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A COMPARATIVE STUDY OF DC AND AC INCLINED PLANE TESTS ON SIR MICRO-COMPOSITE INSULATORS

A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfillment of the requirements for the degree of Master of Science in Engineering.

Sharif Faarah Kaaiye

Johannesburg, 2016

DECLARATION

I declare that this research report is my own unaided work. It is being submitted for the degree of Master of Science in Engineering in the University of Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

(Signature of Candidate)

---------- Day of -----February------- Year ----2016--

ABSTRACT

Presently, there is no test on evaluating the tracking and erosion resistance of DC polymeric insulators under contaminated conditions. Often researchers use a modified version of the widely used AC inclined plane test to evaluate the tracking and erosion resistance of DC polymeric insulators. The results obtained from these modified tests thus far have not been conclusive and show various inconsistencies. This research report presents results obtained from an experimental procedure of inclined plane tests of silicone rubber (SiR) insulation at 3.5 kV and 4.5 kV positive DC and AC using intravenous (IV) system as pollutant supply mechanism. The leakage currents were recorded for the duration of each test. In addition, physiochemical tests such as Fourier transform infrared (FTIR) analysis, Thermo-gravimetric analysis (TGA), scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) were performed on aged and un-aged samples. The findings are that the DC leakage current on the surface tracking activity is bigger (about 2 times) than that under AC for the same equivalent voltages. Furthermore, DC leakage current variations are less random and the average current increases with duration of voltage application compared to AC which doesn't increase with time. The inclined plane test results of 3.5 kV AC and DC are comparable as deduced from the physiochemical analysis of the test samples. Finally, the failure criteria under DC inclined plane test should only be the leakage current being less than 60 mA and should exclude the tracking length criterion as this would not apply for DC.

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LIST OF ACRONYMS AND SYMBOLS

AC	Alternating current
ATH	Alumina Tri-Hydrate
CTV	Constant Tracking Voltage
DC	Direct current
DTG	Differential Thermo-Gravimetric
EDS	Energy Dispersive Spectroscopy
FTIR	Fourier Transform Infrared
HTV	High-Temperature Vulcanizing
HV	High voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
IR	Infrared
ITV	Initial-Tracking Voltage
LC	Leakage Current
LMW	Low-Molecular Weight
RMS	Root Mean Square
SEM	Scanning Electron Microscope
SiR	Silicone Rubber
TGA	Thermo-Gravimetric Analysis

CHAPTER 1: INTRODUCTION

1.1 Introduction

For long distance electric power transmission systems, the high voltage direct current (HVDC) technology is considered to be the most attractive, both technically and economically. Since most of the problems in high voltage (HV) environments arise from dielectric complications, the need to have outdoor high voltage insulators, which are capable of maintaining high dielectric strength under all surface conditions is important [1]. Traditionally, ceramic insulators (porcelain and glass) have been the dominant insulators used for outdoor applications but these are now being replaced by non-ceramic insulators or polymer composite insulators. Polymeric insulators have lower weight, are easier to install and offer better electrical performance in moderate to heavily polluted environments. However, the organic nature of polymeric insulators means they are inherently susceptible to chemical changes and ageing [2-4]. Of all the housing materials of non-ceramic insulators for outdoor applications, silicone rubber (SiR) is the most reliable and widely used. The hydrophobic properties of SiR are superior to other polymer insulators [5-7]. Presently, the biggest challenge with respect to the performance of outdoor SiR insulators is the susceptibility to tracking and erosion degradation under contaminated conditions.

The IEC-60587 standard on inclined plane tests is a well-established technique to evaluate the tracking and erosion resistance of outdoor polymeric insulators used for AC applications but a similar test for DC applications has not been fully developed yet. The current practice in evaluating the quality of insulators for DC applications, is to use the AC inclined plane test procedure. Minor modifications in the standard, such as using the equivalent RMS voltage and increasing the creepage distance are implemented for the DC insulators [8, 9]. These modifications are done to try and account for the differences in breakdown dynamics between AC and DC fields. Over the past few years, a lot of studies on the inclined plane test under AC

and DC have been carried out but mostly on a comparative level and not adequately comprehensive. Furthermore, the relationship between electrical activity and chemical changes have not been adequately explored and documented. Consequently, there are no comprehensive guidelines on inclined plane tests under DC applications. The absence of a suitable testing technique to evaluate the tracking and erosion resistance of DC polymeric insulators coupled with the wide interest in HVDC long distance transmission all over the world, makes the development of DC inclined plane test, a priority research area. Therefore, the intention of this work is to experimentally compare and contrast AC and DC inclined plane tests on SiR insulators.

1.2 Study Rationale

The growing global energy consumption and the remote location of sustainable energy resources, makes long distance HVDC transmission an attractive option both from a technical and economic perspective. In addition, the emergence of renewable energy sources, producing DC output, has further necessitated the use of DC micro-grid systems. One of the essential requirements under these modes of power transmission is reliability. This implies the use of outdoor insulation materials which are capable of maintaining high dielectric strength under all surface conditions in general and in DC stresses in particular [1, 10].

Outdoor polymeric insulators are primarily based on SiR formulations due to their advantages over the traditional porcelain and glass-based insulation materials. Although there is a wealth of literature and standards on AC polymeric insulators, there is not yet an equivalent standard for testing polymeric insulators under DC applications and the current practice is to use and test the AC-designed insulators for DC applications [8]. The standardised test methods for outdoor polymeric insulators are (a) salt-fog tests (b) clean-fog tests (c) rotating-wheel tests and (d) inclined plane erosion and tracking tests. Of these tests, the inclined plane test is the least time-consuming and simplest test to rank insulators in terms of their suitability for outdoor polluted conditions. The inclined plane test was developed

for use of AC-designed insulators only and therefore modifications are necessary when testing insulators intended for DC applications. Presently, the same AC setup is used when testing DC insulators with the exception of DC voltage supply. The DC voltage is made equal to the RMS AC voltage. The same SiR insulators designed for AC applications are used under DC applications with minor modifications such as increasing distance. The implication is that the behavioural differences of identical materials under AC and DC voltages are not taken into account and therefore the relative results of the adapted DC inclined plane test is inconclusive. This has far reaching implications on the integrity of the DC insulators as there is no uniformly agreed methods of assessing the quality of DC insulators.

The AC inclined plane test standard specifies three RMS voltages and corresponding flow rates. The voltages are 2.5 kV, 3.5 kV and 4.5 kV and the corresponding flow rates in millimetre per minute (ml/min) are 0.15, 0.3 and 0.6 [9]. Generally, the RMS equivalent of DC voltage is used in the adapted DC inclined plane test [11-13] but there are studies that have used different voltages and/or flow rates. Rajini & Udayakumar [14] used 5 kV, Sarathi et al and Heger et al [15,16] used 4 kV, Mahatho et al [17] used 4.5 kV and 6.3 kV, Ghunem et al [18] used 2.25 kV for positive DC and 3 kV for negative DC, Bruce et al [19] used 2.25 and 3.15 kV for DC inclined plane test of both polarities. Moreno and Gorur [20] used 2.5 kV but with different flow rates (0.8 ml/min). Although the above researchers have their own well-intended reasons why the used a particular voltage for the DC inclined plane test, the unintended consequences are the addition of more confusion as to what is the best way of comparing AC and DC polymeric insulators with the aid of the well-established AC inclined plane test setup.

Another often overlooked, but yet, critically important parameter is the stiffness of the supply voltage. A weak supply voltage can greatly influence the results of the inclined plane test as there is a considerable voltage drop during discharges. This makes the results of the data collected under weak voltage supply unreliable and with little correlation to service conditions where the power is infinitely large and less susceptible to voltage drops during the occasional insulator arcing. The IEC-

60587 standard stipulates the testing of five samples either simultaneously or individually. It is, however, common practice and convenient to test five samples simultaneously [21-23]. Fewer authors [19, 21] tested one sample at a time while others did not specify whether they tested the samples simultaneously or individually [11-13, 16, 18, 24].

This research investigation is partly motivated by the need to contribute to the ever growing literature on the performance of DC polymeric insulators by comparing and contrasting it with the well-known AC polymeric insulators using the inclined plane test setup. The variables that are of interest are the leakage current, material weight loss and chemical changes.

1.3 Objectives

The objective of this research report is to compare and contrast the accelerated ageing characteristics of SiR insulation materials using the inclined plane test under AC and DC applications with the intention of contributing towards the development of a guideline for DC inclined plane test.

1.4 Research Report Layout

This report is divided into five chapters:

Chapter 1 gives a brief overview of the need and the role of HV insulators. The motivation of the project is also briefly discussed.

Chapter 2 provides a literature review of HV polymeric insulators, particularly SiR insulators. Factors affecting the ageing of polymeric insulators and its performance under HVAC and DC of both polarities are also presented in this chapter.

Chapter 3 presents the design of the test setup. The focus is mainly on the electrical design of the inclined plane test setup and the modifications that were made in order

to make the setup simpler and economical. Finally the method of testing and the equipment used for the experiments are presented in this chapter.

Chapter 4 contains the results obtained from the test. The results are presented in a comparative manner in terms of different excitation voltages and type. Analyses and interpretations of the whole results obtained in the experiment are also presented in this chapter. Finally, comparisons are made between the results of AC excitation and positive DC excitation.

Chapter 5 concludes the findings made in this work. Suggestions for future work related to this study are also proposed.

CHAPTER 2: A CRITICAL REVIEW OF THE LITERATURE ON INCLINED PLANE TESTS

2.1 Introduction

The relatively growing use of HVDC mode of power transmission calls for the need to address the reliability aspect and testing criteria of outdoor insulators. Although SiR insulators are generally accepted to have a superior electrical performance over the traditionally used glass and porcelain insulators [5-8], they are susceptible to degradation effects of tracking and erosion due to their organic nature. While there is a wealth of experience for AC inclined plane tracking and erosion resistance of materials, there is no standard yet or uniformly accepted assessment criteria for DC inclined plane test of polymeric insulators. The absence of a reliable method of testing DC polymeric insulators has caused much confusion and uncertainty as to the validity of adopting the AC inclined plane test for DC insulators and also its relevancy to service conditions. This research report, therefore, aims to contribute to the knowledge on DC inclined plane test with the hope of establishing a tailor-made guideline for DC inclined plane tests.

2.2 Background

The primary function of insulators in overhead lines is to mechanically support the conductors and electrically isolate the power – carrying conductors from each other as well as from the grounded towers [25-27]. The need for electrical insulation was first realised by the telegraph industry in the early 1800s followed by the low voltage DC generation of Thomas Edison in the late 1800s. After many trials of different insulating materials, glass and porcelain eventually became the preferred choice of electrical insulating materials [28-29].

As application voltages increased in the early 1900s, ceramic insulators became heavier and more expensive to install and maintain. In addition, pollution and

humidity greatly affects their performance. In wet and polluted conditions, a continuous conductive film forms along the creepage path of the insulator, resulting in the flow of high leakage current and under adverse weather conditions this could lead to a complete flashover and power failure [29- 30]

Due to the above limitations in ceramic insulator technology, trials of polymeric insulators were carried out in North America and Europe in search of lighter weight, solid insulation material with better electrical and mechanical characteristics. The first trials of non-ceramic insulators were in 1960s but it was not until 1970s that commercial use of non-ceramic insulators was made available [28, 30]. Reviews by Reynders et al [31] and Gubanski [32] stated that, at the beginning, composite insulators encountered several problems, such as tracking, erosion, brittle fracture, loosening of end fittings and poor bonding between the core and the shed material. This was largely due to bad design, poor quality control and incorrect material. Except for tracking and erosion under polluted conditions, as well as problems in very hot and sandy environments, most of the other problems have been eliminated.

Tracking is the development of carbonised conducting channels that cause irreversible loss of insulation properties. Erosion is also an irreversible non-conducting degradation of material loss through physical loss of carbon or in the form of gases [33]. Experiences have shown that most of the failures of the SiR housing materials are due to electrical activities, which take the insulator to its end of life, a process known as ageing [33]. When the surface of the SiR housing is aged it allows the flow of leakage current, which manifests itself as tracking and erosion of the insulator. If the conditions are favourable for the development of high leakage current, this would lead to a complete insulator failure.

2.3 Ageing Mechanisms of Silicone Rubber Insulators

The surface of outdoor insulators deteriorates over time and the mixture of contamination and moisture serves to lower the surface resistance. The water repellence property of SiR, known as hydrophobicity, suppresses the development

of leakage current under normal operation but this property can be lost in heavily polluted locations. When a conductive pollution layer sets on the surface of SiR in the presence of electric field, leakage current begins to flow heating up the surface and parts of pollution layers starts to dry. Due to the non-uniform heating effect, areas of high resistance, known as dry-bands (DB) are formed and this interrupts the flow of leakage current. If, however, the resistance of the unbridged portion of the pollution is not high enough, more dry-bands may follow and the subsequent increase in local field gradients across the dry-bands causes localised arcing. Consequently, temperature increases and ionized plasma is formed. The temperature generated due to repeated dry-band arcing can reach beyond the safe limit of organic material, namely 400 °C. If the temperature exceeds beyond this limit, it can lead to tracking and erosion [23, 34-35].

It is widely accepted that the pollution flashover voltage of DC is lower than its AC counterpart as shown by various researchers [12, 16-17, 19-20, 36-38]. Greater attraction of the airborne pollutants on the insulator surface due to static charge and the absence of the zero current crossings contribute to the lower DC flashover voltage [12, 36]. Due to the larger number of parameters associated with the DC ageing of composite insulators, the associated basic ageing mechanism is not fully understood. Some of the parameters that determine the DC flashover voltages are the polarity of the voltage, the type and nature of the contamination, non-uniform wetting, particle size, surface conductivity, wind, washing, orientation, length, diameter and profile of the insulator [36].

In the design and development of outdoor polymer based insulators, it is necessary to conduct a type test where the quality of the insulation material is evaluated through an accelerated ageing test that simulates severe operational conditions. In the case of insulation in AC systems, an inclined plane test method has been devised and standardised as described in the next section.

2.4 Conventional AC Inclined Plane Test Method

The inclined plane test method, outlined in the IEC-60587 [9] standard, is used to evaluate the resistance of polymeric housing insulators to tracking and erosion under AC voltage in the presence of surface discharges due to pollution. A rectangular test sample with dimensions of 120 mm x 50 mm and a thickness of approximately 6 mm is mounted on a support stand, which is inclined at 45^{o} to the horizontal with the test surface facing downwards. The insulation surface is then polluted with a liquid contaminant, which flows (drips) from the HV electrode at the top of the sample to the ground electrode at the bottom of the sample. The application of a test voltage causes leakage current to flow along the contaminant path, which causes electrical discharges and subsequent tracking and erosion of the material.

The constant tracking voltage (CTV) and stepwise tracking voltage, also known as initial tracking voltage (ITV) are the two standard procedures used in the inclined plane test method [9]. In the CTV method, a constant voltage and a specified flow rate as per the standard is used for six hours or until the insulator fails. Since both the voltage and contaminant flow rate are constant in this method, it is also referred to as time to track method and materials are ranked according to the highest voltage withstood by all the samples for 6 hours without failure. In the stepwise tracking method, a lower initial voltage is selected first and then incremented by 250 V in every hour for six hours or until failure is established. According to the ITV method, the test specimens are classified according to the highest voltage withstood by all the samples in 1 hour. In both methods, the failure criteria is the same. The end-point criteria as given in the IEC-60587 standard [9], are when the current exceeds 60 mA for 2 to 3 seconds or the surface track, measured from the ground electrode reaches 25 mm. Furthermore, in both cases, the test is terminated if a hole develops through the insulation due to erosion or the sample ignites. In the absence of the above failure criteria, the material is accepted as having passed the test [9].

The inclined plane test is performed using higher voltage gradients in the range of 1.2 kV/cm; well above the normal operating levels of 0.2 to 0.3 kV/cm for outdoor insulators in service. Another accelerated ageing agent is the high conductivity salt solution. Such intense pollution is normally experienced in the coastal locations. It is therefore, widely accepted that any insulator that passes this accelerated ageing test will perform well in polluted environments [2, 23]. AC inclined plane tests have proven to be useful in characterising the quality of outdoor SiR insulators. It is desired to have similar test procedures for DC SiR insulators as presented in the next section.

2.5 DC Inclined Plane Tests

The inclined plane test is currently standardised for AC applications and a similar test for DC has not yet been developed. In developing DC inclined plane tests, the same setup of AC standard is used but with DC as the supply voltage. The DC voltage magnitude is made equal to the RMS AC voltage such that measurements are comparable. As expected, the adapted DC inclined plane test has been found to be more aggressive. Furthermore, the correlation between the accelerated ageing and normal field ageing has not yet been established. Some of the other challenges of DC inclined plane tests are conflicting experimental results regarding the polarity effect. There are some studies [16, 19] that show the highest erosion, mass loss and subsequent failure at positive DC. While under the CTV method, negative DC was reported to have the lowest performance in terms of the tracking time [15, 17]. Table 2.1, summarises the results in the literature of the inclined plane test under AC and DC applications. It should be noted that the results from the literature presented in Table 2.1, are those that compared the performance of SiR insulators under AC and DC voltages and those that use DC voltages only. Therefore, papers that only used AC excitation were not considered.

Table 2.1: Summary of the inclined plane test results.

Researchers	**Voltage Magnitude and Type**	**Leakage Current (mA)**			**Mass Loss (g)**			**Time to Track (minutes)**			**Testing Method**
		AC	+ve DC	-ve DC	AC	+ve DC	-ve DC	AC	+ve DC	-ve DC	
Vas et al [11]	±2.5 kV DC	___	9	4.4	___	0.7	0.1	___	___	___	CTV
Heo et al [12]	4.5 kV AC & ±4.5 kV DC	___	___	___	0.3	2.9	1.4	360	45	76	CTV
Raji. & Ud [14]	5 kV AC & ±5 kV DC	20	15	25	___	___	___	___	___	___	CTV
Sara. & Ch. [15]	4 kV AC & ±4 kV DC	___	30	40	___	___	___	353	353	225	CTV
Heger et al [16]	4 kV AC & ±4 kV DC	11	13	8	0.1	3.4	0.1	___	___	___	CTV
Mahatho et al [17]	4.5 kV AC, ±4.5 kV DC & ±6.3 kV DC	___	48	27	___	___	___	___	___	___	CTV
Bruce et al [19]	2.5 & 3.5 kV AC, ±2.25 kV DC & ±3.15 kV DC	___	14.1	7.2	___	1.3	0.2	___	___	___	CTV
Ghun. et al [37]	+2 & -2.5 kV DC for ITV, +2.25 & -3 kV DC for CTV	___	12	4.5	___	___	___	___	___	___	CTV/ITV
Ghun. Et al [39]	3.25 kV AC, +2 kV DC & -2.5 kV DC	4.7	6.7	4	___	___	___	___	___	___	ITV
Comments	A variety of test voltages that are not specified in the IEC-60587 standard were used.	Generally, +ve DC leakage currents is highest, followed by –ve DC and then AC.			Mass loss is lower at AC than DC. Positive DC has a higher mass loss than negative DC.			Time to track is longest for AC than for DC.			Common method used is the CTV.

From Table 2.1, it is clear that there is no consistency in the way the experimental data of the inclined plane test is captured and reported. Generally, leakage current, mass loss and time to track or failure are the parameters used by researchers to assess the quality of SiR insulators using the inclined plane test setup. However, these parameters are not uniformly recorded according to the above table. Out of the nine researchers referenced in Table 2.1, none of them conclusively and consistently reported the leakage current, mass loss and whether the insulator passed or failed the test as well as the time to track as stipulated in the IEC-60587 standard. Furthermore, there was no conclusive correlation of the material loss and leakage current to the quality of the insulator.

Another observation made in the literature was that the results are presented in relative qualitative terms (either 'higher', 'lower or better') and not on absolute quantitative values. As an example, [11] reported SiR insulators perform better under negative DC as compared to positive DC, [12] stated that the surface temperature of SiR Insulators under AC decreased faster due to the contamination solution whereas, under DC, local arc was fixed at the ground electrode and caused greater material loss. The magnitude of the leakage current was not given in [12]. In other studies [14, 17 37, 39] only the magnitude of the leakage currents were reported and no indication of the associated mass loss were given except to say; the tracking resistance was low for positive DC and much lower for negative DC [14], the AC samples showed minimum erosion, the negative DC showed greater erosion than the positive DC [17] and finally, [37] reported earlier failure under negative DC compared to positive DC but observed stable discharge activity under positive DC.

On the other hand, [39] concluded that SiR samples under positive DC performed the worst followed by negative DC and then by AC. The findings by [14, 17, 37] stating that the SiR insulators under positive DC performed better than negative DC is contradicted by other findings in the literature [11, 12, 16, 19, 40], which showed that positive DC is more severe and caused greater material damage than a corresponding negative DC.

From the above literature, it can be concluded that not only is there no systematic consistent methodology of conducting the inclined plane tests of SiR insulators but also the results are presented in vague terms such as ‘better’, ‘higher’ and ‘low’. This is further convoluted by the fact that many researchers [15-19] used different voltages than what the IEC-60587 standard calls for in carrying out the inclined plane test of polymeric insulators.

However, what is currently known and consistently shown by the above literature is the severity of the DC inclined plane test when compared to AC in terms of leakage current magnitude and the subsequent material damage it caused. What is not known on the other hand and still yet to be quantified, is the degree of the DC severity compared to AC. Consequently, different researchers proposed different equivalent DC voltages of the corresponding RMS AC voltage. Ghunem et al [8] suggested that positive and negative DC initial tracking voltages of SiR insulators to be 66% and 85% of the corresponding AC voltages respectively. In another study by Bruce et al [19], it is found that the equivalent DC inclined plane test level to be 90% of the corresponding AC. In addition, Bossi et al recommended that the DC flashover voltages of SiR insulators be made equal to 0.75-0.85 of the corresponding AC [41].

The scattered and disorganised nature of the available literature on DC inclined plane test of SiR insulators, makes the task of forming a guideline a multifaceted one. Especially the use of unregulated voltage sources and the inconsistency of using different parameters to compare AC and DC SiR insulators present some challenges in terms of reliability and reproducibility of the test results. Furthermore, such un-restructured use of the inclined plane test standard will only serve as a source of more contradiction as the one seen in Table 2.1 regarding the polarity effect of the DC voltages and the use of different DC voltages for the same RMS equivalent voltage. Selection of consistent equivalent DC voltages in the inclined plane test is a crucial aspect of the test outcomes. A higher DC voltage may lead to a rapid failure of the test specimen and a lower DC voltage may not provide enough energy and dry band arcing. Finally, it is noted that most of the work on the inclined plane test of SiR insulators is done using the constant tracking voltage (CTV)

method as opposed to initial tracking voltage. This is purely informed by the simplicity of the CTV as there is no need for continually varying the source voltage and thus requires less inspection.

2.6 Problem Statement and Research Question

There is not yet a comprehensive method in the form of inclined plane test to evaluate the quality of outdoor HVDC polymeric insulators. Currently, efforts are towards modifying the AC inclined plane test so that it can be used for DC insulators. Therefore, it is the intention of this research to contribute knowledge on the ongoing endeavours towards establishing initially a guideline and ultimately a standard for DC inclined plane tests. The test results of this work will be compared and contrasted with similar tests as published in the literature, in order to answer the following question: *how can the quality of DC SiR insulation be evaluated in the same manner as that of the well-established AC inclined planed tests?*

The next chapter presents the test and measurement procedure of the inclined plane test experiments for AC and DC SiR insulators.

CHAPTER 3: TEST AND MEASUREMENT PROCEDURE

3.1 Introduction

The inclined plane test outlined in IEC-60587 standard is a well-established test for evaluating the resistance to tracking and erosion of insulating materials. The evaluation of the resistance to tracking and erosion of the insulating material is achieved by using a liquid contaminant which drips on an inclined plane test specimen. Generally a peristaltic pump is used to get the desired contaminant flow. In this investigation, an inclined plane test setup that does not use a pump was designed and implemented. Modifications of the conventional system were done with the intention of making the setup cheaper, simpler and more reliable than the generally used inclined plane structure that uses peristaltic pumps. The design avoids use of electromechanical pumping systems by instead using intravenous drip (IV) schemes. The flow rate is governed by gravity and can be regulated by the valve control of the IV drip system.

A maximum of five samples of both AC and DC voltages can be tested with this scheme. The samples used are commercially available, micro-filled, outdoor high temperature vulcanising (HTV) SiR insulators. A 4.5 and 3.5 kV AC and positive DC voltages were used to compare the performance of outdoor SiR insulators. The physical damage in terms of tracking and erosion, leakage current, weight loss and chemical analysis of the samples were the chief parameters that were evaluated in this research.

3.2 Flowchart of the Data Collection Procedure

Measurement of leakage current in conjunction with material analysis and visual observations were the main parameters used to evaluate the performance of SiR

insulating materials in this work. A flowchart of the procedure used in the data collection phase of the experiment is shown in Figure 3.1. The IEC-60587 standard stipulates the testing of five samples either simultaneously or respectively [9]. In this research, all five samples were connected in parallel and one sample at a time was tested to study the reliability of each method and its conformity to the standard.

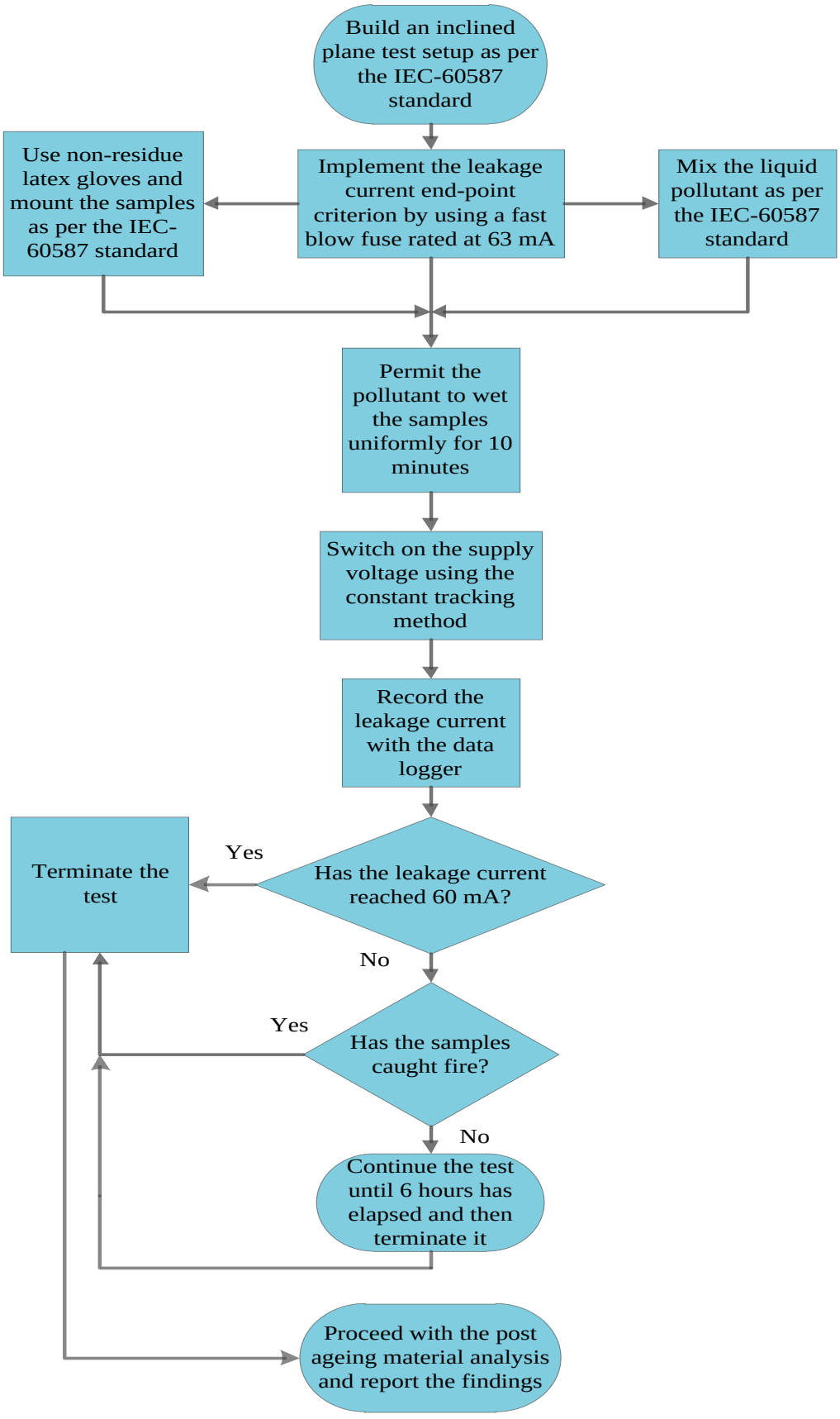


Figure 3.1: Flowchart of the test procedure.

3.3 Inclined Plane Test System

The IEC-60587 inclined plane test was developed to evaluate the resistance of AC polymeric housing insulators to tracking and erosion and it has become a widely used tool both in the industry and in research environment, due to its conveniently short time duration to rank materials that are suitable for field applications. The inclined plane test setup uses a liquid contaminant on inclined plane test specimen. The inclined plane test is designed to accelerate ageing by encouraging the formation of dry-bands and surface discharges in order to monitor surface erosion and tracking. A single line diagram of the test setup used in this research report is shown in Figure 3.2. The system consists of the supply voltage, current limiting resistors, the pollutant drip system, test specimen and accessories for the current measurements. These accessories include HV probes, fast blow fuse for protection purposes, shunt resistance for current measurement and data logger for capturing the leakage current. The setup can accommodate testing of five samples simultaneously. The main subsystems and procedures of the inclined plane test system are described in more detail in the following sections.

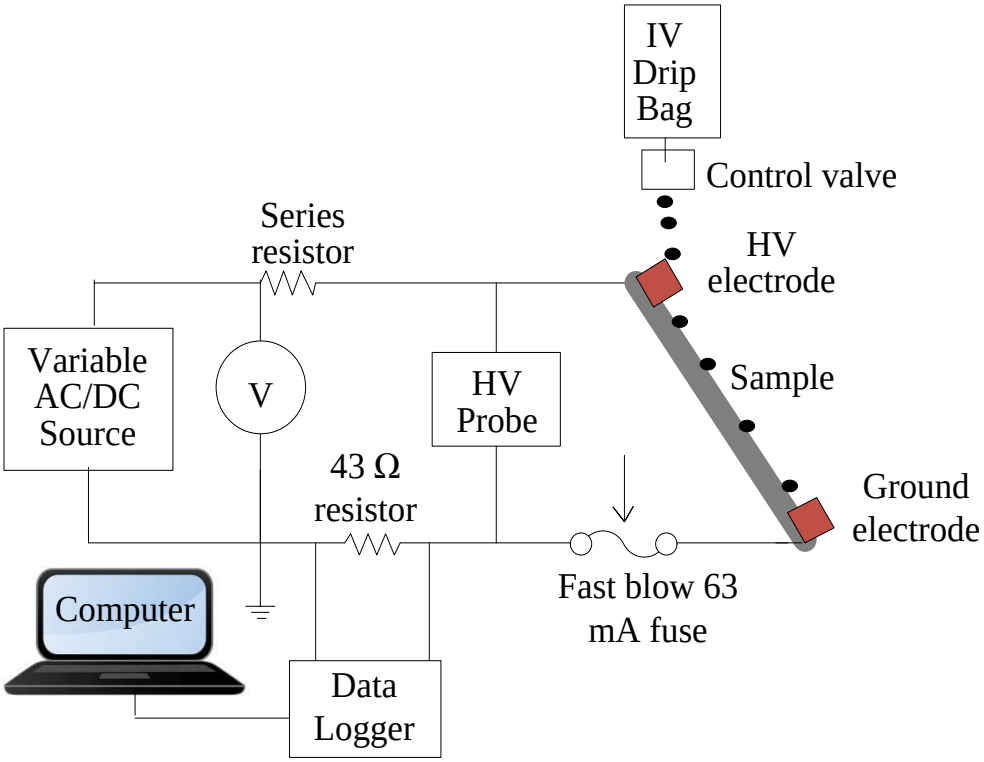


Figure 3.2: Implemented setup of the inclined plane test.

3.3.1 Test Specimen Preparation

Commercially available, micro-filled composite, high temperature vulcanising (HTV) SiR test samples were used. The filler material is Alumina Trihydrate (ATH). The approximate dimensions of the samples were 118 x 49 x 6 mm and weighed about 51 g. All the samples were cleaned with Cleen Green™ liquid detergent and allowed to dry before connecting to the circuit. Nitrile powder-free latex gloves were used in handling the samples before and after testing so that the samples would be free from any external contamination. Weight measurements of the samples were done prior to and after testing.

3.3.2 The Pollutant System

Conventionally, peristaltic pumps are used for the pollution supply in the inclined plane test setup in order to achieve desired controllable flow rates. In this work, however, an adjustable intravenous (IV) drip system is used as a replacement for the conventional peristaltic pumps to get the desired contaminant flow as per the standard. A picture of the modified inclined plane test circuit using intravenous drip systems is depicted in Figure 3.3. Simplicity, cost effectiveness and reliability are the factors considered in designing the setup. Some of the advantages of using this system are that the cost of IV drip is only about 10% of the peristaltic pump. The maintenance cost is nearly negligible due to the absence of electromechanical pumping systems. Notably, unlike the peristaltic pumps, the flow rates of the IV systems can be controlled over a wide range.

The drip bag is hung at a convenient position above the test sample. The contaminant is fed to the sample by means of a tube through an adjustable flow rate valve mechanism. The IV systems were calibrated by measuring the liquid flow per minute and it could be fine-tuned to an acceptable accuracy level of ± 10 % as stipulated in IEC-60587 standard [9].

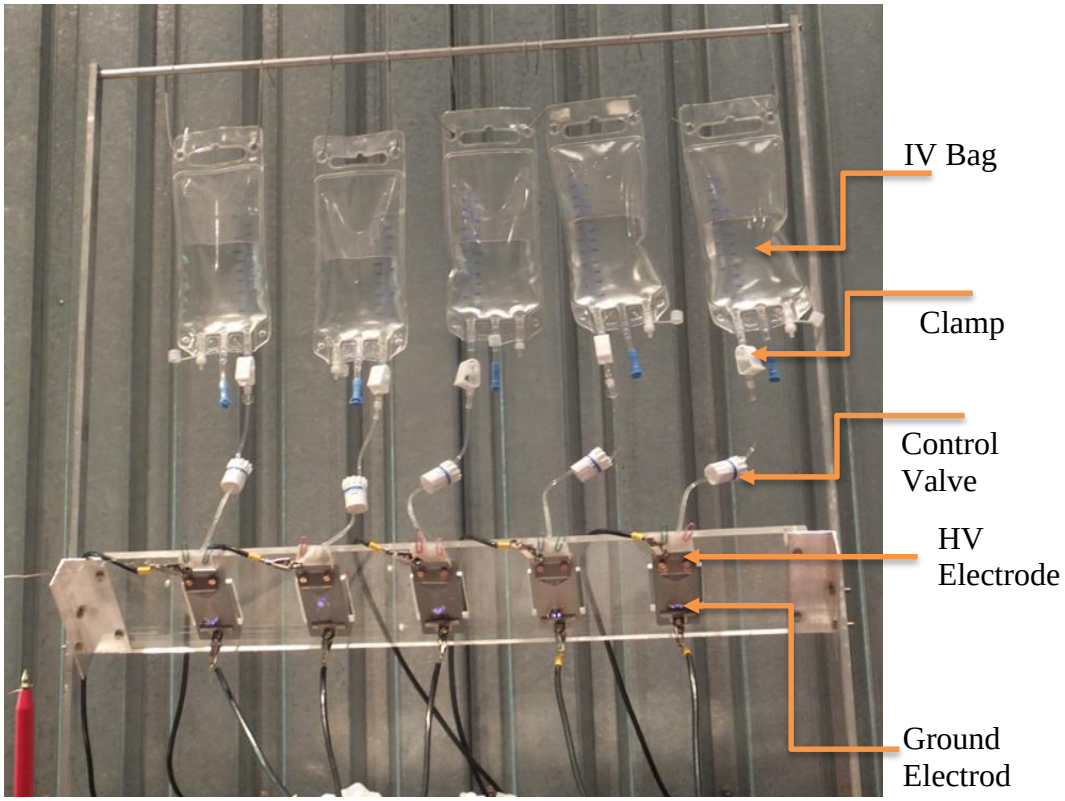


Figure 3.3: Adopted inclined plane test circuit using intravenous drip systems.

The parallel arrangement in Figure 3.3, could accommodate testing of five samples simultaneously. A pair of stainless steel electrodes separated by a 50 mm gap was attached to the surface of a flat rectangular SiR insulator as per the IEC-60587 standard. The samples were mounted at an angle of 45° to the horizontal plane with the test surface facing downwards in accordance with the IEC-60587 standard [9]. A filter paper clamped between the top electrode and the sample was used so that a steady flow of the liquid contaminant on the face of the sample between the electrodes would be established. The surface was then polluted with a liquid contaminant comprising of ammonium chloride (NH4Cl), de-ionised water and non-ionic wetting agent (Triton X-100) mixed according to the IEC-60587 standard. The contaminant flow rate is dependent on the chosen voltage range and the conductivity of the solution was maintained at 2.5 mS/cm. The liquid contaminant flows from the HV electrode along the sample surface towards the ground electrode. The contaminant was allowed to wet the filter paper uniformly and reach the ground electrode before the application of the test voltage.

The application of a test voltage causes leakage current to flow along the contaminant path. The IEC-60587 standard does not specify the humidity or the altitude of the test location. However, the standard recommends an ambient temperature of 23 °C ± 2 °C at the time of carrying out the test. In this research report, all the samples were tested during the month of December and January, which is a summer season, within a space of 30 days and the variation of the environmental conditions were minimum. An average ambient temperature of 26 °C was recorded during the test. The relative humidity was 35% RH and the altitude of the test location was approximately 1700 m above sea level. The laboratory test environment has natural ventilation. Furthermore, the test setup did not have any enclosure walls and as a result steam build-up was removed naturally and no build-up of gaseous products was observed during the test.

3.3.3 Leakage Current Measurement

Leakage current flowing through the surface of an insulator is widely recognised as a convenient parameter to rank the quality and assess the performance of outdoor insulators. In addition, the leakage current flowing through the surface of an insulator is an indication of the presence of contaminants or the deterioration of the insulation material [11, 13, 16-17, 19, 34, 37, 42-44]. In this research report, the leakage current is monitored and recorded throughout the duration of the test for AC and DC voltage applications.

The recording of the leakage current was achieved by measuring the voltage drop across a 43 Ω resistor that was in turn fed to a computer data logger system. The A/D converter used was a 12 channel, 1000 series data logger. The measured leakage current was acquired by recording one value of current in every second at a sampling rate of 5 kHz. Both the RMS and the absolute peak value of leakage current were measured. The RMS leakage current was monitored using multimeters and manually recorded after every 5 minutes whereas the data logger was used for the recording of the peak leakage current. Other variables that were monitored are the speed, shape, colour and frequency of the arc.

When the voltage is applied across the two electrodes of the polluted inclined test sample, leakage current begins to flow along the path of the contaminant. The leakage current causes the contaminant to heat up and evaporate. Consequently, dry-bands start to develop in some parts of the pollutant flow path, resulting in discharges, tracking and in some cases erosion of the material, thus causing insulation failure.

3.3.4 Failure Criteria

For track-resistance materials in the inclined plane test setup, tracking and/or erosion of the test specimens are typical failure modes [8]. The IEC-60587 standard mentions two failure indication criteria:

1) The magnitude of the leakage current exceeds 60 mA ± 6 mA for 2 to 3 seconds.

   or

2) The sample displays a track longer than 25 mm as measured from the bottom electrode or the sample shows a hole due to intensive erosion or it catches fire.

Due to its simplicity, the first criterion of the leakage current was used in this work and implemented by using a fast blow fuse, rated at 63 mA.

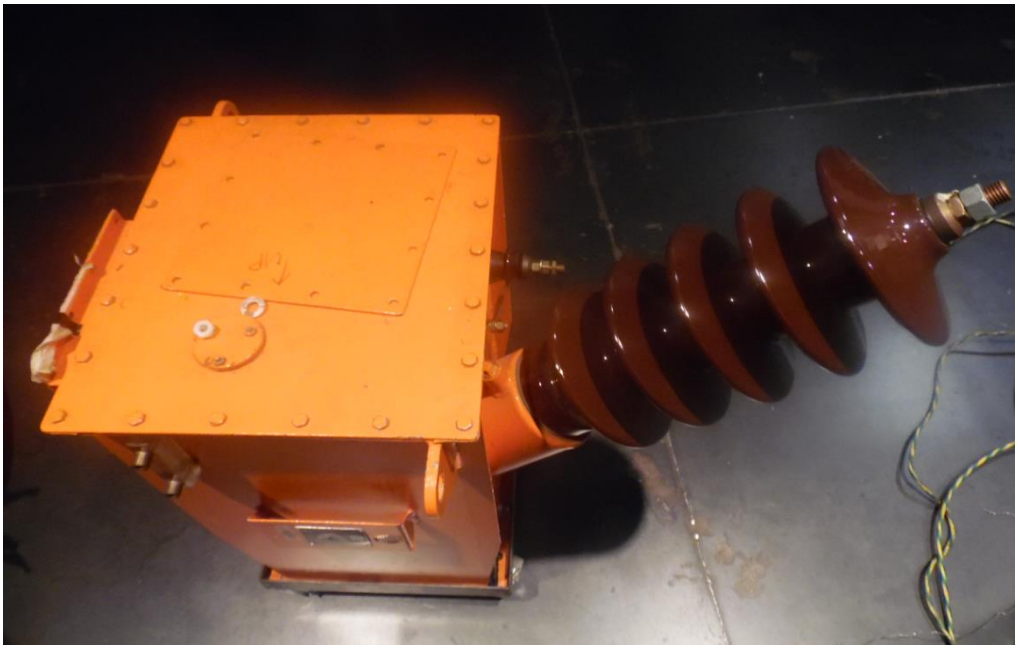
3.3.5 The Supply Voltage Sources

The equipment used for the HVAC test were a 220 V isolation transformer, 30 A variac (autotransformer) and a 5 kVA, 220 V/50 kV HV test transformer. For the DC supply, a stand-alone 50 kV, 80 mA Spellman generator was used. The ripple of the DC generator was less than 3%. Pictures of the autotransformer and HV test transformer are shown in Figures 3.4 (a) and (b) respectively. The HVDC generator is shown in Figure 3.5.

The RMS AC voltages of 3.5 and 4.5 kV are used in the tests. The corresponding DC voltages are chosen to be equal to the RMS AC voltages with the reasoning that the electrical damage in terms of tracking and erosion is energy-dependant and is determined by the RMS values [16].



(a)



(b)

Figure 3.4: AC testing equipment of (a) 30 A autotransformer and (b) HV transformer



Figure 3.5: 50 kV DC source.

For reasons of simplicity and limiting the number of variables, the constant tracking voltage (CTV) method is adopted for this experiment. The preferred voltages for the constant tracking methods are 2.5 kV, 3.5 kV and 4.5 kV with a corresponding flow rate in ml/min of 0.15, 0.30 and 0.60 respectively. In this research, 3.5 and 4.5 kV were used as the test voltages with corresponding flow rates of 0.3 and 0.6 ml/min respectively. Both the supply voltage and the voltage across one specimen were measured using 1000:1 voltage probes. The voltage is supplied to the samples via current limiting resistors whose values correspond to the chosen voltage levels as stipulated in the guidelines.

Only positive polarity DC is considered in this work as it has been shown by studies that have considered the DC polarity effect, that positive polarity DC causes greater damage than a negative DC of the same magnitude [11, 14, 16, 19, 39-40].

3.4 Post Ageing Material Analysis

Material analyses were carried out after the samples were aged in the inclined plane test setup. Physical inspection, weight measurement and chemical analyses were

the main methods used for the post ageing evaluation of the samples. Specimens for the post ageing analysis were cut out from the most degraded regions and compared to the un-aged sample. The tested samples were free from any external contamination as new powder-free latex gloves were used whenever the samples were handled. Since no cleaning was performed on the aged samples, the results of the chemical analysis are true reflections of the condition of the specimen and any chemical or physical changes from the virgin sample would be due to the specific test subjected to the specimen. Moreover, the samples were weighed a day after the testing to allow all the moisture to dry out naturally. The IEC-60587 standard recommends the measurement of the erosion depth instead of the mass loss but due to concern of the current mechanical depth gauge distorting the measured values by compressing the soft materials, it is common practice, as was shown in Table 2.1, to rather measure the mass loss.

The chemical analysis used for the post ageing analysis of the samples include, Thermo-Gravimetric Analysis (TGA) combined with Differential Thermo-Gravimetric (DTG), Fourier Transform Infrared (FTIR), Energy Dispersive Microscope (EDS) and Scanning Electron Microscope (SEM). Each technique is briefly explained in the following sections.

3.4.1 Thermo-Gravimetric Analysis (TGA)

Thermo gravimetric analysis (TGA) is a technique in which the mass of a material is determined as a function of a temperature or time and evaluates the thermal stability of materials. Deterioration due to tracking and erosion of SiR insulators depends on the thermal decomposition of the material and therefore the point at which thermal decomposition takes place can be predetermined using the TGA technique. A thermally stable material is a material in which there is no observable mass change when heated [8, 45].

The TGA procedure entails subjecting the test specimen to a controlled temperature in a controlled environment. Generally, the mass loss of the test

specimen is read directly in units of weight percent of the original sample quantity [45]. The TGA results may be presented by (1) mass versus temperature (or time) curves, referred to as TGA curve, or (2) rate of mass loss versus temperature curve, referred to as Derivative Thermo gravimetric (DTG) curves. While TGA gives the change of weight loss of a sample with respect to temperature in a controlled atmosphere, DTG data indicates the rate of degradation of materials with temperature and it is given as the first order derivative weight loss (%) per °C on the y-axis and temperature on the x-axis [46]. A TGA instrument consists of sample pan, a precision thermo-balance and programmable furnace. Measurements of the sample's mass change as a function of temperature, are made using a thermo-balance. Mass change, temperature and temperature change are accurately measured by the precision thermo-balance [45].

3.4.2 Fourier Transform Infrared (FTIR) Analysis

Fourier Transform Infrared (FTIR) analysis is a useful technique used to detect surface changes of materials by analysing infrared (IR) absorption bands of different materials before and after ageing [14]. Certain chemical bonds absorb specific frequencies of radiated energy and by measuring the transmitted and absorption frequencies of test specimen, specific bonds can be determined. FTIR technique is most useful in providing information about the presence or absence of specific functional groups. The IR spectrum is a plot of transmitted (or absorbed) frequencies against the intensity of transmission (or absorption). Frequencies appear in the x-axis in units of inverse centimeters (wavenumbers) and intensities are plotted on the y-axis.

3.4.3 Scanning Electron Microscopy (SEM) with Integrated Energy Dispersive Spectroscopy (EDS) Analysis

The surface morphology as well as the internal structure of the samples were investigated using FIE Quanta 250 FEG SEM with an integrated Oxford x-max EDS system. SEM images provide qualitative estimates of the type and extent of the degradation while EDS gives a quantitative information about the elemental composition of the materials [47-48]. The technique consists of detecting the signals that are produced when high energy electrons are bombarded at the surface of the solid specimen. These signals include secondary electrons that produce SEM images and characteristic X-rays that are used for elemental analysis. Secondary electrons are generated when a primary electron dislodges a sample electron from its shell. If secondary electrons are close to the sample surface, they can be collected to form the sample image [49]

The beam of electrons depends on the voltage applied across the cathode and anode plates. A voltage of 5 kV is necessary to produce the images while 15 kV is required to generate the characteristic X –rays for all the elemental analysis. When the generated electron beam hits the sample, two sets of radially opposing magnetic coils move the beam across the sample. Magnetic coils allow scanning of the sample in both X and Y directions. The scan pattern covers the specimen by starting in the upper left corner and proceeding to the right, then dropping down one line in each line scanned [49]. In this work, the so-called lawn-mower technique with 100 live-seconds was employed to collect the data. To prevent a charge-build on electrically-insulated samples, test specimens are coated with a layer of conducting material such as carbon, gold or some other metals. Since SiR insulators contain carbon elements, gold-palladium (66/34%) coating was used in this work to minimise the surface charging.

3.5 Concluding Remarks

A modified inclined plane test setup that uses intravenous drips instead of the conventional pumping systems was designed and implemented for this work. The circuit meets the requirements as stipulated in the IEC- 60587 standard [9]. The chapter also outlines the test equipment, materials used for the experiment and the preferred method for the test measurement. Finally, the measured variables, assessment criterion, methods of testing and tools for post ageing analysis of the test specimens are presented in this chapter. The results and analysis of the data will be given in the subsequent chapters.

CHAPTER 4: RESULTS ANALYSIS AND DISCUSSION

4.1 Introduction

This chapter contains the results and analysis of single sample tests under AC and DC excitation voltages. The parallel setup results were not reliable due to the fluctuation of the source voltage beyond the recommended value of the IEC-60587 standard and are given in Appendix A. Consequently, only the results of the single samples were used in the comparative analysis of AC and DC inclined plane tests. The effects of the source voltage on the outcome of the test results are discussed in Appendix A.

4.2 Testing One Sample of AC and DC at a Time

Since the objective of this study was to compare the performance of AC and DC SiR insulators under inclined plane tests, it was logical to run the AC and DC test circuits concurrently but on separate circuits with one sample at a time such that a more comprehensive data would be gathered in real time and subtle differences between AC and DC arcing phenomena identified. Furthermore, the tests would be under the same environmental conditions, thereby making the comparison more realistic as the only variable would be the voltage type.

In addition, the advantages of testing AC and DC samples side-by-side are direct visual comparisons that are available in real time. The arc intensity, shape, colour, sound and moisture evaporation are some of the parameters one could visualise and monitor in addition to the leakage current characteristics. The two samples were connected at the two extreme ends of the test setup and monitored using short video recordings of 30 minute intervals, in addition to visual observations, for the whole 6 hour duration of the test. A picture of this setup is shown in Figure 4.1.

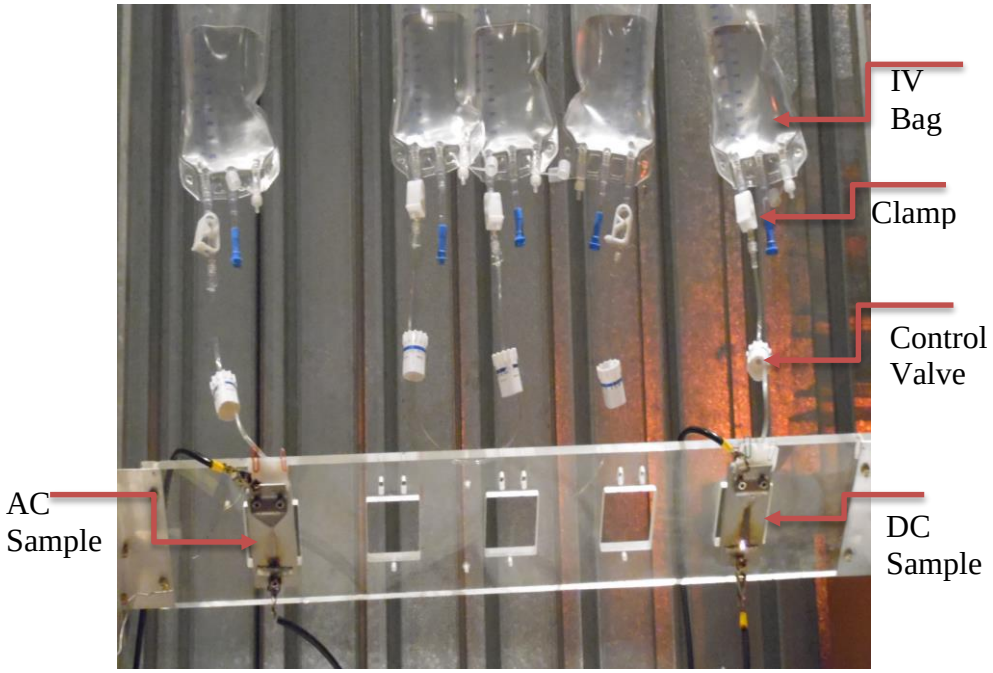


Figure 4.1: Concurrent AC and DC testing of the inclined plane test setup.

To ensure repeatability and consistency, each test was repeated three times and new samples and electrodes were used in each experiment. A summary of the peak leakage current magnitudes averaged for three tests are given in Table 4.1.

Table 4.1: Summary of the leakage current results of AC and DC samples.

Voltage type		**Absolute peak average LC (mA) of the three tests**	**Tracking characteristics**	**Erosion**	**Tracking time**
AC Voltage	3.5 kV	14	Partial tracking	None	6 hours
	4.5 kV	57	Partial tracking	None	4 hours
DC Voltage	3.5 kV	25	Excessive	None	1 hour
	4.5 kV	30	Excessive	moderate	30 min.

4.3 Leakage Currents Analysis

4.3.1 Leakage Current of 3.5 kV AC and DC Samples

The leakage current of both the samples were recorded for the whole six hour duration of the test. The leakage current of 3.5 kV AC and DC sample are shown in Figures 4.2 and 4.3 respectively.

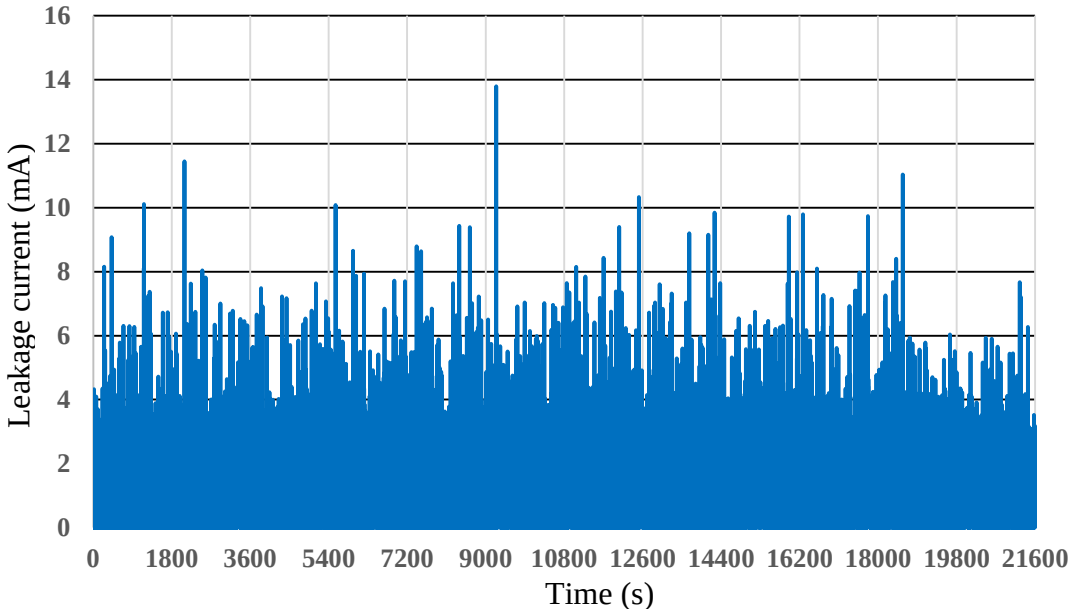


Figure 4.2: Absolute peak leakage current of 3.5 kV AC for one sample.

The AC leakage current in Figure 4.2 does not show any notable increasing or decreasing trend in the six hour duration of the test. Therefore, it was concluded that the tracking length of 3.5 kV AC voltage depends on the stability of the leakage current over a prolonged time which was in the range of 7 mA with the highest peak leakage current recorded as 14 mA. Another implication is that possibly the 3.5 kV AC arcing of the inclined plane test does not alter the surface resistance of SiR insulators since the leakage current did not show any increasing trend as the test specimen is aged.

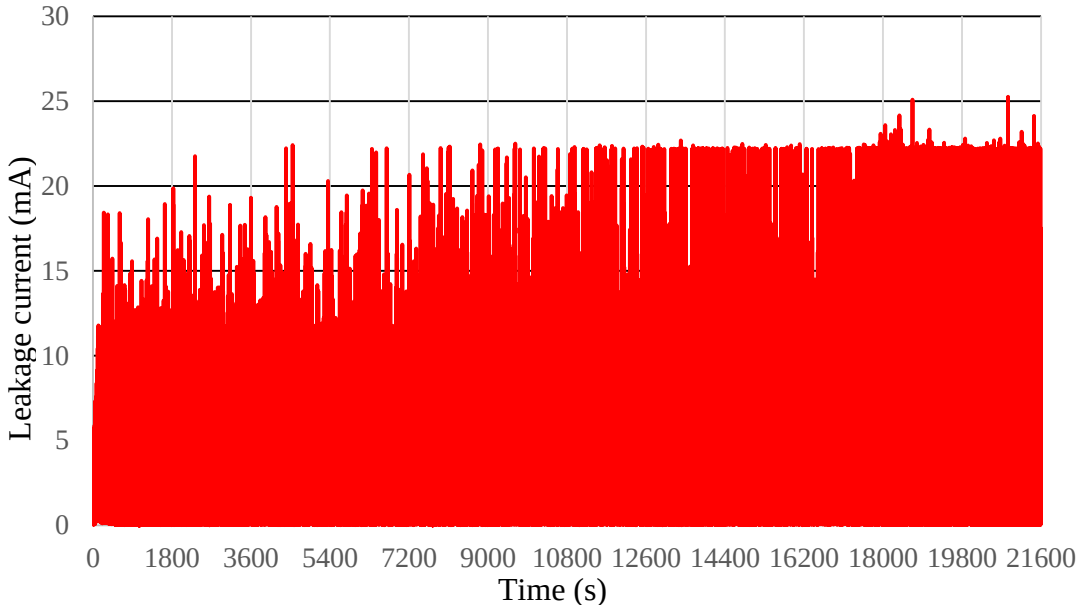


Figure 4.3: Absolute peak leakage current of 3.5 kV DC for one sample.

The voltage fluctuation stayed within the 5% range as stipulated in the standard. DC showed higher average value of leakage current and the current pattern is more consistent (less random variation). There was also a gradual increase of the average DC leakage current for the whole duration of the test.

The AC leakage current on the other hand, had more intermittent value and no real time dependant trend could be established. The maximum leakage current recorded for the six hour duration of the DC samples was 25 mA, this is nearly twice the corresponding AC current of 14 mA recorded in the test for the same period.

To further understand the differences between AC and DC leakage currents, the hourly average leakage current of 3.5 kV AC and DC is analysed as shown in the graph of Figure 4.4. The figure indicates that the hourly average leakage current of 3.5 kV AC is almost constant from the commencement of the test until the last hour. In contrast, the hourly average leakage current of the DC shows a gradual increase, an indication that the surface resistance of the insulator is decreasing. From the above, it is reasonable to assume that the DC leakage current would continue to increase until the gap is permanently made a short circuit. The trend lines that fits on the hourly average leakage currents of AC and DC are shown in Figure 4.4. The trend line that fits on the DC leakage currents has a polynomial shape whereas the one that fits on the AC leakage currents is a straight line of negligible gradient.

Furthermore, the increase of the hourly average leakage currents of the DC is relatively small until the 4th hour of the test and shows a significant increase in the last 2 hours of the test. This possibly signifies that there is a significant material deterioration that is directly related to the length of the exposure time of the DC insulator.

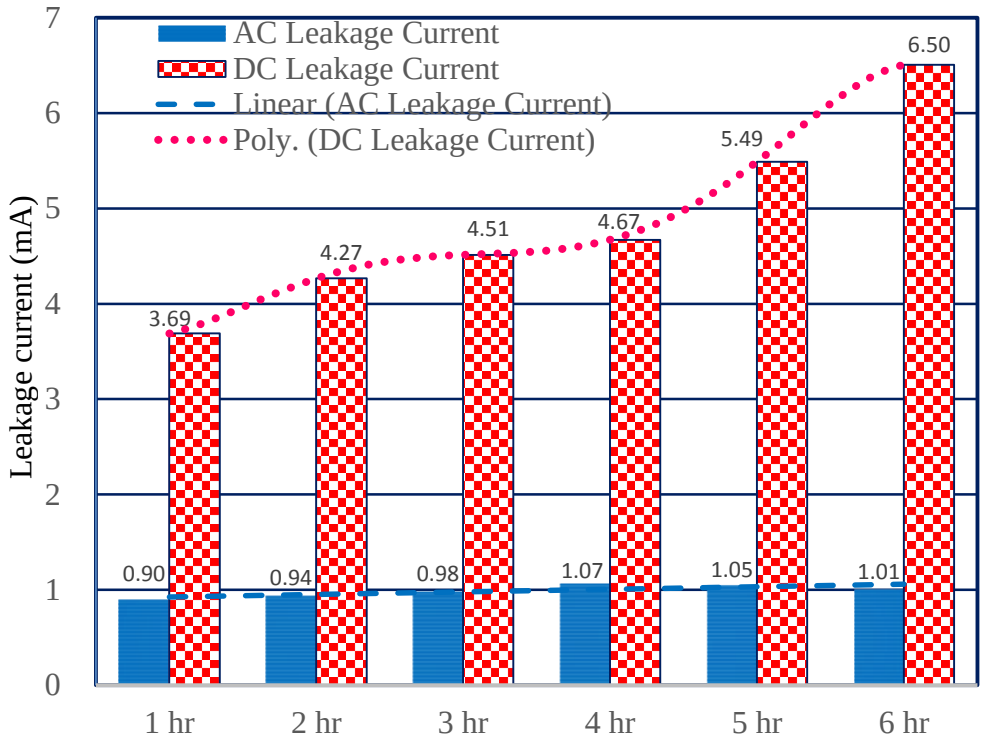


Figure 4.4: Hourly Average leakage currents of 3.5 kV AC and DC samples.

A further statistical analysis of the leakage current was carried out. This includes a quantification of the duration of time when the sample is arcing (in a conductive state) and not-arcing (non-conductive state). A leakage current of 1 mA and above is assumed to initiate arcing, therefore, all the currents below 1 mA are regarded as being non-conductive [19]. The percentage of non-arcing (off) state was calculated to be 48% for the DC condition and 69% for the AC samples. This is in agreement with the observed physical damage where the AC samples which arced for 31% of the test duration showed minor damage compared to the DC samples which arced for 52% of the total exposure time.

4.3.2 Leakage Current of 4.5 kV AC and DC Samples

The AC leakage currents of 4.5 kV AC shown in Figure 4.5 were overall bigger than the 3.5 kV tests.

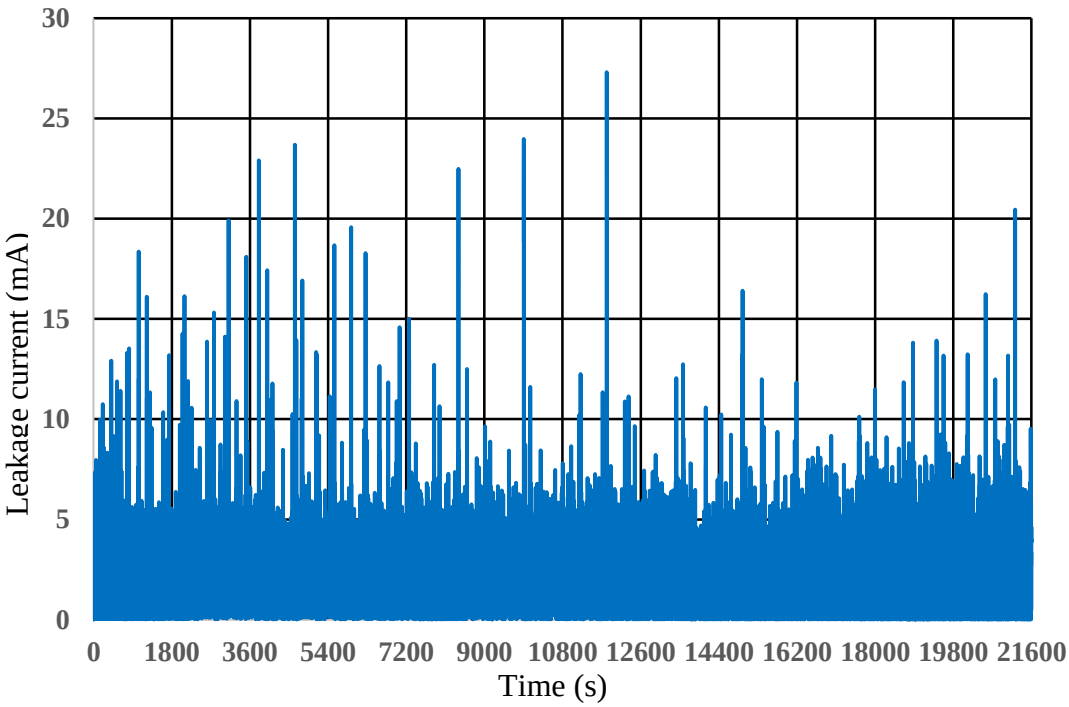


Figure 4.5: Absolute peak leakage current of 4.5 kV AC for one sample.

The leakage current of 4.5 kV DC was consistently higher and the test run for an average of 1 ½ hours before arcing stopped. Figure 4.6 shows the plot of the leakage current for 4.5 kV DC samples. The maximum recorded leakage current of 4.5 kV DC was 30 mA before the arcing/tracking completely stopped. An intensive arcing near the ground electrode caused an erosion of the insulation and subsequently stopped the flow of the leakage current by making the DC circuit open. Before arcing stopped however, the leakage current of the 4.5 kV DC samples caused a consistent tracking that bridged the gap between the electrodes. Furthermore, the pattern of 3.5 kV and 4.5 kV DC leakage currents were consistent and showed relatively less intermittent behaviour compared to the AC leakage currents. It is also worth mentioning that the stable value of the 4.5 kV DC leakage currents for all the

three tests were in the range of 20 mA with the occasional spikes that reached a maximum of 30 mA.

Gorur et al [24], also found that samples degraded more when the majority pulses of leakage currents were in the range of 15- 30 mA. Another study by Kumagai and Yoshimura [50] found that leakage currents in the range of 20 - 25 mA appeared to be the most effective current pulses for causing tracking and erosion.

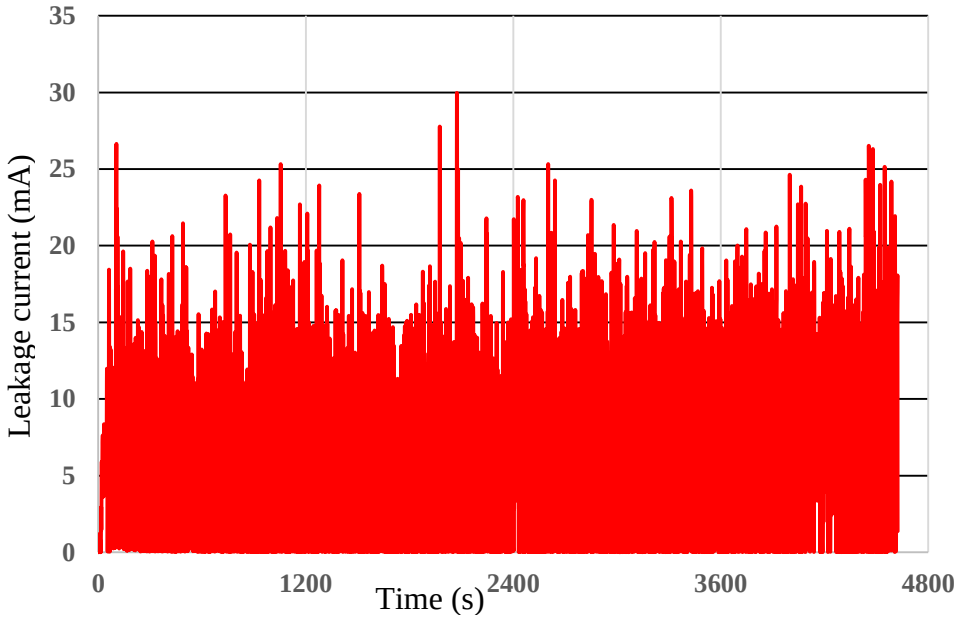


Figure 4.6: Absolute peak leakage current of 4.5 kV DC for one sample.

The AC leakage current of 3.5 and 4.5 kV shows a series of short time peaks separated by longer intervals and did not show any noticeable physical deterioration on the surface of the insulator. Similar trends were reported by [13, 37]. Tracking of the AC insulators were only visible near the ground electrode with the rest of the gap between the electrodes showing only some discoloration. Furthermore, in comparison with the DC leakage currents, the AC currents were highly intermittent and showed higher frequency. However, there are some other researchers who contradicted this findings and reported that the positive DC leakage current is highly intermittent in nature [15, 19, 40]. The findings from this work showing the intermittency of AC leakage current and its lack of material damage is supported by [13, 51].

According to the leakage current failure criterion of 60 mA, all the samples have passed the test but according to tracking failure criterion, all the DC samples would have failed the test within the first hour of the voltage application. The magnitude of the 3.5 kV DC leakage current is 2 times that of the 3.5 kV AC and showed a consistently increased trend for the 6 hour duration of the test. A summary of the leakage current and its effects on the test specimens are given in Table 4.2.

Table 4.2: Summary of the tracking and erosion caused by AC and DC leakage currents.

Voltage (kV)		**LC (mA)**	**Tracking/Erosion**	**Comments**
AC	4.5	± 22 after 6 hours	Moderate tracking and discolouration became more visible & completed the gap after 4 hours	Passed the test. Is highly intermittent
	3.5	±15 after 6 hours	tracking path became more visible completed the gap after 6 hours	Passed the test. Highly intermittent.
DC	4.5	30 became open circuit after 1 & ½ hours	Heavy tracking and moderate erosion. Tracking path became more visible & bridged the gap after 30 minutes.	Failed the test. Showed less intermittent and became an open circuit after 1 ½ hours of testing.
	3.5	21 after 6 hours	Heavy tracking, path became more visible and bridged the gap after 1 hour	Failed the test. Showed a consistently increasing trend.

The procedure of the IEC-60587 standard does not give the same results under the same conditions for AC and DC SiR insulators. Samples that would pass the test under AC would fail the test under DC applications.

4.4 Visual Observations

4.4.1 Visual Observations of 3.5 kV AC and DC Samples

During the earlier stages (especially in the first hour) of the testing, arcing of the AC samples was more aggressive, audible and frequent. As time passed, especially from the second hour, it was less frequent, less audible and less pronounced. This pattern of apparent gradual decrease of arc energy continued until the last hour of the test.

The colour of AC arcing especially at the beginning of the test was more reddish. From the second hour of the test, a less intensive violet arcing was observed towards the HV electrode and became reddish at the ground electrode. On the other hand, the DC arc had a violet colour. This points to different colour spectrum and possibly different materials (the contaminant in the case of AC and the insulator in the case of DC) were burning off. Interestingly, the AC arc seemed more intense and was more audible but caused less damage compared to the DC, which was steadier and less frequent.

AC arcing was more concentrated at the ground electrode and did not start from the top (HV electrode) as was the case with the DC samples. Consequently, the tracking path of the 3.5 kV AC samples did not become visible until the third hour of the test and the arc did not follow a definite path as was the case with DC arc. The zero crossing of the AC current has some influence on the nature of the AC arcing and one possibility is that the alternating current is not fast enough to keep track of the water droplets and initiate arcing. Occasionally, arcing of the AC samples were observed near the top electrode but it was more scattered and less intensive. In some instances, AC arcing showed two parallel paths that only combined at the ground electrode.

The arc of the DC samples during the first hour was violet in colour and less frequent compared to AC, The DC arc could be seen following the contaminant drop from the quill hole at the top electrode all the way to the ground electrode.

Consequently, tracking, which bridged between the electrodes was visible just one hour after starting the test. The individual DC arcing lasted longer in the range of fractions of seconds to more than a second, causing dry bands and prolonging the arcing interval compared to AC. Moreover, DC arc was solid throughout the gap, although it was more intensive from half way the gap towards the ground electrode. In contrast, the AC arc was scattered except at the ground electrode. The scattered effect of AC arc could be due to the intermittency nature of AC leakage current.

Images of the samples taken at various stages during the test, are shown in Figures 4.7 - 4.13. It was observed that the DC arc followed a well-defined path from the top electrode to ground electrode whereas the AC arc was more scattered and more visible at the ground electrode.

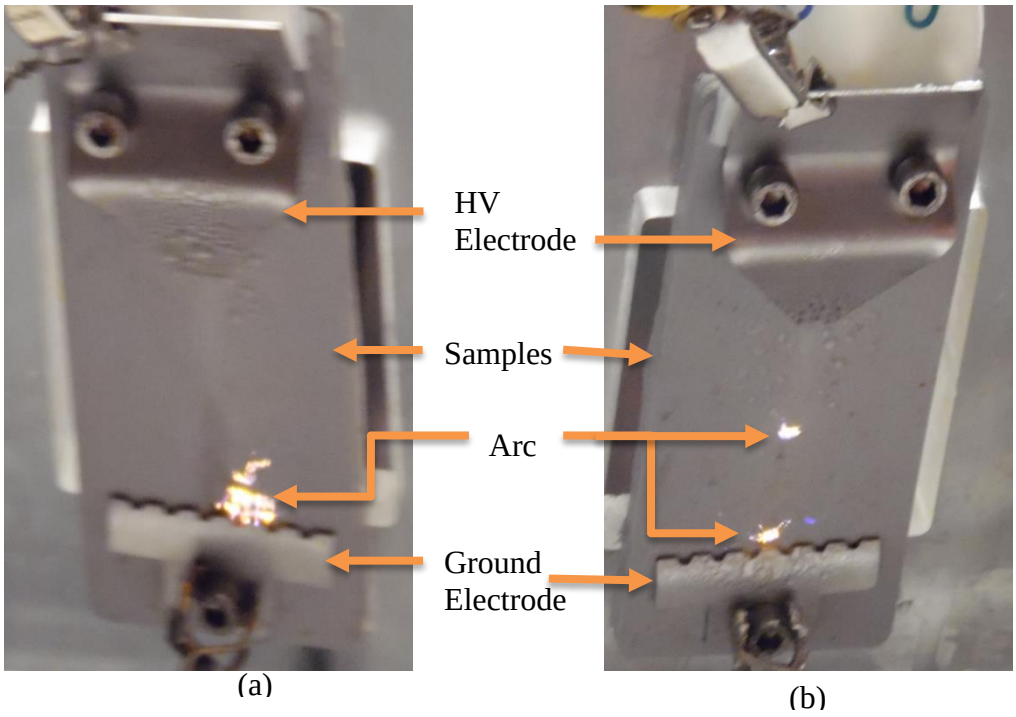
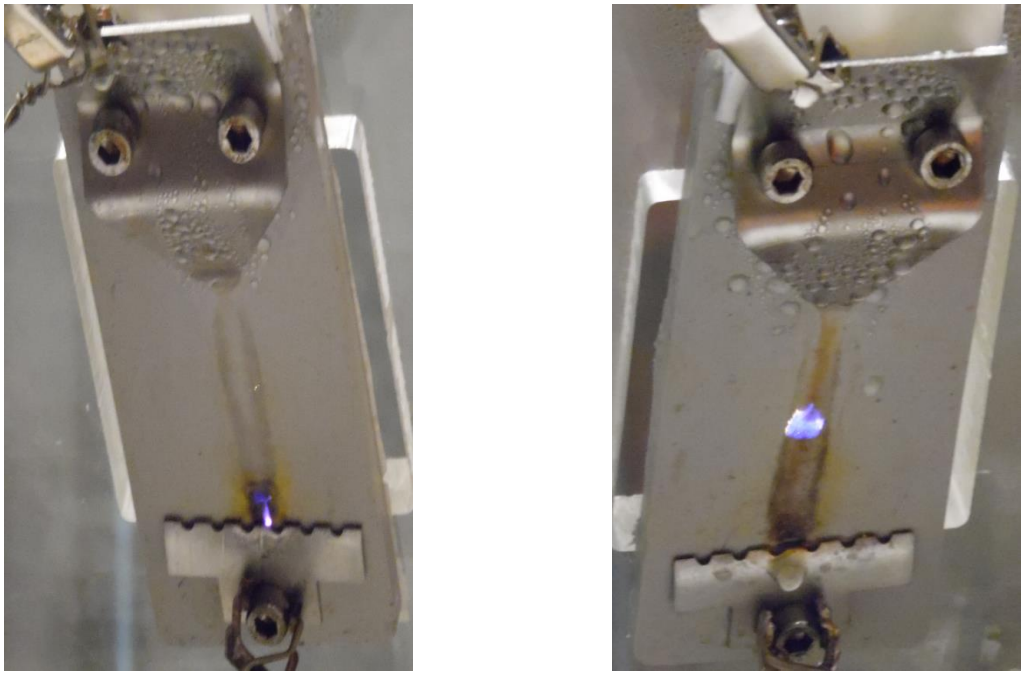


Figure 4.7: Samples of (a) 3.5 kV AC and (b) 3.5 kV DC after 5 minutes.

When the test was started, the following observations were made from Figure 4.7:

- AC arc seemed more intense and covered a bigger area.
- AC arc started and remained at the ground electrode.
- DC arc was thinner and started near the HV electrode.
- Generally, a violet colour of the DC arc was observed.

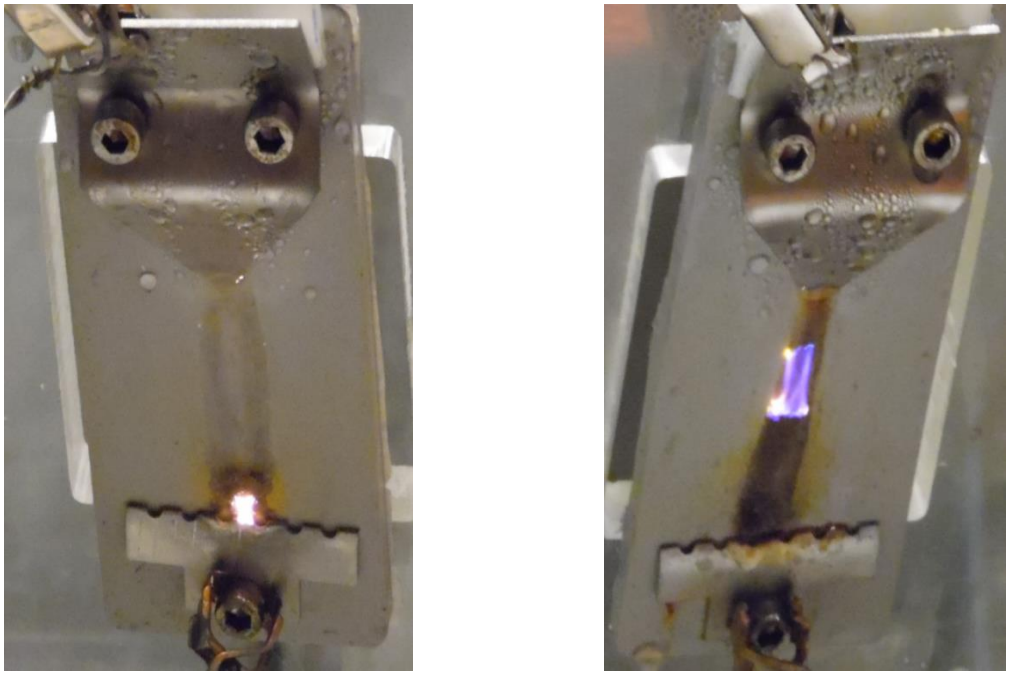


(a) (b)

Figure 4.8: Samples of (a) 3.5 kV AC and (b) 3.5 kV DC after 1 hour.

After 1 hour of the test, the following observations were made from Figure 4.8:

- AC arc showed two weak parallel paths that started from the top electrode and met at the ground electrode.
- AC arc was fast and frequent whereas DC arc was less frequent but lasted longer.
- DC arc was one solid unit that consistenly moved with pollutant drops from the HV electrode to the ground electrode.
- A DC tracking that bridged between the electrodes was visible and in accordance with the tracking failure cretierion, the DC samples had failed after 1 hour of starting the test.
- DC arc followed a consistent straight path from HV electrode to the ground electrode.
- DC arc had voilet colour.

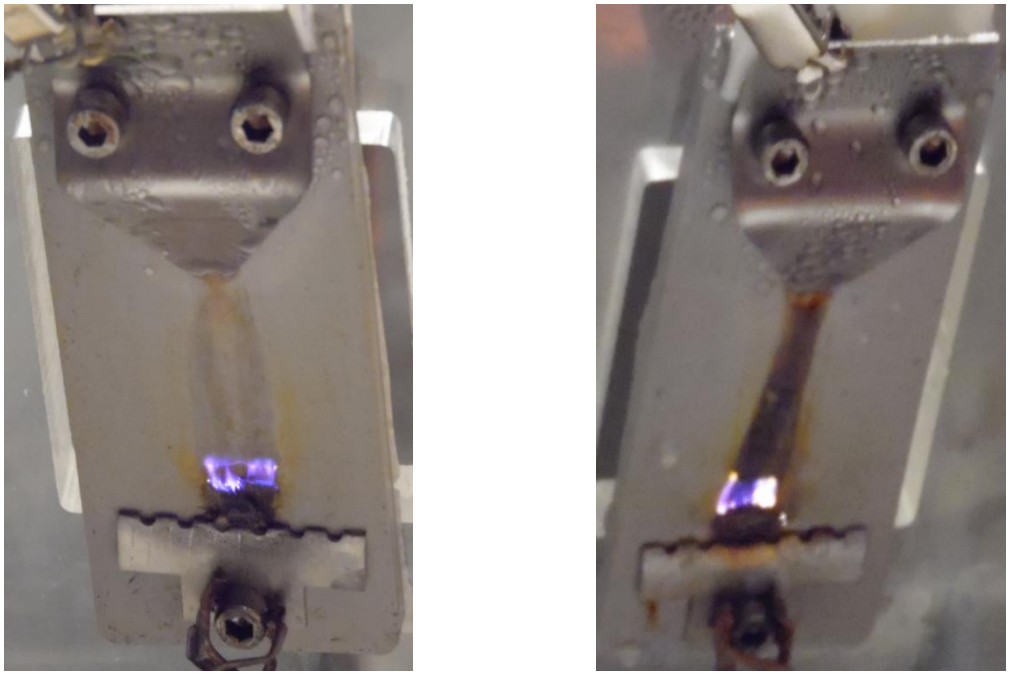


(a) (b)

Figure 4.9: Samples of (a) 3.5 kV AC and (b) 3.5 kV DC after 2 hours.

The following observations were made after 2 hours from Figure 4.9:

- AC arc seemed faint and weak except at the ground electrode.
- AC arc was primarily concentrated at the ground electrode.
- DC arc was longer and followed a well-defined path with longer arcing period.
- DC samples showed a blackened tracking path that completely brigded between the electrodes.
- The colour of the DC arc was still voilet whereas, red colour was observed in the case of AC arc.

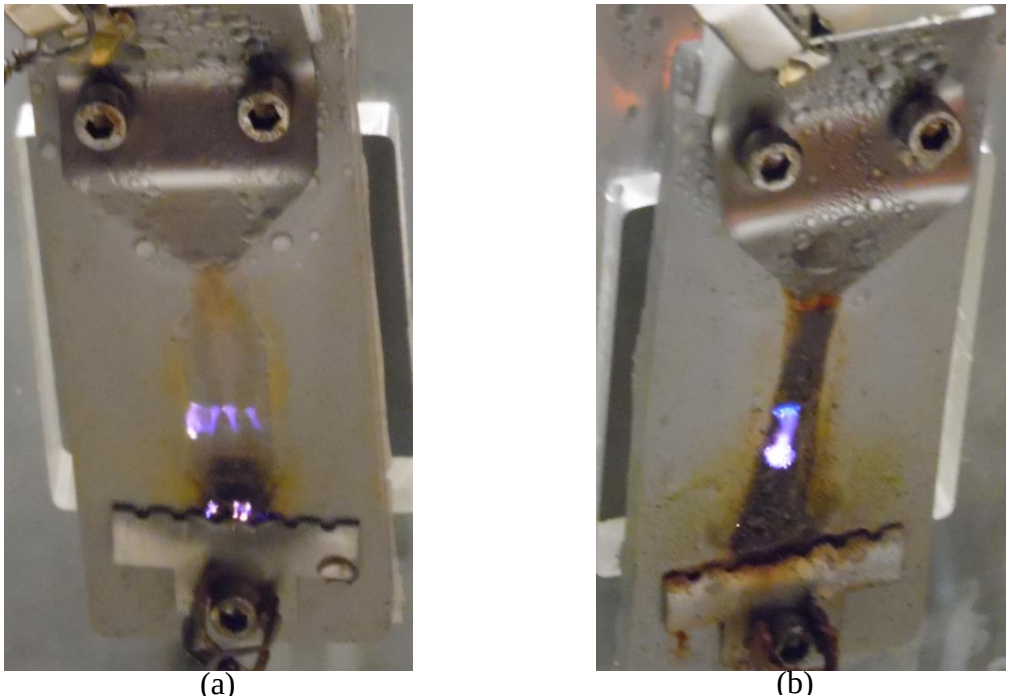


(a) (b)

Figure 4.10: Samples of (a) 3.5 kV AC and (b) 3.5 kV DC after 3 hours.

After 3 hours, the observations made were:

- AC arc was faint, scattered and the tracking did not have a well-defined path or shape.
- It seemed as if the AC arc is due to the burning of the contaminant with little associated material damage in terms of tracking and/or erosion.
- A violet colour of the AC arc was observed.
- DC arc was consistently solid and strong.
- The ground electrode of the DC sample had started to look rusty.

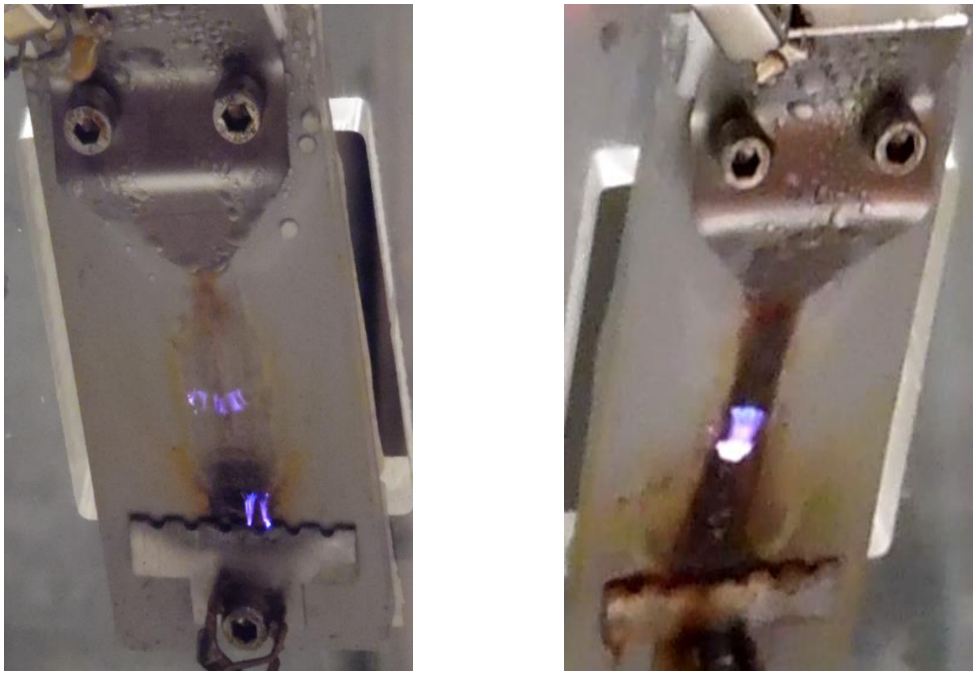


(a) (b)

Figure 4.11: Samples of (a) 3.5 kV AC and (b) 3.5 kV DC after 4 hours.

After 4 hours, the observations made were:

- AC arc was still faint and scattered.
- AC arc showed the evaporation of the liquid contaminant that was flowing on the surface of the insulator.
- DC arc had followed the same path.
- The ground electrode of the DC sample showed signs of corrosion.

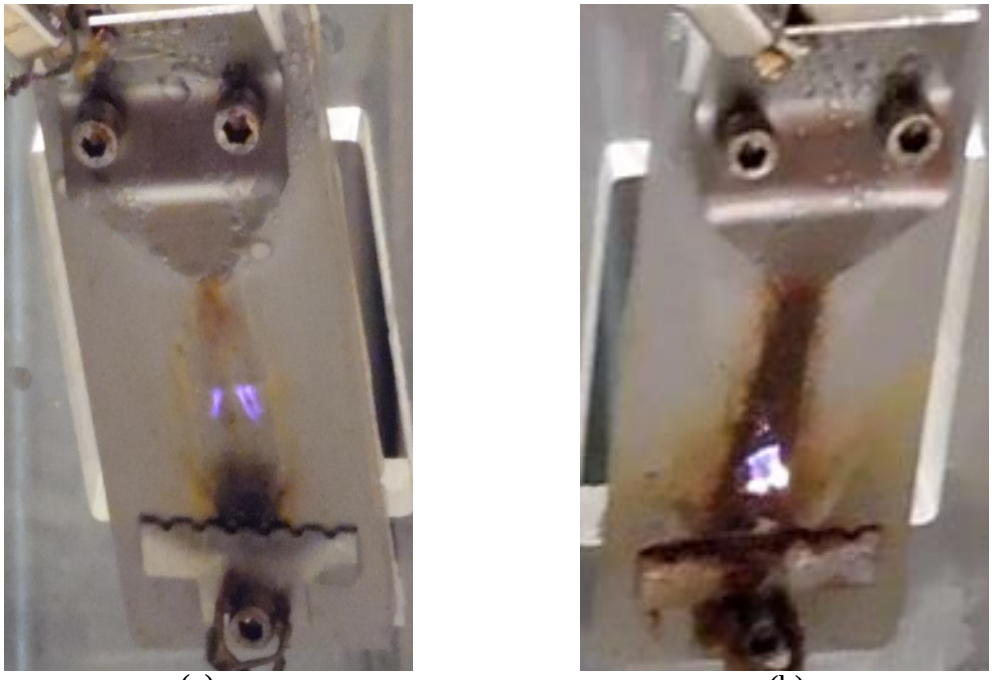


(a) (b)

Figure 4.12: Samples of (a) 3.5 kV AC and (b) 3.5 kV DC after 5 hours.

The following observations were made after 5 hours:

- The AC arc was getting weaker with time and the DC arc was getting stronger.
- The increase of the DC arc is well-correlated with the trend of the hourly average leakage currents, shown in Figure 4.4.
- The DC arc that started from the top electrode was in direct contact with the ground electrode and that is possibly why the ground electrode showed signs of corrosion because during this process, materials would have been transported and transferred to the ground electrode by the arc.



(a) (b)

Figure 4.13: Samples of (a) 3.5 k VAC and (b) 3.5 kV DC after 6 hours.

In the last hour of the test, the following observations were made:

- AC arc was still faint and scattered.
- The ground electrode showed more signs of corrosion.
- There was a clear difference between the AC sample and DC sample in terms of tracking.
- Tracking failure criterion can not be used in the study of AC and DC inclined plane tests of SiR insulators.

4.4.2 Visual Observations of 4.5 kV AC and DC Samples

The same voltage of 4.5 kV was used for both the AC and DC samples. It was then observed that the supply voltage stayed within the prescribed variation limits of 5% during arcing periods. During the first hour of the test, like the 3.5 kVDC, the DC arc of the 4.5 kVDC was steadier and had a definite path. Furthermore, the arc colour of the 4.5 kVDC was similar to that of the 3.5 kVDC, namely violet. In contrast, however, the AC arc of the 3.5 and 4.5 kVAC had a reddish colour. In addition, the AC arc was more audible and frequent. Images of the samples taken

at 30 minute intervals during the test, are shown in Figures 4.14 - 4.17. It was observed that the DC arc followed a well-defined path from the top electrode to ground electrode whereas the AC arc was more scattered and more visible at the ground electrode.

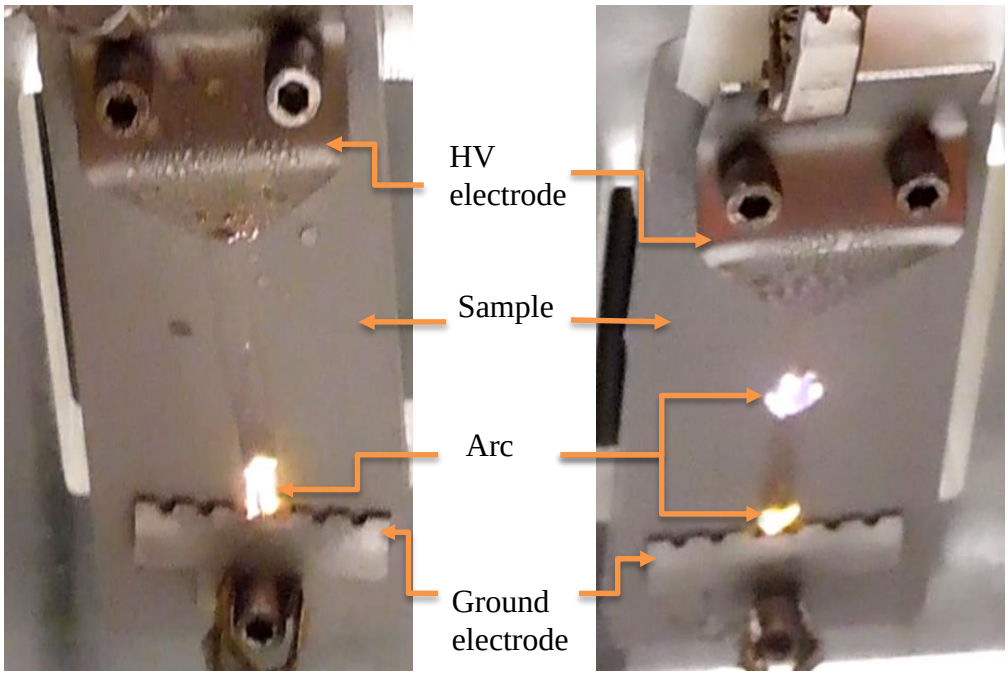
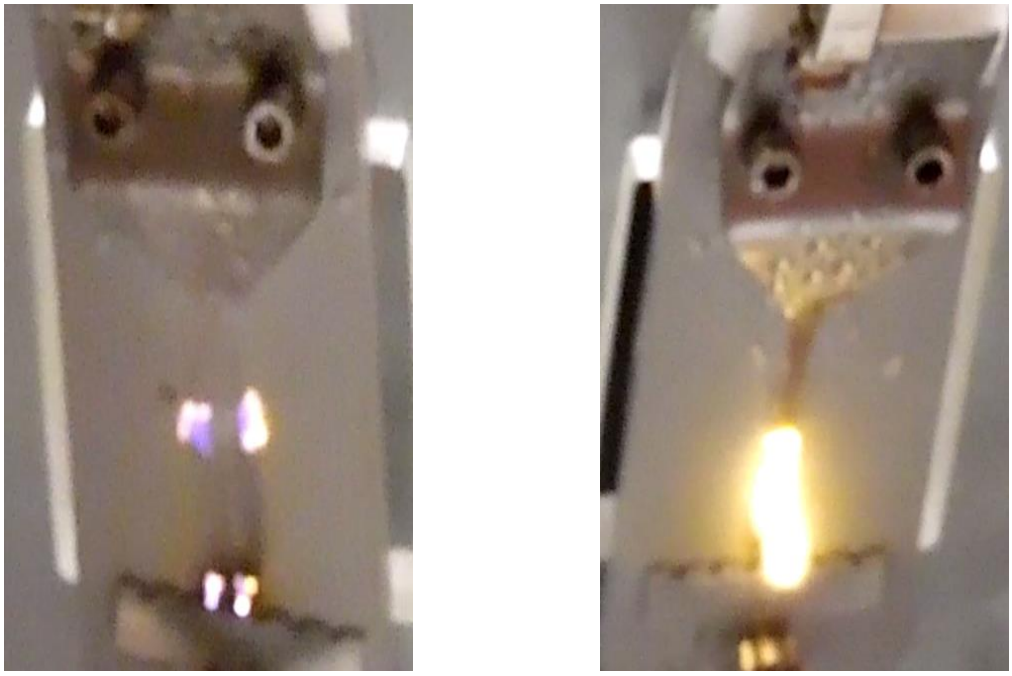


Figure 4.14: Samples of (a) 4.5 kV AC and (b) 4.5 kV DC after 10 minutes.

The observations made from Figure 4.14 in the first 10 minutes of the test were:

- The DC arc started from the HV electrode.
- Generally, the DC arc had a violet colour especially towards the HV electrode.
- Occasionally, the AC arc started near the HV electrode but it was more intensive at the ground electrode.

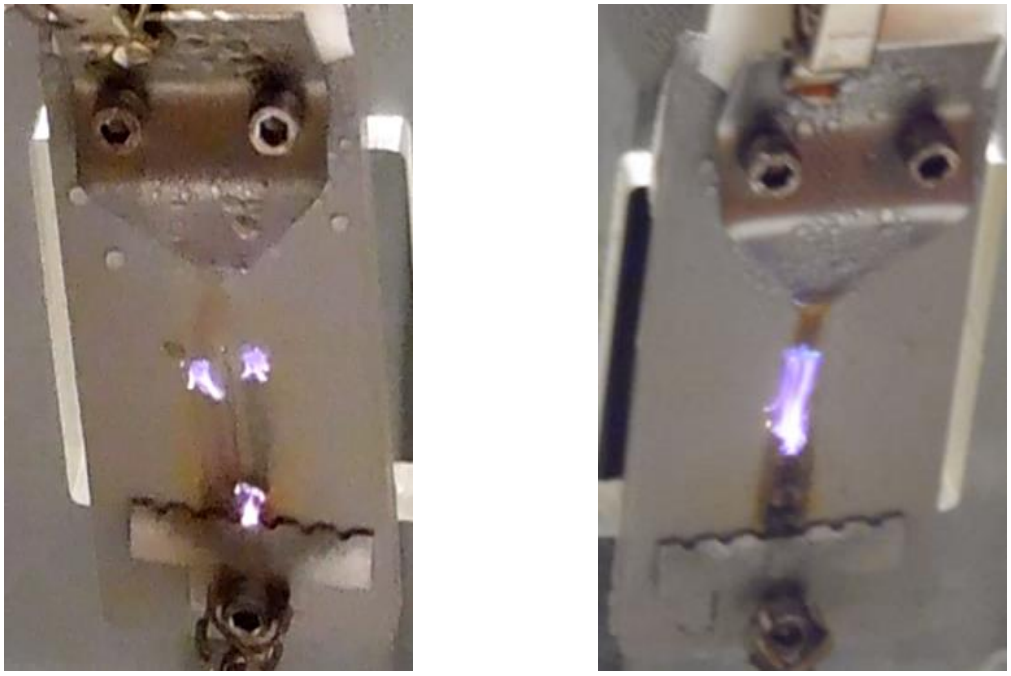


(a) (b)

Figure 4.15: Samples of (a) 4.5 kV AC and (b) 4.5 kV DC after 30 minutes.

After 30 minutes of testing, the following were observed:

- AC arc was scattered and showed two parallel paths.
- AC arc was weak.
- DC arc was more intensive and covered a bigger area especially towards the ground electrode.
- DC arc followed a well- defined single path.
- A tracking path that bridged the gap between the electrodes of the DC samples was visible 30 minutes after the voltage application.

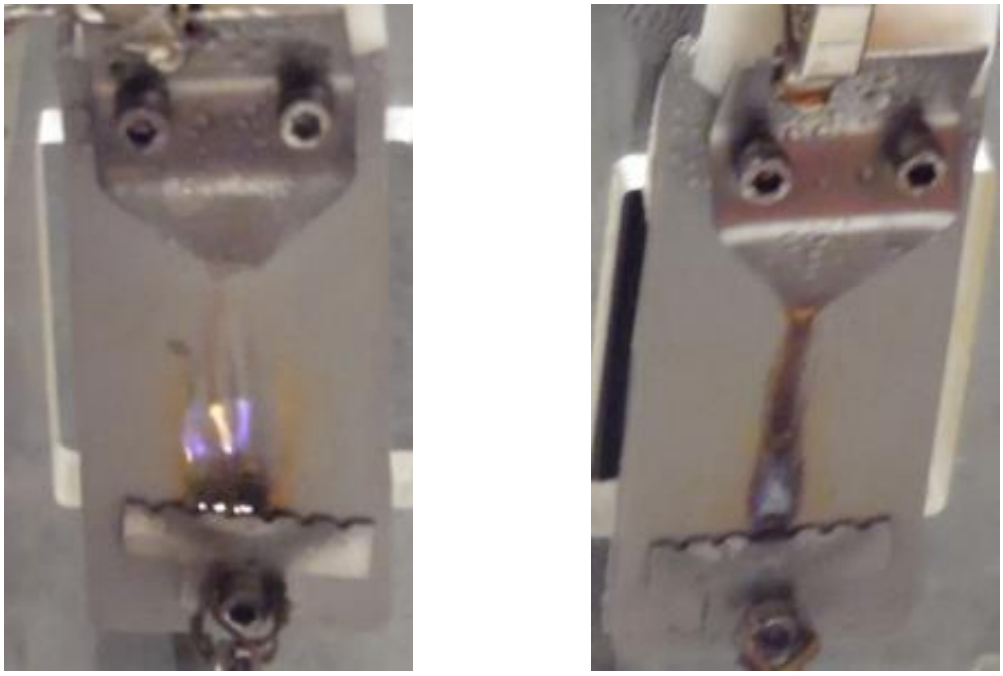


(a) (b)

Figure 4.16: Samples of (a) 4.5 kV AC and (b) 4.5 kV DC after 1hour.

After 1 hour the following observations were made:

- AC arc is still scattered and faint.
- DC arc was solid and had a definite path.
- The colour of the AC and DC arcs was similarly violet especially towards the HV electrode and was more reddish near the ground electrode.



(a) (b)

Figure 4.17: Samples of (a) 4.5 kV AC and (b) 4.5 kV DC after 1 ½ hour.

The following were the observations made after 1 ½ hour of testing:

- AC arc was getting weaker with time.
- AC samples did not show any visible tracking beyond the ground electrode.
- The DC arc removed the carbonised tracking path near the ground electrode which, completely stopped the arcing.
- The DC circuit remained open circuit and the voltage across the DC sample remained constant at 4.5 kV with no associated arcing.
- All the three samples of the 4.5 kV DC, which were tested at different times behaved the same way.
- The current in all the three individual DC samples reached approximately 30 mA before the erosion and the subsequent open circuit.

After 30 minutes of testing, a tracking path that bridged the gap between the electrodes was clearly visible in all the DC samples. The DC samples lasted for an average of 1½ hours before arcing stopped due to open circuit. The voltage stayed constant at 4.5 kVDC. The test was allowed to run for the whole 6 hour duration but once the erosion of the DC sample near the ground was established, arcing could not be initiated. The sample developed an eroded area of whitish colour that removed the conducting channels just above the ground electrode whereas, the conducting tracking channels of the rest of the gap remained intact. It was postulated that the eroded part became hydrophobic, preventing further arcing near the ground electrode. Figure 4.18 shows an image of the sample taken after the test.

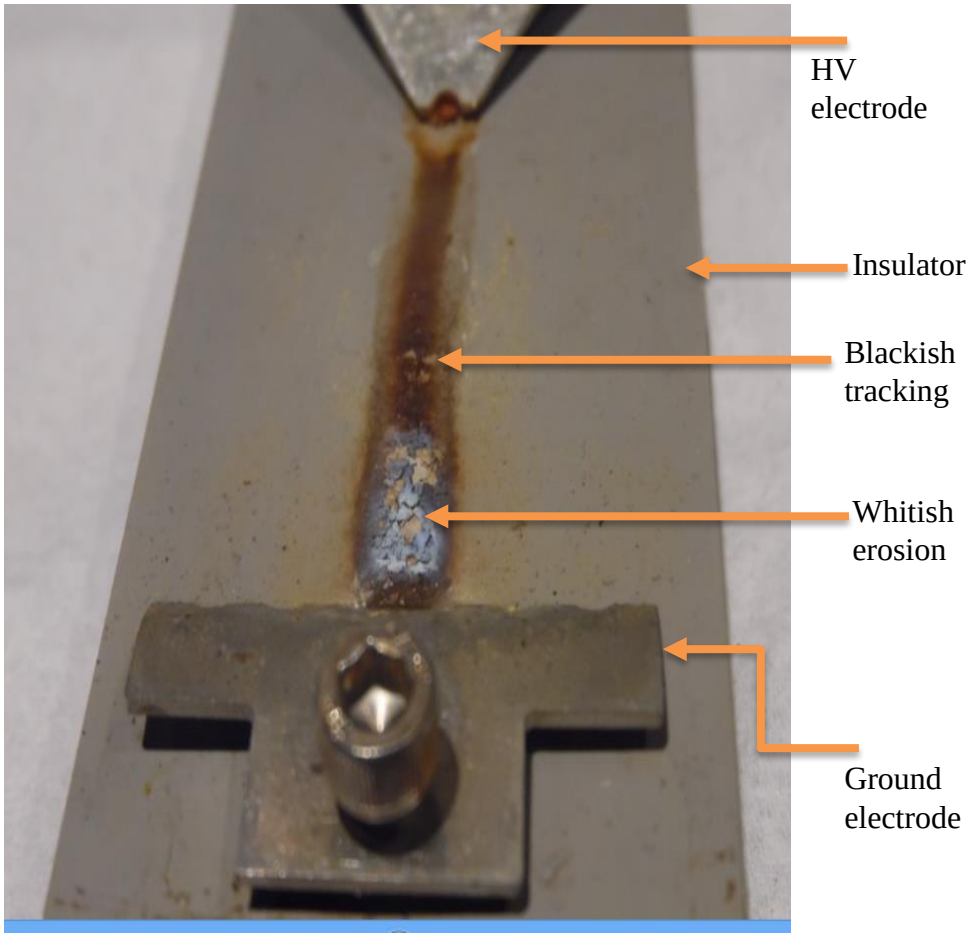


Figure 4.18: 4.5 kV DC sample after 1 ½ hour.

The damage of the DC samples is largely due to the longer periods of stable arcing observed during the test. Gorur and Moreno [20] reported that in addition to the

higher DC leakage currents, the duration of DC electrical discharges was longer than the AC discharges.

However, during the test, AC samples showed a more frequent arcing but with no corresponding material damage. From the observation of the arc in the AC samples, it seemed that in most cases, the surface contaminant was burning off and the arc was not directly in contact with the insulator surface. A frequent arcing of AC samples was observed during the experiment but it appeared as if it was a transparent and one could see the insulator surface through the arc as opposed to the DC arc, which was solid.

This phenomenon is supported by Xidong at al [51] who reported a thin vapour film between the arc tunnel and the sample surface which caused the contaminant to boil off with no associated damage to the surface of the insulation. Therefore, the heat due to the arc, must first pass through this vapour film before it is in contact with the insulator surface. One can therefore, conclude, that in DC samples, this vapour film is breached and the arc heat is absorbed by the insulator surface. Consequently, DC samples show a greater surface damage. This is further supported by the different arc colours of AC and DC samples that was observed during the test and the subsequent damage of the respective samples that were seen during and after the test. It was highly likely that the colour difference between the arcs of the two samples was symptomatic of different by-products as a result of different materials being burned off.

One way to explain why the visible arc of AC samples do not show a corresponding surface damage by burning the surface contaminant, is to decompose AC leakage currents into its components. Ghunem et al [39] reported that AC leakage current has two components; the non-discharge component that leads to joule heating and evaporation of the contaminant, while the second one is the dry-band arcing component which causes heat ablation of the insulator surface. It is probable that the majority of the AC current was of the joule heating type, which was responsible for the evaporation of the contaminant as opposed to insulator surface heating. Therefore, to compare AC and DC samples of the inclined plane test setup, one needs to do more than just equating the DC voltage with the RMS AC equivalent

voltage such as taking into account, the decoupling of the AC currents into its components.

Of all the leakage currents measurements. The 4.5 kV DC was the most aggressive in terms of arcing and the subsequent material damage it caused. When only one sample of 4.5 kV was tested, there was an intensive arcing that caused material loss near the ground electrode. This prevented the pollutant to flow towards the ground electrode, thereby stopping arcing. It is assumed that the whitish erosion that was observed under the 4.5 kV DC test, merely removed the carbonised conducting tracks, making the eroded portion hydrophobic. Material analysis presented in the next section, will attempt to verify this assumption. DC voltages caused non-uniform damage on the insulator surface and this non-uniformity increased with higher voltages. The tracking area near the negative electrode had the most damage under the 4.5 kVDC. Heger et al [16] also reported that most damage is caused when electrolyte flows in a direction away from the positive electrode. This damage was just sufficient enough to remove the conducting carbonised channels thereby inhibiting any further tracking. One can therefore suggest that when DC samples are tested with stiff supply voltage, it results in non-uniform erosion.

A build-up of visible tracking that started from the ground electrode and proceeded to HV electrode on a straight path, was observed in all the samples of 3.5 kV and 4.5 kV. The DC arc however, started from the HV electrode to the ground electrode while the AC arc was more visible at the ground electrode. The DC arc was seen to follow the liquid drop from the quill hole at the top electrode all the way to the ground electrode. The formation of the tracking path that bridged the gap between the electrodes of 3.5 kV was noticeable an hour after the initial voltage application. Similarly, the tracking path of the 4.5 kV DC samples, completed the gap 30 minutes after the voltage application. DC arcing caused dry bands on the insulator surface, thereby stopping the arc. Re-ignition of the arc occurred when the surface of the insulator became wet again. Similar observations were reported by Crespo- Sandoval et al [52].

The AC arc on the other hand, was more frequent and with time, it became weaker and faint except at the ground electrode. There were also two distinct parallel

channels of AC arc that were observed prior to reaching the ground electrode and only became one solid arc near the ground electrode. Crespo-Sandoval et al [52] also reported discharges branching out across the surface from the upper electrode. The samples were not cleaned after the test and the weight measurement did not show any significant difference.

To further understand and analyse the physical changes that are associated with material degradation, chemical analysis were carried out. The peculiar behaviour of the DC sample preventing arcing in the middle of the test was of special interest.

4.5 Material Physiochemical Analysis Results

4.5.1 Thermo-Gravimetric Analysis

The curves of Thermo-Gravimetric Analysis (TGA) and Differential Thermo-Gravimetric (DTG) are shown in Figures 4.19 - 4.22. The samples consists of virgin and aged samples of AC and DC voltages. The TGA curves of Figures 4.19 and 4.20 show all samples lost weight (decompose) at two stages. The first stage at roughly 220 °C corresponds to the release of the water of hydration from the ATH filler material. The second stage refers to the degradation of low molecular weight (LMW), cross-linked silicone elastomer and silica [45, 53].

Since the dehydration of the filler and the decomposition of the backbone occur at different temperatures, filler content can be estimated by measuring the weight loss of a small piece of sample as temperature increases. A closer examination of the TGA curves does not show any notable differences between AC and DC samples.

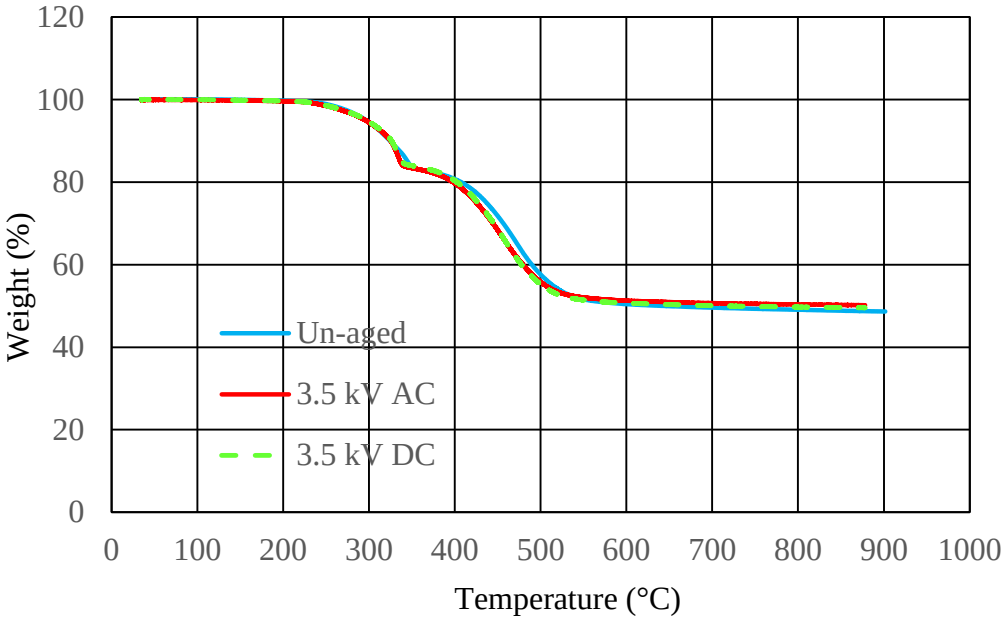


Figure 4. 19: TGA curves of 3.5 kV AC & DC aged and un-aged SiR samples.

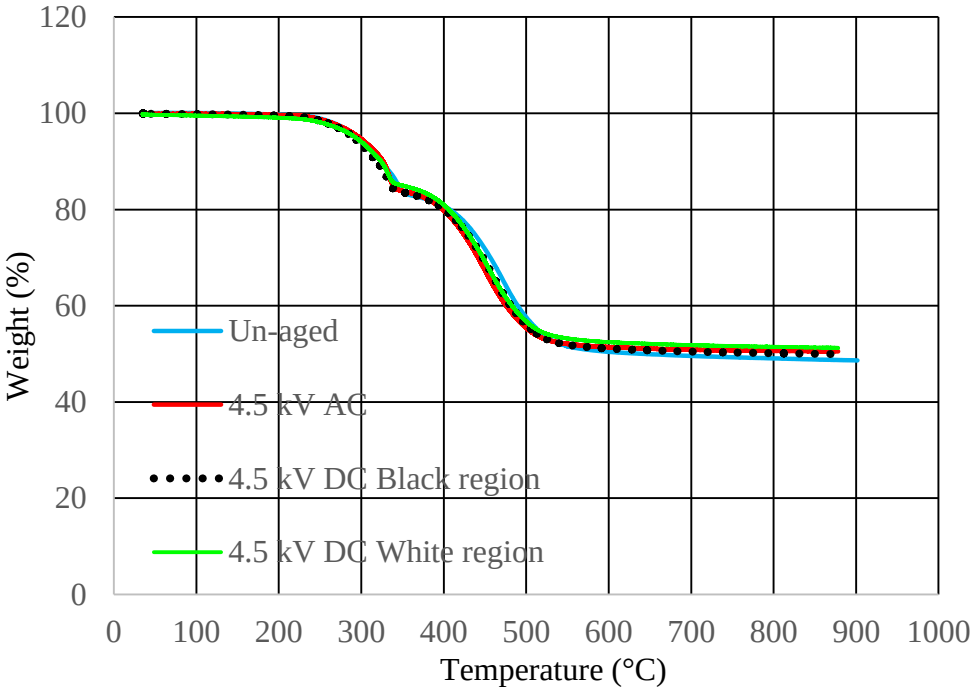


Figure 4. 20: TGA curves of 4.5 kV AC & DC aged and un-aged SiR samples.

The rate of degradation of 3.5 kV and 4.5 kV aged samples are shown by the DTG curves in Figures 4.21 and 4.22 respectively. In Figure 4.21, the first minimum peak (weight loss) of the curve refers to the release of the water of hydration from ATH particles. It is stated by Abdollahian et al [54] that 350 °C corresponds to the temperature at which the ATH filler material loses its water completely. The aged samples of 3.5 kV AC and DC showed nearly twice the weight loss of the un-aged sample at 330 °C. The assumption is that the aged sample lost most of the particles of the ATH filler. EDS analysis will be used to confirm the hypothesis that the aged samples of 3.5 kV AC and DC have a lower aluminium concentration than the un-aged sample. The second weight loss of Figure 4.21 corresponds to the SiR decomposition that occurs above 400 °C, which is the safe limit temperature of organic materials as explained in *section 2.3*. It is also apparent from the second weight loss of Figure 4.21 that all the aged and un-aged samples decompose at roughly the same rate with the DC sample showing an insignificant faster rate flowed by AC and the un-aged sample respectively.

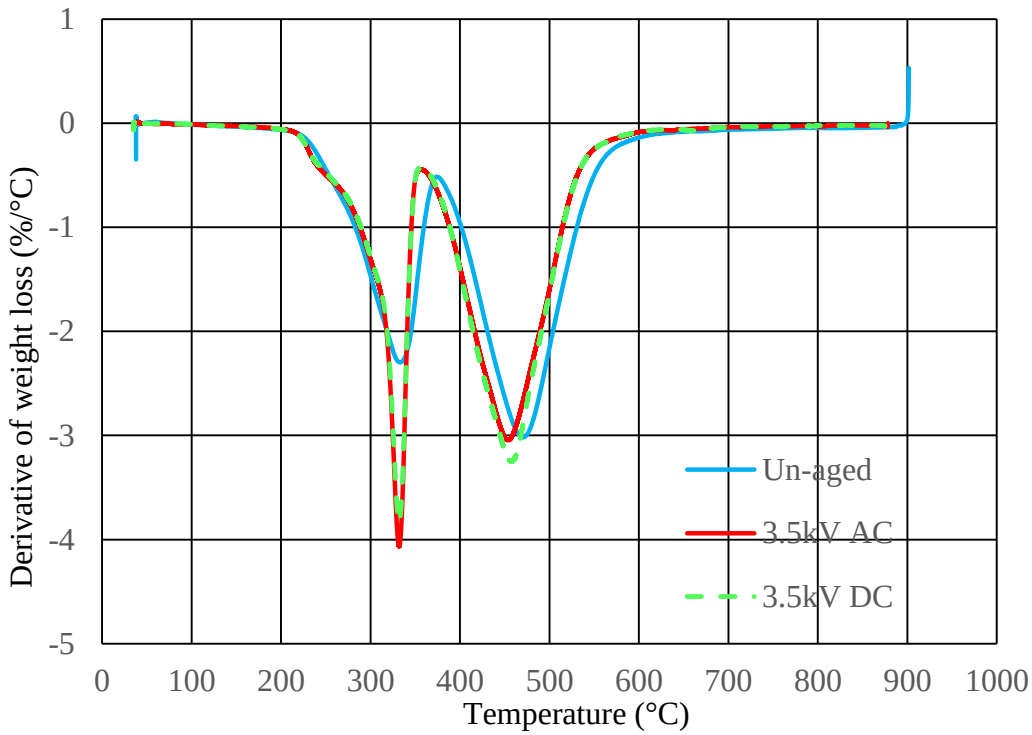


Figure 4. 21: DTG curves of 3.5 kV AC & DC aged and un-aged SiR samples.

The peaks of 4.5 kV AC and DC aged samples in Figure 4.22 followed the same trend as those of 3.5 kV aged samples in Figure 4.21. It is, however, interesting to note that the 4.5 kV AC sample shows a faster rate of decomposition at 330 °C followed by the samples cut from the black tracking and white erosion portion of the 4.5 kV DC sample. The two specimens cut from the 4.5 kV DC sample (black tracking and weight erosion) have about the same peaks. It must however be remembered that the DC sample of 4.5 kV stopped arcing after 1 ½ hours of the voltage application whereas the rest of the samples run for the whole 6 hour duration of the test. Therefore, the interpretation of the longer peaks of the 4.5 kV AC sample should put into context and should not be understood as a sign that the AC sample performed worse than the corresponding DC samples. Similar trends of the TGA and DTG curves in Figures 4.19 - 4.22 can be found in the literature [53-55].

The sharp peaks at the start and end points of the graphs in Figure 4.20 (b) are due to the sensitivity of the TGA instruments, which took some time to settle to a stable operation point.

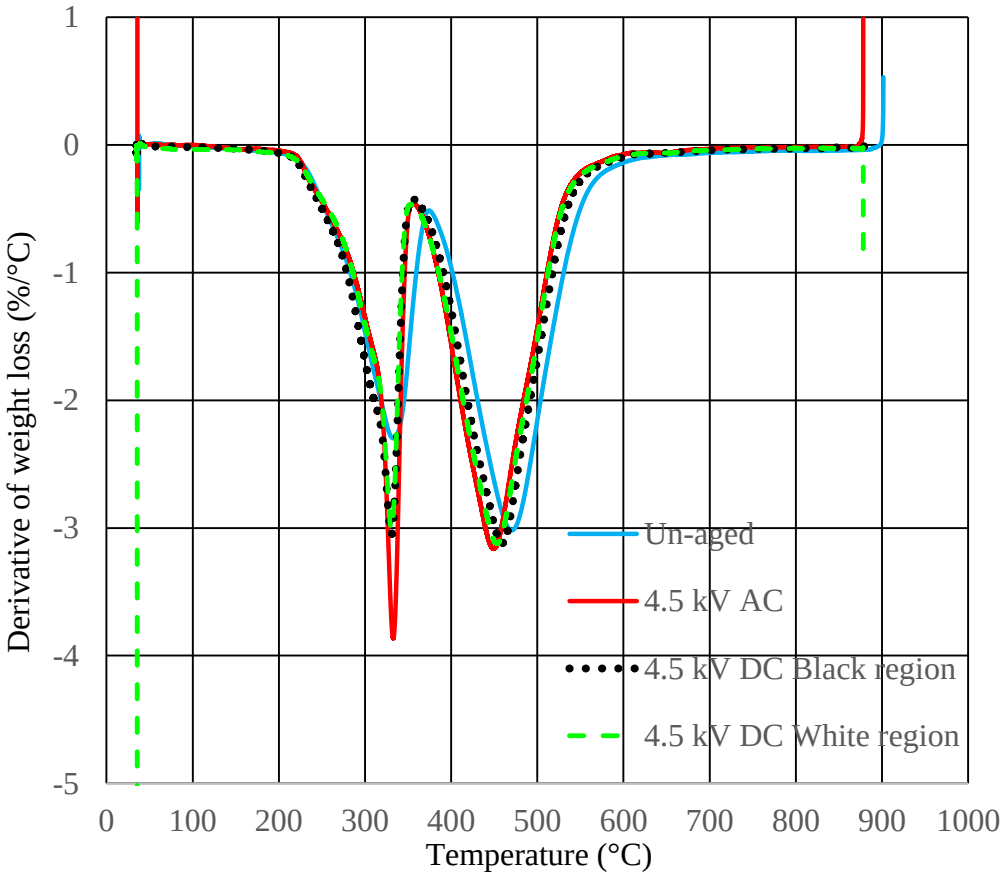


Figure 4.22: DTG curves of 4.5 kV AC & DC aged and un-aged SiR samples.

4.5.2 Fourier Transform Infrared (FTIR) Analysis

In order to simplify the analysis of the Fourier Transform Infrared (FTIR) results and also make the discussion more relevant, the characteristic absorption bands for various functional groups of HTV SiR insulators are summarised in Table 4.3. Although not every SiR sample will have the same characteristic absorption bands, it is nevertheless expected, that The FTIR spectra will contain most of the wavenumbers in Table 4.3.

Table 4.3: Characteristic absorption bands of HTV SiR insulators [14, 56-57].

Group	**Approximate wavenumber (cm^{-1})**
OH in Si-OH and ATH	3700 - 3200
CH in CH_3	2963-2960
Si-H	2507, 2280-2080
Functional group of ATH	2361- 2356
OH in H_2O	1640
Si-CH_3	1270-1255
Si-$(CH_3)_3$	1266, 1250-840
Si-O-Si	1100-1000
Si-O in O-$(CH_3)_3$	870-850
Si--$(CH_3)_2$	840-790
Si in Si -$(CH_3)_3$	700

The spectra for all the samples were recorded from 500-4000 cm^{-1}. The reference material in each case is the un-aged sample. The IR spectra of new and aged samples are shown in Figures 4.23 and 4.24. Figure 4.23 is the spectra of the 3.5 kV aged samples while Figure 2.24 presents the results of 4.5 kV samples.

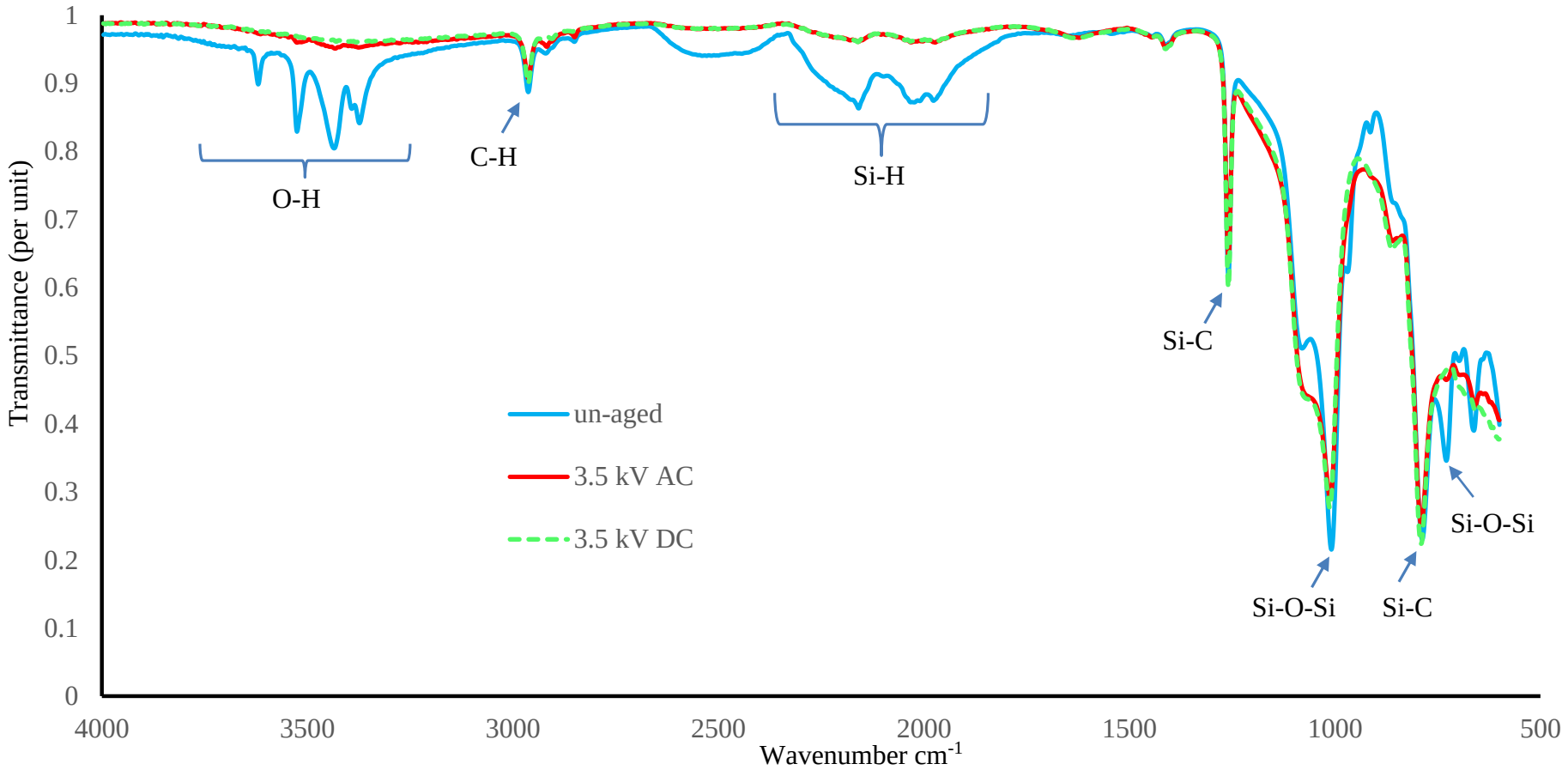


Figure 4.23: Infrared spectra of 3.5 kV AC and DC aged SiR samples with un-aged as the reference.

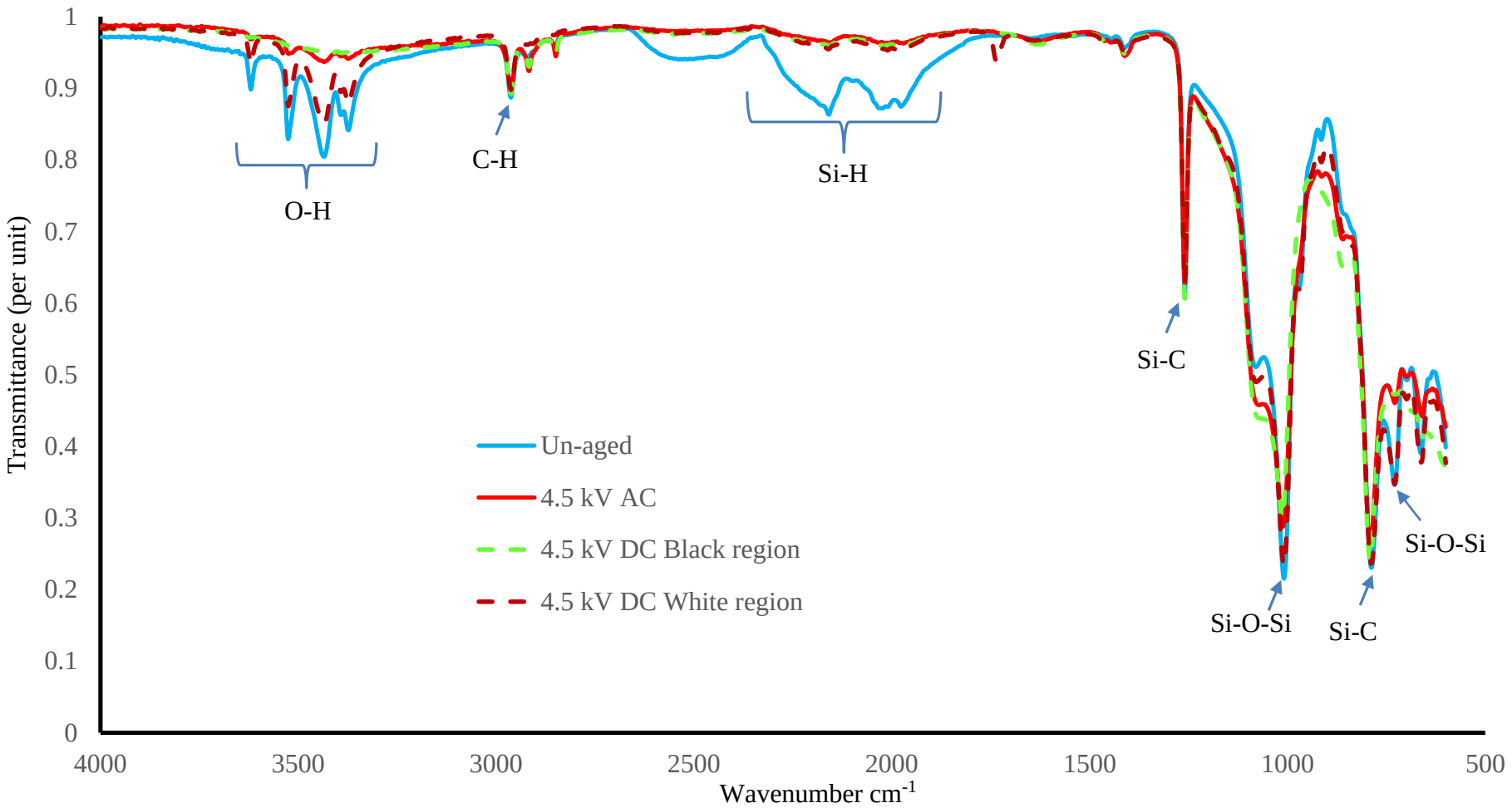


Figure 4.24: Infrared spectra of 4.5 kV AC and DC aged SiR samples with un-aged as the reference.

From Figures 4.23 and 4.24, it is clear that there are distinct absorption peaks between the aged and un-aged samples. A summary of the observed bands in Figures 4.23 and 4.24 are given in Table 4.4.

Table 4.4: Absorption bands of Figures 4.23 and 4.24.

Group	**Approximate wavenumber (cm^{-1})**	**Comments**
OH	3618-3373	within the ATH band
C-H bond in CH_3	2962.52	The stretching vibration of C-H bond in CH_3
Si-H	2507.34, 2160.17 and 2009.73	The stretching vibration of Si-H
Si-C	1259.45	Si-C stretch vibration of Si-CH_3.
Si-O-Si	1008.72	Si-O stretch vibration of Si-O-Si bonds.
Si-C	786.91	Si-C stretch from Si-CH_3 bond.
729.05	729.05	Si-O-Si rocking vibration

With reference to Figure 4.23, one can notice the decrease of the OH group from both ATH and Silanol (Si-OH) in the region of 3373-3618 cm^{-1}. It is suggested that the accelerating ageing of 3.5 kV AC and DC produces large amount of heat, causing the loss of moisture in the SiR samples. From Figure 4.23 it is also clear that there is no distinction between the 3.5 kV AC and DC samples in terms of their absorption peaks. As far as the chemical changes are concerned, 3.5 kV AC and DC samples have the same degradation although there were different physical changes observed as presented in section *4.4.* The 3.5 kV DC samples showed an extensive tracking compared to the corresponding AC sample.

However, what is immediately visible from the 4.5 kV DC and AC samples in Figure 4.24 is that there is a difference in absorption peaks between the whitish erosion part of the DC sample and the rest of the aged samples. The graph in Figure 4.24 shows that the material taken from the whitish portion of the DC sample has the same absorption peaks as the new sample at 3373-3618 cm^{-1}. This region lies in the ATH band [58]. The indication is that either chemical decomposition did not take place or the erosion removed the top degraded layer thereby exposing un-aged layer with the original chemical signature. In a study by [59], it is reported that dehydration of the ATH filler is characterised by a decrease in the absorption peaks of OH groups bonded with ATH in the interval 3700-3200 cm^{-1}. It is known that Alumina Trihydrate (ATH) filler is added to the base polymer of SiR in order to make it more heat resistant. However, above 200 ^{o}C, ATH losses its bond water leaving aluminium oxide (Al_2O_3) behind [60]. From the above, it can be inferred that the ATH filler material did not lose its bond water because the ATH particles in the region 3373-3618 cm^{-1} retained their characteristic peaks

It was observed that whitish portion of the 4.5 kV DC sample did not get wet (water droplets would quickly roll off). It is suggested therefore, that the intense erosion near the ground electrode effectively removed the carbonised conducting surface coating, thus restoring hydrophobicity. It is worth mentioning that most polymer materials contain carbon atoms which, due to tracking can form carbon conducting paths. If however, conducting carbon tracks could be removed without major erosion, leakage current would be inhibited [21].

It is clear that with the exception of the peaks due to the OH group, the rest of the absorption peaks of both figures are similar and therefore the same discussion analysis applies to both the Figures of 4.23 and 4.24.

Around 2962.52 cm^{-1}, there is a decrease in the intensity of the C-H peak. The formation of tracking due to the arc of the aged samples, modify the structure of the SiR polymer, by shrinking the chain of the polymer resulting in the harder spot on the surface of the SiR, this causes less vibrations of the C-H bond, hence the decrease in the C-H stretch intensity. It is also noticeable that this phenomenon also occurred in the white eroded area.

The region between 2507.34 - 2009.73 cm^{-1} shows disappearances of three broad bands from all the aged samples due to Si-H stretch. These disappearances can be attributed to the heat and arc generated as a result of 3.5 and 4.5 kV AC and DC voltage applications. Since there are only few Si-H bonds in the structure of the polymer, the bond is easily broken because of the high electron density of the silicone atom which has the tendency of attracting the lone electron from the hydrogen, thereby making the bond weak and susceptible to breakage.

Around 1259.45 and 786.91 cm^{-1} there is not much change in the peak intensity of the Si-C bond. This is due to the fact that Si-C form the skeleton of the structure of the polymer.

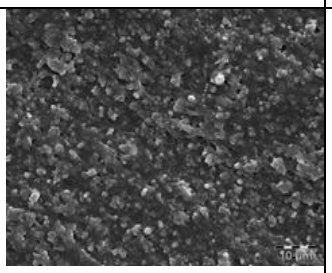
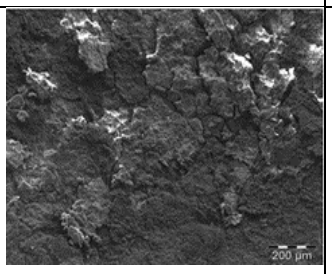
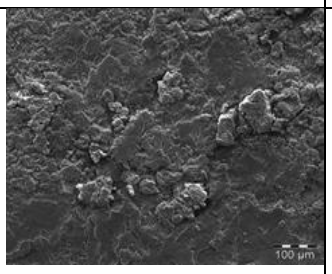
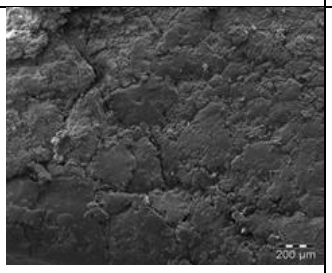
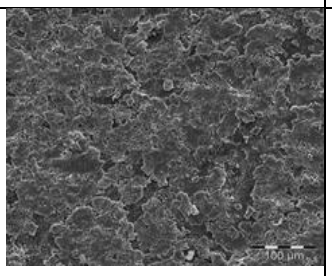
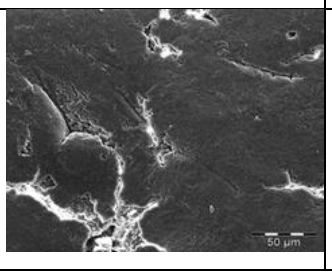
At a wave number of 1008.72 cm^{-1}, one can observe a slight decrease in the peak intensity caused by the Si-O stretch vibration. This decrease is not very significant since Si-O-Si constitutes the major skeleton of the polymer. However, in the region of 729.05 cm^{-1}, the peak of the Si-O rocking vibration has disappeared from all samples except the whitish portion of the 4.5 kV DC. Since the heat and arc modifies the structure of the aged SiR by making it more compact, rocking vibration becomes difficult for the Si-O bond.

In summary, the FTIR analysis results suggest that 3.5 kV_{rms} AC and 3.5 kV DC tracking cause similar degradation in as far as chemical composition is concerned; at higher voltages the phenomenon changes.

4.5.3 Scanning Electron Microscopy (SEM)

The SEM analysis showing the molecular structural changes on the surface of the specimens are summarised in Table 4.5.

Table 4.5: Summary of SEM images of the samples.

Specimen Identity	Image	Comments
New		Fine and uniform particles
3.5 kV AC		The surface has the most cracks and porosity
3.5 kV DC		The surface shows cracks and hills but it is relatively smoother than the 3.5 kV AC
4.5 kV AC		The surface shows less valleys and hills and it is smoother than the 3.5 kV samples.
4.5 kV DC Black tracking region		Has a finer and smoother surface particles.
4.5 kV DC White eroded part near the ground electrode		Has the smoothest surface profile.

The overall impression is that the virgin sample has fine and more homogenous surface particles whereas the aged samples show some degree of degradation, interestingly, the micrographs of the samples aged with smaller voltages of both AC and DC showed more valleys and hills compared to 4.5 kV of both AC and DC samples. Another observation is that the surface profile of AC samples show more porosity and cracks compared to DC samples. Why this is the case cannot be explained thus far. The eroded whitish part of the 4.5 kV DC has the least surface roughness of all the aged samples. This is in agreement with the FTIR analysis which showed that the filler material of the portion closest to the negative electrode has retained its bond water, thus behaving like a new sample.

To further compare and analyse the salient and subtle differences between AC and DC insulators of the inclined plane test setup, elemental composition of the samples are desired and presented in the next section.

4.5.4 Energy Dispersive Spectroscopy (EDS) Analysis

The spectra analysis of the samples using Energy Dispersive Spectroscopy (EDS) were performed and the results showing the elemental compositions are presented in Tables 4.6 and 4.7. The following abbreviations are used for the samples: N = new sample, 3.5A = 3.5 kV AC, 3.5D = 3.5 kV DC, 4.5A = 4.5 kV AC, 4.5DB = 4.5 kV DC Blackish, 4.5DW = 4.5 kV DC white erosion.

Table 4.6: EDS analysis in atomic percent (atomic %).

No.	C	Na	Al	Si	Cl	K	Ca	Cr	Fe	Ni	O
(1) N	19.16	--	7.02	8.32	--	--	--	--	--	--	65.5
(2) 3.5A	19.92	0.1	5.66	7.74	0.62	--	--	0.25	0.74	--	64.97
(3) 3.5D	19.59	0.21	4.5	7.45	0.59	0.05	0.07	0.58	2.39	0.13	64.43
(4) 4.5A	17.72	0.1	7.23	9.12	0.44	--	--	0.1	0.26	--	65.01
(5) 4.5DB	17.16	0.2	2.43	9.78	0.98	--	0.07	0.8	4.85	--	63.74
(6) 4.5DW	19.71	0.3	5.19	8.72	0.45	0.04	0.06	0.07	0.25	--	65.22
Max	19.92	0.3	7.23	9.78	0.98	0.05	0.07	0.8	4.85	0.13	65.5
Min	17.16	0.1	2.43	7.45	0.44	0.04	0.06	0.07	0.25	0.13	63.74
1= New Sample			**2= 3.5 kVAC**			**3 = 3.5 kDC**			**4 = 4.5 kVAC**		
5 = 4.5 kDC Black				**6 = 4.5 kVDC White**							

The atomic composition of the reference sample consists of carbon (C), aluminium (Al), silicone (Si) and oxygen (O). The aluminium originated from the ATH filler material. With the exception of 4.5 kVAC, all the other aged samples showed a decrease in their atomic concentration of aluminium with respect to the virgin sample.

The 4.5 kV DC black tracking, (sample 5), shows the highest drop of Al being 2.43% or a drop of 65% compared to the un-aged sample. Furthermore, all the aged samples indicate a reduction in oxygen concentration and again the 4.5 kV DC black tracking lost the most oxygen. With the exclusion of the whitish part of the 4.5 kV DC (sample 6), some difference in atomic concentration of the elements between AC and DC could be seen from Table 4.6. Firstly, the DC samples; 3 & 5 have lower carbon, oxygen and aluminium concentration compared to AC samples (2 & 4). Secondly, only the DC samples (3 & 5), show potassium and calcium elements and also a high concentration of chromium and iron compared to AC. This is possibly due to DC causing more corrosion of the electrode and the associated conductors. Although both the electrode and the crocodile clips that were used to

connect both the HV and the ground electrode were replaced prior to each new test, more corrosion of the tip of the conductors was seen in the DC samples. The corrosion effect of DC was also confirmed by Heo et al [12], who reported that DC causes more electrode corrosion than AC. In comparing AC and DC samples, the decrease in oxygen content of 3.5 kV DC and 4.5 kV DC black is attributed by [59] to be as a result of ATH filler dehydration upon exposure to high temperatures.

On the other hand, the whitish eroded portion of the 4.5 kV DC has a comparable carbon, silicon and oxygen concentration as the virgin sample. This is in agreement with the FTIR results which shows that the filler material of 4.5 kV DC whitish part, retained its bond water, in addition to SEM analysis showing its surface profile is closest to the new sample.

It was hypothesised in section *4.5.1* that the faster rate of decomposition of 3.5 kV AC and DC samples in Figure 4.21 is due to the complete dehydration of the ATH filler material at 350 °C. With reference to the Table 4.6, it is clear that Al concentration of 3.5 kV AC and DC samples is reduced compared to the new samples, which signifies the decomposition of the ATH filler material, thus confirming the hypothesis. The 4.5 kV TGA analysis also showed a similar trend and is confirmed by the reduction of Al seen in Table 4.6.

Finally, the ratios of the elements of different samples are shown in Table 4.7.

Table 4.7: Ratios of the EDS results (atomic %).

Sample Number	Sample Name	C/Si	C/Al	Al/Si	O/C	O/Al
1	**New Sample**	2.3	2.73	0.84	3.42	9.33
2	**3.5kVAC**	2.57	3.52	0.73	3.26	11.48
3	**3.5kDC**	2.63	4.35	0.6	3.29	14.32
4	**4.5kVAC**	1.94	2.45	0.79	3.67	8.99
5	**4.5kVDC Black**	1.75	7.06	0.25	3.71	26.23
6	**4.5kVDC White**	2.26	3.8	0.595	3.31	12.57

An important conclusion from the energy dispersive spectroscopy (EDS) results as presented in both Tables 4.6 and 4.7 is that the chemical composition of both 3.5 kV

AC and DC aged samples are different from the un-aged samples. However, the differences in chemical composition between the 3.5 kV_{rms} AC and 3.5 kV DC aged are marginal which suggest that these ageing stresses are comparable. A summary of the results obtained from the chemical analysis is given in Table 4.8.

Table 4.8: Summary of the chemical analysis results.

Voltage type	**V (kV)**	**TGA**	**FTIR**	**SEM**	**EDS**	**Comparing AC & DC**
AC	3.5	No difference	No difference	More porosity and cracks	Increased C. Reduced Al, Si & O	AC samples showed more porosity and cracks
	4.5	No difference	No difference	Moderate porosity and cracks	Increased Al & Si. reduced C & O	Showed more rougher surface than the 4.5 kV DC
DC	3.5	No difference	No difference	More porosity and cracks	Increased C. reduced Al, Si & O	Higher Ca, Cr, Fe & Ni
	4.5 Black	No difference	No difference	Less porosity and cracks	Reduced C, Al & O. Increased Si	Higher Ca, Cr, Fe and smoother surface
	4.5 White	No difference	ATH retained its bond water	Least porosity and cracks	Increased C & Si. Reduced Al & O	Smaller Cr & Fe, higher Ca and smoothest surface

An overall important conclusion from the physiochemical analysis is that the 3.5 kV AC and DC aged samples show a relatively similar surface morphology as well as chemical signature. All the material analysis tools used in this work such as TGA, FTIR, EDS and SEM have indicated that there is no notable difference between the 3.5 kV AC and DC samples. One exception is that the tracking of the 3.5 kV DC sample was observed to be excessive compared to the 3.5 kV AC sample. It is reasonable to suggest that tracking alone does not alter the chemical composition of aged samples unless there is erosion. It can also be argued that when comparative analysis of AC and DC inclined plane tests are desired, the 3.5 kV gives the closest correlation both from electrical and physiochemical perspectives.

At higher voltages (4.5 kV) the AC and DC degradation behaviour becomes diverge and cannot be compared.

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CHAPTER 5: CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

5.1 Conclusions

This research work was carried out with the aim of improving the understanding of the fundamental aspects related to the electrical performance of outdoor HV DC SiR insulators in polluted environments. A critical analysis of the available literature on the subject was presented and contradictions were pointed out. Post ageing chemical analysis were carried out and the results were analysed and presented in a systematic way. However, there were some constraints and challenges encountered while doing the experiments. These limitations included a lack of an appropriate thermal imaging camera for capturing the temperature of AC and DC samples on test, as well as the lack of a high speed video camera to capture the speed and shape of the arc. The ultimate goal was to make some kind of contribution to the establishment of a guideline, which is specifically written for DC polymeric insulators under the inclined plane test setup. The findings of this work can be summarised as follows:

i. The use of IV drip systems is a reliable alternative in carrying out the inclined plane tests as per the standard.

ii. There was a considerable voltage drop when five samples were connected in parallel. Testing one sample at a time reduced the voltage drops to acceptable levels as per the IEC-60587 standard.

iii. Leakage current under AC was inconclusive as far as its magnitude and the physical damage to the material is concerned; a large current and a big arc was observed but caused little physical damage.

iv. During the AC test, evaporation of the contaminant without accompanying insulator damage was observed and it was postulated that in AC samples, there is a protective vapour film between the arc tunnel and the sample

surface causing a relatively minor damage as opposed to DC samples where the arc breaches the protective film and is in direct contact with the insulator.

v. The hourly average leakage current of AC was constant, which indicates that surface resistance of the insulator did not change significantly.

vi. DC leakage current on the surface tracking activity is bigger (about 2 times) than that under AC for the same equivalent voltages. Furthermore, DC leakage current variations are less random and the average current increases with time of voltage application compared to AC which doesn't increase with time. The increasing trend of the DC leakage current symbolises a gradual decrease of surface resistance of DC samples.

vii. DC Leakage current showed an increased trend, which symbolises a gradual decrease of surface resistance in DC samples. Furthermore, the DC leakage current was consistent with the damage and followed a definite path.

viii. The inclined plane test results of 3.5 kV AC and DC are comparable as deduced from the physiochemical analysis of the test samples.

ix. The samples aged with 4.5 kV AC and DC voltages showed a contrasting electrical and physiochemical results with the DC voltage causing a greater material damage than the AC voltage.

x. The DC voltages caused non uniform damage on the insulator surface and this non-uniformity became more pronounced with higher voltages.

xi. When a sample is tested with a stiff 4.5 kV DC voltage, it stopped arcing by becoming an open circuit. Upon further investigation, FTIR analysis showed it had retained its hydrophobicity due to erosion that removed the carbon conducting channels.

xii. The leakage current failure criterion is used to compare the relative performance of DC and AC inclined plane test of silicone rubber insulators. If the tracking failure had been used, the DC insulators would have failed one hour after the voltage application. Although the DC current do not reach the 60 mA threshold value of failure criterion, it caused greater damage compared to the AC samples, which only showed minimum damage.

5.2 Recommendations

Although it is acknowledged that a lot of work still needs to be done in the knowledge area of comparing and contrasting AC and DC inclined plane tests of SiR insulators, based on this research work, the following can be recommended:

i. As stated in the IEC-60587 standard, it is essential that the voltage source is stiff and does not vary beyond 5% for the results to be credible.
ii. There is a good correlation of DC leakage current to material degradation and it is repeatable on condition that the voltage is tiff and the ripple is within the limits specified in the standard. Testing one sample at a time is recommended if the test equipment cannot meet the power requirements as outlined in the IEC-60587 standard.
iii. Reproducibility of AC leakage current and its correlation to material damage is still a challenge that needs further study. A comprehensive comparison of AC and DC SiR samples should include decoupling of the AC leakage current into its fundamental components.
iv. The thin vapour film between the arc and the sample of AC needs further investigation.
v. Testing AC and DC samples side by side gives a more comprehensive information in terms of the arc colour, shape, intensity, frequency and should be considered when comparing AC and DC samples.
vi. The failure criteria under DC inclined plane test should only be the leakage current being less than 60 mA and should exclude the tracking length criterion as this would not apply for DC SiR insulators.
vii. The 3.5 kV AC and DC samples performed relatively similar from electrical and physiochemical considerations. However, the concern is, the 3.5 kV might not necessarily give the most representative results since there are different breakdown mechanisms under AC and DC SiR insulators.

5.3 Future Work

One major concern of the AC inclined plane tests has been the reproducibility and repeatability of the test results. In this work, it has been shown that the DC inclined plane tests results is fairly repeatable provided that the ripple voltage is within the prescribed limits. However, further investigation is required to ascertain the range of voltage fluctuations under which DC results of the inclined plane tests are reproducible and repeatable. Under the AC tests, what appeared to be a thin vapour film between the arc and the surface of the insulator was observed. This phenomenon requires further investigation. The effect of the voltage magnitude in the inclined plane tests and how it relates to field experience is another area that requires further investigation. Furthermore, an appropriate thermal imaging camera and high speed video camera would add credibility to the test and would significantly contribute to the fundamental understanding of AC and DC inclined plane tests of SiR insulators and thus, should be incorporated for future studies.

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APPENDIX A – PARALLEL SETUP TESTS RESULTS

When five samples were connected in parallel, a frequent drop of the supply voltage was observed. The drop in voltage is due to the insufficient power rating of the testing machines such as HV test transformer, autotransformer and HV DC generator. Table A.1 shows a summary of the parallel setup test results.

Table A.1: Summary of parallel-connected AC and DC test results.

		LC (mA)	Tracking & Erosion	Tracking time
AC Voltage	3.5 kV	28	Minimum tracking and no erosion	2 hours
	4.5 kV	57	Moderate tracking and no erosion	1 ½ hours
DC Voltage	3.5 kV	----	Moderate tracking and no erosion	------
	4.5 kV	22	Moderate tracking and no erosion	1 hours

A.1 Parallel AC Tests

A.1.1 Accelerated Ageing Tests at 3.5 kV AC Samples

The results of the leakage current was inconclusive as far as tracking and erosion is concerned. The data logger recorded a relatively high current of 30 mA but it caused minimal material damage. Furthermore, the leakage current could not be correlated with the observed arcing intensity, in some instances, a smaller current would show a relatively big arc or vice versa with no corresponding tracking path. Renyu et al [50] also reported a poor correlation between arc current and the degree of sample damage. The high frequency of the AC could play a role, in that an instantaneous current that only lasted in fractions of milliseconds is possibly too fast to cause any noticeable damage. Another influencing factor was the supply

voltage. The source voltage often dropped beyond the recommended 5% that was stipulated in the standard. The voltage fluctuated between 2.8 -3.5 kV. The voltage fluctuation could possibly alter the dynamics of the leakage current as weak source cannot maintain the required load current. Figure A.1 shows a plot of the leakage current for the first 30 minutes, after which arcing could not be sustained by the weak supply voltage. Due to the frequent drops of the supply voltage, the test was terminated after two attempts. It was meaningless to continue the test under these conditions, as the test results would have been unreliable and the voltage fluctuation would not have been in conformity with the standard. Prior to stopping the test, an occasional faint arc that partly evaporated the liquid contaminant was observed.

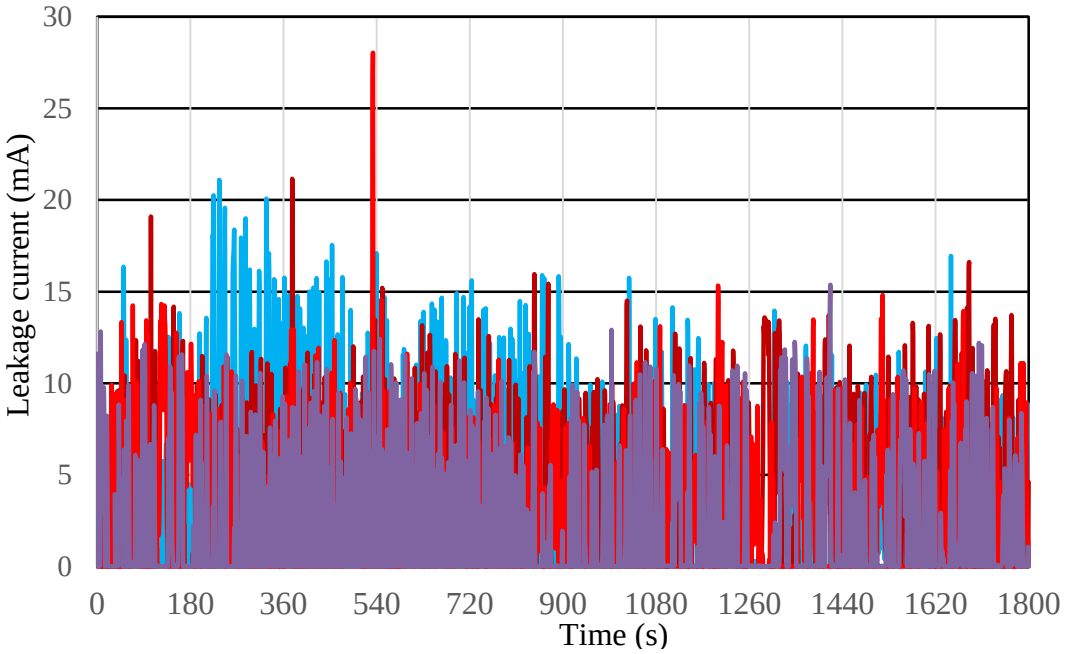


Figure A.1: Absolute Peak leakage currents of 3.5 kV AC samples.

A.1.2 Accelerated Ageing Tests at 4.5 kV AC Samples

Five samples were connected in parallel at 4.5 kV AC. There was significant leakage current fluctuations in the order of 80% accompanied by big voltage drops in the range of 10-20%. Figure A.2 is a plot of the leakage current for the five channels in the last three hours of the test. All the currents from the five channels are drawn on the same axis because the trend rather than the individual channel

currents are important. A maximum current of 57 mA was recorded during the test with the average current being in the order of 20 mA. The graph shows the peaks of the leakage current tending to increase in magnitude over time.

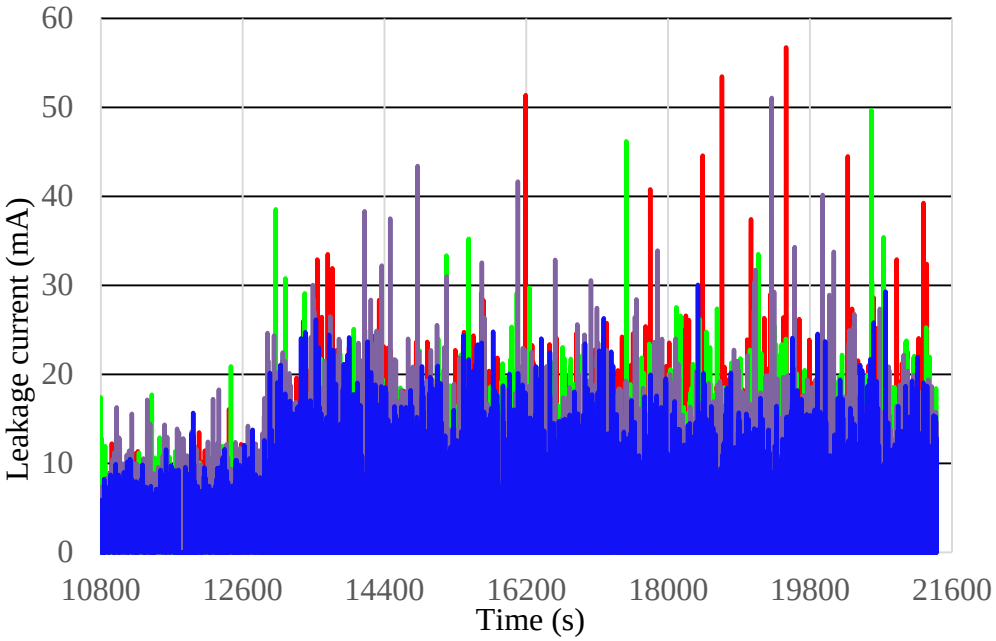


Figure A.2: Absolute Peak leakage currents of 4.5 kV AC samples.

A.2 Parallel DC Tests

A.2.1 Accelerated Ageing Tests at 3.5 kV DC Samples

The 3.5 kV DC was not conclusive and was abandoned after two attempts. In some instances the test ran for only 10 minutes before the supply voltage collapsed. The source voltage fluctuation was between 10-20% and that was a factor why the leakage current was inconclusive with respect to its magnitude and subsequent damage it caused. A similar scenario was reported by Chrzan [21], who tested five samples in parallel at 3.5 kV and reported that after one hour in to the test, the arc extinguished when the voltage had dropped to 2 kV.

A.2.2 Accelerated Ageing Tests at 4.5 kV DC Samples

The voltage was set to 4.5 kV and then connected in parallel with the five samples. A graph indicating the leakage current is shown in Figure A.3, the occasional voltage collapse was noticeable and sometimes dropped as much as 20%. The test lasted for 1 hour and 20 minutes before it was stopped when the voltage had collapsed to 2 kV. During this period of voltage collapse, the arc was extinguished and weak evaporation of the contaminant was observed.

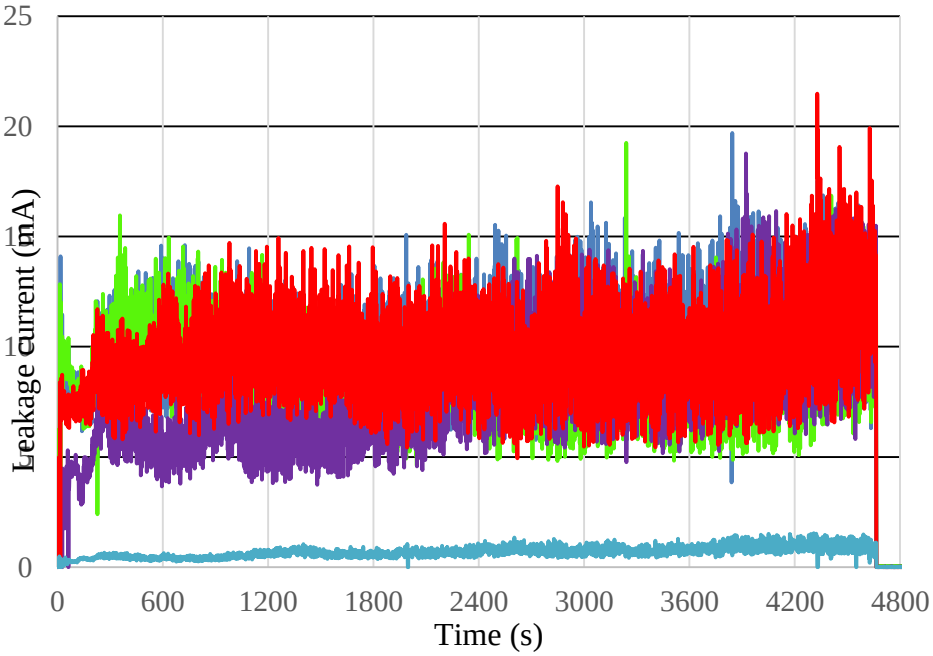


Figure A.3: Absolute peak leakage currents of 4.5 kV DC.samples.

In the first hour of the test, the current was relatively lower and the HVDC generator was able to supply the current. As the material damage became more pronounced, leakage current current had increased to a point where the generator could not sustain it, thereby causing the voltage to drop. To ensure stiff supply voltage that can be correlated to actual HV outdoor conditions where the power is infinitely large and less prone to voltage drops during the occasional insulator arcing, testing one sample at a time should be considered.

A.3 Influence of the Source Power on the Inclined Plane Test Results

A weak supply voltage can greatly influence the results of the inclined plane test as there is a considerable voltage drop during discharges. This makes the results of the data collected under weak supply voltage unreliable and with little correlation to service conditions where the power is infinitely large and less susceptible to voltage drops during the occasional insulator arcing. The IEC-60587 standard stipulates the testing of five samples either simultaneously or respectively on condition that the output voltage, which can be varied up to 6 kV, must not fluctuate more than ± 5%. The IEC-60587 standard further stipulates that the rated current of each sample must not be less than 0.1 A. Assuming all the five samples are tested simultaneously, the total output current drawn by the specimens must be at least 0.5 A. This requirement puts a stringent constraint on the power requirement of the testing transformer and may necessitate the use of high current autotransformer and HV power transformer. So far, the author has come across only two researchers that have tested one sample at a time in order to meet the requirements of the standard [19, 21]. In this project, a high voltage transformer of 5 kVA, 220 V/50 kV was used. The HV transformer was supplied by a 30 A autotransformer. The ratio of the HV transformer is 1: 227. The implication is that if five samples are tested simultaneously, the output of the HV transformer must supply 0.5 A, hence an input current of 114 A must be supplied by the autotransformer to the primary of the HV transformer. An autotransformer with such a high current rating is not common. A 30 A, 220 V autotransformer was the highest current rating that was available in the laboratory and even that could only meet the current requirement of one sample only. The current rating of one sample, namely, 0.1 A will translate it to 23 A input current to the HV transformer, which the autotransformer must supply.

One obvious solution is to use a HV transformer with low turns ratio such that the difference between the input and output currents of the HV transformer is not that big. In this research the maximum RMS voltage was 4.5 kV and as a result, only 19.8 V is required on the input side, which is nearly $1/10^{th}$ of 220 V or the full number of turns of autotransformer. While in theory that is not a cause for concern,

in practice, at least 2/3 (two-thirds) of the regulating windings must be utilised for a satisfactory operation. Therefore, not only a high current regulating transformer must be used but also the voltage ratio of the HV transformer must be such that 67% of the regulating windings are utilised [61]. This could be achieved by using a HV transformer with a low magnification voltage, such as 1:30 and it will also greatly reduce the magnitude of the input current.

The power rating of the DC supply is even in more precarious situation as DC generators are not known for their high power capabilities. Some authors incorporated a shunt capacitor across the output terminals of the HV DC generator as remedial measure of making the supply voltage stiff enough during insulator arcing [17, 62]. However, there is a risk of the capacitor suppressing the arc re-strike [21] and thereby giving a false notion that the insulator has a superior electrical performance. The results of a weak supply voltage that cannot meet the requirement of the load current is unreliable and misleading for both AC and DC voltages. Moreover, the sinusoidal waveform of a weak AC source becomes distorted once arcing of the insulator is initiated [21]. Whatever solution is chosen, as far as possible, every attempt should be made to reproduce the service conditions that are prevalent in the field.