected. Its total years in operation is 13 years.

2.4 Summarising Effects of Stresses on Polymeric Insulators

Summary of effects of stresses on NCIs is in Figure 2.1 giving concisely, the stresses, effects and the results. Depolymerization causes reduction of LMWs, which cause loss of HC as a result reducing the mechanical strength. In addition, the loss of mechanical strength will cause the insulator to break and drop the line.

In depth analysis of damages caused by biofilms on polymer surface can be found in works of Amin & Salman (2006) and Wallström (2005).

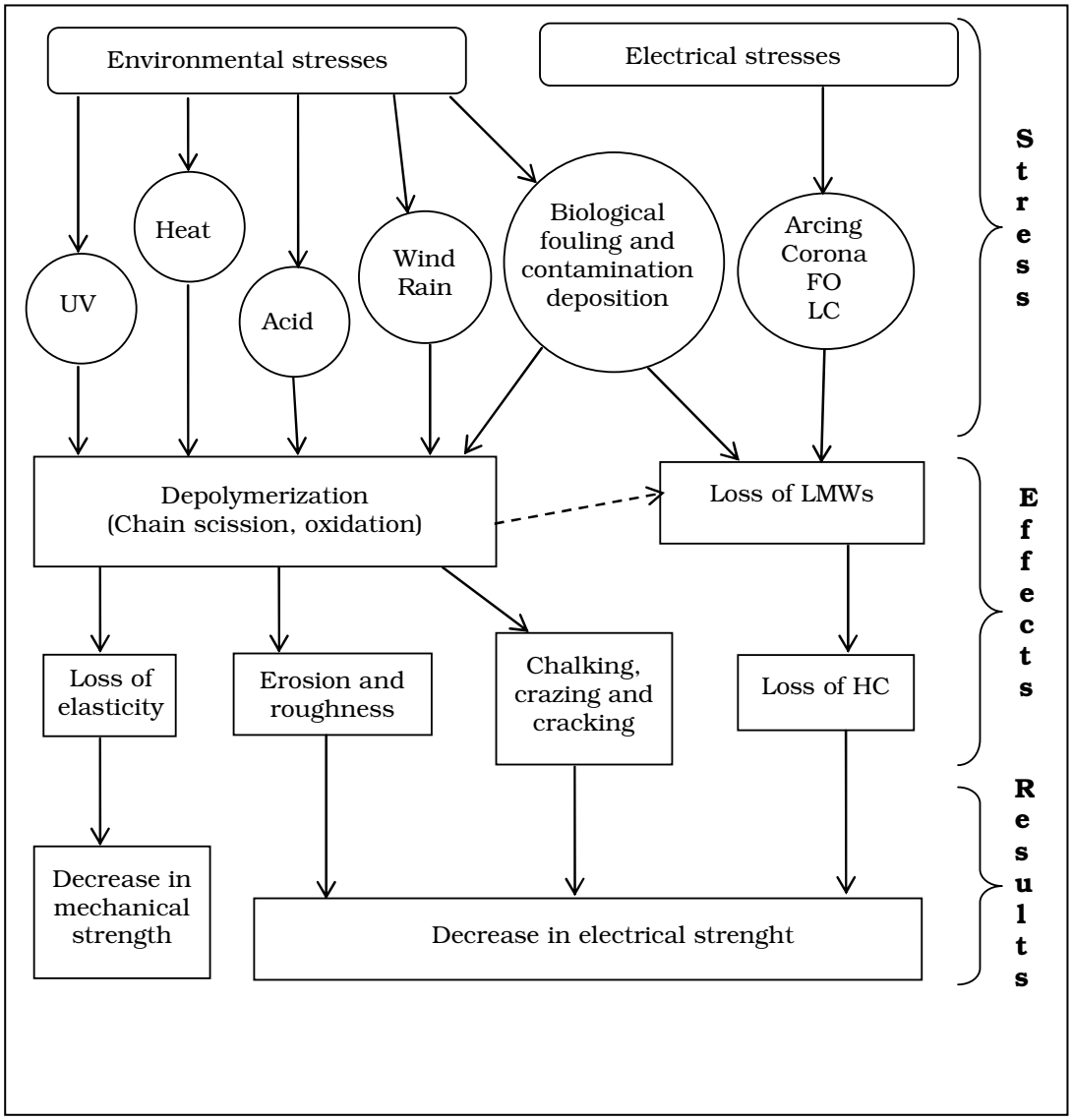


Figure 2.1 Ageing stress, effects and results on NCIs

Source: Amin & Salman (2006)

These stresses act in synergy to cause ageing; meaning that the ageing experienced by an insulator when exposed to such multiple stresses for a given time is more severe than when the various stresses occur individually over the same time (Gorur, 2000). Information about pollution (biological fouling and contamination) which is the major concern for outdoor use of any insulator is in (Hernanz *et al.*, n.d) shown in Table 2.2.

Table 2.2 Transmission lines insulator contaminants and their sources

Contaminant	Source of pollution
Salt	• Coastal areas • Salt industries • Highways with deposit of snow where salt is used to melt the snow
Cement	• Cement plant • Construction sites • Rock quarries
Earth	• Ploughed fields • Earth moving on construction projects
Fertilizers	• Fertilizer plants • Frequent use of fertilizers in cultivated fields
Metallic	• Mining handling processes • Mineral handling processes
Coal	• Coal mining • Coal handling plants/thermal plants • Coal burning/brick kilns areas
Volcanic ash	• Volcanic activity areas
Defecation	• Roosts of birds areas
Chemical	• Wide variety of chemical and process industries, oil refineries e.t.c.
Smog	• Automobile emissions at highways crossing • Diesel engine emissions at railway crossing and yards
Smoke	• Wild fire • Industrial burning

Source: Ramos *et al.* (n.d)

That paper (Ramos *et al.*, n.d) discusses in depth about contaminants types, sources, effects and remedial measures. From this table, it is shown that human's economic and daily living activities play a major role in polluting insulators. One of the best carriers of this pollution is evaporating water and wind. This shows that no matter where an insulator is in field, it will be contaminated.

2.5 Quantifying Pollution on Insulator Surface

Salt Deposit Density (SDD) has been a reliable method to measure pollution severity on an insulator's surface (Ramos *et al.*, n.d). It has served in a number of researches to indicate the corresponding presence of pollutants which are soluble as in (Fernando, 1997, 1999; Gubanski *et al.*, 2000; Ramos *et al.*, n.d; Mbwana, 1996, 1997; Sundhar & Bernstorf, n.d) to mention but a few. There is also another method to determine the amount of non–soluble substances on the insulator surfaces called non–soluble deposit density (NSDD) (Fernando, 1997, 1999; Mbwana, 1996, 1997).

Doing SDD measurement is by taking small amount of pollution and dissolving it in known amount of distilled water. Stirring and dipping a volume conductivity meter gives the salinity of the suspension. Finally, calculations involving volume of the suspension, the area of the cleaned surface and the salinity gives the SDD value. Due to constraints of getting larger samples, this endeavour will not be tried in this work.

Surface layer conductivity (κ) measurements use a special tool named Layer Conductivity Measuring Device (Layer Conductivity Measuring Device SLM 9, n.d). A paper strip is fixed between the probes of the instrument and dipped in de–ionized water in order to become wet. Then excess water is shaked off by swinging. Then the probe is placed on the insulator's surface for about 20 seconds after which a reading is taken. The procedure is repeated for a number of times and at different spots to get an average value of conductivity value in micro-Siemens per centimetre (μS/cm).

The device has function for measuring conductivity (both normal conductivity without temperature correction κ, and mode with 20 °C temperature correction κ_{20}) and temperature; the conversion is done according to (2.2).

$$\kappa_{20} = \frac{\kappa}{1 + 0.0023(\vartheta - 20\,°C)} \tag{2.2}$$

Where: κ = nominal layer conductivity;

κ_{20} = layer conductivity at standard room ambient temperature of 20 °C; and

ϑ = temperature in °C.

The instrument can measure in the range of 0.01 μS/cm and 2 mS/cm. The probe is fixed with a little piece of pH paper (pH 3 – 10), and is dipped in distilled water..

2.6 Quantification of Oxidation, Degradation, Deterioration and Aging of Non–ceramic Insulators

2.6.1 Preamble

A number of prominent scientists varying from Material Scientists, Physicists, Electrical Engineers, Electronics Engineers, and Chemists have researched photo–oxidation of polymers. This is evident in several works e.g. Andersson (2006, pp. 17 – 51); Collins *et al.* (2000); Gustavsson (2002, pp. 14 – 68); Gustavsson *et al.* (2000); Hillborg (2001, pp. 5 – 68); Kao (2004, pp. 204 – 303); Kim *et al.* (1994); Wallström (2005, pp. 20 – 63) to name but a few. These literatures inform of oxidized polymer surfaces acting as charge traps, which could enhance tracking and erosion ultimately leading to aging.

Photo–oxidation occurs in polymers containing di–ene monomers that are more susceptible to oxidation because of the presence of an alkyl group in the polymer backbone (Sundararajan *et al.*, 2004 citing from Grassie & Scott (1985)). Oxidation reactions involve a free radical chain reaction for several stages, after a polymer surface has undergone arcing. Collins *et al.* (2000) reports increasing surface concentrations of the oxygen along with silicone contribution with accompanied carbon concentrations decrease on SIR after artificial ageing in laboratory. The increasing oxygen and silicone concentrations mean presence of oxidized silica layer. There are various methods used to study oxidation and depolymerization two of which are gas chromatography/mass spectrometry and Fourier transform infrared spectroscopy.

2.6.2 Using Gas Chromatography/ Mass Spectroscopy (GC/MS)

2.6.2.1 Procedure

The material to be studied is dissolved in a polar solvent (chloroform or methanol depending on polarity) and then it is put into an evaporating column, where it is heated to evaporate the volatiles. These volatiles then are subjected to a column at which point electron bombardment ionizes the evaporated volatiles. The output is then passed through a mass selective section, which then gives out the distribution of the homologous short chain siloxane in the polymer.

2.6.2.2 Usefulness of GC/MS

GC/MS is a method used to study surface oxidation (silica layer on surface) and ageing of polymers. This method enables observations of molecular distribution in a polymer

as seen in works of: Ezrine & Lavigne (1991, 2001); Hackam (1998); Haji *et al.* (2007); Homma (n.d); Homma *et al.* (1995); Homma *et al.* (2000); Kusch & Knupp (2004); Radhakrishnan (1998); and Thomya (2006).

Homma (n.d) used GC/MS to assess the molecular weight distribution of a polymer matrix with the following principle research results:

(1) the molecular distribution show that virgin samples had less LMW than aged samples on their surfaces; and

(2) the top shed surfaces generated more LMW than the bottom shed surfaces.

In further work, Homma *et al.* (1995) used GC/MS to evaluate the surface degradation of polymer insulating materials. Appearance of peaks corresponding to LMW was characteristic for weathered and energized RTV samples. The paper concludes by stressing that GC/MS is a good method to quantify surface degradation. Further on, in Homma *et al.* (2000), the study employed thermo desorption GC/MS (TD GC/MS) and confirmed results of Homma *et al.* (1995) which prompted the researchers to say that the instrument is suitable to study degree of surface degradation and possible to estimate remaining life of an aged insulator.

Ezrin & Lavigne (1991) proposed and used GC/MS for failure analysis of polymers. GC/MS became useful in determining the causes of failure of an electrical polymer insulation either by unusual or unacceptable condition developed from an external service condition or related to the composition as manufactured. From Ezrin *et al.* (2000), is the observation that photo oxidation and fracture of polyethylene (PE) occurred in polymer, which is in contact with the metal copper due to the oxidative degradation. Further, Ezrin & Lavigne (2001) used TD GC/MS to assess the damage on

plastics due to corrosion. In addition, they examined the effect of corrosion of brass on the PE using TD GC/MS and found the final products of the corrosion as acetic acid and formic acid. In detecting and monitoring additives in elastomeric electrical insulation (EPDM rubber), Bartoli *et al.* (n.d) used GC/MS technique. Analysis gave results of heterogeneity of polymeric compounds and distribution of the antioxidant, presence of paraffin and mineral charges dispersed in high voltage cable insulation.

Kusch & Knupp (2004) used solid–phase micro extraction GC (SPME GC/MS) to study the volatile organic compounds released from expanded polystrene (EPS). The compounds found were styrene monomers with oxidation products formed by thermo oxidative degradation of EPS when exposed to high temperatures and insolation. Using pyrolysis–GC/MS to study thermal degradation of PDMS, Radhakrishnan (1999) and Thomya (2006) found the products were cyclic oligomers, minor amounts of linear products, and methane. The products varied with temperature and extent of degradation. Haji *et al.* (2007) studied surface modification of polymers after corona aging, the GC/MS results showed a distribution of the homologous short chain siloxane in the polymer. When evaluating polymeric insulators, Hackam (1998) identified LMW by using GC/MS of which several studies cited refers to percentages and distribution of polymers found in aged polymers by use of the same.

Those works mentioned above are the ones that provided the justification to use GC/MS in this thesis to study the laboratory and field aged NCIs in the expectation of identifying products of polymeric insulators field aging. However, this was a challenge discussed in Chapter Six.

2.6.3 Using Fourier Transform Infrared Spectroscopy

2.6.3.1 Procedure

The sample is first ground and mixed with Potassium Bromide (KBr) and then it is formed into thin disc at a pressure of approximately 10 tonnes. Thereafter it is placed in a sample holder that is aligned such that it is hit by an IR beam. This beam from an interferometer enters a medium of high refractive index (the reflecting crystal) at such an angle that the beam is reflected inside the crystal. At each reflection point, which occurs at the crystal–sample interface, the radiation generates a standing wave that then penetrates into the surface of the sample that is in direct contact with the crystal and produces a spectrum of the sample. According to Beers law, the peak absorption heights of the IR spectra are proportional to the concentration of the corresponding bonds.

Another method does not need a KBr window. It uses the sample itself cut from the insulator and placed directly onto sample holder to be hit by the interferometer. This method is used in Vlastós & Gubanski (1991), Kim *et al.* (1994), Vosloo *et al.* (1996a) and Sundararajan *et al.* (2004).

2.6.3.2 Important Bonds and their Characteristics Absorption Bands

FTIR gives both qualitatively and quantitatively the changes in the nature of and amount of different chemical functional groups by measuring the changes in the absorbance of wavelengths of infrared (IR) light specific to that functional group of the polymers. IR spectra are information rich: the peak positions; heights (intensities); widths; and shapes in a spectrum all provide useful information about the sample. The

peak intensity of peak height of transmittance (or absorbance) is an indicator of molecular changes compared to the reference value usually taken as the bulk of the polymer insulator material. Table 2.3 shows some expected functional groups with their corresponding absorption bands.

Table 2.3 Characteristic Infra Red absorption bands of functional groups

Wavenumber (cm^{-1})	**Type of Group Vibrating**
3700 – 3200	OH from ALTH
2962 – 2960	Aliphatic CH stretch in CH_3
1735 – 1745	Carbonyl
1469	Hydrocarbons
1440 – 1410	Asymmetric CH_3 groups deformation in Si-CH_3
1270 – 1255	Symmetric CH_3 deformation in Si-CH_3
1100 – 1000	Stretching of Si-O-Si
870 – 850	$Si(CH_3)_3$
840 – 790	$Si(CH_3)_2$

2.6.3.3 Usefulness of FTIR Spectra

The IR spectrum reveals vibrations of atoms in molecules (Launer, n.d). Its beauty is the relationship of the IR bands to the molecular structure given by certain groups of atoms to have vibration frequencies that persist in different compounds. The following citations shed light on some selected literature informing of the observations using FTIR spectrum.

Vlastós & Gubanski (1991) studied changes in the surfaces of naturally aged SIR (and silicone coatings), ceramic and EPDM insulators. For the aged material of the upper side of the shed, the strongly reduced absorption was due to CH_3. The aged material of the under side of the shed showed a similar absorption pattern, but the *OH* absorption

was higher than the upper side of the shed. FTIR verified the reduction of carbon content on the aged surfaces.

Kim *et al.* (1994) undertook to study RTV coatings by subjecting them simultaneously to salt–fog and electrical stress. The employed ATR–FTIR spectroscopy investigated the chemical changes. There was suggestion of possible chemical reactions and processes occurring under dry band arcing. The results indicated the formation of LMW PDMS which came to be corroborated 5 years later by Cherney & Gorur (1999) seen as the reduction in the surface density of CH_3 groups and cross linking of the PDMS backbone chains at the surface. There were main changes observed in the *Si–O* and *Si–* CH_3 bondings. One case reported in South Africa at KIPTS, for which the spectra of one SIR showed that the methyl groups attached to the silicone was totally removed (Vosloo *et al.*, 1996a).

Blackmore *et al.*, (1997) evidenced increasing oxidation towards the HV end of 275 kV EPDM insulators which had been field aged for 34 months. The oxidation products were *carbonyl oxidational* groups. They continued to condition monitor the same insulators and the following year (Blackmore *et al.*, 1998) reported the same results of which they fitted the *oxidation index* data by an equation found in that same paper. The *oxidation index* is the ratio of peak heights associated with *carbonyl group* (vibrating at wavenumber 1735–1745 cm^{-1}) to 'virgin' hydrocarbons (vibrating at wavenumber 1460 cm^{-1}). In 2003, Queensland University researchers published a paper (Zhou & Birtwhistle, 2003) in which they compared *OI* and *ester/ketone* ratio of EPDM insulators. In the said paper, results showed increasing trend of *OI* but with dispersed distribution.

Another study in 2004 (Liu *et al.*, 2004) analyzed the field aged (10 years) vs. laboratory aged (10 simulated years) polymeric surge arresters. There was a good qualitative correlation between field aged vs. laboratory–aged spectra. *ALTH* detected at wavenumber 1014 cm^{-1} had a reduction of 18.4% for field aged sample vs. 20.9% for the laboratory aged sample. Other functional groups showed same degradations but the magnitudes of the laboratory sample were slightly less than the field sample.

Arizona State University (ASU) researchers carried out a study called "In–service aging and degradation of 345 kV EPDM transmission line insulators in a coastal environment" (Sundararajan *et al.*, 2004). The insulators were suspension type removed from service after 5 years due to unexplained outages in the coastal line of New Hampshire. It was a first time a thorough study of the significant differences between chalked (or discolored) surfaces and other surfaces was reported according to the Authors. There was a significant decomposition of the *CH* groups on the chalked surface of the insulators (also reported in Soundarajan *et al.*, 2004). Generally, the bottom surfaces had slightly less reduction than the top surfaces because those bottom surfaces were not in direct exposure of the environmental stresses. The top LV chalked surface had the maximum reduction of the CH_3 bonds of all the samples (about 85% reduction). Gorur & Bernstein (1998b) reported that if the peak height changes are less than 15% compared to virgin, then the surface is in good condition, otherwise is in bad condition. Taking a cue from Gorur & Bernstein (1998b), the ASU researchers (Sundararajan *et al.*, 2004) concluded that since the FTIR peak change is more than 75%; the insulators are degraded and need to be changed (or washed for temporarily extension of usefulness) for reliable performance of the line.

The work of (Gorur & Bernstein (1998b) also found that the chalked surface of the mold line was deteriorated than the other surface of the mold line. Decomposition of hydro peroxides by heat or UV light (photo oxidation) caused formation of *alkoxy radicals* and *hydroxyl radicals*, leading to chain branching as evidenced by FTIR results. The mechanics of the oxidation reactions is in the work of Gorur & Bernstein (1998b) and elsewhere (Grassie & Scott, 1985; Klemchuk Ed., 1985; Neiman Ed., 1965; Jellinek, 1955) cited by the same work.

Another study by ASU researchers (Olave *et al.*, 2005) simulated actual service conditions of Mexico City. The aging was 4 laboratory years (equivalent to 2544 hours); of which one year was made up of one summer and one winter alternating according to the local weather for four years the total is 4 summers and 4 winters. The insulators (28 kV distribution class thermoplastic elastomeric (TPE) and SIR insulators) were sprayed with acid rain of pH 3.3 made from various salts; whilst simultaneously voltage was on. After those four years of aging, the analysis using FTIR gave the following results: the TPE insulator showed loss of *hydrocarbon* bonds whilst its *OH* stretch at wave numbers 3600 cm^{-1} – 3400 cm^{-1} left intact; and SIR insulator showed loss of *hydroxyl* (50% lost) and *hydrocarbon* bonds loss. 15 years aged SIR was analyzed by FTIR in a paper by Xiong *et al.* (2006). Results showed decrease in hydrocarbons, silicone side chains and other groups on the surface of the SIR.

Justification to use FTIR for this thesis is that it will show the bond change to indicate aging, depolymerization and oxidation state of NCIs found in Tanzania. A further argument is that FTIR is an indispensable tool to research silicone-polymers (Launer, n.d; Xiong *et al.*, 2006).

2.7 Leakage Currents on Polymeric Insulators

Once an NCI has aged, it is bound to show increasing LCs when in HV applications even in dry and clean environments. On measurements, Gustavsson (2000) recorded LC on SIR exceeding 8 mA to 19 mA, and it has been found by Dietz *et al.* (1986) that dissipated energy alone can't cause surface erosion but, an LC threshold of 5 mA has been found responsible for the onset of the rapid 'morning star' type of thermal degradation. Creepage length has the largest influence on the electrical performance in restricting LCs (Gustavsson, 2000). In 2002, Gustavsson (2002) noted that 1 mA LC as a performance indicator for deteriorating HC of an insulator, and when LC increased to 4 mA to 8 mA; it surely signifies occurrences of arcing damage. For all his tests, the creepage distance came to be the determining parameter for damage to occur on insulator surface. The effect of adding extra silicone oil was to reduce LC activity on the surface (Gustavsson, 2002, 2004). Gustavsson's LC data correlated well with the visual observations of surface erosion and hydrophobicity changes.

During two salt–storms in Coastal Sweden of 1996, Vlastós & Orbeck (1996) noted that one HTV SIR insulator with specific creepage of 27.6 mm/kV showed continued high surface resistance with maximum leakage current pulses not exceeding 2 mA. On the other side, another HTV unit with specific creepage of 17.3 mm/kV showed currents exceeding 25 mA, which coincided with the maximum current pulses recorded on the porcelain insulator with specific creepage of 30 mm/kV. These observations point out that the creepage distance play an important role in suppressing LC of an energized insulator in field, and also that the creepage of SIR is better in suppressing LCs compared to ceramic (17.3 mm/kV of SIR Vs 30 mm/kV of porcelain).

Dernfalk (2002) measured LC on insulators covered with biological contamination and those not covered in a clean fog chamber by applying ac voltage. The result was that, polymeric insulators with biological contamination suffered from higher leakage currents than clean insulators. The author also noted discharge activity on insulator with fungal growth. Dernfalk (2002, 2004) measured LCs on clean SIR insulators in fog chamber and got typical increase of 2 μA when the fog was increased from dry conditions in the chamber. LC amplitudes on insulators with growths always increased more than clean insulators. The maximum LCs for these contaminated insulators were all bellow 25 μA and most of the time lower than 18 μA. The LCs on the clean insulators increased from 10 μA to 12–15 μA. The difference in current amplitudes between the contaminated and clean insulators seem to be more pronounced in the root mean square (RMS) value compared to the maximum value. This observation, together with the fact that the maximum LC does not vary very much, implies that the current on the contaminated insulators are higher due to reduced resistance, and not due to discharges.

The discharges occurred on the polymeric surfaces of the insulators on certain regions (Dernfalk, 2002, 2004). Most localization was on the regions close to the energized end fittings and on the sheath between sheds and close to the grounded end fittings. Presence, distribution as well as nature of contaminants related more to the discharge activities. The presence of biofilms on surfaces of SIR insulators induce spot discharges in turn leading to thermal degradation. In addition, fluctuations in composition and thermal properties of the compound cause dielectric constant fluctuations from point–to–point. As a consequence, some insulation points are subject to higher electric stresses than other points, and are more susceptible to dielectric breakdown (Bartoli *et al.*, n.d).

Insulators contaminated in field showed low levels of LC and their patterns were sinusoidal with the third harmonic content lower than 5 % (Fernando, 1997). The HC values were also low for these field-contaminated insulators. However, under wet conditions, the typical peak currents increased by about 5 – 10 times higher than what was seen on clean reference insulators in the same study. The maximum current recorded from field-contaminated insulators was bellow 0.3 mA with a typical RMS of 20 – 25 μA. Under laboratory conditions the artificially polluted insulators exhibited rich harmonic content non–linear LC waveforms. The field-aged insulators showed similar LC patterns whether naturally or artificially contaminated.

Taking insulators from field covered with biofilms and testing them in laboratory, Gubanski *et al.* (2001) noted an increased LC by 3 – 4 times compared to clean insulators. However, a paper cautions that the total LC is not a sensitive monitor of surface damage (Giriantari & Blackburn, n.d), then Fernando & Gubanski (1999) provided an extensive review of LC measurements by:

(1) Developing a field LC measuring system; and
(2) Developing a laboratory investigation method of how LC can be used to evaluate materials.

Fernando & Gubanski (1999) pressed for using LC measurements in a wider context to evaluate NCIs in practical situations. Pollock *et al.* (1998) established that field monitoring of LC and pollution severity can lead to develop a pollution performance chart, which can be used to estimate the performance of polymer insulators.

When this research work began, it was thought to measure LCs of field aged NCIs, this was another challenge that is discussed in Chapter Six.

2.8 Flash-over Voltage on Polluted Polymeric Insulators

2.8.1 The Obenaus Polluted Insulator Model

The earliest scientific explanations for contamination flashover (FO) was the theory proposed by Obenaus in the 1930s as cited in Gorur *et al.* (2001), Sundararajan & Gorur (1993) and Venkataraman & Gorur (2006). Obenaus explained flashover in very simple terms. A partial arc generated by dry band activity (discharge) in series with the contaminated section of the insulator (represented as a series resistance) shown in Figure 2.2.

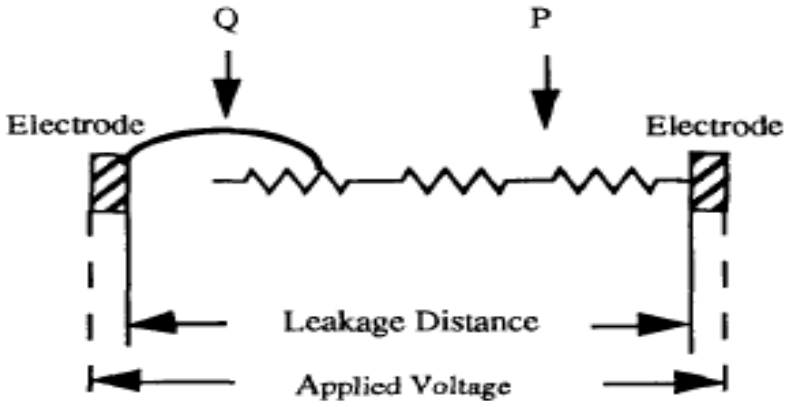


Figure 2.2 Obenaus model of insulator flashover

P is wet pollution layer; and Q is wet layer bridged by an arc

Obenaus outlined the steps of flashover voltage, establishing the importance of surface resistivity and dry band formation. Neumarker completed this work by assuming a uniform pollution resistance per unit length for the pollution layer. However, in practice, the pollution distribution is non–uniform. There is non–uniform wetting and drying, leading to multiple dry bands with a lot other complex phenomena. Hence, to work with the model presented in Figure 2.2 needs simple assumptions, which are single dominant arc, uniform pollution distribution, and uniform wetting. This thesis does not

go into further details about the FO model since it is not the current research objective, but will rather highlight about factors affecting the same and its economic impacts without touching the mechanisms of it. Karady *et al.* (1995) and Shah *et al.* (1995) give better explanation of FO occurrence by outlining systematic FO formation.

2.8.2 Factors Affecting Flashover Voltages

Various factors are responsible for the partial arc to elongate and bridge enough of the insulator (roughly 50%) which will then provide the necessary impetus to result in a FO. An increase in contamination severity on the surface is one factor that contributes to FO by increasing the LCs thus creating more discharges that are intensive by decreasing the surface resistance of the insulator (Gorur *et al.*, 2001; Karady *et al.*, 1995; Shah *et al.*, 1995) thereby causing thermal ionization. The increased thermal ionization can cause thermal bond scission; cross-linking and dissociation in RTV coatings (Kim *et al.*, 1994). The increased contamination distributed along the entire insulator, will force the voltage distribution to become linear, thereby alleviating the problem of electric stress concentration. This would discourage the flashover process to a certain extent.

At a given pollution, the FO depends on the leakage distance and on the insulator profile (Chrzan *et al.*, 2003). With given insulator height or length the FO is proportional to the leakage distance in limited scale only. When the ratio of leakage distance to insulator height is too large, the arc bridging effect lowers the efficiency of leakage distance. It is established and known that different pollution conditions require different insulator profiles (Chrzan *et al.*, 2003). Insulators with simple flat profile (aerodynamic type) behave better in desert conditions where airborne pollution and wetting as

condensation prevails. On the other hand, insulators with complicated shape (anti–fog type) behave better at sea shore, where pollution in the form of small drops impact dominates.

Values of predicted flashover vary significantly for the same insulator and different level of contamination. For a particular system voltage, no flashover should occur for contamination severities that are in the light to medium pollution range as defined in the IEC 60815 (ESDD < 0.1 mg/cm^2). From service experience, this is not entirely true. There have been numerous reports of flashover on relatively clean insulators especially under morning dew and fog (Gorur *et al.*, 2005). In addition, streamer mechanisms due to birds roosting on the insulators have been a cause of FO on insulators (Gorur, n.d; Macey *et al.*, 2006; Zhou *et al.*, 2009). Zhou *et al* (2009) investigated effect of large birds roosting and droppings on the insulators for extra high voltage (EHV) transmission lines in China and found the possible volume of streamer to cause FO to be 30 ml. The paper by Zhou *et al.* (2009) designed several remedies for the problem. Those remedies are found in these papers (Zhou *et al.*, 2009), Macey & Vosloo (n.d), Montaño *et al.* (2007) and Shenoi & Gorur (2008).

2.8.3 Economic Effects of Flashover Occurrences

There are two types of FO across insulator's surface, namely, lightning impulse and contamination flashovers. Flashover of insulators in transmission and distribution systems may cause costly outages for the power company and their customers. Industrial and/or coastal pollution of external insulation is a major cause for such events at the normal power frequency voltage of the system (Fernando, 1997, 1999;

Macey & Vosloo, n.d; Metwally *et al.*, 2006). For dry desert climate, the accumulated dust when combined with early morning mist or fog during certain days or seasonal months result in flashover as discharge takes place (Chrzan *et al.*, 2003; Metwally *et al.*, 2006). That study by Chrzan *et al.* (2003) proved that insulators suspended along the coast showed leakage resistance of transmission line insulators decreasing with accumulation of sea salt blown from the sea, particularly when the relative humidity is high and the shed surface becomes slightly wetted.

Increased flashover cases tops the list of all failures of transmission line insulators in Oman, which necessitated use of live line washing (LLW) to be increased and for some areas it was repeated twice to three times a year depending on weather conditions (Metwally *et al.*, 2006). Insulator failures and specialized washing translates into money and sometimes downtimes when not done LLW, which increases expenditure of the utility. To top it all, these FOs ignite wooden poles causing damage of the same and insulators (Metwally *et al.*, 2006). Faced with such situations utilities–cum researchers developed some methods to overcome FO.

2.8.4 Methods to Reduce or Overcome Flashover

Recently these papers (Fierro–Chavez *et al.*, 1996; Gubanski *et al.*, 2000; Shihab *et al.*, 1996), tested different pollution monitoring systems and found that these developed systems are promising tools to establish suitable maintenance periods and at the same time avoid unpredictable flashovers along insulator surfaces. These systems make it possible to perform maintenance when needed, instead of scheduled activities that may require frequent planned outages of the system for cleaning of insulators. Different

tasks related to pollution use these systems. Three main purposes of using pollution monitor systems are:

(1) Measurement of pollution severity, i.e. to establish pollution zones in local areas;

(2) Online monitoring of the pollution situation of insulators for maintenance purpose in order to determine when cleaning and maintenance greasing of insulators are needed to prevent pollution flashovers; and

(3) Comparison of the behavior of different insulator designs (shape and length) and/or insulator materials under pollution condition.

Apart from the systems above, there is LLW, which helps to minimize FO to some extent as what done in Mexico proves in Fierro–Chavez & Ramirez–Vazquez (1999). The main drawback of the LLW approach is, though, in establishing the correct timing of the operation and the associated costs. In addition, washing is not effective in environments subject to "instantaneous" polluting conductive mist conditions, e.g. where there are plenty of marine salt fogs. In Tanzania there is a location called Kunduchi and Ras Kiromoni which is a marine cable link pump station faced with such problems of instant marine fogs as will be seen later in Chapter Four, but first it is good to see the effect of biofouling on polymeric insulators FO and other aspects.

2.9 Biofouling on Polymeric Insulators

Reports of biological growths colonizing ceramic and non–ceramic insulators in field in both the tropics and temperate climates is found in (Dernfalk, 2002; Gubanski *et al.*, 2000; Magige *et al*, 2003; Mbwana, 1997; Wallström, 2005). The growth does not happen to degrade the polymer material directly, but the silicone rubber could be degraded by the biofilms through secondary mechanisms (Wallström, 2005). These growths are

identified as algae, fungi and lichen. The deterioration caused by the biofilms on the polymer surface is interfacial processes controlled by the local conditions at the surface. The biofilms are highly hydrated and mainly consist of water, which is about 80–95%. The water contained provides a leakage path for LCs when an insulator is connected to HV line.

The main mechanisms of biofilms to influence polymers are by biofouling (contamination), degradation of leaching components, corrosion, hydration, penetration and discolouration. To make the polymer resistant to biofilms: the base polymers are fortified with additives, base polymers are optimized and periodic removal of the biofilms layer from insulators in field is necessary (Gubanski *et al.*, 2000).

2.9.1 Biofilms on Insulators In Tanzania

Growth of biofilms has been reported on insulators in Tanzania on the 11 and 33 kV distribution lines (Fernando, 1997, 1999; Gubanski *et al.*, 2000; Kyaruzi & Gubanski, 1999; Magige *et al.*, 2003; Mbwana, 1997). This growth is mainly concentrated on the side shaded from the direct sun irradiation as shown by Figure 2.3.



Figure 2.3 An insulator with biofilms from Tanzania Ruvu Chini

Source: Gubanski *et al.* (2000)

The biofilms colonizing the polymeric insulators have been shown to be of the same composition regardless of their origin; this was proved by a study (Wallström, 2005) carried to analyze samples taken from Tanzania,

Sweden and Sri Lanka. Algae in association with bacteria dominated the biofilms and provided nutrition for the growth together with the atmospheric carbon dioxide.

An earlier study in Tanzania and Sri Lanka about colonization of biofilms on insulator surfaces (Gubanski *et al.*, 2000) reported that the algae growths mainly localize on the shaded parts of the insulators starting from the second shed. The top shed remained uncovered. One insulator was discolored, whereas another insulator preserved its original color. However, the metal fitting of its cold end was damaged.

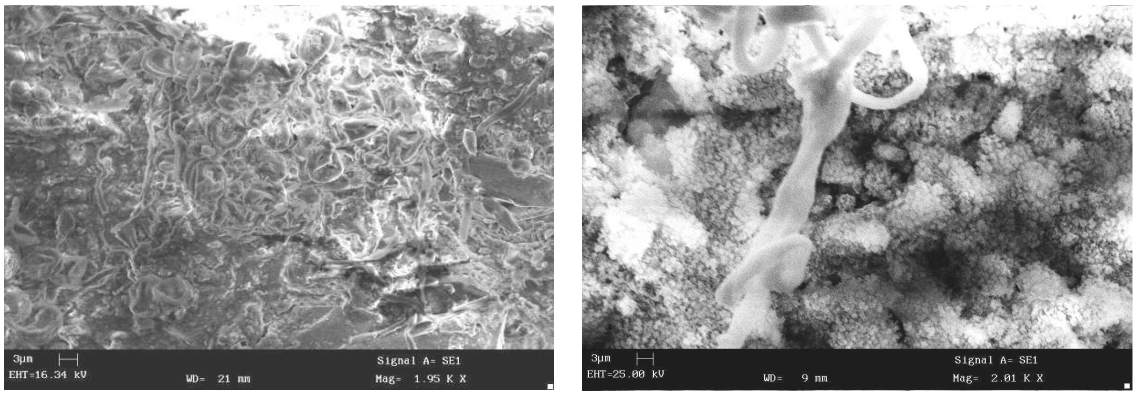
In this study those insulators found with biofilms in Tanzania were photographed and HC tested. The job of determining the type and composition of the biofilms found on the insulators was done in a previous study explained in following section.

2.9.2 Identification of Biofilms on Insulator Surfaces

This work was done by Gubanski *et al.* (2000). Samples of algae and lichen collected from four (4) insulators from various locations in Dar es Salaam and Bagamoyo; the insulators were porcelain and SIR, which went for evaluation of the presence of microorganisms at the Department of Agricultural Microbiology of the Agricultural University of Wroclaw, Poland in 1999 – 2000.

Microscopic visualizations showed green algae as a dominant biotic component covering the surfaces of all insulators. The identified isolated strains of green algae were in all probability *Apatococcus constipatus* (*Chaetophraceae* family, *Leptosiroideae* subfamily). These are species found only in Africa. The cell size varies from 3.5 to 9 μm. The microscopic views of the green algae are shown in Figure 2.4(a) and Figure 2.4(b).

A sporadic growth of fungal mycelia shown in Figure 2.4(b), was also noticed on the organic debris formed during the growth of these algae. Isolates of several fungal species, from genus *Penicillium, Aspergillus, Trichoderma, Fusarium,* and some unidentified *Mycelia sterilia*, were isolated from the tested samples. None of the isolated strain was found as dominant one. It was suggested that air–borne fungi accidentally contaminated the samples during sample collection and transportation.



(a) (b)

Figure 2.4 Microscopic view of (a) algae and (b) fungal hyphae.

Source: Gubanski *et al.* (2000)

In Figure 2.4(a) algae and (b) fungal hyphae grown on organic debris of the algae on the surface of SIR insulator.

In America, the evidence of fungi activity on polymers is in a paper by Gu *et al.* (1998). However, these fungi (*Aspergillus versicolor*, *Cladosporium cladosporiodes* and *Chaetomium*) species were active in deteriorating polymer coating of polyamides (Gu *et al.*, 1998), in such a way that they decreased significantly the impedance of the inoculated samples.

Investigations of algae also revealed that the algae colonies could remain dry for a long period, but after artificial wetting, some of the cells recovered and multiplied (Gubanski *et al.*, 2000). The results of the artificial growth on the silicone rubber sheet showed that the algae had a possibility of covering the sheet with a dense and thin cellular mat and under prolonged wet conditions; they could form a bio–film on the surfaces of insulators.

2.9.3 Effect of Biofouling on Polymeric Insulators

As said earlier on, the biofilms that colonize insulator surfaces consists of microorganisms embedded in a highly hydrated matrix of extracellular polymeric substances, mainly polysaccharides and proteins. Mixed populations of bacteria, fungi, protozoa and algae often coexist in the film. Small unicellular green algae of the *Chlorella* family living in symbiotic with bacteria dominate the biofilms with traces of filamentous fungi. Water is very abundant element in most biofilms and the organic portion of the film is often dominated by extracellular polymeric substances; also, particulates as clay, humic substances, corrosion products etc. The way in which a biofilms affects properties of a polymeric material ranges from discolouration to complete degradation of the polymeric material. The major degrading mechanisms are: *fouling (coating of the surface)* which causes change in surface properties, *degradation of leaching components* which results into loss of mechanical stability, *biotic degradation* through enzymes secreted by the biofilms cause loss of stability, *hydration and penetration* causing increase of conductivity and swelling of the surface, and finally, the *secreted pigments* lead to colour change.

The encouraging thing is that from field studies it has been shown that not all polymer insulators are affected by biofilms. In fact molds from three continents (Asia, Africa and Europe) reacted differently to additives concentration (*zinc borate*), and it has been established by Wallström (2005) that the same additive is capable of prohibiting the growth whilst *ALTH* does support the growth. The outdoor environment provides nutrients for growth of biofilms on insulator surfaces especially the needed CO_2. In addition to that, direct UV irradiation hinders biofilms growth on the surfaces directly facing the sun (Gubanski *et al.*, 2000; Kyaruzi & Gubanski, 1999; Magige *et al.*, 2003).

Laboratory testing revealed a substantial reduction (~70 %) of the wet FO of SIR insulators but the dry FO was not affected by presence of biofilms on the insulator surface (Gubanski *et al.*, 2000). The presence of this growth reduced the average FO by 30 %. This went hand in hand with insulators colonized in field showing lower influence of growth to the FO. Discharge activity was higher after FO compared to before, and this was opposite to what was observed for insulators colonized in laboratory. The insulators contaminated in field performed similarly to those contaminated in laboratory despite the insulators from field to be more covered by growth than the laboratory contaminated ones. The total performance was that the insulators contaminated had reduction of FO of about 33 %.

Now it is time to turn attention to the dielectric characteristics of polymeric formulations. This is the second part of the work, which involve surface and volume resistivity, and dielectric frequency spectroscopy.

2.10 Dielectric Characteristics of Polymeric Formulations

Electric field distributions around insulators surfaces are influenced by permittivity, conductivity and charging of materials used to manufacture the insulator, as well as by geometry of the insulators. Permittivity, conductivity, and charging of polymers manifest themselves into parameters as surface and volume resistivity, and dielectric losses. Although this thesis makes use of guarded electrodes which are considered better in evaluation (Keithley, 2001, 2003a, 2003b), but still there is a certain amount of influence on the results due to fringing effect as analyzed by Lisowski & Skopec (2009). However, this thesis will not pursue nor evaluate effects of fringing.

2.10.1 Resistivity of Solid Insulation Systems

In Filippini *et* al. (1996) quotes that according to ASTM D257–93 and IEC 93 standards the insulating quality of solid insulating materials is characterized by two parameters called *surface* and *volume resistivity* derived from dc voltage and dc current measurements. Using ac voltage to obtain the resistivity of insulating solids is difficult due to the complex ohmic characteristics of the insulating solids. Such ac measurements are better in determining the dielectric losses of insulating materials.

Measurements of resistivity of insulating materials are of prime importance in industrial practice for their characterisation after processing or for reception tests and monitoring of high voltage apparatus (Filippini *et al.*, 1996). In addition, to determine the dielectric breakdown, the dissipation factor, the moisture content, mechanical continuity, and other important properties of a material (Keithley, 2001). Applying a dc voltage between

electrodes in contact with insulating material, the current through it decreases asymptotically toward a limiting value, and the decrease to reach within 1% of this minimum value is after a time between a few seconds and many hours.

Commonly specified test voltages to be applied to the specimen are between 100 V and 15 000 V. This range left room for this thesis to determine the voltage to use, which is 400 V for duration longer than a minute as specified in the said standards. The time duration is longer (over 50 minutes) in order to obtain a time curve (in this thesis it is a resistivity time curve) as remarked in those IEC and ASTM standards cited by Filippini *et al.* (1996). In addition, the longer duration of DC voltage application causes the exponential charging of the insulating material causing the resistivity to increase exponentially (Dakin, 2006; Filippini *et al.*, 1996; Keithley, 2001) and (2.2) shows the charging current decaying as a power law of the type:

$$I(t) = At^{-n} \tag{2.2}$$

over several decades of the time (with $0.6 \leq n \leq 1.1$) and eventually levels off in all types of solids (Filippini *et al.*, 1996). This shows that solids exhibits time dependent resistivity shown as variation of a function of the length of electrification time. The longer the voltage is applied, the higher the resistivity because the material continues to charge exponentially, and the same will be shown by the results of the resistivity measurements in this thesis.

Filippini *et al* (1996) and Maryniak *et al* (2003) cautions about conditioning the samples before measurements, since resistivity measurements are susceptible to: thickness of sample (volume resistivity); environmental conditions; contact between the sample and

the electrodes; and voltage levels. Such care and conditioning when measuring resistivity in this thesis is spelled in Chapter Three under section 3.4.2.

Volume resistivity of some insulators, such as sapphire and Teflon®, can be as high as 10^{16} to 10^{18} Ω–cm (Keithley, 2001). Because of such large magnitudes, measuring the resistivity of insulators can be difficult unless proper test methods and instrumentation are used. The resistivity measurements described in this thesis involve use of *Electrometer* because of its ability to measure small currents, and *Resistance Test* fixture (Keithley, 2001, 2003a, 2003b).

2.10.2 Measuring Volume Resistivity

Volume resistivity is the electrical resistance through a cube of insulating material. It gives how much an insulator can limit LCs flow within the material bulk as shown in Figure 2.5. It is a material property expected to be constant but subject to conditions stipulated above in section 2.10.1.

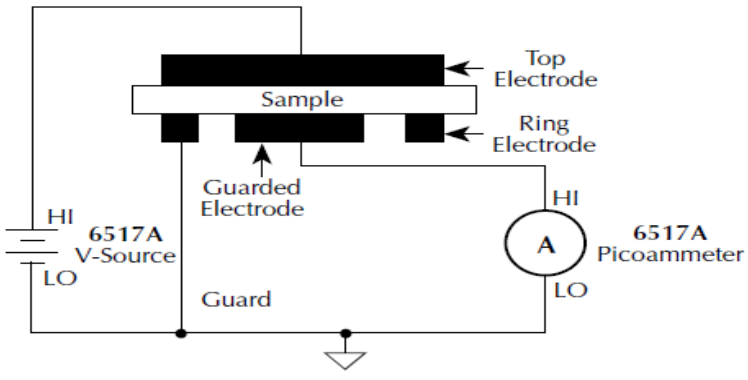


Figure 2.5 Volume resistivity measurement technique

Source: Keithley (2001, 2003a)

Volume resistivity is measured by applying a dc voltage across opposite sides of the insulator sample and measuring the resultant current through the bulk as shown in

Figure 2.5. Model 6517A automatically performs calculations as per (2.3) and displays the volume resistivity reading (Keithley, 2001, 2003a):

$$\rho_V = \frac{K_V}{d} R \tag{2.3}$$

ρ_V is volume resistivity (Ohm-cm); R is measured resistance in ohms (V/I); K_V is the effective area of the guarded electrode for the particular electrode arrangement employed; and d is average thickness of the sample (mm).

2.10.3 Measuring Surface Resistivity

Surface resistivity is defined as the electrical resistance of the surface of an insulator material. It is measured from electrode to electrode along the surface of an insulator sample; see the *ring electrodes* and the *guarded electrode* between them in Figure 2.6. Since the surface length is fixed, the measurement is independent of the physical dimensions (i.e. thickness and diameter) of the insulator sample (Keithley, 2001). The technique to measure surface resistivity is in Figure 2.6:

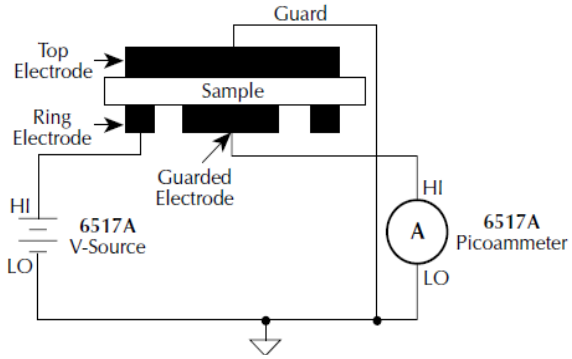


Figure 2.6 Surface resistivity measurement technique

Source: Keithley (2001, 2003a)

The voltage is applied across the surface of the insulator sample and resultant current is measured as shown in Figure 2.6. Model 6517A automatically performs calculations as per (2.4) to give out surface resistivity reading (Keithley, 2001, 2003a):

$$\rho_S = K_S R \tag{2.4}$$

ρ_S is surface resistivity per square; R is measured resistance in ohms (V/I); and K_S is the geometry factor of the electrodes (a unit-less quantity).

Theoretically this property should remain constant regardless of the method and configuration of the electrodes used for the measurements, but in reality this is not the case as will be shown later in results.

2.10.4 Frequency Spectroscopy of Solid Insulation Systems

Within researches of polymeric insulators, frequency spectroscopy investigation has had its fair share, since these measurements can tell the molecular, ionic and electronic states of dielectric material, which are vital for the effective performance of polymer insulators. Moreover, these researches are important: as diagnostic tools in investigating level of dielectric conduction in outdoor polymeric insulators (Capaccioli *et al.*, 1998; Dakin, 2006; Desheng *et al.*, 2000; Ehsani *et al.*, 2007; Myślińsk & Łazowski, 1993). In addition, these literatures discuss conduction levels of polymers (Nguyen *et al.*, 2004; Riande & Díaz–Calleja, 2004; Seifert *et al.*, 1998; Serdyuki *et al.*, 2002; Tuncer, 2006; Tuncer & Gubanski, 2000).

Discussion about molecular structures of polymers is in (Dakin, 2006; Nixdorf & Busse, 2001; Riande & Díaz–Calleja, 2004; Tuncer *et al.*, 2002). Other literatures discuss about detecting ageing effects of polymers (Seifert *et al.*, 1998); discussion of effects of interfaces within polymers (Andersson, 2006), and studying surface properties of polymers (Jonscher, 1999).

In the current thesis, dielectric loss (or tan delta) of silicone joined in series to epoxy resin specimens will be investigated and characterised.

2.10.4.1 Dielectric Properties of Solid Insulation Systems

Polymeric materials comprises of composites, which exhibit enhanced properties that the constituent materials cannot (Akram *et al.*, 2005). Dielectric relaxation affects electrical properties of polymers. In 1942 Kauzman defined relaxation to be the time lag in the response of a system to a change in the physical forces (temperature, electric field, magnetic field, stress, etc.) to which it is subjected (Kauzman, 1942; 14:12 as quoted by Zong *et al.*, 2005). That makes the dielectric relaxation time to be an indication of the average amount of time required for a collection of dipoles in an electromagnetic field to revert to a random orientation after removal of the field. Polymers show some pretty characteristics when subjected to electric field either ac or dc.

Serdyuki *et al.* (2002) did dielectric measurements and compared these results with computer simulations. From measured values of complex permittivity, they observed pronounced distinction of imaginary part in one of the composites for which it obtained three orders of magnitude at low frequencies, as well as at higher frequencies. In addition, there was a general relaxation of the composites at frequency range of *10 mHz – 1 Hz*, and they concluded that the computer simulation provided a qualitative estimation of the dielectric properties measured. Tuncer & Gubanski (1999) investigated mixtures of silicone polymer with *ALTH* filler. They found out that *ALTH* concentration had bigger impacts on silicone rubber conductivity at various temperatures. The higher concentration of *ALTH* acted as charge traps at higher

temperatures. Nguyen *et al.* (2004) investigated dielectric properties of silica filled silicone rubber. They identified two polarization mechanisms, with a hopping charge transport at moderate higher fields. Dakin (2006) discussed the mechanism concept for the magnitude and the trends of conduction and polarization in dielectrics with molecular and physical structure, frequency, and temperature some of which will be discussed in the following paragraphs.

Alternating current and direct current conductivity in polymers vary significantly with temperature, while ac conductivity varies also with frequency. Conduction is related to the dielectric constant or permittivity of the material; also with the polarization. Jonscher (1999) discussed broadly the dielectric relaxation in solids, stressing that with the evident complexity of the relaxation processes certain very simple relations prevail which give better understanding of the polarization processes.

Reading variety of literatures regarding relaxations in solids, one comes up identifying four principle types of polarizations namely: electron, ionic–interfacial, atomic–ionic, atomic–ionic displacement and dipolar.

2.10.4.2 Dielectric Polarization

Electron polarization occurs over the entire frequency range from dc i.e. zero frequency up through optical frequency. Ionic–interfacial polarization is observed only in lower frequencies. Atomic–ionic polarization occurs over the entire frequency range from dc through optical frequency.

Atomic–ionic displacement extends from dc through infrared frequencies, and it is dominant in inorganic crystals, glasses and ceramics.

Dipolar polarization occurs from dc up to microwave frequencies, depending on the presence of dipolar molecules and the resistance to molecular rotation presented by the material's internal structure.

Ionic–interfacial and dipolar polarization are the most important for most organic liquids and resin electrical insulation, since they are associated with conduction and dielectric loss at commonly used frequencies.

Molecular dipoles are commonly discussed in respect of their relation to polarization and dielectric constant, but they also contribute to conduction in insulation for short times and over lower frequencies of ac voltage. Dipolar molecules occur as a major or minor impurity in insulating liquids and resins (Dakin, 2006; Nguyen *et al.*, 2004; Riande & Díaz–Calleja, 2004). When a polymer is in an electric field, there is a torque, which tends to align these dipoles to its direction rotating them, causing short time flow of current through the polymers and this amount to conduction and polarization.

2.10.4.3 Tools for Measuring Dielectric Properties

Seifert *et al.* (1998) studied extreme low frequencies (ELF) responses and low frequencies dispersion (LFD), to detect and classify ionic conductivity problems, and material damages due to electrical over stresses respectively in developing a new tool to detect and classify the ageing in composite insulations. The study commented that, the

results of the interactions at the large internal filler surfaces are an increase in the conductivity and an intensification of interfacial polarization effects. Das–Gupta & Scarpa (1996) as quoted in (Seifert *et al.* 1998) used an ELF dielectric diagnostic tool to investigate the changes in the dielectric relaxation behaviour of ac–aged cross-linked polyethylene (XLPE) for cable insulation.

Also the study (Seifert *et al.*, 1998) cited Houhanessian & Zaengl (1996) who used both time and frequency domain dielectric diagnostic tools to characterize the impregnation quality and the moisture content of oil–paper insulations in large high–voltage transformers. Based on these literatures, Seifert *et al.* (1998) did dielectric measurements and estimated the dielectric response function in the low frequency (LF) range.

Through the dielectric spectroscopy technique, it is possible to study polarization mechanisms such as electronic, atomic and molecular both in time and frequency domain (Dakin, 2006; Jonscher, 1999; Riande & Díaz–Calleja, 1998; Seifert *et al.*, 2004). A paper (Zong *et al.*, 2005) went on and defined types of relaxations occurring in epoxy resins during microwave cure.

In cases of insulating materials, this method can give information about moisture content and degree of inclusions of the insulator. Moisture content and inclusions affect the overall insulation property as well as the lifetime of the insulation system. In study by Tuncer & Gubanski (1999), the researchers observed charge trapping by filler particles at lower frequencies.

Such spectroscopy methods allow the study of molecular structure through the orientation of dipoles under the action of an electric field; the experimental devices which are used for this task can cover the frequency range of 10^{-4} – 10^{11} Hz (Riande & Díaz–Calleja, 2004). However such a wide range of frequency can not be covered by a single instrument, so it usually is covered by a combination of instruments.

In the current thesis, the range covered by the used instrument (Keithley, 2003a, 2003b) is 10^{-4} – 10^{3} Hz so there was no need to employ other instruments. These measurements were used to provide the dielectric characteristics of different polymer materials studied.

2.10.4.4 Dielectric Properties of a Polymer under the Action of an Electric Field

Under the action of an electric field, the dielectric loss and complex permittivity of a polymer are related as shown in the following (2.4) to (2.9). The complex permittivity is given by:

$$\varepsilon^*(w) = \varepsilon(w) - j\varepsilon'(w), \tag{2.4}$$

for materials with a single relaxation time and considered as simple polymers, as that in Figure 2.9, their complex dielectric permittivity will be given by:

$$\varepsilon^*(w) = \varepsilon_\infty + \frac{\varepsilon_o - \varepsilon_\infty}{1 + jw\tau} \tag{2.5}$$

whereby the real part referred to as permittivity is

$$\varepsilon(w) = \varepsilon_\infty + \frac{(\varepsilon_o - \varepsilon_\infty)}{1 + w^2\tau^2} \tag{2.6}$$

and the imaginary part referred to as loss is

$$\varepsilon'(w) = \frac{(\varepsilon_o - \varepsilon_\infty)w\tau}{1 + w^2\tau^2} \tag{2.7}$$

Then, the dielectric loss factor is defined as ratio of magnitude of imaginary part of complex permittivity to the magnitude of its real part, mathematically given as:

$$\tan \delta(w) = \frac{\varepsilon^{'}(w)}{\varepsilon(w)} \tag{2.8}$$

which results into

$$\tan \delta(w) = \frac{(\varepsilon_o - \varepsilon_\infty)\, w\tau}{\varepsilon_o + \varepsilon_\infty w^2\tau^2}. \tag{2.9}$$

These are the Debye equations for permittivity, dielectric loss and dielectric loss factor of a dielectric material. The symbols: $\varepsilon^*(w)$ is the frequency dependent complex permittivity, $\varepsilon(w)$ is the permittivity, $\varepsilon'(w)$ is dielectric loss, j is the complex quantity, w is the frequency, ε_o is the permittivity at very high frequencies, ε_∞ is the permittivity at very low frequencies, and τ is the Debye macroscopic relaxation time. However, (2.5), is only true for polymers with very short chains and sufficient number of dipoles (Dakin, 2006; Seifert *et al.*, 1998); in most practical polymers, the relaxation time is distributed and given by:

$$\varepsilon^*(w) = \varepsilon_\infty + \frac{\varepsilon_o - \varepsilon_\infty}{1 + (jw\tau)^{1-\beta}} \text{ where} 0 < \beta < 1. \tag{2.10}$$

The significance for this type of response shown in (2.10) is that there are different relaxation times, which are all laying near each other, for example, polarized chains of polymers that do not have the same length or dipole moment. This will be taken care of by the shape factor β. This behaviour of materials to have distributed type of relaxation is called non–Debye relaxation.

In measuring dielectric properties, time domain and frequency domain measuring devices are used. However, the far and better-developed measuring instruments are

those that measure in frequency domain than in time domain (Riande & Díaz–Calleja, 2004). For disc materials between circular electrodes, the current traversing the condenser is given by:

$$I^* = (G + jwC)V_o \tag{2.11}$$

Where I^* is the total current, G is the conductance, C is the capacitance, and V_o is the applied step voltage; equivalently the equation for current through the condenser can be written as:

$$\frac{I^*(w)}{V_o} = jwC_o\varepsilon^* = Y^* \ , \tag{2.12a}$$

or alternatively,

$$I^*(w) = jV_oC_o(\varepsilon'(w) - j\varepsilon''(w)) . \tag{2.12b}$$

In these equations; Y^* is the complex admittance of the material, C_o is the vacuum capacitance given by:

$$C_o = \frac{\varepsilon_o S}{d} \tag{2.13}$$

of which ε_o is the vacuum permittivity, S is the surface area of the circular electrodes which touches and covers the specimen under test, and d is the thickness of the dielectric material specimen between the electrodes shown in Figure 2.7. The voltage source applies ac voltage V_1 to the sample, the current–to–voltage (I–V) converter changes the current I_s into voltage V_2. What the instrument is doing is comparing the amplitude and the phase angle between these two voltages (V_1 and V_2), and then it gives out the complex impedance Zs of the sample as:

$$Z_s = \frac{V_1 - V_2}{I_s} = \frac{V_1 - V_2}{V_2} R \tag{2.14}$$

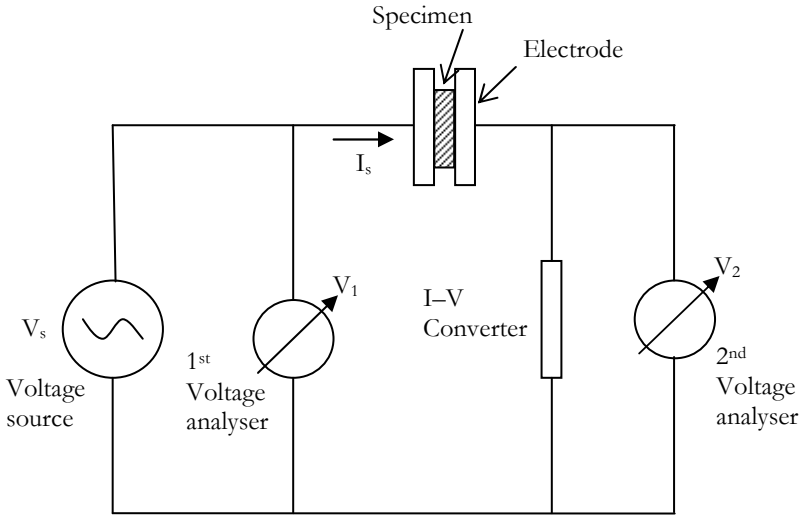


Figure 2.7 Dielectric frequency analyzer
Source: Riande & Díaz–Calleja (2004)

2.10.4.5 Simple Series and Parallel Dielectric Networks

For simple analysis, the insulation material can be considered to be simple circuits of *RC* networks which are either (a) parallel, or (b) series as shown in Figure 2.8(a) and (b). Equivalence of the parallel and series *RC* networks is achieved if the admittance Y^* is equal to the reciprocal of the impedance Z_s. The admittance and impedance are given by:

$$Y^*_p = R^{-1}_p + jwC_p, \text{ and} \tag{2.15}$$

$$Z_s = R_s + \frac{1}{jwC_s}. \tag{2.16}$$

Y_P, R_P, C_P, Z_S, R_S, and C_S are functions of frequency (w).

With (2.15) and (2.16), the following expressions are obtained:

$$R^{-1}_p = G = \frac{R_s}{R^2_s + (wC_s)^{-2}}, \tag{2.17a}$$

$$\text{which gives, } R_p = R_s\left(1 + \frac{1}{(wC_sR_s)^{-2}}\right), \tag{2.17b}$$

$$C_p = \frac{C_s}{1 + (wC_sR_s)^2}, \tag{2.17c}$$

$$R_s = \frac{R_p}{1 + (wC_pR_p)^{-2}} = \frac{G}{G^2 + (wC_p)^2}, \tag{2.17d}$$

$$\text{and} \quad C_s = C_p\left(1 + \frac{G^2}{(wC_p)^2}\right). \tag{2.17e}$$

By virtue of these equations, it should be noted that the loss factor is

$$\tan\delta(w) = wC_sR_s = \frac{1}{wR_pC_p}. \tag{2.17f}$$

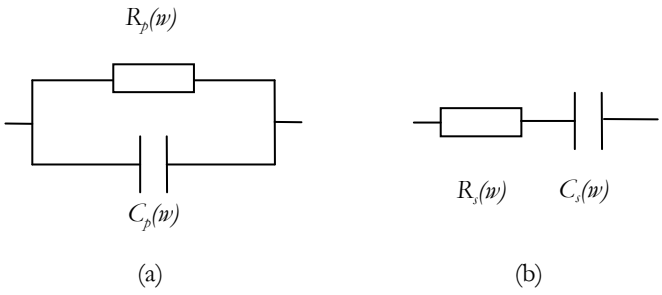


Figure 2.8 Simple: (a) parallel; and (b) series RC networks representing dielectric materials.

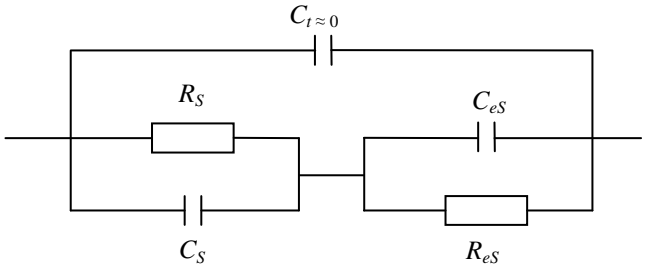


Figure 2.9 Circuit analogue of electrical insulation with a single relaxation time.

Source: Dakin (2006)

Nevertheless, under the influence of electric fields, the polymers can be represented by one relaxation time shown in Figure 2.9 (Dakin, 2006).

This is the circuit analog of Maxwell–Wagner polarization. In this circuit, the shown parallel capacitor $C_{t\approx 0}$ is the capacitance associated with high frequency polarization, which is independent of frequency. The series *RC*

circuits can be represented with a single relaxation time constant called "Maxwell–Wagner Time Constant" τ_{mw} given by:

$$\tau_{mw} = \frac{R_s R_e (C_s + C_e)}{R_s + R_e} \tag{2.18}$$

2.10.5 Conductance of Polymer Networks

In analog circuits for polymers, the dc resistance accounts in the real part of complex conductivity. Complex conductivity is related to the complex permittivity by the following equation:

$$\sigma^*(w) = \sigma + j\sigma' = \varepsilon_0 w\varepsilon' + jw\,\varepsilon \tag{2.19a}$$

The real part of the conductivity $\sigma = \varepsilon_0 w\varepsilon'$ represents the loss factor due to dc conductivity as:

$$\tan\delta = \frac{\sigma}{\varepsilon_O w\varepsilon'}. \tag{2.19b}$$

Where δ = *delta.*

The imaginary part of the conductivity, $\sigma' = w\varepsilon$ represents loss due to displacement current; and ε_O is the vacuum permittivity. Log log plots show that tan delta varies as w^{-1} in low frequency regions after the dc conductivity (Capaccioli *et al.*, 1998; Ehsani *et al.*, 2007; Tuncer, 2006; Tuncer & Gubanski, 2000). An extension to (2.19b) involves the dielectric loss factor assumed to be comprised of the dc conductivity and the dipole relaxation ε'_{relax} (Nixdorf & Busse, 2001).

$$\tan\delta = \frac{\sigma}{w\varepsilon_o} + \varepsilon'_{relax}. \tag{2.20}$$

(2.19b) is reflected as the first term to the right of (2.20). The second term in (2.20) is the dipole relaxation. Insulation systems diagnostics easily make use of (2.19b) which has characteristics shown in Figure 2.10 for low frequency regions:

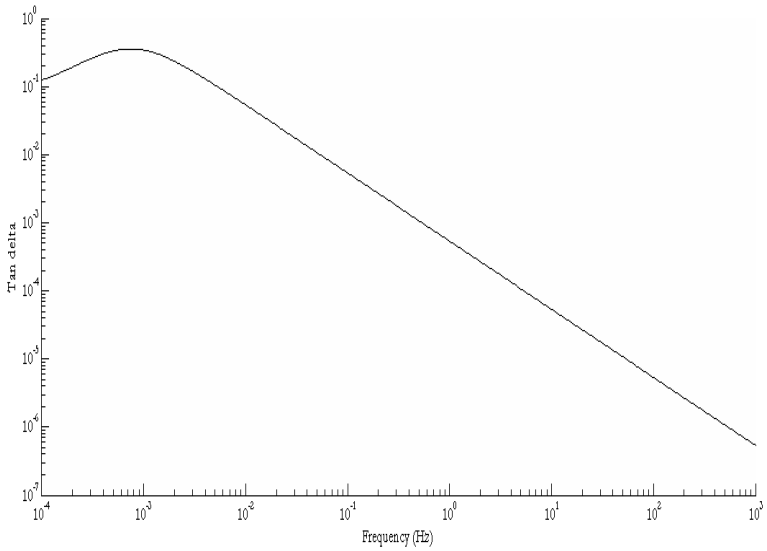


Figure 2.10 Simple dielectric characteristics for low frequency regions

In above figure is shown relaxation at lower frequencies, but this model does not seem to cater for relaxation at higher frequencies (>1 kHz) as (2.20) suggests. This model shows dominance of orientation polarization (Akram *et al.*, 2005). Psarras *et al.* (2006) described 'the ac universality law', which describes satisfactorily the ac response of numerous different non–crystalline solids at constant temperature as:

$$\sigma^*(w) = \sigma_{dc} + \acute{A}w^S \tag{2.21}$$

This equation is sort of combining (2.19) to (2.20). The first term σ_{DC} is dc conductivity, $\acute{A}$ and s are parameters depending on temperature determined experimentally. In (2.21) the second term shows the variation of the real part of conductivity as power law.

In this thesis, dielectric loss was measured in the low frequency region of *0.1 mHz* to *1 kHz*, for which it will seen that the behaviours mentioned in previous paragraphs are evident.

2.11 Review of Past Work on Insulation Systems in Tanzania

The history of researching polymeric insulators in Tanzania goes as far as the 1990s as seen in the following discussions. In addition, it is in the introductory part of this thesis (in Chapter One) that there were some polymeric insulators installed in Ruvu Chini substation in Bagamoyo since 1974. The review of studies will be divided into two sections namely:

(1) Review of undergraduate research works; and

(2) Review of postgraduate works.

These reviews will establish some important findings and corroborate them to the current study.

2.11.1 Review of Undergraduate Research Works

These were works mainly done by undergraduate Electrical Engineering Department (EE) students of the University of Dar es Salaam (UDSM). They began in 1994 when one student researched ageing and lifetime of insulators along Coastal areas (Kilua, 1994). Four years later, another student undertook to investigate how climate affect substation and transmission line insulators (Peter, 1998). These two simulated the environmental salt conditions in laboratory using sea salt water of concentration shown in Table 2.4. These were followed by investigation of effects of salt pollution on 33 kV distribution line insulators (Chiwawa *et al.*, 1999) by using salts of varying concentration to simulate environmental conditions. Another one studied the suitability of composite insulator in tropical conditions (Kihwele, 2001) by using rainwater mixed with salts to

simulate environmental pollution. Table 2.4 shows some results from two of the researchers Peter (1998) and Kihwele (2001).

Table 2.4 Concentration of cations and anions on seawater and insulator dust in High Voltage Yard

Element	**Cations**							**Anions**	
Concentration in ppm	K	Na	Ca	Fe	mg	Mn	Pb	SO_4	Cl
Sea water	15	114	141	NIL	5.50	2.80	0.23	262	22000
Washing from insulator	NIL	1.4	3.4	0.2	45.6	3.20	0.23	110	2767

Source: Peter (1998) and Kihwele (2001)

These researchers (Chiwawa *at al.*, 1999; Kihwele, 2001; Kilua, 1994) observed that:

(1) Salt (equalling marine salts) deposits are the major environmental degrading factor to insulators;

(2) Humidity increases conductivity of pollution layers leading to observations of FO during rainy seasons; and

(3) The breakdown voltage decreased significantly with humidity shown by wet FO test.

Peter (1998) and Kihwele (2001) went on further to measure the ESDD and observed that its increases cause lowering of wet breakdown voltage of insulators.

Chiwawa *et al.* (1999) observed that salts from ground dissolve during rainy seasons; actually, this is source of soil contamination. When it is sunny days, the water evaporates with small amounts of dissolved salts which then deposits on insulators surfaces. The same happens also for sea salt water, which evaporates and gets blown landside to deposit on insulator surfaces thereby enhancing marine contamination.

2.11.2 Postgraduate Research Works

One year (i.e. exactly in 1995) after the EE UDSM undergraduate students began researching these NCIs; Chalmers University (CTH) and UDSM started an extensive research to study usefulness of NCIs in Dar es Salaam and Coast Region beginning 1995. For this project, three different sites of 33 kV power lines were selected and polymer insulators installed (Gubanski, 1998; Kyaruzi & Gubanski, 1999; Mbwana, 1995, 1996, 1997). The sites are Masaki substation, Ohio street feeder, Kimara feeder, and Ruvu Chini water pumping station. Details of these installed insulators are in Table 2.5. The aim of this project was to address properly the existing gap of knowledge on composite insulator performance in tropical climates. General outcome of these studies was that the installed insulators performed well as of 1999 (Fernando, 1997, 1999; Kyaruzi & Gubanski, 1999; Mbwana, 1995, 1996, 1997).

Table 2.5 Dimensions of test NCIs installed in Dar es Salaam and Coast Region

Insulator number	**1**	**2**	**3**	**4**	**6**	**7**
Material	Silicone rubber	Silicone rubber	Silicone rubber	EPDM	RTV coated	Silicone rubber
Arcing distance (mm)	345	400	345	345	260	385
Creepage distance (mm)	790	853	840	840	500	930
Number of sheds large/small	4	4/3	6	6	5	7
Distance between sheds (mm)	62	40	50	50	45	40
Shed diameter large/small (mm)	160	122/81	126	126	105	115
Core diameter (mm)	22	27	26	26	45	32

Source (Gubanski, 1998; Kyaruzi & Gubanski, 1999; Mbwana, 1995, 1996, 1997)

2.11.3 Pollution Severity of Insulators in Tanzania and their Electrical Performance up to 1999

These studies (Gubanski *et al.*, 2000; Kyaruzi & Gubanski, 1999; Mbwana, 1995, 1996, 1997) give pollution severity that is encountered in Tanzanian climates and explained in the following paragraphs.

The pollution severity was determined by ESDD in August 1995 even though the insulators were washed by heavy rain on a previous day; and in August 1996, luckily with no rain recorded for seven days before the measurements. The ESDD results are in Table 2.6. HC measurements of the insulators was done when new (at installation) in 1995, 1996, and 1998 as shown in Table 2.7 adopting the STRI HC method.

Table 2.6 ESDD of installed insulators

	ESDD in mg/cm^2				
Insulator number	1	2	3	4	7
Masaki – 1995	0.012	0.022	0.026	0.032	
– 1996	0.003	0.077	0.127	0.064	
Ohio street – 1995	0.005	0.003	0.004	0.005	
– 1996	0.029	0.073	0.056	0.028	
Bagamoyo water pumping station – 1996					0.025

Source: Kyaruzi & Gubanski (1999)

Table 2.7 Hydrophobicity of installed insulators

		Insulator number					
Location	Year	1	2	3	4	6	7
Masaki	1995	HC1	HC1	HC1	HC1	HC1	
	1997	HC5	HC1	HC3	HC6		
	1998	HC5	HC1	HC4	HC7	HC3 – 7	
Ohio street	1995	HC1	HC1	HC1	HC1		
	1997	HC2	HC1	HC1	HC5		
	1998						
Ruvu Chini	1995						HC4 – 6
	1997						HC6
	1998					HC4 – 6	

Source: Kyaruzi & Gubanski (1999) and Mbwana (1995, 1996, 1997)

Visual observations of the insulators installed by July 1998 showed the following observations in Table 2.8.

Table 2.8 Visual observation of insulators as of July 1998

Insulator No.	Masaki	Kimara	Ohio street	Ruvu Chini
1.	Contaminated by soil deposit	Small area of insulator covered with green biological growth	Contaminate by black car exhaust with higher concentrations of live end	
2.	Contaminated by soil deposit, there is some corrosion at one of the fittings	Large area of insulator surface covered with green biological growth in the shaded parts	Strongly contaminated by black car exhaust with higher concentrations of live end	
3.	Contaminated by soil deposit	No sign of contamination or biological growth	Lightly contaminated by black car exhaust with higher concentrations of live end	
4.	Whole surface chalked, deterioration of sealing material between core and sealing	Whole surface chalked, contaminated by black car exhaust	Whole surface chalked	
6.	Some coating erosion close to end fitting			
7.				Greenish biological growth covered whole insulator

Source: Kyaruzi & Gubanski (1999)

Insulator number 7 (the one found in Ruvu Chini which was installed in 1974) was further subjected to dry and wet FO tests with either shortened creepage distance or as a whole. Summary of the FO results is in Table 2.9.

Table 2.9 HC and flashover of biologically contaminated and uncontaminated insulators from Ruvu Chini

Insulator	Material	Creepage distance (mm)	HC	Dry FO value (kV)	Wet FO value (kV)
1st field exposed	Silicone rubber	Whole - ~ 930	5, 6 TU – 4	166.3	85.7
		Short - ~ 800		-	69.4
2nd field exposed	Silicone rubber	Whole - ~ 930	5, 6 TU – 4	162.4	90.7
		Short - ~ 800		-	85.0
3rd field exposed	Silicone rubber	Whole - ~ 930	4, 5 TU – 5	164.3	91.7
		Short - ~ 800		-	81.0
1st reference	Silicone rubber	Whole - ~ 930	1, 2 TU – 4	163.4	88.7
		Short - ~ 800		-	99.2
2nd reference	Silicone rubber	Short - ~ 800	1	142.6	115.0

Source: Kyaruzi & Gubanski (1999)

Key: TU – upper side of top shed

2.11.5 Pollution Severity of Insulators in Tanzania and their Performance from 1999 Todate

Four years later, i.e. in 2003, researchers from UDSM found out that those installed polymer insulators in these papers (Kyaruzi & Gubanski, 1999; Mbwana, 1995, 1996, 1997); their electrical performances' were degraded by biofilms growth on their surfaces (Magige *et al.*, 2003) which agreed with the research results of biodegradation by biofilms in work of Wallström *et al.* (2001).

That work by Wallström *et al.* (2001) reported five types of silicone rubber formulations that could host fungi. The rubber becomes a host and never does it become the primary source of carbon for the growth, so an external source of carbon must be available to feed the fungi. This source is thought to be air CO_2.

Further analysis of the biofilms growth showed presence of scattered *coccoids* in the *green filament algae* (Magige *et al.*, 2003). At that time, the researchers concentrated on investigating Kimara feeder and Ruvu Chini pumping station insulators, which were named previously in (Kyaruzi & Gubanski, 1999; Mbwana, 1996) as insulators number 1, 2 and 7. Their dimensions are in GRAY shaded parts of Table 2.5 on page 74 above. By visual scrutiny, all insulators both at Ruvu Chini and Kimara were covered with biofilms; insulators at Kimara were covered with motor vehicle black soot and brownish soil dust. Moreover, insulator number 2 had markings of dryband. The insulators from Ruvu Chini had on damage marks on the fringes of the sheds. With all these pollution, the insulators maintained integrity as no problems were reported so far.

At Chalmers University of Technology (CTH), investigations on the algae growths revealed important information (Gubanski *et al.*, 2000). These algae growths were mainly localized on the shaded parts of the insulators starting from the second shed. The top shed remained uncovered. It was revealed that the biological growth (algae) on NCIs revealed could grow on different types of SIR, independently of their different polymer–filler constitutions. On the other hand, no algae growth was found on hydrophilic EPDM surfaces. The reference insulator was discolored, whereas another test insulator preserved its original color. However, the metal fitting of its cold end was damaged. Measurements done were HC; LC inside the fog chamber and FO (both wet and dry tests). In order to equalize the test conditions, the field–exposed insulators and the reference insulator were shortened to a creepage distance of about 800 mm by short-circuiting the shed close to the cold end shown in Table 2.9.

Figure 2.11 shows the time variation of LC levels for the biologically contaminated silicone rubber insulators (Gubanski *et al,* 2000; Kyaruzi & Gubanski, 1999). All the LC levels were in the order of a few tens of μAs indicating low surface conductivity. The LCs increased initially with the time and later decreased to a saturated level. This behavior was caused by the formation of dry band on the core close to the live end. However, such behavior could not be seen on reference insulators. Instead, the LC levels increased continuously to a saturated level.

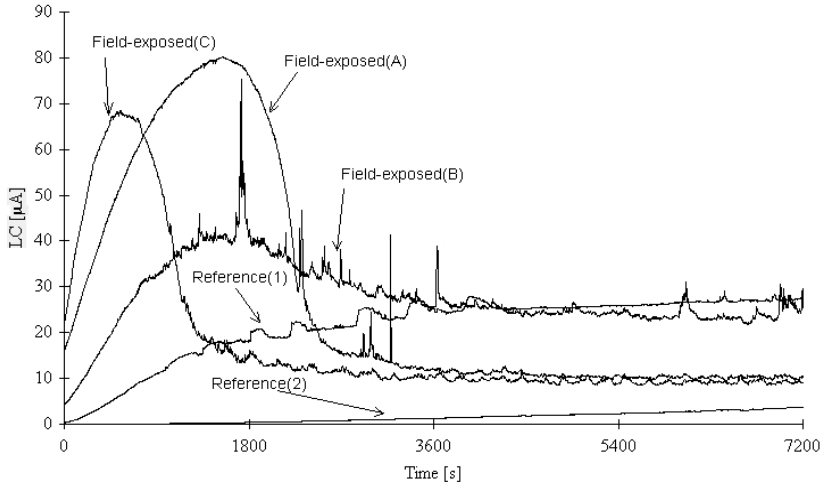


Figure 2.11 Time variation of LCs on Silicone Rubber Insulators from Ruvu Chini Tanzania

Source: Gubanski *et al.* (2000)

The HC of the field–exposed insulators were slightly high (Gubanski *et al.*, 2000; Kyaruzi & Gubanski, 1999). The obtained values were HC5–6. Accordingly, the LC levels were relatively high. Among the field–exposed insulators, it was found that less time was required for wetting thinner growths than thicker ones. The reference insulators were hydrophobic and the LC levels were low. These findings provide evidence of a good agreement between surface hydrophobicity and LC level; look at Table 2.7 and Figure 2.11.

If it were possible to have the required instruments the LCs of the NCIs would have been measured also in this study to elucidate (if any) the difference between the LCs by then to current days performance. However, coverage of this challenge and others is in Chapter Six.

It might as well suffice to say that it has been established of a strong correlation between leakage currents and hydrophobicity (Sörqvist & Vlastós, 1997). The insulators with a high degree of hydrophobicity show lower leakage currents.

CHAPTER THREE
METHODOLOGIES AND EQUIPMENTS

The study is divided into two categories:

(1) Field and laboratory investigation of field installed NCIs in Tanzania; and

(2) Laboratory characterisation of polymeric formulations.

3.1 Field and Laboratory Investigation of Installed Non–ceramic Insulators in Tanzania

3.1.1 Hydrophobicity Measurements

Installed polymeric insulators in Tanzania were studied for their HC properties using the STRI HC evaluation technique. This method is handy for providing rough estimation of the wetting of insulator surface. The HC is estimated by visual evaluation of how covered is a surface of an insulator after being sprayed with distilled deionised water. It is suitable and cheap to apply since all that is needed is distilled water and a spray bottle. With this HC evaluation, photographic documentation using a digital camera was done on the insulators in field and those found lying in HVL UDSM.

3.1.2 Determination of Pollution and Damage

The extent of pollution, biofilms and damage (caused by pollution and biofilms) evaluation were done according to STRI (2005), guide for visual identification of

deterioration and damages on suspension NCIs. These were done during field visits by taking down (if possible) those insulators and examining them.

3.2 Determination of Soluble/Salt Deposit Density and Layer Conductivity

3.2.1 Surface Conductivity (κ)

Layer conductivity meter (SLM 9) was used to measure the surface layer conductivity. The probe was fixed with the wet absorbent tip and placed on the dry contamination layer. The value was read once the κ values became stable. This exercise was done on five insulators (NCI-1 to NCI-4 and M1). Using the inbuilt functions of the instrument, the layer conductivity was corrected to T = 20 ºC by using (2.2) of Chapter Two.

3.3 Determination of Aging, Oxidation, Degradation and Depolymerization of Polymeric Insulators

The extent of aging, depolymerization and oxidation was supposed to be determined at the Government Chemist Laboratory Agency (GCLA) and the Physics Department of UDSM in Dar es Salaam. However, only the GCLA was accessible. The techniques used were GC/MS using *Digilab* and FTIR using the *Digilab Excalibur HE Series*.

3.3.1 Method of Gas Chromatography/Mass Spectrometry

Taking a small amount of sample and dissolving in known suitable solvent. It is important to select a solvent with respect to polarity of the sample dissolved. For example a trifluoro-trichloro ($CF_3–C–Cl_3$) used in (Homma *et al.*, 1998) is good for

dissolving silicone rubber (PDMS) which have the same polarity. Then the solution gets a heating to a temperature of 200 ˚C for 2 minutes. Thereafter, injection of the volatile components into a capillary GC column subjected to a temperature program. Variation of the column temperature is from 35˚C to 300 ˚C at a rate of 15 ˚C/min. Then, the output from the GC column passes to an MS for chemical identification and quantification of the volatile components.

3.3.2 Method of Fourier Transform Infrared Spectrometry

A small amount of the powdery surface material typically found on degraded polymeric insulator was scraped from the surface with a razor blade. Infrared spectra were obtained by grinding approximately 5 g of the surface material with approximately 100 g of potassium bromide (KBr) powder, which is transparent to infrared light, and pressing into a 13 mm diameter disk under a pressure of 10 tonnes. This produced a clear KBr disk with finely divided sample material evenly dispersed, which gives infrared transmission or absorbance spectra.

Beers law of absorption provides a relationship between IR spectrum absorption peak heights to the respective concentration of the responsible functional group for generating that peak. The relationship can be clearly followed in Blackmore *et al.* (1998, p. 135) and Osland (1989, ch. 7). Then this thesis will calculate the *OI* and *CI* with slight modifications to the functional groups considered. The considered groups will include *virgin hydrocarbons*, *aliphatic CH stretch in* CH_3, *asymmetric* CH_3 *deformation in Si-*CH_3, $Si(CH_3)_3$, and $Si(CH_3)_2$. This will differ from earlier research (Blackmore *et al.*, 1998; Zhou *et al.*, 2003); for which use of the *OI* and *CI* the considered groups were virgin

hydrocarbons. This will enable to get a clear understanding of the state of those different groups compared to the amount of oxidation or chalking that has taken place within them.

3.3.3 Calculating Oxidation Index and Chalking Index

Blackmore *et al.* (1997, 1998) provided a convenient method of calculating *oxidation index* (*OI*) and *chalking index* (*CI*) from FTIR peak heights at certain wavenumbers. Respectively the formulas are:

$$OI = \frac{P_c}{P_h} \text{ and } CI = \frac{P_f}{P_p} \tag{3.1}$$

P_c is the peak height of the carbonyl, P_h is the peak height of the hydrocarbon or other functional groups containing hydrocarbons, P_f is the peak height of the *ALTH* filler, and P_p is the peak height of the polymer or other functional groups containing polymers.

3.4 Polymeric Material Characterisation

This part of the work was done at the Division of High Voltage, Department of Electric Power Engineering (*Elteknik*) of the Chalmers University of Technology (CTH) in Sweden. In this section, the measurements done were:

(1) Volume resistivity;

(2) Surface resistivity; and

(3) Dielectric frequency spectroscopy.

Measurements were carried out on disc polymeric materials in laboratory ambient conditions. SIR and epoxy resin were manufactured in laboratory using commercial available silicone elastomer and resins, and other silicone rubbers were industrially made and delivered to the laboratory.

3.4.1 Polymeric Sample Manufacturing

Test samples consisted of silicone rubber and epoxy resin. There were silicone rubber samples prepared in laboratory while others were prepared in a factory. However, for the case of epoxy resin they were all prepared in laboratory.

First type of silicone rubber was prepared from a commercially available silicone elastomer. These rubbers were two groups depending on the manufacturing temperature and time: first group comprising of S1 and S2 cured at an oven temperature of 120 °C for 120 minutes and second group comprising of S481 and S482 cured at room temperature (22 °C – 25 °C) for 48 hours as shown in Table 3.1. These are called 'Silicone Rubber Type 1'.

A second type of silicone rubber was HTV rubber manufactured in industry and delivered to the laboratory. First was a group of SF1 and SF2 used for insulator shed manufacturing delivered to the laboratory by manufacturer and is named 'Silicone Rubber Type 2'.

A third type of silicone rubber was a HTV rubber group PS used for insulator-shed manufacturing delivered to the laboratory by the manufacturer; this will be called 'Silicone Rubber Type 3'.

These types allowed having silicone rubber with different characteristics, i.e. silicone rubber with no additives (S1, S2, S481 and S482), silicone rubber with additives (SF1, SF2 and PS) and different curing times and temperatures (see Table 3.1).

Epoxy resin was made into thin discs in laboratory using commercially available resins. Looking at Table 3.1 bellow, the epoxy resins are named as 'Epoxy Resin'. These were cured at different temperatures to get epoxy discs with different cross-linking degrees. All samples were first cured for 4 hours at an oven temperature of 80°C, and then followed by additional different curing times at temperature of 130°C as follows:

(1) First is E141 & E142 for 10 hours;

(2) Second is E241 & E242 for 20 hours; and

(3) Lastly is E481 & E482 for 44 hours.

Table 3.1 shows epoxy resin thickness varied from 1.2 mm to 1.6 mm due to difficulties in ensuring uniform settling. This happened during the stirring and pouring stages of the production. SIRs manufactured in laboratory had the thickness of 1 mm and those delivered to the laboratory by manufacturers thicknesses are 2 mm and 3 mm respectively for PS and SF.

Thereafter, resistivity and frequency spectroscopy measurements followed. Sometimes a sample was tested more than once to be sure of the outcomes, but it needed conditioning. This conditioning was staying in oven for about three hours at a certain temperature (50°C and 70 °C for epoxy resin and SIR respectively).

Table 3.1 Sample manufacturing parameters

Sample	Material	Name	1st Curing time and temperature	2nd Curing time and temperature	Thickness
Epoxy resin	Epoxy Resin	E141	4 hours in oven at 80°C	10 hours in oven at 130 °C	1.2 mm
	Epoxy Resin	E142	4 hours in oven at 80°C	10 hours in oven at 130 °C	1.2 mm
	Epoxy Resin	E241	4 hours in oven at 80°C	20 hours in oven at 130 °C	1.2 mm
	Epoxy Resin	E242	4 hours in oven at 80°C	20 hours in oven at 130 °C	1.2 mm
	Epoxy Resin	E481	4 hours in oven at 80°C	44 hours in oven at 130 °C	1.6 mm
	Epoxy Resin	E482	4 hours in oven at 80°C	44 hours at 130 °C	1.4 mm
Silicone rubber	Silicone Rubber Type 1	S1	120 minutes in oven at 120 °C		1.0 mm
	Silicone Rubber Type 1	S2	120 minutes in oven at 120 °C		1.0 mm
	Silicone Rubber Type 1	S481	48 hours in room temperature of 22 – 25 °C		1.0 mm
	Silicone Rubber Type 1	S482	48 hours in room temperature of 22 – 25 °C		1.0 mm
	Silicone Rubber Type 2	SF1	HTV rubber industrially made		3.0 mm
	Silicone Rubber Type 2	SF2	HTV rubber industrially made		3.0 mm
	Silicone Rubber Type 3	PS	HTV rubber industrially made		2.0 mm

3.4.2 Resistivity Testing Methods

Resistivity measurements were carried out in room ambient conditions of 22 °C – 25 °C and relative humidity of 32% – 40%. Electrometer high resistance meter called *Keithley Model 6517A* supplied the test dc voltage of 400 V (Keithley, 2003a). Test sample was placed in a resistivity test fixture called *Keithley model 8009* with ring electrodes (Keithley, 2003b). The test voltage was applied for about 50 minutes, 100 minutes or more depending on the need.

The Electrometer was used to display the instantaneous resistivity values and it was connected to a desktop computer through a general purpose interface bus (GPIB), which allowed data to be collected in hard disk of a computer. Data sampling was done by using LABVIEW™ software virtual instruments (VIs) collecting data at an interval of 90 ms. Data analysis was done with the help of a MATLAB™ software.

3.4.3 Analysis of Resistivity Data

Instantaneous resistivity values were having a big spread. A decision was made to use linear regression techniques (Matlab, 2005) to smooth the data to obtain smooth curves when plotting. This is a curve-fitting tool of Matlab. Each smoothed value was determined by neighbouring data defined within a span of 15%. The local regression weights are calculated via the tricube function shown below:

$$D_i = \left(1 - \left|\frac{p - p_i}{d(p)}\right|^3\right)^3 \qquad (3.2)$$

p is the predictor data value associated with the resistivity value to be smoothed, p_i are the nearest neighbours of p as defined by the span, and $d(p)$ is the difference along the abscissa from p to the most distant predictor value within the span. The weights have these characteristics: the data point to be smoothed has the largest weight and the most influence on the fit. Data points outside the span have zero weight and no influence on the fit. The smoothed value is given by the weighted regression at the predictor data value of interest. The smoothing process used *1st degree polynomial* functions of linear *least squares* regression (Matlab, 2005).

In addition, to eliminate the effects of outliers the smoothing process employed robust methods. These robust methods include an additional calculation of robust weights, which is resistant to outliers. The robust smoothing procedure follows these steps: calculations of the residuals from the smoothing procedure described in previous paragraph. Then computation of the robust weights for each data point in the span. The weights are given by the bisquare function shown below:

$$D_i = \begin{cases} [1 - (r_i/6M)^2]^2 & |r_i| < 6M \\ 0 & |r_i| \geq 6M \end{cases} \tag{3.3}$$

r_i is the residual of the *ith* data point produced by the regression smoothing procedure, and M is the median absolute deviation of the residuals: M = median ($|r_i|$). The median absolute deviation is a measure of how spread out the residuals are. If r_i is small compared to $6M$, then the robust weight is close to 1. If r_i is greater than $6M$, the robust weight is 0 and the associated data point is excluded from the smooth calculation. Then the data is smoothed again using the robust weights. The final smoothed value is calculated using both the local regression weight and the robust weight.

3.4.4 Dielectric Loss Factor Measurements

To measure dielectric loss factor *Insulation Diagnostics System* (IDA 200 Programma) with resistivity test fixture (Keithley model 8009) with ring electrodes were used. The ring electrodes of the resistivity test fixture provided the necessary pressure to hold the test specimens. The conditions of testing were room temperature (22 °C – 25 °C), humidity of 32% – 40% and room pressure. The dielectric loss measurements were in two steps:

(1) Each sample (silicone rubber or epoxy resin) was energized on its own at the frequency range of *0.1 mHz* up to *1 kHz* using sinusoidal voltage of *140* V_{rms}; and

(2) Two samples i.e. silicon rubber and epoxy resin samples were combined in series using the pressure exerted by the ring electrodes only as the binding force and same voltage applied as in (1) above.

The data for (1) and (2) were collected and stored in the hard disk of the IDA instrument which later was transferred to a PC for analysis via a floppy drive. In the hard disk of the IDA instrument, it was possible to obtain plots showing frequency response of: *tanδ*, complex capacitance and complex permittivity depending on the need. For the scope of this thesis, emphasize is centred on *tanδ*. These data needed no smoothing processes.

CHAPTER FOUR
RESULTS OF FIELD INVESTIGATIONS

4.1 Performance of Polymeric Insulators in Tanzania

4.1.1 Polymeric Insulators Installed by Local Utility

Tanzania's transmission and distribution lines are installed with ceramic insulators for the large part, but since 2001, there is increasing usage of polymeric insulators in 11, 33, 132 and 220 kV distribution and transmission lines (Notes, 2008). The main type of polymer insulators preferred by the local utility is silicone rubber (especially PDMS) from different manufacturers. According to TANESCO personnel, the utility prefers over designed polymer insulators with the highest creepage distance of either 25 mm/kV or 30 mm/kV (Notes, 2008) which is the specific creepage distance for heavily polluted environments.

Importation of two types (i.e. 11 kV and 33 kV) NCIs to be installed in various parts of Tanzania is cited from *The Technical and Economical Report* of TANESCO in (Magige, 2002). The 11 kV insulators imported from USA are: PIN TYPE silicone rubber with 4 sheds; and INCLINED EPDM with 4 sheds. Those 33 kV insulators imported from Italy have 6 large and 5 small sheds are INCLINED and PIN types. Magige (2002) went further to elucidate that using NCIs has economic savings compared to ceramic insulators regarding right of way (RoW), installation costs, upgrading and maintenance.

When engineers and planners of TANESCO order polymer insulators, Table 4.1 is an example of the guide used which can also be found in (Macey & Vosloo, n.d) who cited from IEC 60815. This guide considers Tanzanian system voltages shown in Table 4.2.

Table 4.1 IEC 60815 pollution severity and the creepage distances recommended for insulators

Pollution Class	Pollution Index (mg/cm^2)	Specific Creepage (mm/kV) U_m
Light	0 – 75	16
Medium	76 – 200	20
Heavy	201 – 350	25
Very Heavy	> 350	31

Source: Macey & Vosloo (n.d)

Table 4.2 Tanzania's transmission line and system/maximum design voltages

S/N	Line Voltage (kV)	System/Maximum Design Voltage (kV)
1.	11	12
2.	33	36
3.	66	72
4.	132	145
5.	220	245

Source: Notes (2008)

Another factor to consider is pollution levels of the environment of application. Table 4.3 gives the pollution levels and the maximum electric field strength that can be sustained by an insulator for safer operation. For an engineer designing insulation for Dar es Salaam which is considered to be heavily polluted with marine salts, smoke, dust and biofilms will likely make considerations shown in Table 4.3 by picking an insulator with creepage distance that will be either: 25 mm/kV for 'medium pollution;' or 30 mm/kV for 'heavy pollution.'

Table 4.3 IEC 60815 pollution levels and maximum electric field strength

S/N	Pollution Level	Maximum Electric Field Strength (mm/kV)
1.	Light Pollution	20
2.	Medium Pollution	25
3.	Heavy and very Heavy Pollution	30

Source: Macey & Vosloo (n.d)

With such a decision, TANESCO have bought and installed insulators some of which are those seen in Figure 4.1, which have four inclined sheds.



(a) (b)

Figure 4.1 Polymeric insulators installed in Tanzania along TAZARA industrial area in Dar es Salaam

These insulators are part of TANESCO upgrading its distribution lines from ceramic to polymer insulators. In Figure 4.1(b), that insulator is detached from the pole due to loss of nut and screw caused by tension due to the wire. There are also other installed insulators with 10 alternate sheds (5 large/5 small) seen along Sam Nujoma road in Dar es Salaam and others with about 12 sheds seen on concrete towers going to Twiga cement factory. So far, there have been no reported problems with these newly installed insulators in transmission lines. Nevertheless, according to TANESCO personnel, rodents in a warehouse ate some EPDM insulators before installation when stored

(Notes, 2008). The common feature of all installed NCIs seen around Dar es Salaam, Coast region and other places of Tanzania is that they are covered by contaminants of different kinds from smoke, dust, biofilms, soil and some cement dust at cement factories.

4.1.2 Performance of Test Polymeric Insulators

Kobayashi *et al.* (2002) estimated the lifetime of NCIs to be close to 34 years for which only slight deterioration may occur; thus proving usefulness of insulators installed in Ruvu Chini since 1974, which are part of the current study specimens. These NCIs have sustained shed damages. Research by Vosloo & Holtzhausen (2003a) and Fierro–Chavez *et al.* (1996), established that wind is the main carrier of pollution resulting in directional depositions of contaminants on insulator surface. Test insulators in this study had same effects.

4.2 Results from Field Test Sites

This study used different insulators from field and others found in HVL yard of CoET. Some of those found in HVL were in field in previous years (covered in previous studies in Tanzania as discussed in Chapter Two). Their specifications are in Table 4.4.

4.2.1 Kimara Feeder

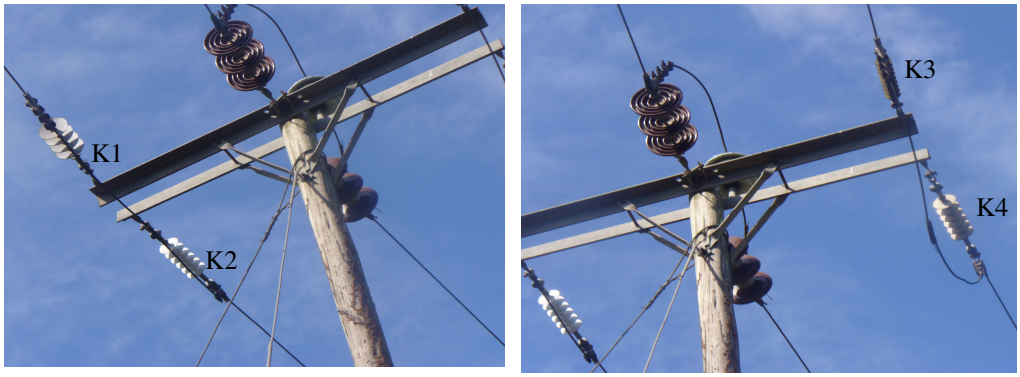
The area is located at the outskirts of Dar es Salaam, 13 km from the city center and 14 – 15 km from the Indian Ocean. There are no industries around, and there are very few houses. Economic activity taking place at the area is agriculture. However, the poles on

which the insulators are installed, are located close to the vicinity of a very busy Morogoro road, which connects to central, northern and southern parts of Tanzania. Pollutants found here are highway hydrocarbon fumes from the automobiles using the road and soil dust. The area can be classified as class I pollution level (light pollution) according to (Fernando, 1997).

Table 4.4 Test insulator specifications

Insulator name	Arcing distance (mm)	Location	No. of sheds large/small	Shed circumference large/small (mm)
K1	345	Kimara feeder	4	503
K2, K4	345	Kimara feeder	6	396
K3		Kimara feeder	9	
M1	400	Masaki substation	4/3	388/264
M2	345	Masaki substation	4	503
MC1		Masaki substation	3 cap & pin	
NCI-1	340	HVL yard	7	308
NCI-2	300	HVL yard	6	392
NCI-3	240	HVL yard	6	308
NCI-4	400	HVL yard	4/3	388/264
HVL-1	340	HVL (kept inside a cabinet)	7	308
Oh1	345	Ohio street feeder	4	503
Oh2	400	Ohio street feeder	4/3	383/255
R1, R2	385	Ruvu Chini substation	7	361
R3	400	Ruvu Chini substation	4/3	388/264
R4, R5, R6		Ruvu Chini substation	5/4	
T1	345	Tazara feeder	6	396
T2	345	Tazara feeder	4	503
W1	345	Wazo hill substation	6	396
W2	400	Wazo hill substation	4/3	
W3		Wazo hill substation	9	

The transmission pole with the polymer insulators is single pole, located 15 m from the center of Morogoro road. The insulators installed are 4 SIR. These support transmission lines in phase 1 (Red) and phase 3 (Blue) shown in Figure 4.2(a) and (b) respectively.



(a) (b)

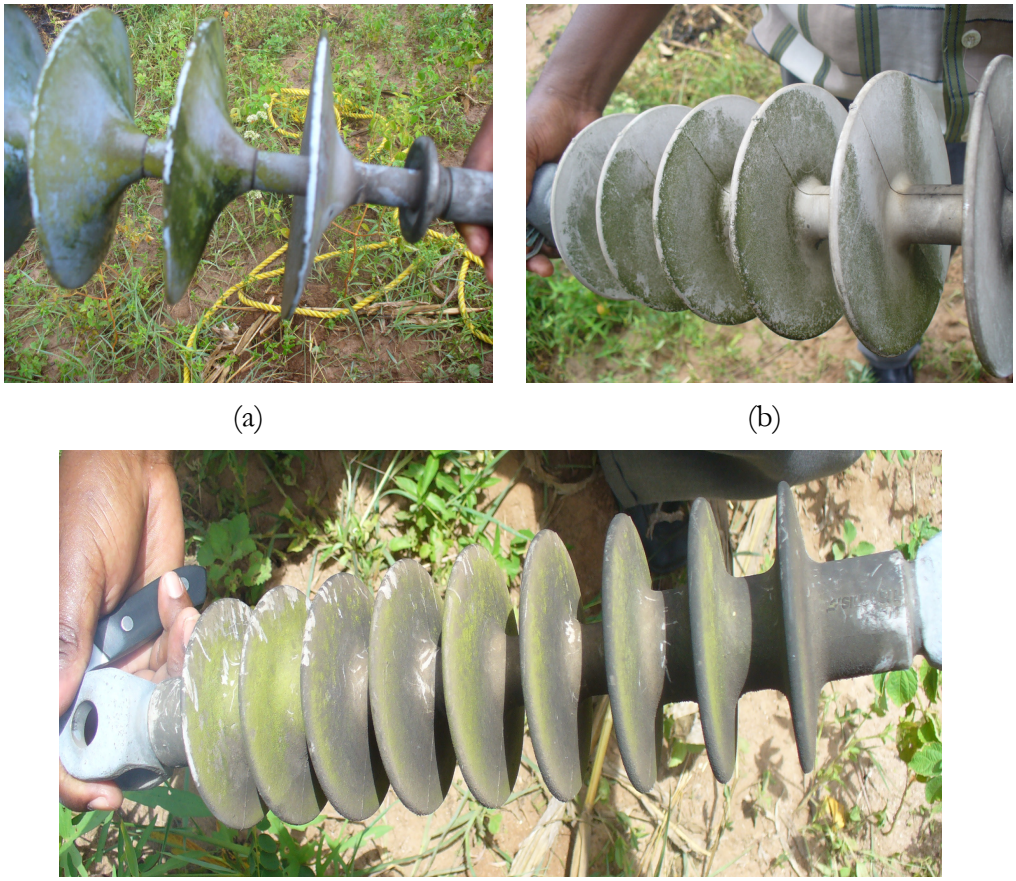
Figure 4.2 Kimara polymeric insulators.

K1 to K4 are the names designed for the insulators for the sake of this study. The central phase of the feeder is strung with cap & pin porcelain insulators

4.2.1.1 Observations at Kimara Feeder Insulators

Biofilms and Dust Contaminations: Dirt, dust and biofilms are visible in all insulators shown in Figure 4.3. Insulators K1 & K2 sheds are dark and sooty; insulators K3 & K4 sheds are dirty and their colours have changed to brown.

Insulators shown in Figure 4.3 are (a) K1, (b) K2, and (c) K3. Insulators K2 and K4 are of the same make from the same manufacturer. In the above figure biofilms, dust and soot cover all three NCIs. Figure 4.3(c) shows insulator K3 that has the thickest biofilms and contaminants layer. In Figure 4.4 is the HC measurement of Kimara insulators.



(a) (b)

(c)

Figure 4.3 Kimara polymeric insulators showing biofouling, dust and soot on sheds, shank and end fittings of insulators



(a) (b)

Figure 4.4 HC of Kimara insulators

Hydrophobicity: Figure 4.4(a) and (b) show HC measurements for these Kimara insulators; insulator K3 shows HC1 – 3 that is good compared to the other insulators. Note that there was heavy rain in Dar es Salaam a week prior to these HC measurements in March 2007. Figure 4.4(a) is insulator K1 with water spreading at all sheds and shank, and (b) is insulator K3 showing good HC values irrespective of the contaminant's thickness.

Summary of Observations at Kimara: Table 4.5 summarizes the observations at Kimara 33 kV feeder site with the best performance (in terms of HC) shown by K3 albeit it's thick pollution layer.

Table 4.5 Observations at Kimara feeder test site with light pollution level

Insulator number	HC	Remarks
K1	6 – 7	Covered with algae mainly on top of sheds close to the ground end, soot at both end fittings, and on the fringes there are soot and dusts.
K2	5 – 7	It has changed colour from grey to whitish, and has little cover of algae.
K3	1 – 3	Completely covered with thick layer of green algae, soot and dust.
K4	T2 – 3, Other parts 5 – 7	Covered with green algae, soot and dust. Algae are mainly located at the bottom of sheds i.e. side that receives little direct sunlight.

T – Top of a shed

From these observations, it is reasonable to say that the Kimara feeder insulators are still performing well despite the evident surface contamination and the obvious hydrophilic surfaces. Recommendation is to wash them from time to time to remove the contaminants lest they initiate FO during light rains. The washing can be live line washing (LLW) using soft cotton cloths and foam water done two times a year since the

place does not have much serious pollution. Care is of import when cleaning lest the pressurized water tore off some parts of the insulators.

4.2.2 Tazara Feeder

At the junction of Mandela road and Nyerere road, there are two poles located on the left of Mandela road when facing the East. The place is approximately 8 km from the harbours on Indian Ocean. Polymeric insulators (T1 and T2) are installed on a two-pole six wire (i.e. double circuit lines) tower seen in Figure 4.5. The red phase insulator sheds are dark, dull and dirty. The yellow phase insulator sheds are brownish.

This site is a very busy section, with large number of vehicles going by. There are industries just about 100m from the poles (Azania Mills and others), and business activities close to the TAZARA train station. The atmosphere is full of heavy vehicle smoke, dust and hydrocarbons. The location can be classified as class II pollution level (medium pollution) according to (Fernando, 1997).

It was not possible to remove the insulator for further analysis (i.e. HC measurements, material analysis and inspection of damages) due to reasons of the line being in use for a very long time with no maintenance planned during the time of this study. Only the visual observation from ground is reported though it is not enough.

It can be concluded that the NCIs in TAZARA feeder are performing satisfactorily because there has been no reported problems on the line due to them. They should not be taken from the poles unless they fail in service, that is when they can be analysed.



Figure 4.5 Polymeric insulators at TAZARA

4.2.3 Ohio Street Distribution Line

The site is in down town Dar es Salaam at the junction of Ohio Street and Ali Hassan Mwinyi road. It is about 1.5 km from the Indian Ocean. The insulators are strung on two steel poles 5 m from the centre of Ali Hassan Mwinyi road. The NCIs are strung on red and blue phase. These polymeric insulators are shown in Figure 4.6 named as Oh1 and Oh2.

Vehicle density on the roads junction is high; one would expect the atmosphere to be filled with smoke from the cars and marine pollution from the nearest Indian Ocean coupled with high humidity and heavy rainfall. During this study, it was not possible to study these insulators even to shut down the line for a short time, which then forced the study to rely on data from a study in 1996 by (Mbwana, 1996).



Figure 4.6 Polymeric insulators at Ohio street

In 1996 the SDD measurements of these insulators one year after installation was between 0.029 mg/cm^2 and 0.073 mg/cm^2 for the SIR insulators and 0.028 mg/cm^2 for the EPDM insulators (Mbwana, 1996). The corresponding HC measurements gave HC 1 – 2 for SIR insulator and HC5 – 6 for EPDM insulator.

With those data, and little information that could be gathered from discussions with TANESCO personnel it can be concluded that the insulators are still in good conditions and will continue to hold the line for quite a time before any replacement is done.

4.2.4 Masaki Substation

4.2.4.1 Installation Work and Early Performance

The substation is 700 m from the coast of Indian Ocean in Dar es Salaam. At this substation, there have been reports of salt contamination problems causing frequent power outages at the Msasani and Mikocheni areas of the city (Mbwana, 1995). The

polymer insulators had been installed at two places in the substation. Two SIR insulators were installed on a junction pole about 100 m from the substation.

Other two polymers (EPDM and SIR) insulators were installed in the vicinity of the substation transformer on a steel tower in 1995. The place is characteristic with sea winds and dusty environment. This area is characterised by high humidity and heavy rainfall during the months of March, April and May and salt particles brought over by sea winds. The insulators are on red and blue phases and are covered with brown dust deposition.

One year after installation, (i.e. in 1996) the HC values were HC1, 2, 3 and 5 for SIR insulators and HC6 for EPDM insulators (Mbwana, 1996). These values show that those insulators were heavily polluted and the EPDM had shown clear signs of surface degradation shown in Figure 4.7.

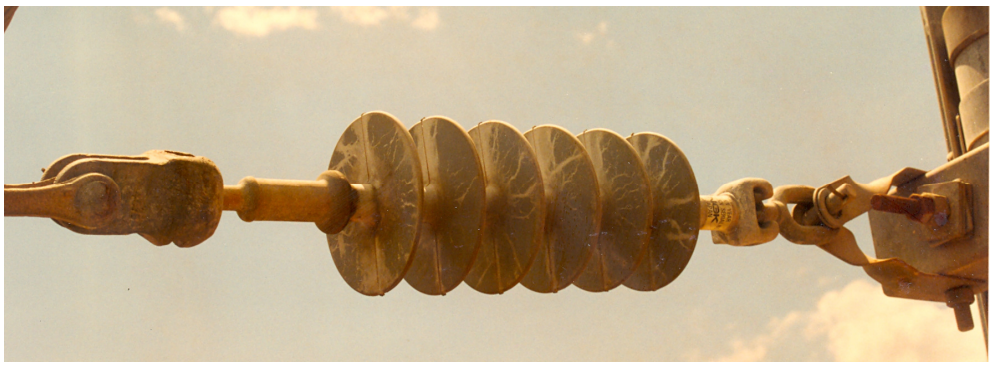


Figure 4.7 Masaki insulator one year after installation in 1996

Source: Mbwana (1996)

ESDD measurements gave 0.033 mg/cm^2, 0.077 mg/cm^2, 0.127 mg/cm^2 for SIR insulators and 0.064 mg/cm^2 for EPDM insulators as of 1996 (Mbwana, 1996).

4.2.4.2 Visual Observations

When visited in 2006, the insulators were contaminated with brownish dust from the local soil seen in Figure 4.8(a); the situation got worse such that between December 2007 and April 2008 there occurred outage problems on the line. The utility conducted investigations to establish the cause of the outages and discovered one silicone rubber insulator (M1) had flashed over. M1 was removed in April 2008 and in its place cap & pin porcelain insulators (MC1) were installed shown in Figure 4.8(b).

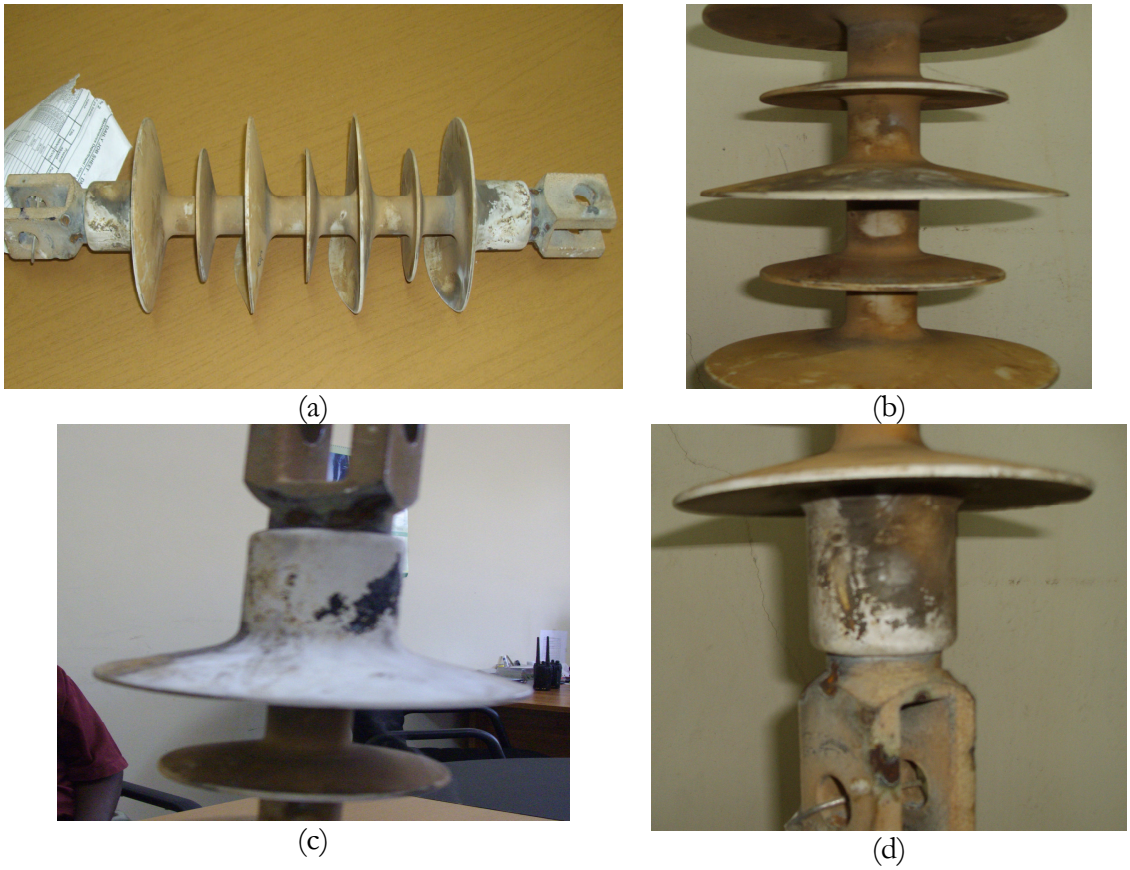


(a) (b)

Figure 4.8 Masaki substation insulators

In the above figure; (a) situation in 2006 when both M1 and M2 were operating, and (b) the situation in 2008 when M1 was replaced by ceramic MC1.

By visual observations in 2008, M1 showed clear markings of deterioration according to (STRI, 2005). The damage includes burn marks at the end fittings, brittle surface, corrosion marks on the polymer and the end fittings shown in Figure 4.9. These damages are due to higher temperatures generated during the FO arcing processes.



(a) (b) (c) (d)

Figure 4.9 Damaged insulator (M1) from Masaki substation

In the figure above; (a) shows the full insulator with contaminants, (b) burns, chalking and erosion marks on sheds, (c) burn marks, chalking and erosion marks on live end and on the metal end fitting (pin), and (d) burn marks, erosion and chalking on ground end and on the pin.

This is a great deal of damages on insulator M1. The marks due to FO are evident on the live and ground ends. There are notches, burn marks on the metal end fittings shown in the figure above. But this insulator had good hydrophobicity of HC1 on surface covered with dust and HC2 – 3 on dark and white surfaces. The insulator's creepage distance and surface characteristics were compromised.

4.2.4.2 FTIR Results

FTIR at the GCLA laboratory showed the following vibrations at wavenumbers in Figure 4.10. Note the two curves showing dark surface and the white surface collected from sheds of M1.

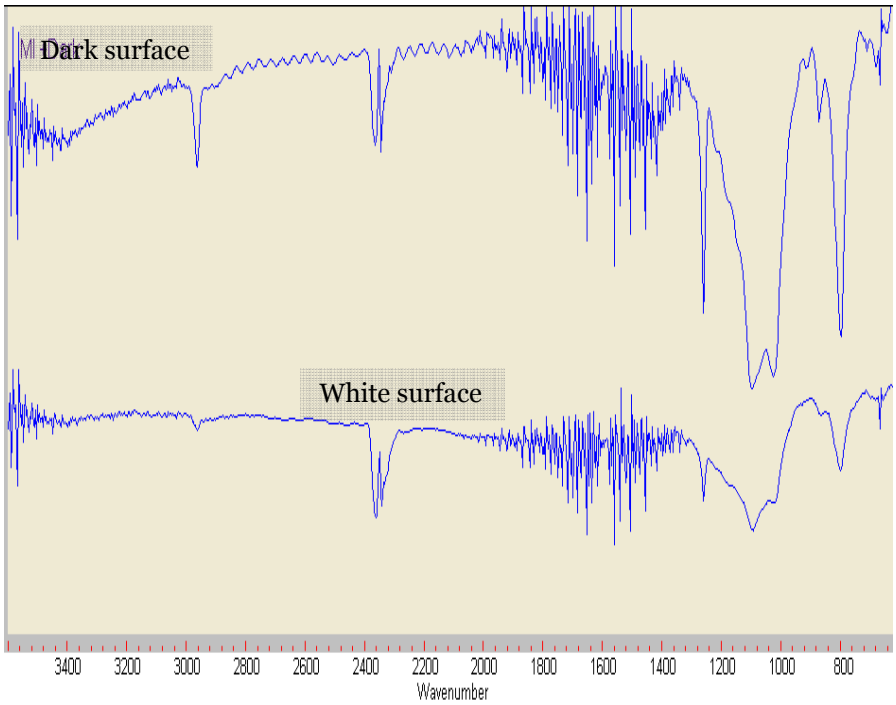


Figure 4.10 FTIR results of insulator M1 showing transmittance of dark surface and the white surface.

It was not possible to scrap or ground the bulk material from M1 because it was rubbery. This situation could be handled through dissolving the rubber in a suitable solvent as in (Blackmore *et al.*, 1998). This difficult prevented the possible comparison of bulk functional groups to those on the white and the dark surfaces. Possibility of obtaining samples to ground with KBr were left to the white and dark surfaces. Then it was possible to compare between the functional groups available on the white and the dark surface shown in Figure 4.11.

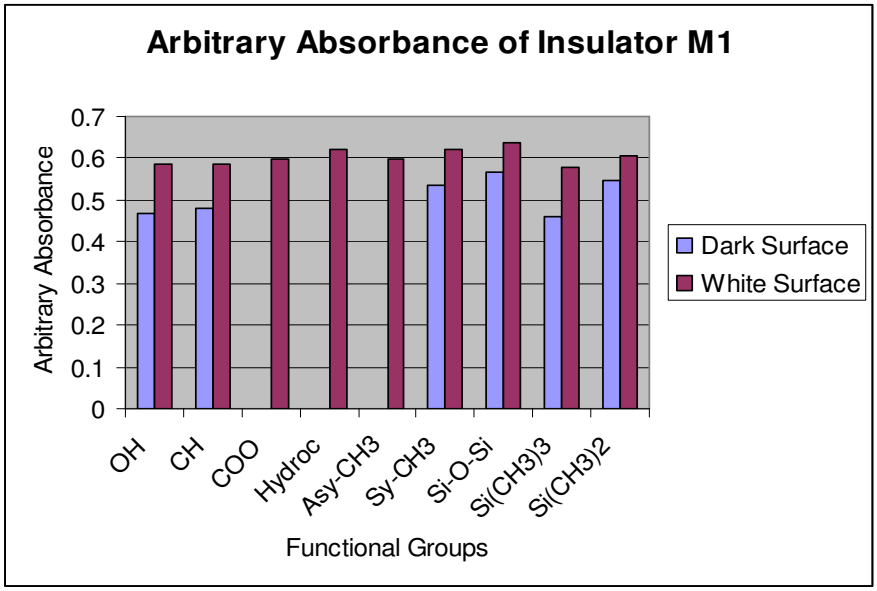


Figure 4.11 Comparison of content of dark and white surface of insulator M1.

Conclusion drawn from this arbitrary absorbance peaks bar chart is that the arcing caused formation of *COO* (oxidation products) and *OH* (chalking product of decomposing *ALTH*) functional groups seen on the white surface. These two functional groups indicate oxidation and chalking of the surface. Relative concentration drawn from Beers law suggests that the concentration of *carbonyl* and *ALTH* fillers on the white surface indicate that this insulator has undergone deterioration such that it is damaged. In addition, the high temperature caused by the arcing has depleted the material present at the dark surface as shown that the peaks of white surface are higher than of dark surface.

Dark surface displays no absorbances for wavenumbers corresponding to *carbonyl* compounds, *virgin hydrocarbons*, and *asymmetric CH_3 deformation in Si-CH_3*. These is an indication of occurrence of destruction or burning of these functional groups by the high temperatures generated by the arcing process. This insulator has been degraded by operational stresses.

4.2.4.3 Leakage Currents

The argument is that if the LC of these insulators could have been monitored online, or in laboratory then the electrical performance and the amount of damage on M1 could have been close to those shown by insulators in KIPTS (Vosloo *et al.*, 1996a). The similarity between KIPTS and Masaki are their proximity to the seashore, which guarantees marine pollution. The degradation of M1 insulator at the last time observed in 2006 was ongoing up to the point when it reached extent to causing the outage problems reported with subsequent removal of the same. MC1 in Figure 4.8(b) with the remaining NCIs at Masaki have been operating smoothly with no problem reported since removal of M1.

4.2.5 Wazo Hill Substation

There are two independent 33 kV feeders supplying to the 33/3.3 kV substation for the Twiga cement factory. In this substation, there are three polymeric insulators on feeder TG4–Kunduchi, which were installed for performance study purposes in 1997 (Gubanski, 1998).

The location at Wazo hill makes it subjected directly to the sea winds. The most severe period observed is between November–January when the strong winds blow from the Indian Ocean and bring both limestone dust and marine salts. The atmosphere is full of cement dust and marine moisture; the insulators are covered with the cement dust in Figure 4.12. This site is definitely a class IV pollution level. According to TANESCO personnel, the substation insulators are cleaned once or twice per year to maintain their credibility and reliability.



Figure 4.12 Wazo hill polymeric insulators covered in cement dust

In Figure 4.12 from left to right: the left most has 6 equal sheds; the center has 4 wider sheds, and rightmost has 9 sheds of equal width.

It seems the washing procedure is working to counter the pollution brought by the winds as no faults have been reported up to the time of writing this thesis and in all other previous studies cited earlier. The suggestion is that the cement dust protects the insulators from attacks by the marine salts as Fernando (1997, 1999) pointed out. The lines bringing power to the factory now contain 12 sheds NCIs on concrete poles.

4.2.6 Ruvu Chini Water Pump Station in Coast Region

The area is 62 km northwest of Dar es Salaam in the Bagamoyo District of Coast Region. It has a climate as that of Dar es Salaam since it is also a coastal region and the location is about 3 km from the Indian Ocean. The region is agricultural and the pollution observed is salt pollution from the Indian Ocean and normal soil dust.

There are six polymeric insulators probably installed in the 1974–1976 (Mbwana, 1996) which means they have been in operation for over 34 years now. In studies by:

Gubanski (1998); Kyaruzi & Gubanski (1999); Gubanski *et al.* (2000) some insulators were removed and sent to Sweden for analysis; and
Magige *et al.* (2003) four insulators were removed and sent to Sweden for analysis.

All these were returned. Due to poor handling some were damaged and could not be re–installed. Replacement NCIs are R3, R4 and R5. Nevertheless, two (R1 and R2) of those taken in (Magige *et al.*, 2003) were re–installed at the same site in 2002 and are functioning to date.

In 1996 SDD of these insulators at this site gave values ranging from 0.021 – 0.029 mg/cm^2 (Gubanski, 1998) with HC measurements values between HC4–6. The surfaces of the insulators were covered with biofilms (greenish layer on all sheds) and visible signs of surface degradation. Degradation on the sheds was observed, but still, the insulators did not fail in service by then or by now.

Ruvu Chini NCIs are in Figure 4.13 with names R1 through R6. In addition, the HC of some of them is shown in the same figure. Those oldest insulators could not be removed then they were evaluated as is on the line.



Figure 4.13 Ruvu Chini insulators showing hydrophobicity, contamination and damages

HC measurements of these insulators revealed good performance with values of HC2–4 shown in Figure 4.13(d) and (f). The oldest insulators R1 and R2 up to now have operated for 34 years and increasing with no failure in service. The HC values and visual observations of Ruvu Chini insulators are in Table 4.6.

Table 4.6 Observations at Ruvu Chini substation site with light pollution level

Insulator number	HC	Remarks
R1	3 – 4	2nd shed from ground end is damaged shown in Figure 4.13(e) and algae cover this shed on fringes away from direct sunlight. The surface is chalked and the insulator is brittle.
R2	3 – 4	1st shed from ground end is damaged shown in Figure 4.13(f) and algae cover this shed, and on the fringes away from direct sunlight. The surface is chalked and the insulator is brittle.
R3	3 – 4	Covered with algae and dust on sheds, and core in the direction away from sunlight.
R4 (installed in 2002)	2 – 4	Covered with algae and dust on sheds, and core in the direction away from sunlight.
R5 and R6		Covered with algae and dust on sheds, and core in the direction away from sunlight.

At the time of writing this thesis, all insulators at Ruvu Chini are still performing well since discussion with TANESCO personnel of Bagamoyo revealed that there has been no problem caused by the same. It is advised that R1 and R2 be not removed from their tower since they are brittle and could easily break if held carelessly. In addition, natural washing by rain is enough as it has kept these insulators functioning.

4.2.7 Kunduchi and Ras Kiromoni Marine Cable Link to Zanzibar

The Kunduchi substation is the control of 132 kV at 42 MW maximum pressure–oil–marine cable link to Zanzibar. All insulators are ceramic except few cable terminations. The site is in the direct vicinity (less than 50 m) of the Indian Ocean; it suffers greatly from salt contaminations. When Gubanski visited Tanzania in 1998, he wrote a report that there were discharge activities observed by the station operators (Gubanski, 1998).

The steel structures are aluminium painted every two to three months. In addition to that, the insulators are cleaned as much as every two to three months at the current cost (of 2008) of $70 per washing (Notes, 2008). From that report (Gubanski, 1998), it is

learnt that there was an attempt to use RTV coating on the ceramics, but it was not successful due to very thin layer of the coating applied, and no further attempt was made.

In November 2008, the steel structures had corrosion marks whilst they had been aluminium painted in the previous month (Notes, 2008). The staff reported of a plan to relocate the substation from the seashore for a few hundred meters as well as an expected project to construct other two marine cable links close by which will allow for more power and more efficiency. This can be a good location to apply SIR insulators due to its class IV pollution level. It can also be used as a good location to build a studying station of NCIs.

4.2.8 High Voltage Yard at University of Dar es Salaam

4.2.8.1 Visual Observation

These insulators were in cupboards in HVL in different degrees of deterioration, some were in good condition while others had chalked and discoloured. These included NCI-1 through to NCI-4 and HVL-1. Parameters of these insulators are in Table 4.4. They had collected a large amount of dust with the field-removed insulators displaying thick dust cover. Summary of the conditions of HVL insulators in 2006 is below:

NCI-1: Previously this insulator was in field, probably in Ruvu Chini. It has deterioration marks along shed fringes and it is brittle. Its hydrophobicity on most parts is HC4 – 7, on shed close to HV is HC7 and shed close to cold end is HC5.

NCI-2: Previously this insulator was probably in field. On top of sheds, it has chalking marks (crazing). On bottom of sheds, it contains light grey spots. Its hydrophobicity on most parts is HC3 – 4, on shed close to HV is HC5 and shed close to cold end is HC3.

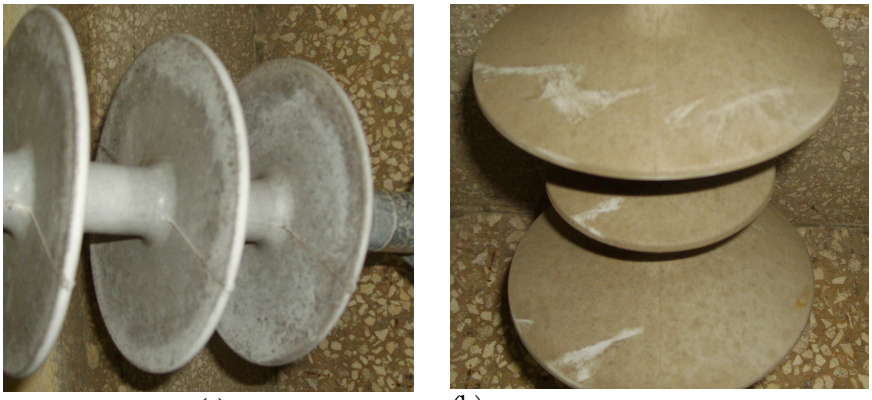
NCI-3: New insulator and has never been in outdoor application. It has no visible deterioration marks. On most parts, it has HC1 – 2.

NCI-4: New insulator has never been in outdoor application and it has no deterioration marks.

HVL-1: An aged, old insulator with some sheds broken. It has turned brittle and breaks at the slight pull or touch on sheds. This insulator is twin to NCI-1, and it has HC the same as NCI-1.

The five insulators were being kept in HVL cupboards where they gathered a lot of dust. Insulators NCI-1 and HVL-1 could be those insulators from Ruvu Chini mentioned in Gubanski *et al.* (2000), which could not be reinstalled due to handling damage.

HVL-1 was returned to the cupboards for safekeeping while the rest (i.e. four insulators) were washed, dried and hanged at the HVL yard on a steel structure. During washing water tended to spread over the surfaces of those hydrophilic insulators. These insulators stayed in outdoor environment without energization for two years (since 2006 to 2008). Nevertheless, over time they attracted dust and contamination. Dust particles adhered to the surfaces shown in Figure 4.14(a) and (b). Wind blew dust particles, which ended up on these insulators' surfaces, at the same time some insects found these surfaces suitable to build their nest as on NCI-3.



(a) (b)

Figure 4.14 HVL insulators with two years dust contamination

Figure above shows two of HVL hanged insulators, which are NCI-2 and NCI-4 after removal from the steel structure. NCI-4 accumulated more dust than others did. In 2009, some of these insulators showed change in HC values from those in 2006. NCI-1 had HC4 – 6 in most parts, indicating no substantial change from its values of HC4 – 7. NCI-2 showed deterioration in HC values from HC3 – 5 to HC4 – 7. NCI-3 showed change from HC1 – 2 to HC3 – 5. NCI-4 retained its HC1 value. For all insulators HC was worse on the shed fringes with the shanks showing good HC values.

Some of these HVL insulators were sent to GCLA for material analysis by FTIR. These are HVL-1 (from the cupboards), NCI-1 and NCI-2. FTIR results are discussed in the following section.

4.2.8.2 FTIR Results

This section begins by discussing absorbance peaks of HVL-1. This insulator was easy to scrap the surface and bulk material due to its brittle nature. A piece that had broken off was used to get the samples to grind with KBr. Figure 4.15 shows transmittance

peaks related to functional groups available on top of shed, bottom of shed and the bulk material.

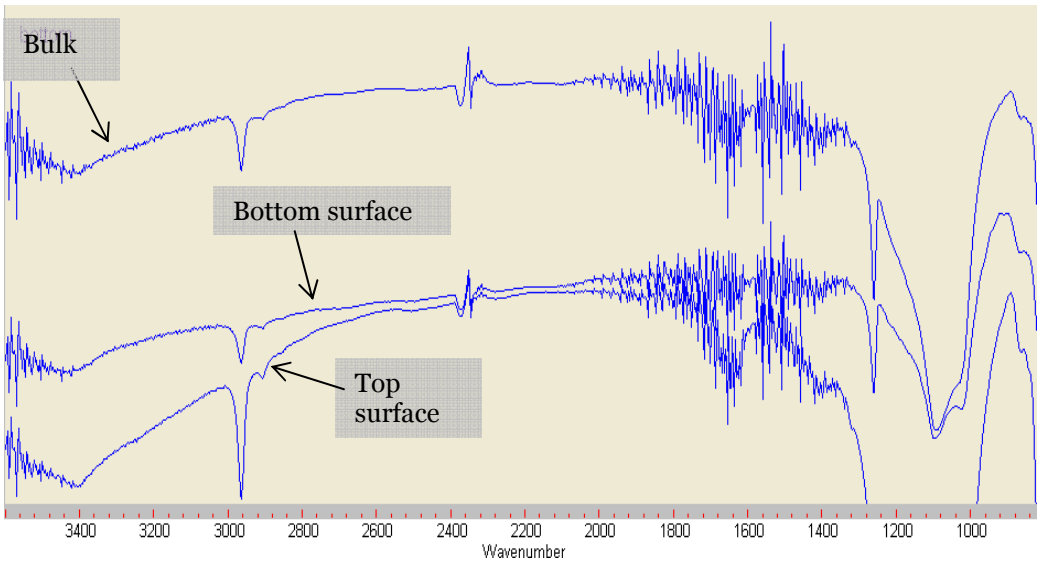


Figure 4.15 FTIR of HVL-1 displaying the top surface, bottom surface and bulk transmittance peaks

Figure 4.15 enabled the construction of bar chart in Figure 4.16, which shows the relative reduction of functional groups in top and bottom of sheds compared to the bulk material.

In these figures, Top means top surface of the shed and Bottom means the underside of the shed. Top surface faces the HV side and directly gets sunshine, whereas underside is shielded from direct sunlight and faces the cold end.

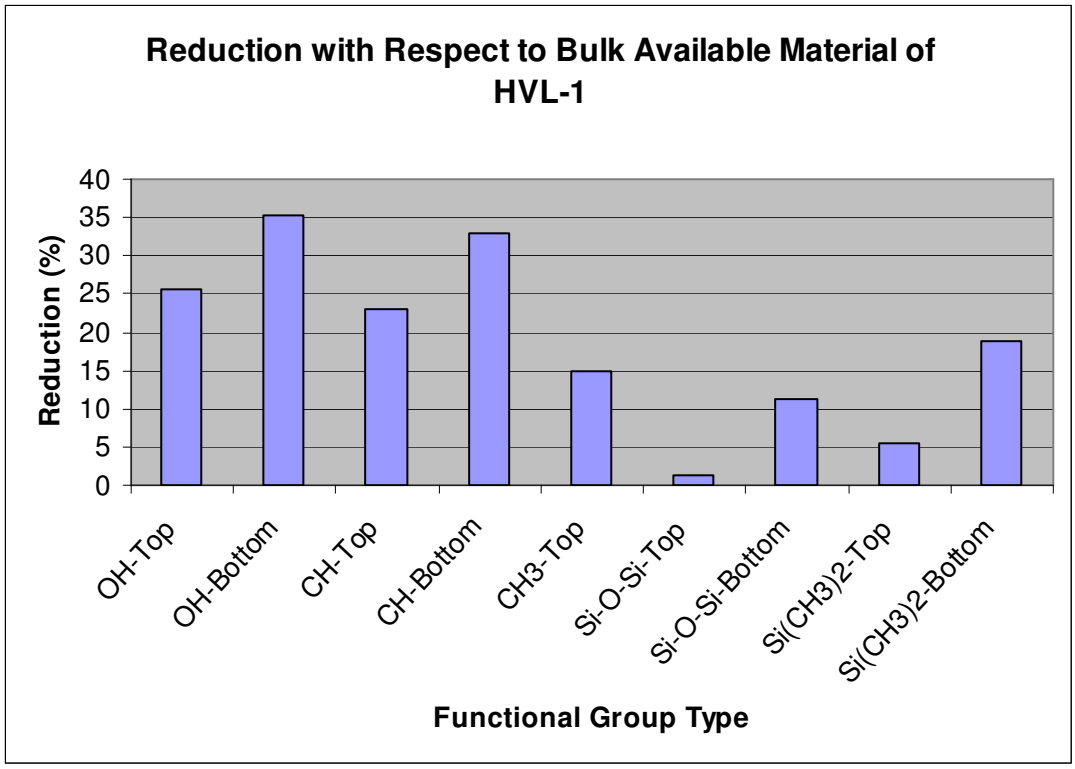


Figure 4.16 Reduction of functional groups with respect to the bulk available material of HVL-1

Reduction was pronounced for almost all groups shown by the bar chart in Figure 4.16 except for backbone stretching of *Si-O-Si* on the underside of the insulator shed. Other observations are that there was no *COO* on top or underside of the shed, but only on the bulk of the shed. There was no peak to indicate absorption by virgin polymers at range of wavenumber 1469 cm^{-1}. This suggests that both oxidation and depolymerisation have taken a greater toll on the material. Asymmetric CH_3 deformation in $Si\text{-}CH_3$ was missing on the underside of the shed material. Symmetric CH_3 deformation in $Si\text{-}CH_3$ was missing in both top and underside of the sheds. These missing asymmetric and symmetric absorptions were topped by no absorption due to functional group $Si(CH_3)_3$.

General reduction of groups on the surfaces is more than 15% then the insulator is degraded a method used by Sundararajan *et al.* (2003) to condemn field aged EPDM insulator.

On the other hand, NCI-1 showed different characteristics portrayed in Figure 4.17. Important functional groups on the surface of the insulators showed increment from the bulk material in contrast to HVL-1. The leading in abundant functional groups are the stretching backbone *Si-O-Si* on the top of shed, CH_3 symmetric deformation in *Si-*CH_3 on the top of shed, and the $Si(CH_3)_2$ on the top of shed. The only slight reduction is the stretching backbone *Si-O-Si* on the bottom of shed. However, this is minimal.

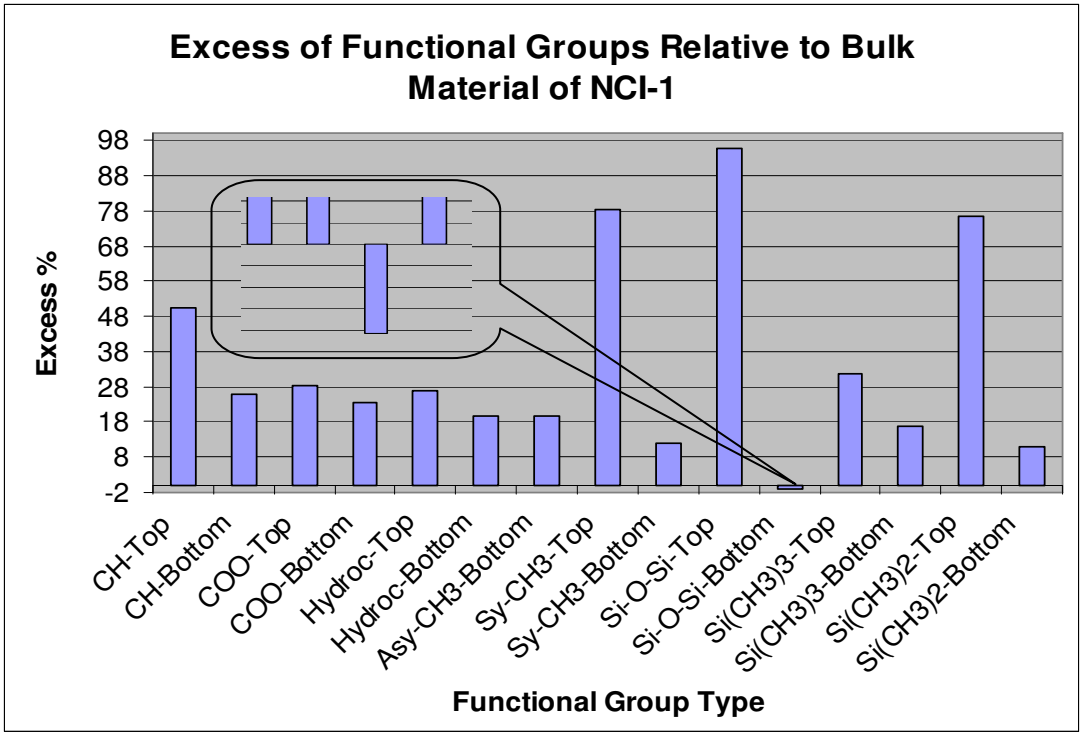


Figure 4.17 Excess functional groups displayed by insulator NCI-1

This insulator showed excess of *OH* groups, *carbonyl* groups as well as *virgin hydrocarbons* and others as said in previous paragraph. This insulator is considered not degraded since it has a fair concentration of *virgin hydrocarbons*; nevertheless, it is on the stages of deterioration due to the presence of abundant silica on the surfaces.

The third HVL insulator is NCI-2. With this insulator, it was difficult to obtain the bulk material to be ground with KBr because of its nature of being elastic. Then the possible samples scrapped and collected were from top and bottom of shed. The FTIR of the two surfaces is in Figure 4.18.

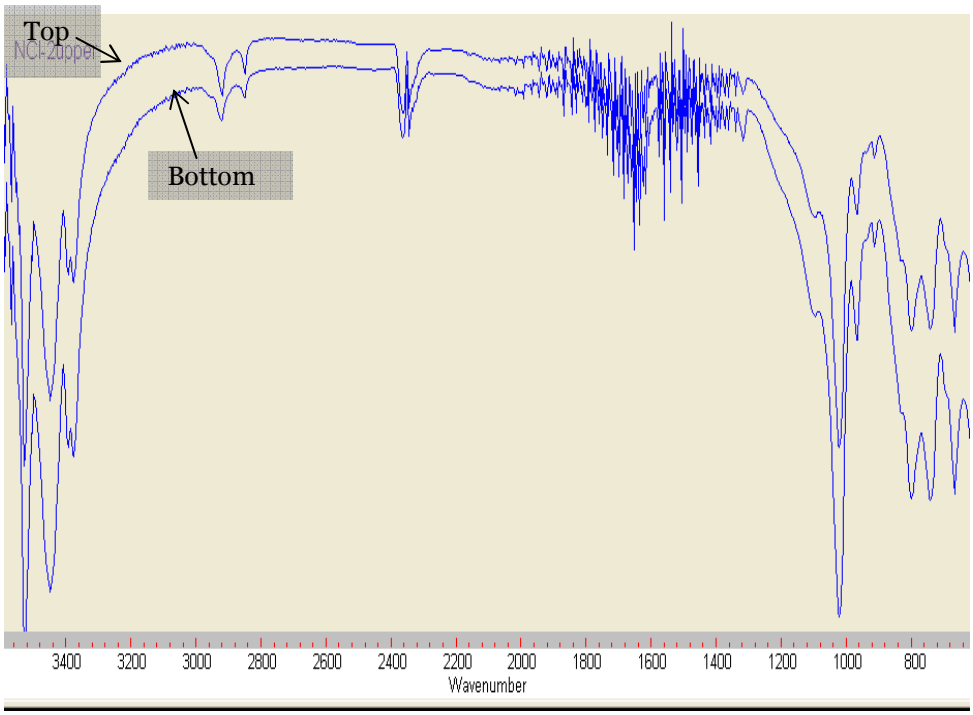


Figure 4.18 FTIR of NCI-2 depicting bottom and top surfaces' peaks

There was missing absorption due to *symmetric CH_3 deformation* in *Si-CH3* together with *$Si(CH_3)_3$* shown by Figure 4.19. Generally, the bottom of shed seems to have functional groups in excess to the top of shed.

This unavailability of *symmetric CH_3 deformation* in *Si-CH3* and *$Si(CH_3)_3$* indicate that the polymer is weakening. Availability of *carbonyl* and *hydroxyl* products indicates oxidation of the surface and leaching of the *ALTH* filler. However, those *virgin hydrocarbons* and *alkyl-silicone* functional groups indicate that this insulator still has its useful functional groups and has suffered little oxidation or chalking, and if possible can still be put outdoor. However, the *stretching backbone Si-O-Si* is a sign of increasing silica on the surfaces.

The crazing marks and light spots are the silica. It can be assumed that this insulator aged by UV and other factors at the HVL cupboards and then at the HVL yard.

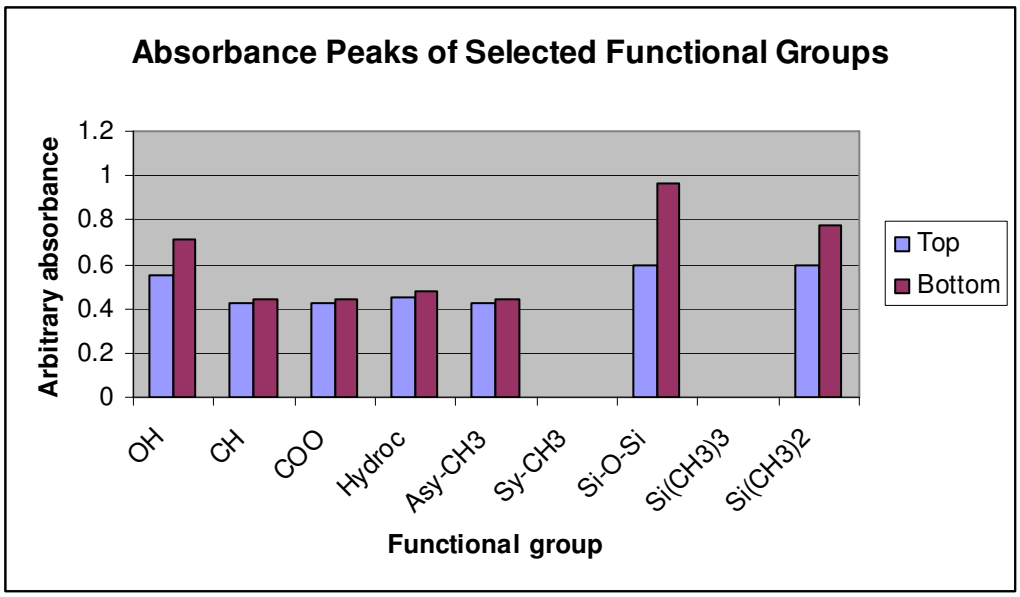


Figure 4.19 Relative presence of functional groups in top and bottom surfaces of NCI-2

4.3 Oxidation and Chalking Indices

Calculations of oxidation and chalking indices yielded **Figure 4.20**. The relationship portrayed is that *OI* and *CI* has a linear relationship. This argument is drawn from drawing a curve $y = x$ from the origin; then scatter plots of HVL-1 and M1 could be approximated by this curve, while on the other hand, the scatter plots of NC-2 and NCI-1 lie to the left of the said curve. The figure shows that insulator NCI-1 and NCI-2 have chalked more than oxidized, whilst HVL-1 and M1 (for both white and dark surfaces) have undergone equal amounts of *oxidation* and *chalking*. However, the surface of NCI-2 shows more *chalking* than NCI-1.

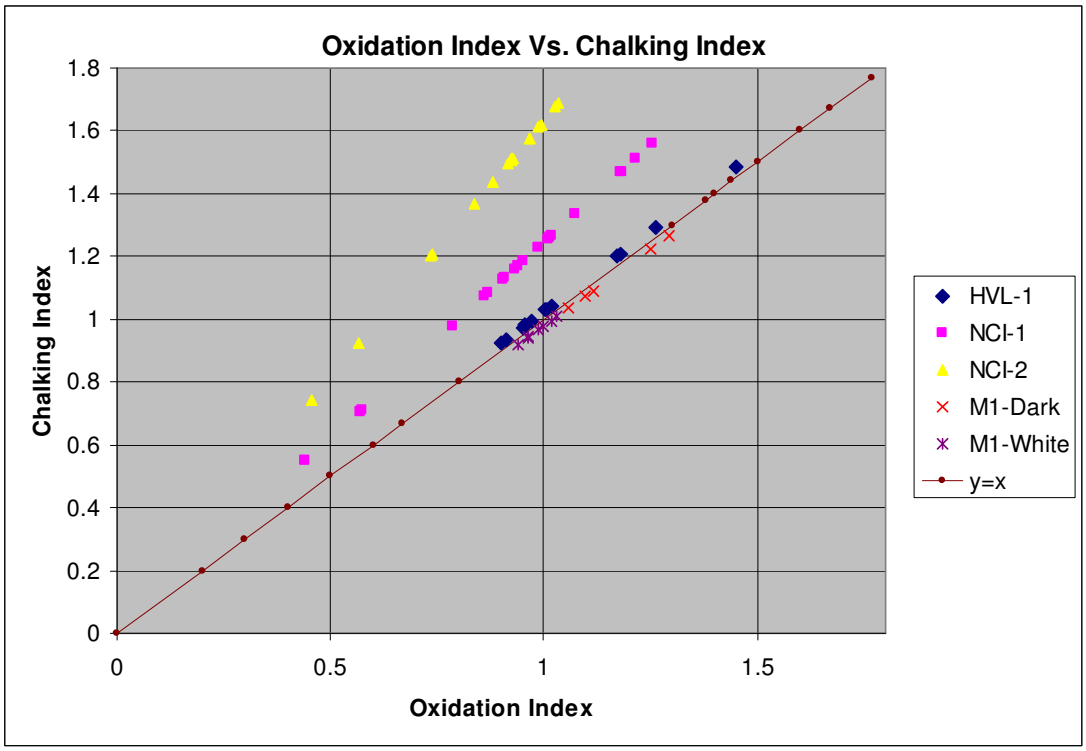


Figure 4.20 Scatter plots of oxidation and chalking indices of polymeric insulators

4.4 Conductivity of Insulators' Surfaces

SLM-9 layer conductivity meter gave results with scatter depicted in Figure 4.21. All insulators obtained from HVL showed correlations, except for a slight deviation by NCI-2. M1 deviated from other insulators by showing relatively high conductivity. This was due to layer of marine dust from Masaki substation.

The contamination obtained from the HVL yard is not detrimental to the functioning of NCIs proved by the low conductivity values. This proves that M1 flashed over in service due to the heavy contamination suffered leaving the surface with highly conductive layer. The highest conductivity values attained by M1 are from the dark spots and the areas with chalked surfaces. This is an indication that the contamination covering M1 is conductive and therefore detrimental to the insulator's earlier performance.

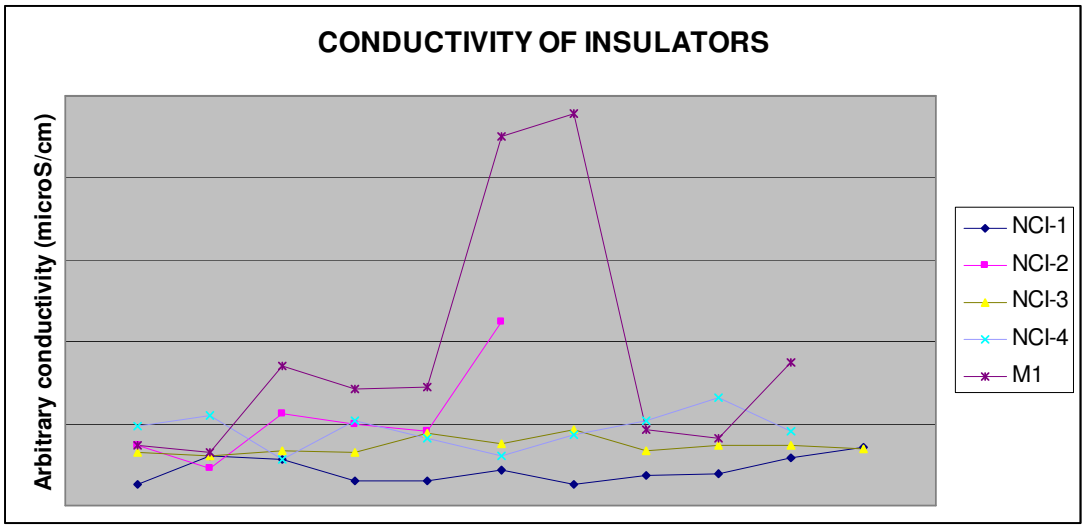


Figure 4.21 Conductivity of HVL and Masaki insulators

CHAPTER FIVE
DIELECTRIC CHARACTERISATION OF POLYMERIC FORMULATIONS

5.1 Surface Characteristics of Polymeric Formulations

5.1.1 Surface Resistivity

Surface resistivity values are given in log scale for resistivity values and linear scale for time values in order to accommodate very small values and very high values in the range $0 \sim 10^{17}$ (Ohm/square). It is worth explaining here that the units used are not SI units of surface resistivity rather, are units which are used for convenience of differentiating surface resistivity from surface resistance (Keithley, 2003a, 2003b; Maryniak *et al.*, 2003) since, both have Ohm as their standard unit according to dimensional analysis.

SIR materials surface resistivity values are summarized in Figure 5.1. These values were obtained by testing under ambient room conditions. Measurements of S2 resulted into higher and wider spread such that it is not presented here. The highest values were shown by SF1 peaking at 4×10^{18} *Ohm/square*. PS, SF2 and S482 displayed values close together peaking at 2×10^{17} *Ohm/square* with PS exhibiting slowly increasing resistivity values. S1 and S481 displayed lower resistivity values, which peaked at 7×10^{15} *Ohm/square* with no tendency for abrupt increase as others did.

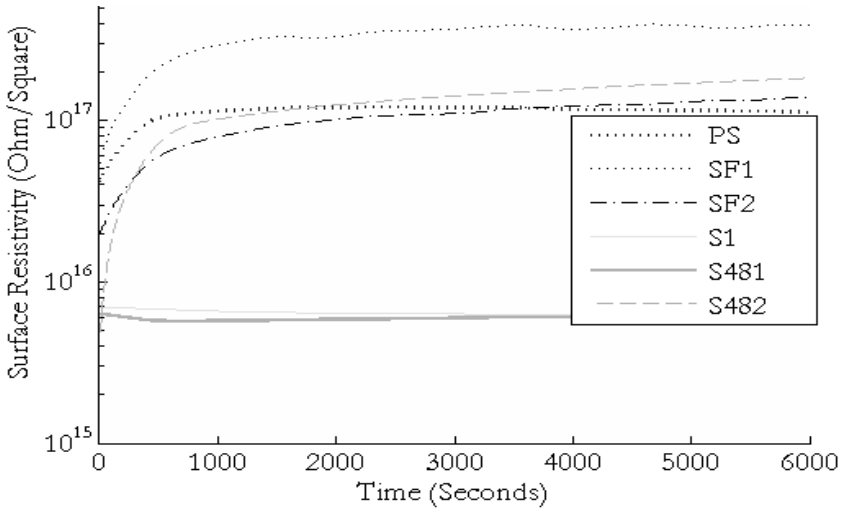
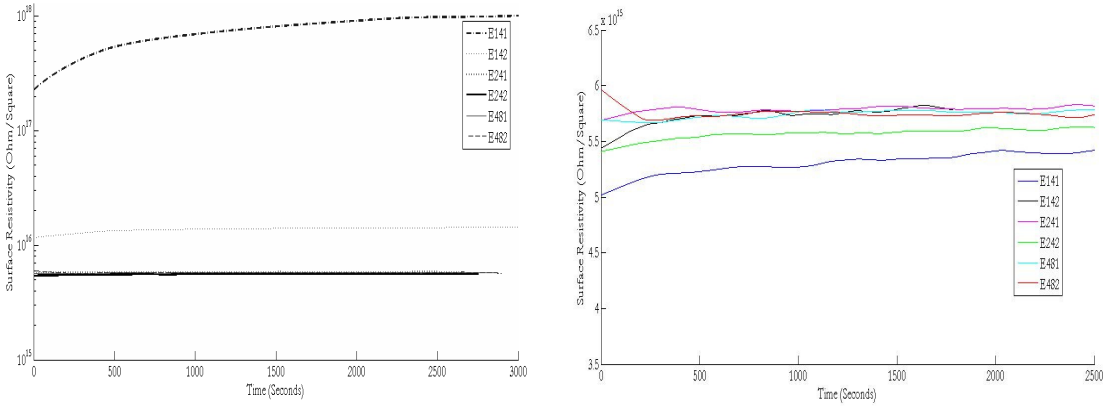


Figure 5.1 Surface resistivity of silicone rubber formulations at room ambient conditions

Surface resistivity results for epoxy resins are in Figure 5.2. The first figure displays the first measurements of which there is a bigger spread. After that, another set of measurements was done and the values are displayed in the Figure 5.2(b).



(a) (b)

Figure 5.2 Surface resistivity of epoxy resins formulations in room ambient conditions

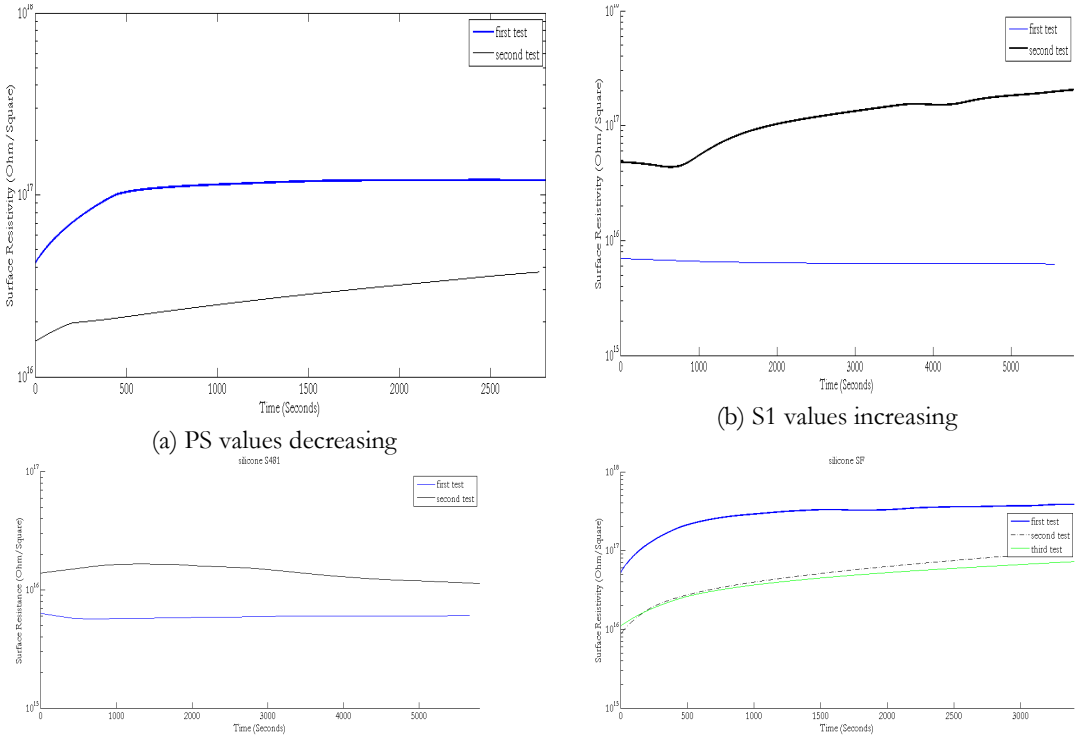
In Figure 5.2(a) highest values are shown by E141 peaking at 1 x 10^{18} Ohm/square with possibilities of increment. Its twin i.e. E142 followed suit peaking at approximately 1.5 x 10^{17} Ohm/square. The remaining i.e. E241, E242, E481 and E482 display values at approximately 6 x 10^{16} Ohm/square. After the conditioning and the other set of

measurements, resistivity values of epoxy formulations is shown in Figure 5.2(b) with small spread of results.

5.1.1.1 Repeating and Prolonging Resistivity Measurements

These polymer formulations exhibited memory effect by displaying different surface resistivity values on subsequent surface resistivity measurements. In order to show this some samples were subjected to repeated and prolonged measurements (for as long as 24 hours whilst their surfaces were kept dry). The discussion starts on silicone rubber formulations.

In SIR formulations effect of repeating surface resistivity measurements is in Figure 5.3, which displays one sample each from the SIR formulations. Silicone rubber delivered by manufacturers (PS and SF) showed decreasing values for the first two measurements in Figure 5.3(a) and (d). The third measurements for PS had negative values (which are undesired) at the beginning maybe due to interference. These values shoot abruptly from negative at the beginning to very high values and then came down close to those values of the first measurement. Since it would have produced a log plot with truncated values it is not presented here. SF1 did not show big spread in Figure 5.3(d). Its second and third measurements are shown by curves near each other.



(a) PS values decreasing

(b) S1 values increasing

(c) S481 values increasing

(d) SF1 values decreasing

Figure 5.3 Surface resistivity of silicone rubber formulations obtained from consecutive tests

It is different story for S1 and S481, which display increasing values in Figure 5.3(b) and (c). Both display a big spread of the order of a tenth between first and second measurements. It was not possible to get third measurements on these SIR formulations as values kept on fluctuating between very low values (close to zero or negative at times) and very high values (of the order of 10^{20} *Ohm/square*) which is out of the range of the electrometer used.

This characteristic of these polymer formulations showing very small values, negative values or high values was due to overflow occurring in the electrometer (Keithley, 2003; Keithley, 2003). This overflow is not given discussion here but in those references cited.

Another attempt was to subject the SIR formulations to dc voltage for more than 19 hours. Figure 5.4 presents the resistivity values obtained.

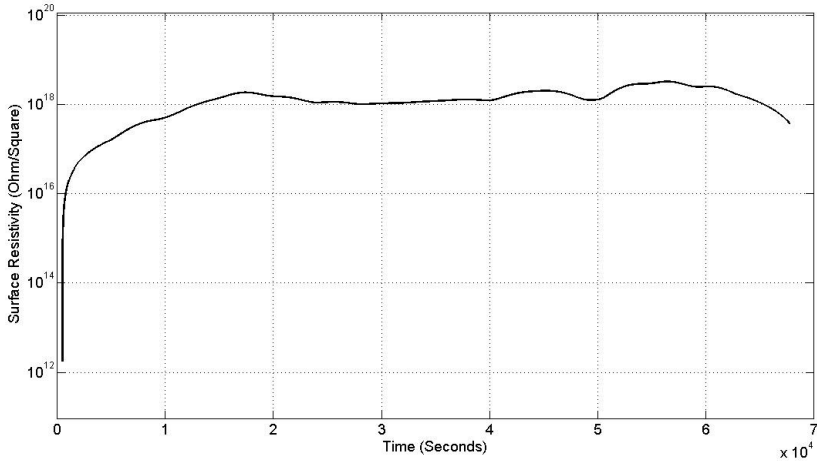


Figure 5.4 Surface resistivity of silicone rubbers when tested continuously for 19 hours in dry conditions

In figure 5.4 the surface resistivity kept on increasing for the first 3 hours until when it peaks at around 10^{18} *Ohm/square*. It is thought that maybe the values could have kept increasing if the limit of the Keithley meter was higher than that, because the charging continued to affect the surface. The reason for making the surface dry was to avoid possibilities that moisture could bridge the gap between the electrodes after such long time charging.

In case of epoxy resin formulations, effects of repeating measurements are in Figure 5.5. E141 and E142 are selected as model for all other epoxy resins, which showed same behaviour for re-testing. The second test was done more than 24 hours after the first test. The epoxy samples were allowed to rest in room ambient conditions for 24 hours before carrying out the second test. E141 is represented in Figure 5.5(a) with three test results. E142 is presented in (b) with two test results, the reason for missing one test was that the obtained data had a big spread with overflows. These epoxy resin formulations resistivity values kept on decreasing. With these results, it is argued that

epoxy resin reach very high surface resistivity values the first time of testing with a dc voltage application, but tendency to decrease as consecutive surface resistivity measurements are carried out.

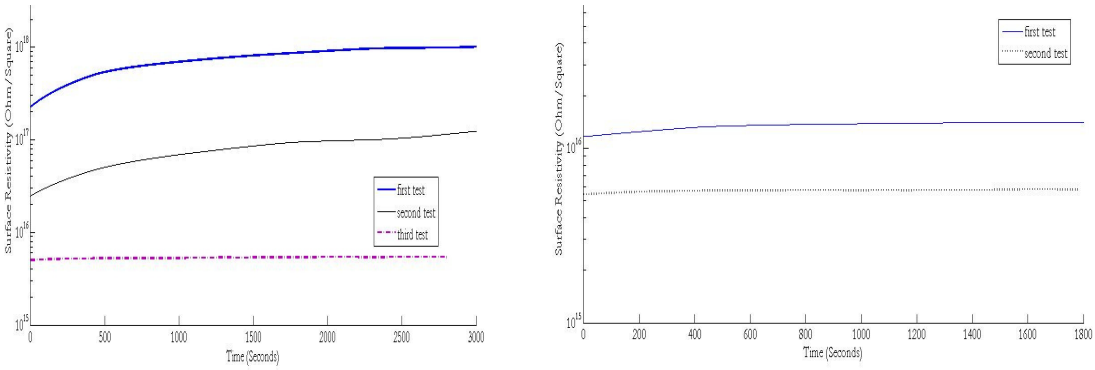


Figure 5.5 Surface resistivity of epoxy resin formulations obtained from repeating measurements

Prolonged application of dc voltage to the epoxy resin formulations displayed Figure 5.6. Testing conditions were as those of SIR formulations whereby the moisture was limited.

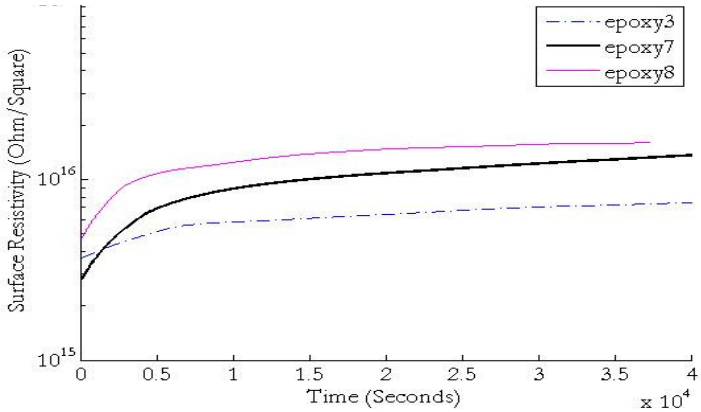


Figure 5.6 Surface resistivity of epoxy resin sample for a prolonged application of dc voltage

These results from three epoxy resin formulations show small spread. The highest values attained are of the order of 10^{16} *Ohm/square.*

5.1.2 Reflections on the Surface Resistivity Results

The main reason for differing values of laboratory made polymers is a contact problem between the ring electrodes and the samples. This means the manufacturing process could not guarantee perfect smooth surface such that there existed a gap between the electrode and sample. Another reason could be the electrodes affecting charge formation (Chen *et al.*, 2005) on the materials surface. Another reason is reorientation of the materials surface dipoles under the action of an electric field (Escribe–Filippini *et al.*, 2001). Inconsistencies in sample humidity, sample temperature, initial voltages, and other factors from such tests cause significant variability in results as explained in ASTM D257–99 of 1999 cited by Green *et al.* (2006). In addition, the neglected fringing effect had a role to play in results obtained.

5.2 Volume Resistivity Results

5.2.1 Summary of Epoxy Resin Results

Epoxy resin formulations had volume resistivity values with little scatter shown in Figure 5.7. This is an indication that for this type of commercial resin, the effect of cross–linking degree does not manifest itself in altering the volume resistivity results.

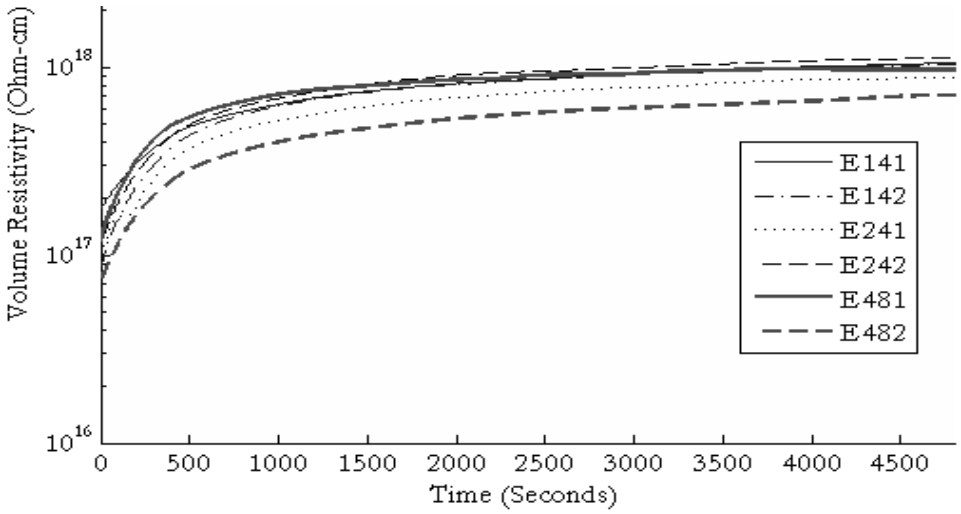


Figure 5.7 Volume resistivity of epoxy resin formulations

Peak value reached is of the order of *10^{18} Ohm-cm*, but there is no way of knowing if it could have increased beyond that since the instrument cannot sense such small currents.

5.2.1 Summary of Silicone Rubber Results

There was a big scatter between the volume resistivity values of silicone rubber formulations shown in Figure 5.8. Formulations that attained highest values are SF1 and SF2 peaking at *10^{16} Ohm-cm*.

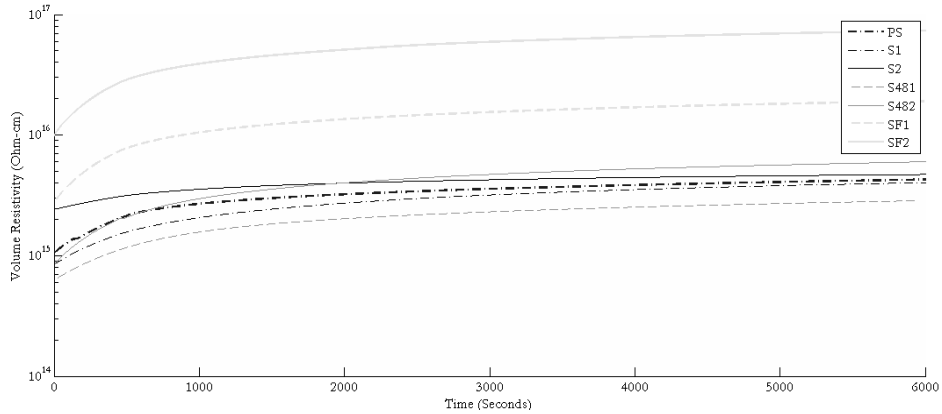
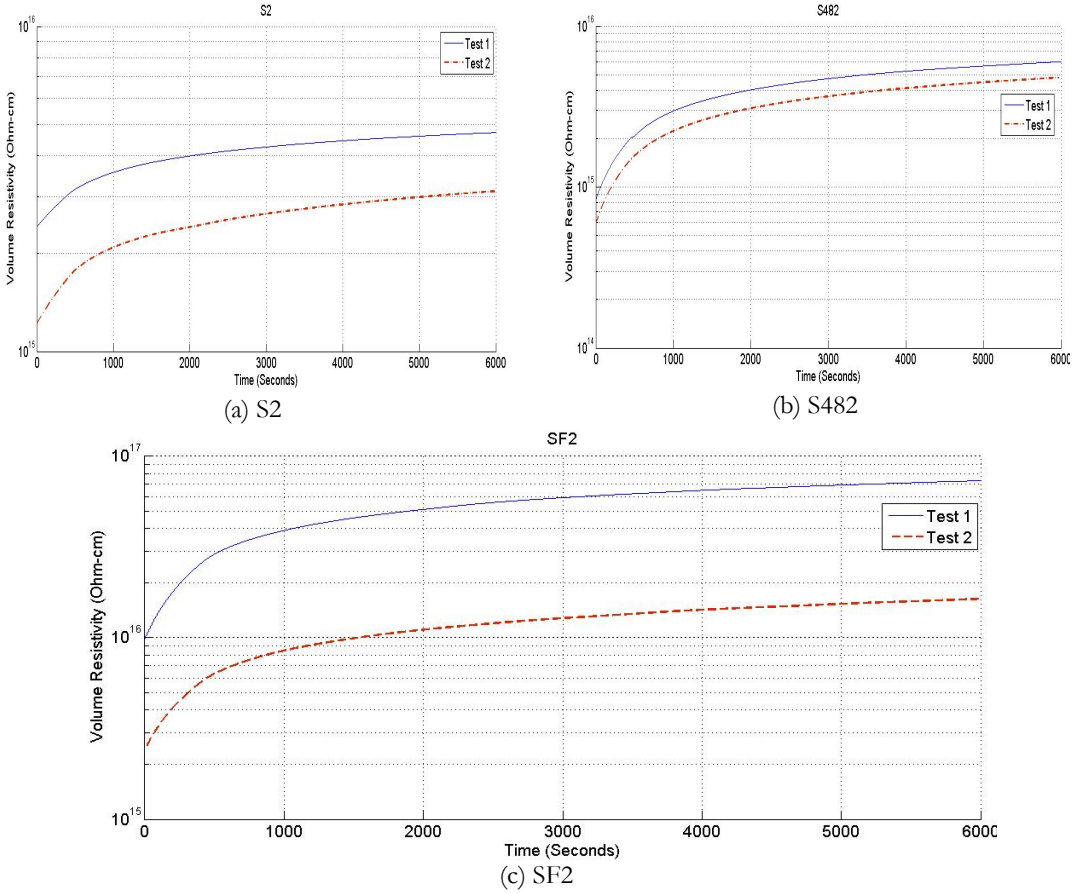


Figure 5.8 Volume resistivity of silicone rubber formulations

Nevertheless, other silicone rubber samples (S type and PS type) showed small scattering since their volume resistivity values were of the order of 10^{16} *Ohm-cm*. Possible reasons for formulations of type SF to have higher values is due to the nature of the added fillers in them.

5.2.1 Repeated Volume Resistivity Measurements

Repeating measurements on SIR formulations resulted into reduction of the resistivity values. Figure 5.9 displays such reduction of three selected samples S2, S482, and SF2. All three selected samples showed decreasing values from test 1 to test 2. Values of the first test were greater than values of second test.



(a) S2 (b) S482

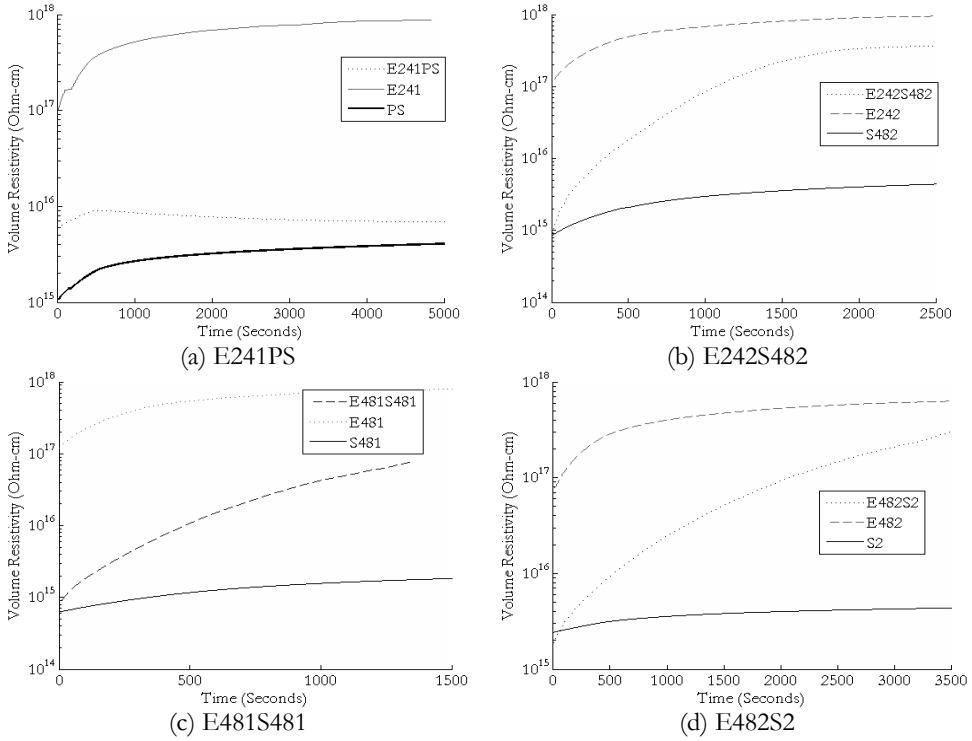
(c) SF2

Figure 5.9 Volume resistivity of silicone rubber formulations in repeated measurements

Epoxy resin samples showed similar behaviours in consecutive measurements of volume resistivity and it has been deemed not important to represent them again since it will be presenting the same graphs as in Figure 5.7.

5.2.3 Volume Resistivity of Series Joined Silicone Rubber and Epoxy Resin

When silicone rubber was combined with epoxy resin formulations, the observations are shown in Figure 5.10. There is a big spread observed between the epoxy resin, SIR and combination.



(a) E241PS (b) E242S482

(c) E481S481 (d) E482S2

Figure 5.10 Plots of volume resistivity of series combination of silicone rubber and epoxy resin

The resistivity values for the combination is between that of silicone rubber and epoxy resin. In the figure above is shown that epoxy resins have higher volume resistivity than silicone rubber, and than the combination of silicone rubber and epoxy resin. This could

be due to the closely packed molecules in epoxy resin making it harder than silicone rubber.

5.3 Summary of Resistivity Results

From all those resistivity measurements, it was possible to deduce the resistivity values shown in Table 5.1. These values are taken according to ASTM D257–93 for the *60 seconds* duration of applying dc voltage of *400 V*.

Table 5.1 Resistivity values of polymeric formulations

Formulation	Surface resistivity ($x\ 10^{15}$ Ohm/square)	Volume resistivity ($x\ 10^{16}$ Ohm-cm)
E141	5.13	18.4
E142	8.69	10.5
E241	5.98	10.0
E242	5.51	13.2
E481	5.71	14.7
E482	5.83	8.15
S1	7.01	0.0896
S2	1.70	0.244
S481	6.36	0.068
S482	15.2	0.095
SF1	27.3	0.301
SF2	18.3	1.07
PS	22.4	0.0976

These values are obtained by averaging values obtained around the sixtieth second. Surface resistivity values of all polymeric formulations lie in the range of 10^{15} to 10^{16}

Ohm/square. Volume resistivity of SIR formulations is lower than of epoxy resin formulations. This is due to the hardness of the epoxy resin.

5.4 Dielectric Loss Results

5.4.1 Single Polymer Results

Tan delta (dielectric loss) varying with frequency for silicone rubbers is shown in Figure 5.11 in which few silicone rubbers show tan delta peaks at frequencies close to *1 mHz* and a turning point close to frequency of 1 Hz (for laboratory prepared specimens) and *1000 Hz* (for industrial made specimens).

Shapes of the curves in Figure 5.11 of tan delta of S1, S2, S481 and S482 look like a loose **S–shape** depicting relaxations. S1 and S2 show peak values at frequency of *0.5 mHz* whilst all others do not, except for S481 and S482 which show a small peak close to frequency of *0.1 mHz*. PS and SF do not show peaks at low frequencies. Peak (tan delta = 1) is attained by S1 and S2 at frequency of *0.5 mHz*. S481 and S482 attains tan delta = 2.6 and tan delta = 1.7 at *1 mHz* respectively. SF1 attained tan delta = 0.4 and PS attained tan delta = 0.8 at *1 mHz*.

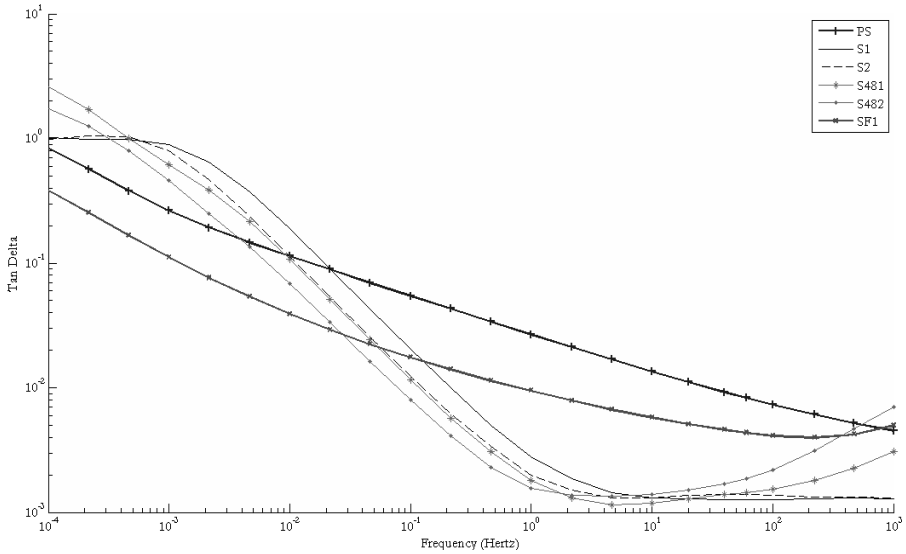


Figure 5.11 Tan delta of silicone rubber formulations

Dielectric loss of epoxy resin formulations are presented in Figure 5.12. Except for the lower frequency and the high frequency, all epoxy resins are exhibiting same characteristics regardless of their curing time and temperatures. They show higher frequency relaxations at same frequencies.

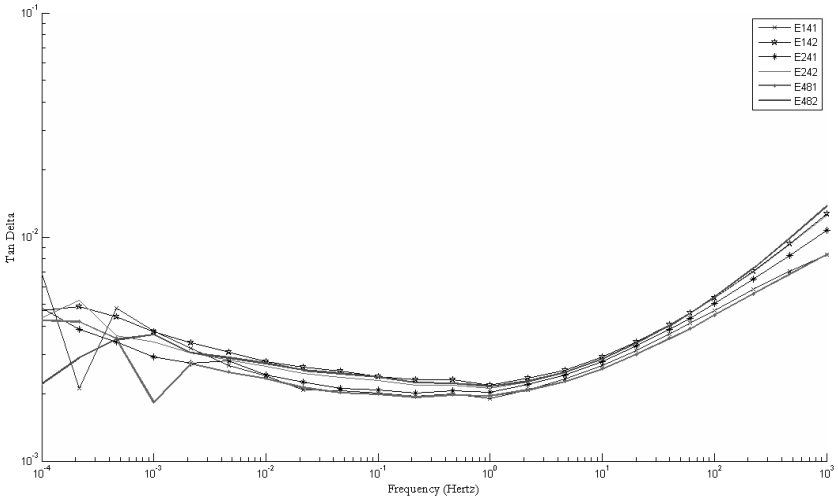


Figure 5.12 Experimental results of tan delta for epoxy resin formulations

The values of tan delta of E141 and E242 at low frequencies have values approximately equal to 0.002 at *1 mHz*. At *1000 Hz*, highest value is attained by E482 and lowest value is attained by E481. Lowest value is shown by E482 at *0.1 mHz* whilst E141 shows a highest value. For a few points along the curves, the following is observed: at *0.1 mHz* specimen with highest value i.e. tan delta = 0.006925 is E141 and specimen with the lowest value i.e. tan delta = 0.002214 is E482; At *1 mHz* values are between tan delta = 0.001838 for E481 and tan delta = 0.003811 for E141. At *1000 Hz* highest value is shown by E482 i.e. tan delta = 0.01378 whilst lowest value is shown by E481 i.e. tan delta = 0.0083553 followed closely by E141 i.e. tan delta = 0.0083697. Then there followed joining the SIR and epoxy resin formulations as discussed in following section.

5.3.2 Losses of Series Joined Silicone Rubber and Epoxy Resin

When the polymers were joined in series, the curves obtained are shown in Figure 5.13. All formulations have noticeable peaks except E241PS. Highest peak is shown by E241S481 at *1 mHz*. The curve of E241PS shows minimal tendency of turning at higher frequencies, whilst it shows increments at lower frequencies. The other specimens' curves peaks congregate between *0.8 mHz* and *1.4 mHz*. The specimen showing highest dielectric value is E241S481 at frequency of *1 mHz* at which the tan delta value is 0.11329. E142S2 follows with a peak of 0.009872 at a frequency of *0.046416 Hz*. E482S2 shows a peak at *1 mHz* of tan delta equal to 0.25574. At frequencies between *1 Hz* and *10 Hz*, all curves except that of E241PS are turning signifying the start of increasing losses at low and high frequencies called *low* and *high frequency relaxation*. The noticeable *relaxation* is observed at *1 mHz*.

Curve of E241PS behaves differently from others as it shows *relaxation* at around *100 Hz*. At *1 kHz*, the curve with the highest tan delta value is E482S2, which is tan delta equal to 0.010536, and the one with lowest value is E142S2 with tan delta equal to 0.0052393.

Due to their thickness of *3 mm*, SF1 and SF2 could not be joined in series to epoxy resin for measurements, since the total thickness would have exceeded the maximum thickness that the resistivity test fixture could hold.

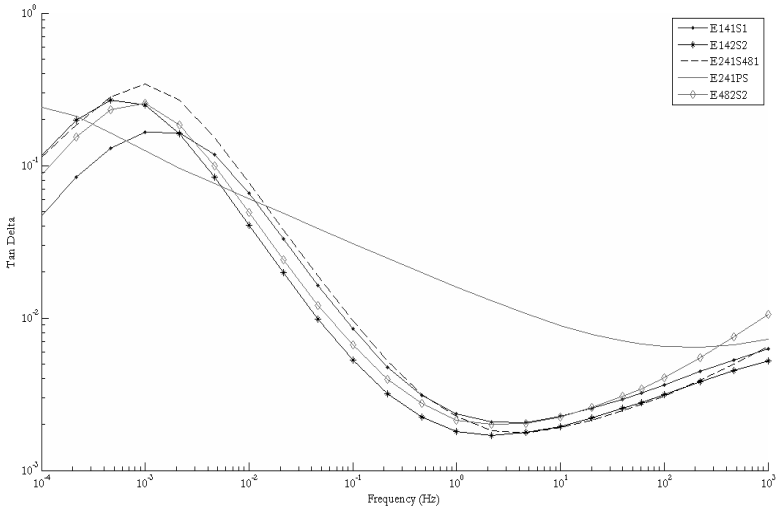
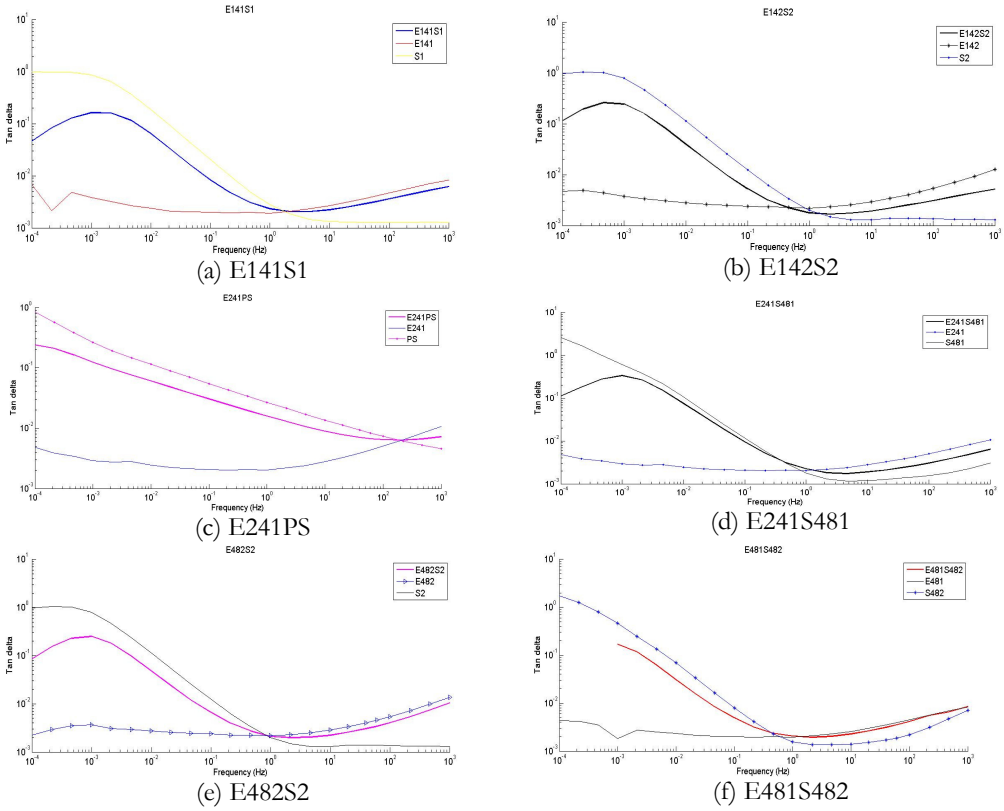


Figure 5.13 Tan delta of series joined silicone rubber and epoxy resin formulations

There after in Figure 5.14 is a display of losses of series joined silicone rubber and epoxy resin compared to those of their constituent formulations.



(a) E141S1 (b) E142S2

(c) E241PS (d) E241S481

(e) E482S2 (f) E481S482

Figure 5.14 Dielectric loss (tan delta) of single and series combined polymer formulations

In Figure 5.14, measurements on E481S482 were done for a shorter duration that is why its curve is shorter than the rest since it does not reach to *0.1 mHz* but only ends at *1 mHz*. *1 Hz* is the start of *relaxation* for of all curves except for Figure 5.14(d) where E241PS shows *relaxation* as the frequencies begin to decrease around *100 Hz*. It is seen that for frequencies higher than *1 Hz* silicone rubbers have higher losses than epoxy resin and the combination. Lower than *1 Hz*, the epoxy resins have higher losses than silicone rubber, and the combination.

CHAPTER SIX
EVALUATION OF THE THESIS

This chapter discusses challenges and achievements of this thesis. There were several challenges such as problems in getting proper instruments for research, few samples for the research and logistical shortcoming. These challenges made it fun to work on the thesis. At the end, the chapter gives achievements obtained.

6.1 Instrumentation Challenges

One challenge was to obtain some data as expected and proposed. This was due to:

1. lack of proper FTIR machine for material analysis;
2. lack of GC/MS gases for material analysis;
3. lack of LC measuring setup to assess field performance;
4. defective layer conductivity measuring device; and
5. lack of enough (in terms of weight) samples to determine ESDD and SDD.

Missing these important instruments and processes made it impossible to accomplish all the objectives of the project.

Blackmore *et al.* (1997, 1998) explained of difficulties in using FTIR instrument (*Digilab*) and proposed to extract material by a solvent and evaporate it to grind and make a KBr disc. It was not possible to do so here, so that is why for samples that were not brittle it was difficult to ground with KBr. The obtained IR spectra of the materials were not clear as the peaks were low and this made it difficult in discussing the results. The earlier objective was to cut small pieces of the sample and analyse them with ATR–FTIR as

done in Sundararajan *et al.* (2004), Gorur & Bernstein (1998b), Olave *et al.* (2006), Liu *et al.* (2004), and Blackmore *et al.* (1997) to mention but a few.

The layer conductivity measurements used an instrument that had undergone damage on the power supply side and possibly on the circuit board. It kept on giving varying values of the same point. This was used after cleaning the battery connections, drying, and carrying out a simple modification in the power supply.

The GC/MS instrument did not have helium gas (He) used in mass spectrometry. This hindered the measurements to quantify oxidation and crosscheck with the FTIR oxidation result.

In field and the HVL, the LC setup was not available thus preventing acquisition of LC data. This was an important data for the assessment of the electrical performance of the studied insulators. Therefore, this thesis relied on data from earlier researches.

6.2 Logistical Challenges

In the proposal stage, there was a plan for study tours to Sweden every year at a minimum of two times and attend at least two conferences. The study tours would have enabled to get literature and some courses, do practical and measurements. However, this was not the case; there was one study trip to Sweden in 2007 and one conference trip to Ghana in 2008. The study tour to Sweden saw the doing of laboratory research on dielectric properties of silicone rubber and epoxy resin formulations and getting literature reviews on polymeric insulation systems.

In addition, it was not possible to publish and attend ICIEA 2009 following an acceptance of the second paper due to unavailability of funds at the time. Thus, it prevented a wider dissemination of the findings at the mentioned international conference. In addition, this unavailability of funds hindered gathering of rainfall data (in 30 years averages) in order to determine RAF.

The above shortcoming was due to getting minimum research funds, which were not enough to pay for the data, transportation and upkeep allowances. Sometimes getting those few funds consumed time.

Another logistic shortcoming as described in section 6.1 involves instruments. Those mentioned instruments and processes were impossible to access in Tanzania. If a second trip to Sweden was possible, there was a possibility of using those facilities there. Further analysis of those expected results would have resulted into important outputs and significances to the electric power community. This was critical as it reduced the limited amount of results to be included in this thesis.

6.3 Data and Sample Challenges

Getting field insulator samples for testing was a problem. Some information obtained from the utility is that NCIs have not been used in Tanzania for a long time and that it would be difficult to help in case of needed data. In addition, the researcher missed some of the planned outages of the power system to undertake measurements of the

NCIs. This was due to poor coordination between the researcher and TANESCO personnel.

There was no reliable transport to move around Dar es Salaam and Coast Region collecting data since depending on the central technical services (CTS) vehicles was time consuming and ineffective. This resulted into NOT travelling to places like Musoma, Arusha, Singida, Dodoma and others where there are installed polymeric insulators, which are contaminated with lots dust and local soils. Due to this, it was not possible to collect enough larger dust samples, which could have given out the results of layer conductivity and identification of elements contained therein. The dust samples collected were small about 0.1 mg maximum for each insulator scraped. The measurements needed about 10 mg for each sample to study.

The failure to determine or develop the RAF was due to not having data of rainfall and temperature. It needed to have averages of temperature and rainfall for thirty years with the monthly minimums and maximums. To obtain such data meant incurring some costs, and since the same was not available, that exercise was futile.

6.4 Achievements

6.4.1 Field Investigation of Polymeric Insulators

After thriving through those challenges mentioned in section 6.1 to 6.3, it was possible to achieve writing up of the thesis and two conference papers. The thesis managed to

study and investigate field NCIs installed by local utility. This study reports that these insulators are operating satisfactorily.

The study established that the test NCIs in various sites are still operating smoothly, albeit heavily contaminated and damaged. Of those test insulators, one in Masaki substation failed in service. Material analysis by FTIR revealed that the insulator had oxidised, depolymerised and chalked but with good HC values. Those NCIs found in HVL had different HC values and some showed reduction of functional groups with increasing concentration of oxidation, silica layer and chalking. The *oxidation index* and the *chalking index* showed linear relationship.

6.4.2 Dielectric Characterisation of Polymeric Formulations

It was possible to characterise surface and volume resistivity, and dielectric losses of the formulations. There were identified electrode and dc polarisations dominating the dielectric response of the systems at these lower frequencies. In addition, the combination showed both low and higher frequency relaxations, which contained dc conductivity, electrode polarisation and hopping conductivity.

CHAPTER SEVEN
CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

7.1 Field Activities in Tanzania

7.1.1 Conclusions

Encouraged by the promising outcome of installed polymeric insulators, TANESCO has started installing NCIs at various feeders in Dar es Salaam, Bagamoyo and other places. All installed insulators are operating satisfactorily with no reported failures in service, although it was not possible to get them for testing. Importation of some EPDM was discontinued due to rodents finding them attractive in a warehouse where they began feeding on the same.

Test NCIs showed varying degrees of deterioration from visual observations, HC measurements and material analysis. At Kimara feeder, the test insulators were covered with thick green biofilm-growth, which was mixed with soot, and soil dust. Heavily contaminated insulator displayed good HC, while others poor. So far, there has not been reported an insulator related problem up to the writing of this thesis.

At Tazara feeder, the test NCIs were covered with soot and dust. Their service performance is still reported satisfactory. It was only possible to assess them by visual observations only.

At Ohio street feeder, the test NCIs are still in operation. As at Tazara, it was possible only to do visual observations, and there has not been any reported service failure.

At Masaki substation, the test NCIs are still in operation excluding one insulator that failed in service in 2008. It was replaced by a cap & pin insulator the same year. This insulator has burn marks and crazed surface. It showed high layer conductivity but with good HC values. Further material analysis showed that the burnt and chalked areas have undergone depolymerization and oxidation. The rest of the substation insulators are covered with red soil dust.

At Wazo Hill substation, the test NCIs with those installed by TANESCO are still good. It seems the cement dust offers a protective cover from UV and marine salts.

At Ruvu Chini substation, the test NCIs performance is satisfactory although they are covered by green algae. The old insulators are brittle and their sheds are broken, but still they are in service with no reported failure sporting good HC.

At Ras Kiromoni and Kunduchi marine cable link to Zanzibar there is marine salts attacks. This causes severe corrosion to the steel structure. The area could be earmarked for installation and study of NCIs.

At the HVL the test NCIs showed varying accumulation of dust which had low conductivity compared to that of Masaki NCI. These insulators sported varying HC values, with some showing deteriorating HC values while others maintaining HC values. In addition, material analysis showed some insulators had suffered from oxidation;

depolymerisation, chalking, and the rest are undergoing the same. One has broken sheds, which render it useless.

The chalking indices and oxidation indices sported a linear relationship between each other for all insulators studied. This suggests that aging factors causing oxidation would also prompt chalking and both occur at slightly different rates.

This study agrees with (Cherney, 1996; Shaowu *et al.*, 2001a) about severe pollution accumulation on the lower surface of these insulators' sheds occurring on several sheds close to the live end, because of the highly strengthened electric field. In addition, these lower sides were the ones screened from direct UV irradiation.

The successful service experience and the measurements/observations of hydrophobicity/pollution in the field prove the excellent pollution performance of majority of NCIs in Tanzanian climate.

7.1.2 Recommendations and Future Work

Since the field investigations proved the usefulness of the NCIs in Tanzania, the utility is urged to speed up the insulation upgrading from ceramics to NCIs. Other benefits realized with the use of these insulators are compactness of the line; reduced right of way for the transmission towers; and less – total life cycle cost.

Future field investigations could be continued by obtaining online monitoring tools to record surface temperature, FO activity, LC, pollution build-up and layer conductivity

on the surface of all NCIs in field. SPECIAL emphasis to be given to those test insulators supplied for the study, and FEW of those installed by the utility keeping in mind that the latter insulators are overdesigned (Notes, 2008). Another possible area of research is to perform *electrical impedance spectroscopy* on the field–aged insulators, since this method was adapted in Sundararajan *et al.* (2006) and gave good results about aging of 28 kV polymeric insulators. In addition, other investigative methods such as scanning electron microscopy (SEM), x-ray photo spectroscopy (XPS) and electron scanning calorimetry (ESCA) are useful in quantifying aging of NCIs.

In addition, the CoET especially Department of Electrical and Computer Systems Engineering could strengthen the cooperation with TANESCO. The aim is to encourage the utility to establish a R&D Department to follow up and implement these studies of pollution on polymeric insulators. In addition, the utility could borrow an advice from Cherney (1996) about using insulators with smooth profile; disk shaped sheds because they are ease to clean (naturally by rain and wind or by pressurized water) than the ones with the downward conical sheds.

7.2 Resistivity Measurements

7.2.1 Conclusions

These measurements expounded the idea of current through and across a dielectric material decaying exponentially. Results showed this behaviour following the application of dc voltage for duration longer than 1 minute. This was the case for both industrially prepared and laboratory prepared SIR and epoxy formulations. In addition, these

formulations showed memory effect. Laboratory prepared SIR formulations showed increasing surface resistivity values whilst those industrially prepared showed decreasing values of the same. The effect of repeating volume resistivity measurements was for the values becoming lower for all laboratory and industrial formulations.

For the case of epoxy resin, the surface resistivity results showed a decreasing trend for all materials albeit they cured differently, showing that the characteristics imparted were the same and all had memory effect. Their volume resistivity was the same regardless of previous testing.

One thing noted was that the samples had a tendency of retaining some charges inside them. Chen *et al.* (2005) explain this although in that paper, it was ac stress aging of polymers. In this work, if an energization of roughly 5 minutes was stopped and then continued later on, the material quickly reached the level of the previous value. This tendency implies polarization of the polymer surface by the dc voltage; and higher relaxation times of the polymers (Jonscher, 1999).

7.2.2 Recommendations and Future Work

Future studies could use more samples with different filler concentrations, aging them by different treatments and monitoring the resistivity values. In addition, quantification of charging, memory effect and the fringing effects due to the electrodes are important to investigate.

7.3 Dielectric Measurements

7.3.1 Conclusions

The higher losses in SIR formulations is explained by the higher ion motion in rubber under electrical field (Myślińk & Łazowski, 1993). The negative slope of log-log plot at lower frequencies is caused by the dc conductivity (Boudefel & Gonom, 2006; Ehsani *et al.*, 2007; Tuncer & Gubanski, 2000). The dielectric relaxation seen at lower frequencies can be related to the so called *'electrode polarization'* which is caused by the existence of a non-negligible conductivity seen in conducting systems such as ionic glasses or in some polymers at high temperatures (Boudefel & Gonom, 2006). Another possibility is polarization due to hopping conduction (Boudefel & Gonom, 2006; Desheng *et al.*, 2000; Tuncer & Gubanski, 2000; Capaccioli *et al.*, 1998; Myślińk & Łazowski, 1993; Nixdorf & Busse, 2001). However, it is needed to conduct further research to establish and pinpoint those polarizations for the said polymeric formulations.

Danikas (Ed.) discussed with Gorur & Orbeck (1992) about the influence of fillers in polymeric insulation performance. Mentioning several fillers e.g. *ALTH* and others, those which significantly strengthen the mechanical properties and the tracking resistance of silicone rubber as in (Suksri & Tonmitr, 2005). Nevertheless, on the other hand the permittivity becomes larger, which does not favour other aspects of the electrical behaviour of the insulator. (Danikas Ed. in Gorur & Orbeck, 1992; Suksri & Tonmitr, 2005) realized that functional performance of HV insulators relates to the long–term protection of the FRP rod, as well as the dielectric properties of the housing. It is therefore challenging to establish a simple relationship between the permittivity (as

well tan delta, surface resistivity and volume resistivity) of the housing material and the HV performance of a polymeric insulator under contamination. This is also a view of this thesis.

The results also proved that the performance of cured polymer housing is very much dependent on the manufacturing method of which the silicone rubbers made in laboratories differed to those made industrially; but the epoxy resins behaved the same since they were manufactured the same.

7.3.2 Recommendations and Future Work

In future, these dielectric measurements could be carried out on actual insulators in service and other samples could be conditioned (aged) in the laboratory. As an extension of the results analysis, a model of the aging materials could be determined with the help of fitting tools.

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APPENDIX A

PAPER A: presented in the *International Conference on Research and Development*, Kwabena Nketia Conference hall, Institute of African Studies, University of Ghana, Accra, Ghana, 25 – 27 November, 2008.

Surface Resistivity of Silicone Rubber Formulations Tested in Room Ambient Conditions: *The case of silicone rubber formulations with and without filler materials*

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Abstract: - Silicone rubber formulations in the form of thin discs have been studied under room ambient conditions for their surface characteristics. The samples were silicone rubber manufactured in laboratory and those industrially manufactured. The measurements were done using an electrometer high resistance meter, applying dc voltage under normal room ambient conditions. The results show that the silicone rubber samples show higher values of surface resistivity when the dc voltage was applied. Silicone rubber samples manufactured in laboratory seem to exhibit erratic behaviour unlike their corresponding silicone rubbers manufactured in industry; this could be due to manufacturing shortcomings in laboratory and the irregularities in the way the silicone rubber adhered to the concentric ring electrodes. The empirical

current traversing the surface of the silicone rubbers does not decay exponentially but rather it decays as an exponential power of the energization time.

Key-Words: - Silicone Rubber, Surface Resistance, Surface Resistivity, Surface Charging

1 Introduction

NCIs are increasingly being used in new power lines, which are installed in polluted environment as well as for replacements of installed ceramic and glass insulators during maintenance. The excellent performance of the polymeric insulators in polluted and wet conditions is attributed to the ability of the material to maintain the hydrophobicity of the surface in the presence of severe contamination and wet conditions (Gubanski *et al*., 2000; Zhang & Hackam, 1998). This is because of the presence of low molecular weight (LMW) mobile fluid in the bulk of the silicone and EPDM rubbers, which diffuses to the surface and to the above contamination layer. The diffusion process occurs when the outer film of LMW is removed in the presence of dry band arcing and then washed away by the rain. Polymeric insulators thus have a good surface hydrophobicity which suppresses the onset of leakage current and increase the withstand voltage. The electrical, physical and chemical properties of the surface of the polymer insulator become critical to its continuing satisfactory and reliable service throughout the lifetime of the insulator (Zhang & Hackam, 1998).

Other benefits of employing polymer insulators are their: resistance to weathering, excellent suppression of leakage currents, higher flashover voltage even

when wet and polluted, resistance to vandalism, higher puncture strength and the famous excellent hydrophobicity.

There has been extensive research on polymeric outdoor insulation (Chen *et al*., 2005; Dakin, 2006; Escribe–Fillipini *et al*., 2001; Gorur *et al*., 2001; Gorur *et al*., 2006; Gubanski *et al*., 2000; Jonscher, 1999; Thornley & Shocket, 1994; Zhang & Hackam, 1998) to mention a few, which has resulted into better materials for outdoor insulation which can resist worst environmental conditions (Gubanski *et al*., 2001; Zhang & Hackam, 1998; Gorur *et al*., 2006).

Despite these developments there are still many interesting phenomena worth studying which include surface resistance and resistivity, ageing of interfaces and change of dielectric properties of these polymer materials. Surface resistance measurements can be used as an indicator of polymer ageing in outdoor environment (Gorur *et al*., 2006; Gorur *et al*., 2001), despite the earlier problems to establish a specific value for which problems in field can occur (Gorur *et al*., 2001). Surface resistivity and surface resistance values are related by a simple factor of 50, which account for material geometry and electrode configurations of the electrometer probe, used (Keithley, 2003a, 2003b). These means that the values obtained in this study are for those silicone rubber when in room ambient conditions using concentric ring electrodes and energized by a 400 Vdc.

2 Sample Preparation

Test samples consisted of silicone rubbers, some of which were manufactured in laboratory and some were industrially manufactured. First type of sample of silicone rubber was prepared from a commercially available silicone elastomer. These

silicone rubber samples were in two groups; first group (sample S1 and sample S2) were cured at an oven temperature of 120 ˚C for 120 minutes and second group (sample S481 and sample S482) were cured at room temperature (22 ˚C – 25 ˚C) for 48 hours, see Table 1. Second type of sample of silicone rubber was a HTV silicone rubber (sample SF1 and sample SF2), and third type of sample of silicone rubber was a HTV silicone rubber (PS) used for insulator shed manufacturing delivered to the laboratory by the manufacturers. These variations gave silicone rubber samples with different characteristics, i.e. silicone rubber with no additives (S1, S2, S481 and S482), silicone rubber with additives (SF1, SF2 and PS) and different curing times and temperatures (see Table 1).

Table 1: Sample Manufacturing Parameters

Name	1st Curing time and temperature	2nd Curing time and temperature	Thickness
S1	120 minutes at 120 °C		1.0 mm
S2	120 minutes at 120 °C		1.0 mm
S481	48 hours at 22-25 °C		1.0 mm
S482	48 hours at 22-25 °C		1.0 mm
SF1	HTV rubber		3.0 mm
SF2	HTV rubber		3.0 mm
PS	HTV rubber		2.0 mm

For those silicone rubber samples manufactured in laboratory had thickness of 1 mm and those delivered by manufacturers had 2 mm and 3 mm as shown in Table 1. In addition, it must be noted the naming of the silicone rubbers has some letters and some numbers. The name contains information such as the type and the curing time. For example, sample S481 means it is a first sample made from an elastomer, which has been cured in laboratory at a room temperature of 22 – 25 °C in the duration of 48 hours.

2 Experimental

Surface resistivity measurements were carried out in room ambient conditions of 22 ˚C – 25 ˚C and relative humidity of 32% – 40%. Electrometer high resistance meter (Keithley model 6517A) supplied the test dc voltage of 400 V and sample was placed in a resistivity test fixture (Keithley model 8009) with concentric ring electrodes. The test voltage was applied for about 50 minutes. The Electrometer was used to display the instantaneous resistivity values but it was also connected to a desktop computer through a GPIB bus, which allowed data to be collected in a computer. The data sampling was done by using LABVIEW^{TM} software collecting data at an interval of 90 ms. Data analysis was done with the help of a MATLAB^{TM} software.

2.1 Data Analysis

Instantaneous surface resistivity values were having a big spread. Due to this it was deemed important to use linear regression techniques (Matlab, 2007) to smooth the data to obtain smooth curves when plotting. Each smoothed value was determined by neighboring data defined within a span of 15%. The process employed robust functions to make the resulting values resistant to outliers by using 1st degree polynomial function of linear least squares regression.

3 Results

Results from the experiments are presented in Fig.1 for the time variations of surface resistivity in first 50 minutes.

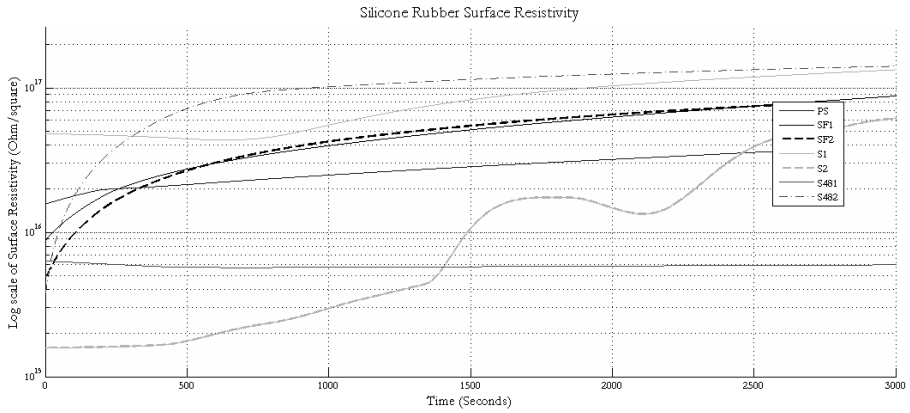


Fig.1: Silicone rubber samples surface resistivity variation with time for the first 50 minutes. The conditions of the test were room temperature, pressure and humidity i.e. temperature = 22 ˚C – 25 ˚C, humidity = 40 %.

It can be seen that surface resistivity values are given in log scale to accommodate very small values and very high values i.e. 0 ~ 10^{17} (Ohm/square) in horizontal axis of Fig.1. It is worth explaining here that the units given are not the SI units of surface resistivity rather, are units which are used for convenience of differentiating surface resistivity from surface resistance (Keithley, 2003a, 2003b; Maryniak *et al*., 2003) since, both have Ohm as their standard unit according to dimensional analysis.

3.1 Discussion of the Results

In the plots of Fig.1 silicone rubber samples resistivity values for the duration of 3000 seconds (50 minutes) is presented. Silicone rubber shows varying values of surface resistivity after the first 2 – 3 minutes (120 – 180 seconds) as seen in Fig.1. Samples S1 and sample S2 shows very different values from each other, since S1 shows a stable behavior but S2 shows an erratic behavior. It is seen that sample S2 had a lot of spikes even after smoothing the data. This could be due to the reason of

interference since during that time there was transformer measurements being undertaken in the same laboratory.

Samples S481 and S482 both shows stable but different values. S481 shows pretty stabilized values for the increasing time, whilst S482 shows a higher value but slowly increasing after 1000 seconds. Samples SF1 and sample SF2 both exhibit same curves. Sample PS exhibited behaviour similar to samples SF1 and SF2 although at a slightly lower values of surface resistivity.

The main reason for the differing values exhibited by samples S1, S2, S481 and S482 could be a contact problem of the electrodes, since the manufacturing process could not guarantee perfect smooth surface finish, and the rubber was very soft such that it could adhere to one part of the electrode and leave a gap on another part, for which case industrially made rubbers (SF1, SF2 and PS) showed some consistent behaviour with one another due to their smooth surface finish and hardness. Another thought reason could be caused by the electrodes affecting charge formation on the materials (Chen *et al*., 2005) and other reasons as explained elsewhere (Escribe-Fillipini *et al*., 2001).

3.2 Comparison with other Surface Resistance Measurements Results

From measurements it was possible to estimate the average value of surface resistance of the silicone rubber (see Table 1) for the first five minutes. Comparing results of this study with the resistance results of Gorur *et al*. (2001) measurements on full polymer insulators, the lowest values of surface resistance for the uncontaminated insulators are slightly lower than the values obtained in this study. This difference is due to the fact that for those measurements in Gorur *et al*., a stress

of 15 kV was used on full insulators while in this study only 400 V was used for disc samples.

4 Conclusion

One thing noted was that the samples had a tendency of retaining some charges inside them which could be a little explained elsewhere (Chen *et al*., 2005), although in that paper emphasis was done on ac stress aging; (Dakin, 2006; Jonscher, 1999) which explain about the charging of dielectrics. After energizing the material for roughly 5 minutes, if the energization process was interrupted and resumed later, the material quickly reached the level of the previous value. This tendency implies polarization of the samples by the dc voltage and higher relaxation times of the samples (Dakin, 2006; Jonscher, 1999).

If the energization was done for longer than 50 minutes the resistivity values continued to increase up to the point that the data obtained was not useful since the values became so high that the instrument generated overflow (Keithley, 2003a, 2003b). This has to be explained by the fact that the current measured becomes so low to be measured by our instrument (Keithley, 2003a, 2003b; Escribe–Fillipini *et al*., 2001).

From these results depicted by Fig. 1, it becomes obvious that the complex nature of the dielectrics studied; the empirical current that traverses the surface of the insulating materials does not decay exponentially but rather as an exponential power of the time as by equation (1) from (Dakin, 2006):

$$I = A_o t^{-n} \tag{1}$$

Until now it is still very difficult to establish the lifetimes of polymeric insulators in field (Gubanski *et al*., 2000; Zhang & Hackam, 1998) but the ongoing researches on the surface behaviour are promising. Consequently as done by Filippini *et al*. (2001); Gorur *et al*. (2001); and Gorur *et al*. (2006): square wave is used to characterize the surface resistance of fully polymeric insulators. It can be stressed out that the study of surface resistance and surface resistivity is a promising research area for both Materials Scientists and Electrical Engineers.

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APPENDIX B

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Dielectric Properties of Series Joined Silicone Rubber and Epoxy Resin Formulations

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***Abstract*–Dielectric frequency spectroscopy measurements of polymer materials were done in laboratory. The aim was to investigate the (1) differences in dielectric losses of the industrially prepared silicone rubbers against laboratory prepared silicone rubbers, (2) differences in dielectric losses for the epoxy resin samples prepared in laboratory, but with different curing time, and (3) differences of dielectric losses between each single polymer to the losses of the series joined specimens of the two polymers. The measurements were done using the Insulation Diagnostics System in laboratory at ambient room conditions. It has been found out that for different frequency ranges, silicone rubber prepared industrially differ with the laboratory prepared specimens. The series joined specimens show higher influence of the silicone rubber in both curve shape, and values of losses at frequencies lower than 1 Hz. At frequencies lower than 1 Hz, the joined specimen losses are higher than losses for epoxy resin and lower than those for silicone rubber. At frequencies higher than 1 Hz, the losses of the joined samples are close but slightly lower to those of epoxy resin and higher than those of silicone rubbers. Lastly, the curves of the joined specimens have shapes that strongly resemble those of the silicone rubbers with the outcome that the paper results are useful for industry applications.**

***Index Terms*–polymers, insulation, dielectric, relaxation, losses**

INTRODUCTION

Polymeric materials are gaining more usage worldwide in outdoor insulation systems; as a result, there are various researches, which have been undertaken to investigate their properties [1 – 6, 8 – 15, 17 – 18]. These researches have made it possible to have state of the art polymer insulators, which have been proved to be effective in transmission and distribution lines. Within these researches, dielectric properties investigation has had its fair share, since these measurements can tell the molecular, ionic and electronic states of the dielectric, which are vital for the effective performance of polymer insulator. Moreover these ongoing researches are important as diagnostic tools in investigating level of dielectric conduction in outdoor polymeric insulators [1, 3 – 6, 8, 12 – 15, 17 – 18], their molecular structures [9, 11, 13, 18], and detecting ageing effects [15] and surface properties. In this paper, dielectric loss tangent (or tan delta) of silicone joined in series to epoxy resin specimens have been investigated.

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