Study of Degradation of Composite Insulators at Material Interfaces

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Abstract

Degradation of composite insulators at material interfaces

High-voltage (HV) outdoor composite insulators used in transmission lines are made of two polymers, comprising the core and housing, bonded together with metallic end-connections. The interface between these polymers is parallel to the electric field, which makes the insulators more prone to interfacial problems at these common points [1]. If interfacial ageing occurs, degradation and catastrophic breakdown can result [2]. Therefore, the design reliability of outdoor composite insulators depends on the high-strength bond between the core and the housing [3],[4]. Research findings by Kutil and Froshlic [5] indicate that delaminated areas, cavities and/or micro cracks in the medium are enough to initiate streamer discharges along the interface that are capable of degrading both insulating materials. The heat, UV radiation, and high-energy electrons produced from such discharge activity resulted in the growth of carbon paths along the interface, known as ‘tracking’, ultimately causing failure [6].

This investigation focuses on the development of tracking between silicone rubber and epoxy resin, with a view to replicating the tracking phenomena seen within composite insulators in service. A fine wire is placed between the dielectrics materials to enhance the local electric field magnitude and initiate discharge processes. The resulting partial discharge (PD) activity has been monitored. This Information has been used to understand the inception and propagation of the interfacial tracking. A strong relationship was found between maximum PD magnitude and track length. PD patterns and unique detailed images of the interfacial tracking development, allowed identification of the growth characteristics of interfacial channels and phases of tracking growth. Furthermore, a correlation in the mechanisms of interfacial degradation was found between the lab-fabricated samples and commercial composite rods. Finally, a growth model of interfacial ageing has been developed with the information from FEA models, PD patterns and the detailed images of tracking growth. The physical structure and chemical analysis of interfacial tracking is also disclosed to provide an insight into interfacial ageing mechanisms that occur in the composite insulators under electrical stress.
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Dedication

I would like to dedicate my humble effort to Hanna, Nuri, Sam and Eli because they are my source of inspiration and the great motivation that keeps me going!
“Trust in the LORD with all your heart, and lean not on your own understanding; in all your ways acknowledge Him, and He shall direct your paths.”

THE BOOK OF PROVERBS
Chapter 3, verses 5 and 6 (NKJV)
Introduction

Electric power must be delivered from the power plant to the consumer. Overhead lines are essential for long-distance transmission, and use high-voltage (HV) outdoor insulators to support the line conductors, whilst preventing leakage current flow to the metallic support tower[7],[8].

There are three main types of insulator materials for this application: ceramic, glass and composite (polymer) [8]. Glass and porcelain insulators provide outstanding dielectric and thermal properties, but due to their brittle characteristics and their weight, they are being replaced by composite insulators in more and more locations [9],[10]. Composite insulators normally have a weight of about 10% of their glass or porcelain equivalents, making handling easier, reducing breakage and damage during construction, lowering the overall installation cost of overhead lines as well as offer better vandal resilience [7],[11].

HV composite insulators have been developed over many years with better electrical and mechanical performance. Their performance is now comparable to ceramic and glass insulators. General Electric introduced the “non-ceramic / non-glass insulator” in 1959 for transmission of 138 kV [12]. The development of the non-ceramic non-glass insulator, known as the polymer or composite insulator has increased throughout the power transmission and distribution system since that time. However, these insulators are still subject to the inherent electrical, mechanical and environmental stress of the working environment.
A common composite insulator consists of a core-rod made of Glass-fibre Reinforced Polymer (GRP), which gives mechanical strength to the insulator — providing a high tensile stress level of 690 MPa [11]. The sheath of composite insulators is designed to protect the core-rod by surrounding it with an elastomer such as Silicone Rubber (SiR). This ensures excellent protection of the GRP rod against environmental pollution and UV rays [12],[13], and exhibits excellent performance in heavily-polluted environments [7],[14]. Other materials can be used, and at lower voltages cheaper materials such as Ethylene Propylene Diene Monomer (EPDM) and Ethylene-Vinyl Acetate (EVA) are widely deployed. The weather-sheds of most high voltage composite insulators, also known as the housing are made of SiR. The sheds are used to lengthen the surface creepage distance, which is required to avoid the development of an external arc when conditions are wet or involve ambient pollution [11]. This housing has high temperature resistance (up to 300 °C) and maintains its resilience even at low temperatures (down to -50 °C)[15]. At both ends of the composite insulator are attached metal fittings, which are made from cast iron or aluminium. The metal fittings are firmly fixed to the core by swaging (crimping) or gluing [8],[11]. Finally, a corona ring is an extra device to control electrical stress at the energized end, which are generally only used in systems at voltages of 230 kV and above [16].

1.1 Interfaces in outdoor composites insulators

Morshuis [17] defines the term interface as “a surface forming a common boundary of two bodies, spaces, or phases”. A distinctive characteristic of composite insulators is their many interface areas, which can be classified as microscopic or macroscopic [18]. Both cases need to be considered carefully, since these regions can lead to interface problems from several ageing mechanisms. According to Janssen et al. [19], there are four different types of interface in the structure of composite insulators:
- **Microscopic**: those small areas separating two different materials (resin/glass-fibres)

- **Macroscopic**: those large areas between two different insulating materials (core/sheath)

- **Internal**: within the insulation matrix

- **External**: solid surface at the rainwater/surrounding air interface

Kamer and Ieda [1] highlighted that the microscopic interfaces are always internal, whilst the macroscopic interfaces may be internal or external. For example, the microscopic interface is typically related to the components formed during the manufacturing of the rod with its glass-fibres and the epoxy resin to form the rod-core.

Comparatively the external macroscopic interface will always refer to the surrounding air, pollutants or the formation of rain-water films on the surface of the composite insulator. While the internal macroscopic interface refers to the interface between two solids which form the composite insulator, i.e. the glass-fibre rod and the polymer sheath [1]. Figure 1-2 illustrates the macroscopic and microscopic interfaces. This research focuses on the interfacial degradation at the internal-macroscopic interface formed by the sheath and the core.
In addition, in the macroscopic interfaces there are two triple points, firstly between the sheath, the metallic fitting and the air. The second triple point is between the core, the sheath and the metallic fitting where the intensity of the electrical discharges at the sheath, core-rod and metallic end fitting can produce degradation of the seal (Figure 1-3), allowing moisture ingress to the core. This is a critical problem in design consideration because it is the weakest point in the insulation system [1]. It is, therefore, crucial to achieving good bonding of the sheath to the core, and the seals at the metal ends, as this interface appears to be responsible for many of the reported moisture-ingress-related insulator failures [12].
Moreover, if moisture or defects are present at the core/sheath interface, internal tracking can occur because the resins used in the glass-fibre composite form carbon deposits in the presence of electrical discharges, as Figure 1-4 and 1-5 shows. The insulator’s electrical/mechanical strength can be compromised with conductive or semi-conductive carbon deposits along the interface [20],[21]. If interfacial tracking extends along a substantial length of the insulator, it may result in flash-under failure [2],[18].

Figure 1-4. Interfacial tracking development and failure reported in composite insulator in service [2]

Figure 1-5. Interfacial tracking due (a) moisture ingress into the rod and (b) internal cracks [21]
Furthermore, due to the nature of the insulator (opaque colour) and a large interface in composite insulators, interfacial tracking is difficult to detect or monitor visually than surface tracking because it is invisible from the outside of the equipment, unless in a very advanced state, when the insulator parts are affected by carbonized areas that are particularly large, increasing the local temperature (see Figure 1-6) [2],[22].

Degradation at the core/sheath interface becomes visible only after interfacial tracking through the housing has already progressed to its final stage [23]. These interfacial mechanisms of degradation have been reported for as long as this type of insulator has been used. The reliability of polymeric insulators depends on a strong interface, since the presence of moisture or defects at the core/sheath interface can lead to breakdown, as Figure 1-7 shows [18],[23]. This is a point of concern for the utilities, because during production, especially at the manufacturing stage, routine tests that ensure that polymeric insulators are free from internal defects are not yet devised.
1.2 Motivation and purpose of this project

It is evident from field experience that insulator failures are located at the core-to-sheath interface, due to electrical and mechanical stress, or to non-uniform fields, resulting in interfacial breakdown [1],[17],[24]. The reasons for interfacial ageing remain poorly defined [17]. An insufficient quality of the core-to-sheath interface appears to be responsible for the interfacial tracking failures since internal discharge activity may occur due to internal defects such as voids, micro-cracks, and delaminated areas [25],[26].

These events give rise to the consideration of several aspects that influence the degradation between the core and the sheath. For example, outdoor composite insulators are subject to various dynamic mechanical loads, causing material fatigue, allowing the loss of the hoop tension, and de-bonding of the sheath within the composite insulators [27],[28],[29]. Moreover, loss of adhesion at the core/sheath interface was seen due to an increased internal gas pressure from discharge activity, promoting the formation of micro-cracks due to thermal stress [25]. Thermal shock and stress failure occurs when the temperature in a structure is very different between two or more regions causing uneven thermal expansion [30],[31],[32]. This, over time, will result in increasing the crack and delaminated areas [4],[25]. These ageing events allow enhanced electron mobility in high field regions, generating high energy electrons, and resulting in internal discharge activity at the rod-to-sheath interface [1]. Tanaka observed that interfacial defects will reduce an insulator’s life by 75% due to the associated partial discharge activity that enhances the electric field in surrounding areas, degrading the internal macroscopic interface and causing precipitate insulator failure [3].

The traditional view of service failure is that these ageing events cause an enhancement of the local field, resulting in internal discharge activity at the rod-to-sheath interface [2],[16],[33]. This, in turn, forms conductive carbon deposits in the resin matrix as a result of high-energy electron discharges [20],[26]. The subsequent development of conductive carbon along a substantial length of the insulator may result in either a flash-over or flash-under [2],[23]. The development of conductive
tracks along surfaces has been actively studied by both commercial and academic organisations for many years [34]–[41]. Tracking test procedures exist for the evaluation of insulating materials due to degradation by surface discharges [38],[42]–[44], and models have been developed to understand their growth and propagation [4],[45]–[52].

However, regarding interfacial ageing, there has been little effort to develop interfacial tracking growth models. Presently, there are no standards, guidelines, or test procedures in the area; there is a need to evaluate interfacial ageing in order to optimise the design of composite insulators, to protect various components that are connected to the system, and to provide asset management tools for utilities [22],[53].

The purpose of this project is to study in detail the growth and propagation of tracking that occur at the core/sheath interface in composite insulators in service, due to electrical stress and loss of adhesion between the core and the sheath. Therefore, test methods and procedures for sample preparation were designed and developed, in order to obtain consistent and repeatable test results. Two experimental facilities were developed, allowing for the study of interfacial tracking growth [54],[55]. The first experimental system consists of a full-scale, long-rod configuration, to replicate the electrical stresses that composite insulators may experience while in use. The second experimental system used planar insulating materials to study the effects of pressure between the core and the sheath materials. Furthermore, in both experimental systems, silicone rubber and epoxy resin were used to mimic the structure of composite insulators. A stainless steel wire of 45 μm thickness was placed between the dielectrics to enhance the local electric field magnitude. This generated partial discharge activity capable of initiating the growth of interfacial channels.
1.3 **Aims and objectives**

The main objective of this project is to establish models of tracking at the interface of two different polymeric materials. The growth characteristics of interfacial tracking as a function of the applied voltage, field enhancement and the loss of bonding between the core-to-sheath interfaces in long-term tests were also studied. In addition, the research is intended to:

- Design an experimental facility where full-scale, long-cylindrical samples that mimic composite structures can be tested to study the interfacial ageing that takes place in composite insulators in service. Moreover, with the aid of the Finite Element Analysis (FEA) design an electrode configuration, where the earthed electrode will not interfere with the growth of the interfacial tracks. The model includes a stress control device to eliminate electrical stress at the HV connection, with the aim to reduce the background noise lower than 5 pC at 50 kV.

- Develop a second experimental facility to investigate the degradation that is caused by the loss of adhesion between the core and the sheath. Furthermore, analyse tracking growth characteristics whilst varying the interfacial pressure.

- Design a FEA model of the electric field magnitude and distribution in the presence of a metal defect between two polymer materials.

- Develop a simple/consistent method for sample preparation and assembly of a two-layer structure with an electrode sandwiched between the two dielectrics, able to initiate electrical discharge activity at the interface. The pressure between the materials must be variable and the dimension of the samples will be in centimetres.

- Record images of the progression of interfacial degradation, whilst partial discharge data is used to identify partial discharge inception voltage and monitor the level of interfacial degradation.
• Combine information from partial discharge data and images of the tracked areas to establish phases of growth, including relationships between tracking growth according to partial discharge magnitudes and patterns.

• Identify growth characteristics of interfacial channels, in order to understand the mechanisms of degradation that occur at the interfaces.

• Develop methods to monitor interfacial degradation in commercial composite rods using partial discharge magnitudes and patterns to monitor tracking growth.

• Analyse the physical and chemical structure of interfacial tracks.

This thesis is disclosed in chronological order, to highlight the steps of the aforementioned aims and objectives that were achieved. The limitations and difficulties experienced whilst developing the test methods and procedures to fabricate and assemble samples are also discussed; so these procedures can be implemented for future investigations that aim to study interfacial degradation. They will also help in establishing procedures and tests methods that can be used as tools to diagnose existing/new insulating materials. This will result in new designs and more consistent insulation systems, thus improving the life of insulators in service.

1.4 Contributions of this project

The main achievements in this project are the development of two experimental facilities that allow the investigation of interfacial ageing in polymeric materials. The FEA models determined the threshold field magnitude required to enable the growth of interfacial tracks. Moreover, a novel methodology was developed for the purpose of fabricating and assembly of samples (cm-size) to mimic the structure of composite insulators. This approach overcomes problems associated with traditional small scale tests using samples of 2 to 10 mm in which the electrode configuration change the propagation rate of tracks as they grow. In this project, the test geometry was designed to allow the tracks to grow in a constant field unaffected by the earth
electrode. So, once initiated by the artificial tip of the electrode, the track is able to propagate in a constant field. Furthermore, the geometry of the samples used and the transparent nature of epoxy resin allowed for the direct observation of interfacial damage, as it progressed between the epoxy and silicone.

Other achievements obtained in this research project are summarized as follows:

- The two experimental facilities were developed, allowing for the study of interfacial tracking growth as a function of mechanical pressure; applied voltage and field enhancement.
- A consistent and reproducible methodology was developed to fabricate and assemble the two layer sample structure.
- Quantitative measurements of tracking growth between two dielectrics and the resulted partial discharge patterns were analysed. Therefore, it is possible to determine the level of interfacial degradation from partial discharge patterns and magnitudes.
- A theoretical model was developed to understand the mechanisms of degradation that take place at the core/sheath interface.
- A correlation in the mechanisms of interfacial degradation was found between the lab-fabricated samples and commercial composite rods.
- An analysis of the physical and chemical structure of interfacial tracking allowed detailed nano-chemical maps of the interfacial tracks.

The outcomes of this research provide test methods, procedures, FEA analysis, and growth models of the interfacial tracking, to increase knowledge about the mechanisms of degradation at the core/sheath interface. Thus, the information provided in this study contributes to the establishment of tests procedures and guidelines for assessing, or improving the designs of interfaces in HV insulation systems. In addition to the achievements mentioned, this project has yielded two conference and one journal; the details of which are disclosed in the Appendix.
1.5 Structure of the thesis

This thesis is divided into eight chapters and is organised as follows:

- **Chapter 1 — Introduction**
  This Chapter provides an overview of the structure and design of composite insulators; a summary identifies the areas of investigation. It also presents the aims and objectives for the study.

- **Chapter 2 — Literature review and background**
  Chapter two identifies the structure and properties of the materials used to form the composite insulator. The ageing mechanisms that occur at the core-to-sheath interface, as a result of electrical discharge activity are identified. Previous work on interfacial tests and the limitations of that work are also reviewed.

- **Chapter 3 — Initial developments of experimental design**
  In this work, great effort has been put to standardise experimental facilities to investigate interfacial degradation that occurs in composite insulators. This Chapter provides details of the developments of two well-controlled experimental systems for planar and cylindrical experimental systems. Furthermore, it shows the stages of development of the experimental method. Each procedural step is then described as challenges arose, and also how they were overcome.

- **Chapter 4 — Materials used and sample preparation**
  This chapter describes the types of structures and materials used to investigate the interfacial tracking. The assembling processes also provide information on how to place the components to form a specimen for testing. Finally this chapter suggests the method to prepare samples for testing commercial rods.
• **Chapter 5 — Experimental results**

Chapter five provides the results obtained in each experimental structure described in chapter three. The stages of growth and the characteristics of interfacial channels are identified, which help to understand the factors involved in the initiation and development of interfacial tracking. Furthermore, experimental results presented here contribute to the development of growth models, which are proposed to assess the quality of interfaces in composite polymeric insulators.

• **Chapter 6 — Physical and chemical analysis of interfacial tracking**

Chapter six presents the physical and chemical characteristics of the interfacial erosion/tracking formed on epoxy resin and silicone rubber. Optical and Laser Scanning Microscopy were used to investigate the physical structure of the tracks formed on epoxy resin and silicone rubber plaque. On the other hand, spectroscopic techniques such as AFM-IR, ATR-FTIR and Raman spectroscopy was utilised in this investigation to identify nano-chemical maps of interfacial tracking between epoxy and silicone rubber.

• **Chapter 7 — Growth models for interfacial ageing in composite insulators**

A theoretical model is presented, after partial discharge magnitudes and patterns from both experimental systems are analysed. In addition, partial discharge inception voltage and FEA models helped to quantify the electric field needed to initiate interfacial tracking.

• **Chapter 8 — Discussion, conclusions and future work**

The growth characteristics, conditions, electric fields and voltage required to cause ageing events in composite insulators are further discussed in this Chapter. The conclusions and outcomes achieved in the present study are presented. Finally, areas for future work are identified and discussed.
Chapter 2

Literature review and background

2.1 Introduction

This Chapter reviews the structure and design of HV outdoor composite insulators as well as the degradation process that outdoor composite insulators experience in service. The insulating materials used are critical to ensure a strong and reliable composite insulator structure [53]. Therefore, the selected materials used for the glass-fibres core and Silicone Rubber (SiR) sheath must be compatible to avoid reduction of the dielectric strength or the development of cracks at the interfaces [4], [56]. Furthermore, the loss of adhesion between the core and the sheath due to relaxation of materials at the interface, and resulting in de-bonding areas is capable of enhancing the local electric field strength, leading to internal discharge activity [1],[24],[57]. Consequently, achieving a good chemical bond to the core surface is vital to ensure a strong and reliable composite insulator structure [4],[30].

2.2 Design and materials used for commercial insulators

The insulating materials used in HV composite insulators provide low weight and vandalism resistance [8]; but the major advantage is their high dielectric strength with excellent mechanical properties [4], and long-term endurance with a wide operating temperature range [11], to withstand high temperatures during service or under stress conditions [7],[11],[16],[33]. All these factors significantly increase the reliability of insulators in heavily-polluted areas, giving distinct advantages compared to ceramic materials [14],[16].
The design and materials used for commercial insulators highly depend on the operating voltage, environmental conditions. The International Electro-technical Commission (IEC) 60815-3 standard [58], provides specific guidelines for polymeric insulators in certain pollution environments for the creepage distance, which is measured along the surface of the insulator between the metallic end-fittings (given in mm/kV). The surface creepage distance is increased by changing weather-shed, diameter, thicknesses and spacing; depending on pollution severity and moisture exposure [8],[12]. Moreover, the dimensions of composite insulators are classified by the dry-arc distance, which is the shortest path between the metallic end-fittings (see Figure 2-1) [58]. Table 2-1 provides information about the dry-arc distance at different operating voltage.

<table>
<thead>
<tr>
<th>Nominal operating voltage (kV)</th>
<th>36</th>
<th>66</th>
<th>132</th>
<th>230</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulator length (mm)</td>
<td>440</td>
<td>720</td>
<td>1340</td>
<td>2180</td>
<td>3560</td>
</tr>
<tr>
<td>Core diameter (mm)</td>
<td>16</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

In the insulator design, the electric field magnitude and distribution is also considered, and this is normally highest at the HV end [20],[26]. The field distribution can be controlled by increasing the creepage distance, when the working voltage is lower than 230 kV [62]. In an operating voltage of 230 kV and above a corona ring are implemented for stress control at the HV end [20]. Whereas at 400 kV and above corona rings are fitted at both ends of the composite insulator [63],[64],[65].
2.2.1 Materials used for polymeric HV outdoor insulators

The properties of the materials used in HV insulation are critical to the reliability of insulating systems. Polymer material is divided into three main groups according to their structure: thermoplastic, thermoset and elastomers [56]. Thermoplastics are reported to have low water uptake but can melt under the increment of temperature (polyethylene (PE) and polyvinylchloride (PVC)) [30]. Thermosetting are the opposite: they will not melt under higher temperatures but chemically degrade (epoxy resin typically softens at 75 - 100 °C); moisture uptake is a problem (epoxy resin (EP), polycarbonate (PC)) [66]. Elastomers can resist high temperatures of up to 600 °C and its main property is moisture repellence (silicone rubber (SiR)) [56],[67]. Thermosets (epoxy) and thermoplastics can be used to form the core [10]; both use glass-fibres. Figure 2-2 shows the components to form the HV composite insulators, mainly composed of a pultruded glass-fibre core for the core and elastomeric weather-shed that covers the core of the insulator [11],[12],[53].
Figure 2-2. Shows the three main components to form the composite insulator: the glass-fibre core, SiR housing and metal end-fittings

**a) The pultruded glass-fibre core**

The core is manufactured with glass-fibres embedded with an organic resin, either E-glass or ECR-glass fibres are used. The latter is corrosion resistant [12],[21],[53]. The resin matrix consists of either polyester or epoxy resin and the rod is pultruded. The size of the glass-fibres affects the bonding of the resin matrix, since the number of fibres influences the ability of the core to bear continuous mechanical and dynamic loads in tension, bending or compression [68]. The tensile strength of the rod therefore depends on its diameter: greater glass content means that the insulator can sustain a greater load. The composite insulator core typically consists of a 60 – 75% fibre weight fraction, so in the cross-section of a 16 mm diameter GRP rod there are roughly 800 thousand fibres [29].

The core-rod is typically crimped to the metallic end-fitting, which is then protected by polymeric housing, including weather-sheds [9],[13],[69]. This is because the core alone is not suitable for outdoor high voltage application as it is susceptible to degradation by environmental and electrical stress [11],[12],[14].

**b) The SiR housing**

Silicone rubber is widely used for the housing of HV outdoor composite insulators, because SiR exhibits excellent hydrophobicity (water repellency), which prevents films of water from forming on the surface of the insulator [70],[71],[72]; thereby increasing
resistance to electrical discharges and consequently avoiding erosion of the sheath [53],[70],[73]. SiR maintains its hydrophobic surface for a much longer time than the EPDM samples [72], this is the main reason why SiR material is preferred to be used in heavily-polluted environments: It provides a high surface resistance, even in the presence of moisture and contamination. Therefore, SiR reduces the incidence of insulator breakdown, because it provides a long-term ability to limit leakage current [71],[72],[74]. These materials have been improved to create outstanding housing materials over the past few years [71], and have been tested in polluted areas [73]. The industry has implemented additives and inorganic fillers in the SiR compounds [75]–[81], to improve the properties of the insulator, such as Alumina trihydrate filler (Al₂O₃·3(H₂O)) this provides better resistance to tracking and erosion [72],[82] and Silica filler (SiO₂) improves the mechanical strength of silicone compounds and reduce costs of production [83].

2.2.2 The assembly process

In the manufacture process of medium, high and very high voltage composite insulators have several types of designs and manufacturing methods to assemble the core-rod, housing and metal end-fittings [29],[58]. The composite core is surrounded by a housing made of a selected elastomer. The elastomer can be moulded directly onto the core before or after the metallic end fittings have been attached to the core [69]. Generally, silicone rubber is classified either as Room Temperature Vulcanised (RTV) or High Temperature Vulcanised (HTV) curing rubbers [15].

a) Injection moulding method

The injection moulding method involves two moulding processes: (i) low-pressure injection that uses low viscosity silicone rubber and (ii) high-pressure injection moulding that uses high viscosity silicone rubber [84].
i. The low-pressure injection method used unfilled silicone rubber with insignificant injection pressure. Low viscosity silicones do not contain fillers, so it is considered as a soft elastomer. Hence, the manufacturer does not recommend this type of composite insulators for very high voltages or for a high pollution environment, as this product is easy to erode under surface discharges [10].

ii. The high-pressure injection method uses high viscosity filled silicone rubber, which is injected at high pressures above 150 MPa [29]. The fillers act to strengthen the silicone material in order to withstand erosion degradation under continuous electrical discharge activities (dry-band arcing) on the surface [10],[69]. The mould used for the moulded process can be seen in Figure 2-3.

![Mould for Low-Pressure Injection](image1)

![Mould for High-Pressure Injection](image2)

Figure 2-3. (a) mould for low-pressure injection, (b) full housing moulded into the core by high-pressure injection [29]

b) Extrusion method

The extrusion manufacture method is used for medium and high voltage insulators. The pultruded glass-fibre rod is first made and impregnated with a primer over its surface and heated at 70 °C. After this, silicone rubber is supplied to an extruder and used to form a sheath on the core-rod. The weather-sheds are manufactured in a separate mould and placed onto the sheath later, as Figure 2-4 shows.
Once everything is in place, the whole assemblage is vulcanized for 10 minutes at 120 °C, which allows the bonding for all three parts of the insulator (core, sheath, and sheds) [85],[86].

Some manufactures vulcanize the sheath and the weather-sheds separately, and then at the final stage the metallic end fittings are attached to each end of the insulator. However, during the vulcanization process the applied temperature is critical, as it can damage the core [29],[69],[85]. The sheath and the weather-sheds can vulcanize at temperatures between 120 - 160 °C for a maximum period of 70 minutes. The high vulcanization temperatures exceed the glass transition temperature of the resin-and-hardener mixtures used to form the composite core, meaning that the core can soften and deform. Thus, by improving the hardener material, the glass transition temperature of the core increases from 170 to 190 °C. Through this, the core can resist deformation at higher temperatures in the manufacturing process, particularly during the demoulding of the full insulator structure at the end of the fabrication process [69],[84]. The core can also be deformed or cracked if the metal end fittings are fastened to the GRP core, before the core is jacketed with the sheath [69].
c) **Bonding mechanisms between the sheath and the core**

The bonding mechanisms between the sheath and the core are critical and two techniques are used to enhance this bonding in the manufacturing process. The first and most widely used involves vulcanizing the silicone rubber of high temperatures and effectively producing a strong cross-linking bond between the core and the sheath. The second method, which causes more concern with regard to degradation at the interface, involves the use of high strength primers to adhere the core to the sheath in order to achieve long-term stability of interfaces in composite insulators [3]. It is crucial that the primer/adhesive agent used has high performance and resistance to electrical stress [87]. Furthermore, it must be compatible with the materials used to bond and the cure temperature of the material. While there are several types of adhesives, epoxies or elastomeric-based adhesives are predominantly used in composite insulators.

In addition to this, the presence of defects/contaminants on the surface will reduce the contact area for the adhesives and the bonding strength of the adhesive agent, as it will be difficult to achieve an even contact between materials. Consequently, the loss of adhesion energy tends to generate crack propagation, affecting pressure-sensitive adhesives’ bonding strength in the long-term [15].

Silopren-1-1 LSR and primer TP 3790 have been used in composite insulators. A single application of the primer solution can be applied to a clean and degreased surface of the core by brushing, spraying or dipping. It results in the formation of a uniform film once the solvent has evaporated after drying at room temperature for approx. 30 minutes [15]. Thereafter the primer agent will form a strong bonding to the GRP core during the vulcanization process [88].
2.3 Factors that affect the material properties in composite insulators

It has been previously discussed that a composite insulator is manufactured with two different polymeric materials for the core and the housing with a metal connection. The presence of these jointing regions can lead to interface problems, as interfaces between two materials with different dielectric characteristics can result in accumulation of local charge \[89],[90]\ making the insulators vulnerable to interfacial problems at these common points \[1\]. Tanaka \[3\] reviewed the ageing of polymeric and composite materials based on their interfacial performance. It was highlighted that interfacial aging processes in composite insulators are complex due to a large number of ageing factors such as: (i) electrical discharge activity from high/non-uniform fields at the interfacial region \[24\], (ii) mechanical loads/stress that insulators have to encounter in service \[27\], or/and (iii) local thermal degradation due to electrical and mechanical stresses \[1\],[17],[24\]. These stresses are serious threats to the interfacial degradation due to the effect of one stress over another \[3\],[7\]. The following sections discuss these factors in order to understand the ageing mechanisms that occur at the core-to-sheath interface, which affect the reliability of materials used in outdoor composite insulators in service.

2.3.1 Electrical effect

Polymeric materials used for HV outdoor insulation are determined by their dielectric strength in order to insulate the current flow from conducting components to the ground \[8\],[14]. Thus the dielectric strength of a polymeric material is a highly considered property in the design of HV insulating systems, as this determines the maximum electric field magnitude that the polymer can bear without suffering a puncture or breakdown \[14],[16\]. However, the dielectric strength in the interface at the composite structure is lower than the bulk of each insulating material. This makes the macroscopic interface prone to the development of interfacial tracking or breakdown events \[1\],[3],[25\]. This is usually caused by a high or non-uniform electric
field magnitude within the core-to-sheath interface, which can initiate internal discharge activity [6],[26]. Whereas an increment of leakage currents flowing within or over the surface of the insulator will result in corona discharge or dry-band arcs, consequently accelerating the interfacial ageing processes [45],[53],[91].

In HV outdoor composite insulators leakage currents and the non-uniform electric field distribution plays an important part in polymer material degradation [14],[73]. If the electric field strength and leakage currents are excessively large or non-uniform in certain areas, these electrical stresses will compromise the longevity of the insulator [34],[72],[92],[93]. Even small but repetitive discharge activity can cause permanent degradation of the solid dielectrics, leading to mechanical failure of the entire insulator [42],[73]. The IEC 60060-1 standard [94] have divided electrical discharges into two main groups: disruptive and non-sustained disruptive discharge, allowing a clear distinction between electrical discharge activity in composite insulators in service.

a) Disruptive discharge

Disruptive discharge occurs when insulation fails under electrical stress; the discharge bridges the insulation completely and results in a collapse of voltage. This means that the voltage between electrodes drops drastically, collapsing practically to ‘zero’. A disruptive discharge in a solid dielectric produces permanent loss of dielectric strength whereas in a liquid or gaseous dielectric the loss may only be temporary. To reflect these differences, disruptive discharges are classified depending on the medium in which they take place [94].

When disruptive discharge occurs in a gaseous or liquid dielectric it is called a “sparkover”. Disruptive discharge through a solid dielectric is called a “puncture” while a “flash-over” describes disruptive discharge over the surface of a solid dielectric [94]. According to Hampton’s criterion [95], a flash-over will occur if a discharge across the dry-bands extends over the wet surface of the insulator. After dry-bands arcs are formed, they can develop into a flash-over if the resistance per unit length of the discharge is lower than the resistance per unit length of the electrolyte (liquid
contaminant) on the insulator surface. Usually, this requires at least 100 mA to reduce the resistance of the rest of the insulator surface [45],[96]. The accumulation of pollutants over the insulator surface causes an increment in the leakage current magnitude above 100 mA along the insulator surface. The leakage current and discharge intensity will continue to develop throughout the insulator, until flash-over occurs over the polluted and wet surface [95],[97].

**b) Non-sustained disruptive discharges**

Non-sustained disruptive discharges occur when the insulating material is only momentarily bridged, either by sparks or localised arcs. During these discharges the voltage across the solid dielectric decays temporarily. Depending on the characteristics of the dielectric material, it may fully recover its strength and insulating capabilities. However, if non-disruptive discharges occur repeatedly over long periods of time, they will gradually age the material and eventually lead to a disruptive discharge.

The typical types of non-sustained disruptive discharges that affect the reliability of the composite insulators in service due to a non-uniform electric field in a localized area are (i) dry-band arcing, (ii) corona and (iii) partial discharge within the solid dielectric. These discharges are only partial and local as it does not bridge the electrodes [94]. The long or short-term discharge activity of the insulator may be significantly affected, causing the degradation of the polymer material [20],[98],[99].

**(i) Dry-band arcing**

The formation of dry-bands arcing is mainly due to leakage current flows over wet polluted surfaces of a composite insulator. Dry-band arcing is a self-sustaining discharge. It can result in a high leakage current level, which determines the severity of the surface degradation of the housing, leading to a flash-over [42],[45],[93],[96]. The Joule heat raises the local temperature on the insulator’s surface as dry-band arcing continues with local surface temperatures in the range of 260 to 400 °C [72], leading to
either the erosion of the sheath exposing the core [82], or in the accumulation of layers of residues composed of substances such as cristobalite $\text{SiO}_2$, moissanite $\text{SiC}$, organic hydrocarbon and carbon amorphous deposits, due to the thermal decomposition [38],[93],[100].

\text{\textbf{(ii) Corona discharge}}

According to the IEC 60270 – 2001 [101], corona discharge is classified as a partial discharge, it normally takes place around the electrodes. Corona discharge is initiated when the threshold value of 30 kV/cm is exceeded, at this magnitude the electric field intensity is high enough to ionize the surrounding air around the electrodes [102],[103],[104]. The ozone, nitrogen oxides and acids from corona discharge activity will chemically age the surface of the insulating materials [7],[105], resulting in several types of material degradation such as crazing, cracking, chalking, tracking and erosion [4],[16],[42]. These ageing mechanisms cause permanent degradation on the polymeric materials, shortening the life-span of the composite insulator [20],[26], [97],[98],[99].

Corona discharges are formed due to a large or non-uniform electric field magnitude, which results in high-energy electrons in avalanches. This leaves positive / negative ions and space charges around the HV electrode. Corona discharge can be visible including luminous glows and haloes, spots, brushes, or streamers. The development into these different modes is based on factors like the electric field intensity, gas medium, and discharge condition. For example, discharge plasma appears as a streamer channel discharge, which is caused by the presence of a higher number of positive ions in the tip of the HV electrode with high luminous glows and low current in the range of micro to milli-amps [104],[106]. Corona streamers are characterized as non-thermal plasma, with high-energy electrons (1 – 5 eV), which ionize the gas around at ambient temperature [107].
The streamer criterion is related to electrons in the avalanche due to a high electric field magnitude, sufficient to cause ionization by collision with atoms and molecules in the air [104],[106],[107]. Gallimberti [106], identifies two different regions of ionic space charge, where the corona streamers develop based on their condition, these are classified as passive and active regions. In the active region, the new ionization takes place at a sharp electrode (tip of the needle) encouraging streamer discharge activity, where avalanches develop under a high electric field. It is noteworthy that the ionization is only high in the active region, so a new avalanche can be produced; hence the charge in the tip of the electrode is high due to a higher potential energy [106],[107].

(iii) Partial discharge

Partial discharge (PD) might initiate a short-term and localized electrical discharge activity and it does not directly result in breakdown or insulator failure. However, PD activity always indicates that the insulator is subject to a process of degradation. The discharge activity within or on the surface of the insulator is normally due to a local non-uniform electric field [6],[91]. The accumulation of slight damage from very small PD pulses are enhanced by internal defects, e.g., voids, air-filled cavities, delamination or de-bonding [17],[20]. Partial discharge has the most influence on the interfacial degradation, as repetitive discharges form conductive carbon deposits in the resin matrix [25]. Carbon paths along the rod-to-sheath interface may grow to extend across a significant length of the polymeric insulator, and eventually lead to failure [26],[47],[97].
2.3.2 Mechanical effects

Outdoor composite insulators in-service encounter various dynamic mechanical loads that involve compression/tension from external sources, e.g., vibration from the wind or bending whilst installing the insulators in transmission towers. Long-term mechanical loads are strongly associated with dynamic loads (Aeolian vibrations, sub-span oscillations and conductor galloping). This affects the performance of the material and causes deformation of the polymeric material, this effect is known as “material fatigue,” which lowers the material strength or cause failure due to repetitive dynamic stresses [3],[27]–[29].

- Material deformation under mechanical stress

Under various mechanical loads/forces the polymeric material can be compromised to reduce the mechanical integrity of the insulator until failure happens [29],[87]. The deformation (strain) of the material can occur under tensile stress which elongates the material or under compressive stress resulting in a lateral expansion of the material [30]. In either case the elastic deformation may disappear once the applied stress is reduced or removed [108]. The arrows displayed in Figure 2-5 indicate the direction of the compressive or tensile stress.

![Figure 2-5. Material under (a) compressive and (b) tensile stress](image-url)
The load (stress) sustained by the polymeric material, which is directly proportional to the area where the load is acting upon, can be expressed as \( \sigma = \frac{F}{A} \), where the stress (\( \sigma \)) can be tensile or compressive, (\( F \)) is the applied mechanical force that spreads over the area (\( A \)) of the sample, and the units are N/m\(^2\), psi or Pa [108],[109].

**Tensile strength**: describes the capacity of a material to stretch before the fracture point, so the tensile strength of a solid material is associated with the yield point when a material breaks and fails [87],[110].

**Compressive strength**: the capacity to deform materials under compressive loads, in which the material tends to expand in lateral directions. However, the molecules of solids are tightly bonded and molecular mobility is limited. Thus, materials can only change the shape but not their volume under compressive loads, this is regarded as incompressible to a certain extent depending on their molecular mobility [108],[111],[112].

- **Mechanical strength of materials**

Young modulus determines the stiffness of the material and the stress required to deform the solid material, whilst Poisson’s ratio is related to the deformation of material under compressive stress [110]. Table 2-2 displays the mechanical properties of the materials used in this project.

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Epoxy resin</th>
<th>Silicone rubber</th>
<th>E-Glass-fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (GPa)</td>
<td>2.35 – 3.07</td>
<td>0.005 – 0.02</td>
<td>75 – 85</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.35</td>
<td>0.45 – 0.50</td>
<td>0.21 – 0.23</td>
</tr>
</tbody>
</table>
Table 2-3 displays the mechanical strength properties of the materials used in this project, which allowed the comparison between the strength and load capacities of these materials under elastic deformation.

Table 2-3. Mechanical strength properties of materials investigated in this project [110],[113]

<table>
<thead>
<tr>
<th>Mechanical strength properties</th>
<th>Epoxy resin</th>
<th>Silicone rubber</th>
<th>E-Glass-fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (MPa)</td>
<td>45 - 89.6</td>
<td>2.4 - 5.5</td>
<td>1950 - 2050</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>10 - 40</td>
<td>10 - 30</td>
<td>4000 - 5000</td>
</tr>
<tr>
<td>Yield stress (MPa)</td>
<td>36 - 71.7</td>
<td>2.4 - 5.5</td>
<td>1100 - 1600</td>
</tr>
<tr>
<td>Ultimate stress (MPa)</td>
<td>30 - 77</td>
<td>7 - 20</td>
<td>3300 - 3450</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>1.8</td>
<td>1450</td>
<td>4.8</td>
</tr>
<tr>
<td>Fracture strength (MPa√m)</td>
<td>0.4 - 2.22</td>
<td>0.03 - 0.5</td>
<td>0.5 - 1</td>
</tr>
</tbody>
</table>

**Yield stress:** the maximum stress reached that a material can withstand before its shape and dimension are permanently deformed [87],[110].

**Ultimate stress:** the limit strain before the polymer breaks and fails. At this stress point, material deformation is evident, thus the material will not return to its original size/shape [87].

**Elongation:** the extent to which a material has stretched at the moment of failure. The polymer has deformed permanently, so the size and shape of the solid dielectric have changed under this tensile strain. For instance, epoxy resin has the lowest percentage of elongation because it is brittle, whereas unfilled silicone rubber can be stretched from 500 to 1000% elongation without being permanently deformed [108],[109].

**Fracture strength/toughness:** refers to the resistance of fracture propagation, and it is defined by how quickly a crack can propagate in a material under tensile stress. Polymers with low fracture toughness can fail with brittle fracture. However, if the fracture toughness is high, then the polymer will fail by ductile fracture [110].
It is noteworthy that the relationship between strain and stress changes with the influence of temperature, and determines the characteristics of the polymer; such as soft-strong (elastomer), hard-brittle (thermoset), or soft-tough (thermoplastic) [30],[109]. Figure 2-6 shows the tensile toughness “true stress - strain curve” of epoxy resin. It can be seen that the strength of epoxy resin decreases with the increment of temperature, and epoxy becomes brittle at low temperatures [114].

![Figure 2-6. Shows the tensile toughness of epoxy resin under the variation of temperature [114]](image)

The stress-strain curve also determines the material properties. In a steep slope the material resists deformation or has a high tensile modulus. A gentle slope shows a low tensile modulus or an easily deformed sample. Glass-fibres have the highest tensile modulus, elastomers have the lowest, and thermoplastics in between [87],[109].
• **Mechanical deformation in composite structures**

When an excessive tensile stress is exerted on the resin matrix; the resin matrix transfers the load to the glass-fibres, causing voids or micro-cracks around the fibres [87]. As the cracking continues, it will also expand to break the glass-fibres.

These deformations in the core change the load transmission between the fibres and matrix. So, the load from the broken fibre will affect the adjacent fibres due to shearing of the load stress until these break as well, decreasing its effectiveness as there are less intact fibres to support the applied load. This initiates an unstoppable chain wherein each broken fibre damages the healthy fibres in its surroundings, causing cracks in the core, and ultimately initiating internal discharge activity [29].

Figure 2-7 displays the model of the fracture between the fibres and matrix, decreasing the elastic modulus of the entire composite structure. As the fibres break and create micro-cracks in the matrix that will continue to grow under a constant applied load. Micro-voids can form around the fibre, the propagation of the voids will result in cracks and delamination between core and sheath [87].

![Image of fracture model](image-url)
- **Influence of the mechanical stresses in interfacial discharge**

As discussed above, outdoor composite insulating materials are subject to various mechanical stresses. Thus, dynamic motions can cause a loss in the sheath hoop tension that directly affects the adhesion of the sheath to the core [24],[57],[115]. Furthermore dynamic motions, loads or movements in the structure of the insulator, contribute to form large voids at the core/sheath interface due to weakened material, leading to splits/cracks at the interface. Therefore, de-bonding areas and the growth of the cracks at the core/sheath interface, will promote internal discharge activity leading to the formation of tracking or erosion of the sheath (from the inside). Depending on the intensity of the internal discharges, tracking may develop or the sheath may be pierced, allowing water ingress to the core/sheath interface; leading ultimately to failure [1],[24],[57].

### 2.3.3 Thermal effects

Organic polymeric materials consist of carbon and hydrogen compounds, which comprise the main structure of the polymer [56]. Generally polymers used for HV applications provide a great dielectric strength and thermal properties to withstand temperature rising during service, since thermal stress is a serious threat and compromises the polymer structure leading to thermal decomposition [42],[45],[92],[93].

For example, HV outdoor composite insulators are exposed to high electric field; as the AC field alternates, charges oscillate back and forth, and may cause dielectric losses, resulting in incremental heating in local areas [109]. Thus, as a material’s temperature rises, they can degrade or carbonize, leading to failure by thermal fatigue [7],[30]. Three main thermal effects concerning the polymeric decomposition and interfacial ageing are reviewed as followed:
a) Non-uniform heating and polymers degradation

When a HV outdoor composite insulator experiences non-uniform heating, it results in local expansion in some areas. Similar materials with different thermal coefficients of expansion will change dimensions at different rates [116],[117]. Non-uniform expansion can result in material fatigue by stressing the material or material boundaries and causing delamination, de-bonding or the polymeric material to stretch and break even if the stress does not exceed the material’s yield strength [31]. In addition, material fatigue can also occur during contraction as the material cools down [30],[32].

b) Thermal degradation by thermolysis and photolysis

Continuous electrical discharge activity, such as corona discharge or dry-band arcing on the surface, and partial discharge at the core/sheath interface can result in local temperature rises [7],[34],[39],[118]. Polymers such as epoxy resins can degrade under the high temperatures generated through such mechanisms initiating polymeric decomposition [39],[42],[93] Thermal degradation can take place through thermolysis and photolysis degradation that occurs in the presence of oxygen. Figure 2-8 shows the model of degradation under pyrolysis temperatures and UV photon energy, the decomposition reactions produce low molecular weight volatiles, ultimately leading to ablation of the material, erosion and then tracking [39],[118].

Although polymer degradation is the result of multiple stresses, including thermal degradation, it is observed that free radical formation is the main factor in the ageing process. In addition, Tanaka noted that eroded areas in polymeric materials had a smoky appearance, supporting the hypothesis that thermal degradation is the key degradation pathway [6].
Exposure to high temperatures and thermal stress commonly results in the oxidation of polymeric materials as the first stage of thermal decomposition [30],[87]. Oxidation of hydrocarbon polymers by surface discharges typically manifests in the detectable formation of hydroxyl moieties, carbonyl groups, and free radicals. A prerequisite for oxidation is the presence of oxygen, at the external macroscopic interface, which is related to surface tracking [119].

Bolliger and Boggs [119] proposed that when a considerable amount of oxygen is present in the interface, for example air inclusion/trapped or de-bonded areas, then species are formed as a result of free radical mediated oxidation, such as carboxylic acids. These chemicals reactions are a result of the intermediate peroxide and carbonyl formation, which are products of interfacial oxidation [120]. Shimizu and Laurent [121] presented a similar model of the auto-oxidation processes that takes place in the presence of molecular oxygen in a micro-cavity.
As Figure 2-9 shows, the auto-oxidation process involves the loss of a hydrogen atom in the polymer structure, due to thermal stress. Moreover, the reaction of a free radical with oxygen (peroxy type ROO\(^*\)) will result in the production of hydro-peroxide. Then many hydro-peroxides degrade reproducing free radicals as follows: ROOH → RO\(^*\) + *OH. When this process occurs repeatedly, the polymer chain breaks. Whilst, RH + *OH → R\(^*\) + H\(_2\)O reaction is followed by hydrogen atoms abstraction. As Figure 2-9 shows, the main key in the auto-oxidation process is the presence of oxygen molecules that encourages the continued formation of new free radicals, by the following propagation steps: R\(^*\) + O\(_2\) → ROO\(^*\) and ROO\(^*\) + RH → ROOH + R\(^*\).

![Figure 2-9. Model of the auto-oxidation process presented by Shimizu and Laurent [121]](image)

The resulting unpaired electrons are highly reactive radicals, and the presence of oxygen molecules encourages the continued formation of new free radicals. As a consequence, free radical oxidation is a molecular degradation process which directly affects interfacial tracking. In the auto-oxidation process of epoxy resin, the C–C, C–H and CH\(_3\) groups are combined with OOH and OH groups that were formed in the oxidation reaction due to the electrical stress.
Chapter 2

2.4 Ageing mechanisms at the interfaces

The following section will discuss the aspects of interfacial degradation between two non-homogenous dielectrics. Most composite insulation system failures appear at the interfaces between two insulating layers due to electrical stress, non-uniform fields at the interfacial region and thermal stress will result in interfacial degradation [1],[24]. The union of two different materials allow areas of weak contact between them, leading to interfacial problems such as: space charge accumulation, interfacial polarization and dielectric losses [122],[123]. The difference between the flow of charges at the interface of two solid dielectrics as well as the electrical discharges at the interface results in permanent interfacial degradation [1],[124]. This might be due to the fact that the dielectric strength in the interface is lower than the bulk of each polymer, this increases treeing/tracking sensitivity at the interface [121].

It was observed that electrical tree development can be encouraged at higher voltages in a shorter time, which is dependent on the electric field enhancement and electron avalanches from the HV pin electrode [121]. The electron energy increases with a localised high field, this suggests that high-energy electron development for polymeric material degradation can only occur when the electric field enhancement is above the ionisation value [122].

2.4.1 The influence of defects in interfacial discharge

Ageing at the interface of two solid dielectrics is associated with localised high electric field that is formed at conductive elements or interfacial defects such as voids, micro-cracks or delaminated areas. According to Morshuis [17] the presence of voids, gas-filled cavities or defects within the solid dielectric can enhance the local field strength above the required ionisation level sufficient to cause damage in the polymeric material through high-energy electrons within micro-voids/cavities that are created gradually by electron trapping and de-trapping, causing polarons and molecular displacements [123]. These events lead to localised electrical discharges around the gas-filled voids, allowing an increment in the dimension of the cavity to sustain electric
discharge activity [123],[124]. The movement of electrons in micro-voids/cavities can generate energies of about 5 eV, whilst the presence of defects/impurities can further excite the movement of electrons from 4 to 10 eV. This is because conductive defects in dielectric material can cause high electric field magnitudes that enable electrons to reach high energy levels and cause molecular dissociation/displacements or chemical reactions [123].

Therefore, the extent of degradation depends on the energy level that the electrons have reached. For example, electrons with high velocities in a weak solid/solid interface resulting in energy exchange within the atoms, molecules or bonds of the polymer [123]. These repeated events will also generate space charge accumulation and leakage current, usually at the interfaces near the high voltage electrode [121]. The subsequent events age the polymeric material, associated with a combination of electro-mechanical stress factors induced to crack propagation in the polymer causing the development of an electrical tree structure [125]. Reactive species are also involved in this non-thermal process and their participation may lead to new compounds, resulting from positively or negatively charged ions and charged traps from electrons in a high electric field [5],[123]. All these events provoke chemical damage in the dielectric material, leading to PD activity high enough to encourage an electrical tree to grow, which is the initiation of the insulator failure [17].

2.4.2 The influence of pressure on interfacial degradation

At the contact surface between two solid dielectrics such as epoxy resin and silicon rubber, the presence of voids or cavities is unavoidable. Since each material has its own surface roughness, this can reduce the contact spots and allow the formation of cavities, allowing an oxygen rich interface. The number of voids and dimensions presented at the interface enable electron mobility, which reduces the dielectric strength of the interface considerably [126],[127].
Several studies [127]–[131] applied the elastic contact theory to investigate the dielectric strength between two polymers. It was observed that the elastic modulus and the surface roughness of each material are the main variables to alter the dimensions / number of voids at the interface of these solid dielectrics. The increment of the interfacial pressure considerably improved the dielectric strength of a weak interface [115]. For example, silicone rubber has a low elastic modulus, thus the tall summits and number of voids at the interface can be reduced by applying mechanical pressure [131]. As Figure 2-10 depicts, the formation of multiple and large voids at the interface can enhance the local electric field magnitude, causing partial discharge activity at the solid/solid interface and subsequently initiating interfacial degradation [127],[130].

Geene et al. [57] agreed that defects, scratches or cavities at the interface can cause partial discharge activity. It was also observed that the degree of those defects/irregularities depend on the applied mechanical pressure. So, when the mechanical pressure was increased, the size of the cavities decreased. This was achieved by the application of external mechanical forces applied to a rubber slab against an epoxy body.
Kutil and Froshlic [5] proposed an interfacial degradation model, using glass-fibre and epoxy resin plaques with voids of 2 and 4 mm diameter. Initially, the ionisation of gas-filled voids enhances first electrons mobility. If the field in gas-filled voids is high enough, electron avalanches can occur. The field intensity inside the air-filled void causes an increment in the dimension of the void due to thermal erosion depending on the amount of ions and high-energy electrons. So depending on the amount of high-energy electrons in front of the avalanche, the electrical field in front and in the rear of the avalanche head is sufficiently high to initiate new avalanches in these regions and a streamer discharges can develop. Figure 2-11 depicts these conditions.

![Diagram showing formation of voids at the interface and the stages to initiate streamer discharge in a gas-filled void, once the field inside the void exceeds the critical value [5]](image)

New avalanches are also formed as charged carriers increase the surface current on the wall of the void, resulting in an enlargement in the cavity size; eventually the cavity is long enough to sustain streamer discharges. Figure 2-12 illustrates these events.
Moreover, the development of streamer discharges results in the formation of electrical trees and the increment of the void size next to the glass-fibres. Over time, the intensity of PD activity provokes micro-cracks and thus breaks chemical bonds, resulting in the formation of carbonized deposits at the wall of hollow/air-filled channels. This further enhances the local field as carbon deposits and cracks develop and propagate internally. Consequently the PD activity increases as electrical trees grow in the bulk of the polymer [132]. The growth of these channels was controlled by the influence of the interfacial pressure [115]. As it was noted, the variation of mechanical pressure influenced the recorded PD activity [5],[132].

Hasheminezhad [133], applied the elastic contact theory to the development of a model of interfacial breakdown in a weak interface containing air-filled cavities. The surface roughness and interfacial pressure on the interface were considered key elements in developing this model. It was observed that a smoother surface and the increment of mechanical pressure from 3.7 to 8.2 bar increased the dielectric strength at the interface. The model considers the voltage drop in a dry air-filled cavity, called $V_{dry}$, which is equal to the sum of the short-circuited paths along the contact spots at the interface $\sum_i V_{void}^i$, plus the sum of contact areas along the interface $V_{contact}^j$ in order to obtain the total interfacial breakdown voltage. Equation 2-1 shows this.

\[ i_{PD} = i_{puls} + i_{wall} \]

$i_{puls}$ ... Current carried by the pulsating PD (avalanches)
$i_{wall}$ ... Surface current carried by pseudo-free charges

Figure 2-12. PD magnitude depends on the increment of the current inside the void and the surface current at the wall of the void which enable the growth of the void in length [5]
\[ V_{dry} = \sum_i V^i_{\text{void}} + \sum_j V^j_{\text{contact}} \] (2-1)

Figure 2-11 shows electrical discharge activity in each cavity formed at the solid/solid interface, which causes a short-circuited path along the contact areas at the interface. To compute the Paschen curve for the breakdown of the strength of the cavities at the interface, the pressure inside the voids was considered to be 1 bar. It was observed that the increment of mechanical pressure (from 3 to 8 bar) improved the dielectric strength of the interface, as the partial discharge inception voltage increased [129],[133].

The elastic contact theory was used in several studies [126],[127],[129]–[131],[133] to calculate the dimension of the voids at a solid/solid interface and predict the partial discharge inception voltage. Data from the surface profile, elastic modulus of the material, and interfacial pressure was used to estimate the average void size. It was proposed that in a weak interface, there is one contact area between two air-filled cavities as Figure 2-13 illustrates.
Du and Gu [134] highlighted that interfacial degradation is caused by the development of short-circuited paths in a weak interface; where small amounts of oxygen are trapped. Thus the discharge activity and the heat from discharges will induce the formation of carbon paths along the interface. Kutil and Froshlic [5] added that interfacial degradation is related to the electrical discharge intensity at the interface, which is the initiation of streamer discharges in micro-cracks, de-bonding and delaminated areas along the interface. This can cause interfacial tracking failure.

2.4.3 Summary of the ageing mechanisms at the interfaces

The electrical stress aspects on the external or internal macroscopic interface of the composite insulator can cause thermal fatigue and physical sheath relaxation that results in large voids, delamination or loss of adhesion between the core and the sheath [3],[7],[14]. This allows enhanced electron mobility in high field regions, generating electrons capable of reaching kinetic energies higher than the ionisation threshold, resulting in internal discharge activity at the rod-to-sheath interface [123]. Moreover, the presence of defects or a weak interface can cause electron mobility, leading to the acquisition of the energy needed to break chemical bonds roughly in the range of 4 to 10 eV. Electrons can also be accelerated in the presence of voids, micro-cavities, and low-pressure gas regions, causing intramolecular bond rupture depending on electron energy [17]. The dissociation of molecules can be accompanied by ionisation mechanisms that can also develop in streamer discharges [122].

2.5 Review of previous studies and interfacial degradation test methods

This section will review previous interfacial ageing and breakdown test regimens, to gain knowledge of the: electrode configuration, procedures, and technical details, about how the interfacial degradation has been investigated and the limitations of that
work. This helped to develop new methods in order to study interfacial ageing in composite insulators.

For example, several studies have investigated the effect of surface roughness and contact pressure [134]–[137]. Using compression forces to avoid air bubbles trapped at the interface facilitate investigation of adhesives or grease in cable joints. Hasheminezhad and Ildstad [129] proposed a model based on mechanical pressure and surface roughness to calculate the dimension of voids at the interface of two insulating materials. The experimental results showed that contact pressure did not influence the air pressure inside voids.

Fournier and Lamarre [138] investigated the interfacial dielectric breakdown using two approaches. The first investigates the influence of interfacial pressure at an EPDM/EPDM interface and the second approach, at an XLPE/EPDM interface. The physical properties of the samples under different temperature are investigated. Needles were used as electrodes, placed 4 mm apart from each other at the interface of the samples. The findings were as follows:

a) Silicone grease between the EPDM slabs improves the dielectric strength from 1.0 kV/mm to 5.5 kV/mm in comparison to when there is no grease. Hence, the use of silicone grease at the interface will improve the dielectric strength even with minimum pressure. When a pressure of 50 kPa or more was applied, its dielectric strength did not further improve.

b) At the XLPE/EPDM interface, the XLPE deforms in temperatures above 105°C, weakening the dielectric strength at the XLPE/EPDM interface. Therefore, XLPE-based joints show weaker dielectric strength than EPDM joint at high temperature.

Dang [139] combined several types of interfaces to investigate the dielectric strength of the samples tested, as a function of the interfacial pressure and the distance between electrodes. The dielectric interfaces consisted of high dielectric constant material, insulating grease and plain contact between the slabs. EPR, XLPE and epoxy resin, samples were compressed with mechanical pressure from 10 to 200 kPa.
The breakdown strength was tested by continuously raising the AC voltage at 0.5 kV/s at room temperature. The results were divided into samples with insulating grease, and those that were non-greased at their interfaces, whilst the electrodes were separated by 5 mm from each other. It was observed that the dielectric strength at the interface was directly proportional to the pressure in the samples with non-greased interfaces. For the samples with grease at the interface, the dielectric strength increased gradually with an increment in the mechanical pressure of up to 100 kPa; above this pressure, the dielectric strength at the interface remained constant despite any increment in the pressure. Regarding the gap distance between electrodes, a large distance between electrodes showed a good relationship with the dielectric performance even in the non-greased samples. However, Dang suggested that the presence of air/voids at the interface can change the outcome. It was noticed that the dielectric strength was reduced in samples with sharp electrodes for the same interface and electrode distance. Electrode specifications were not given.

Du and Gu [134] analysed the tracking development at SiR/XLPE interface. The dimensions of the slabs were 40 x 25 mm and 1 mm thick, electrodes 2 µm thick were placed 10 mm apart from each other in a needle-to-plane configuration. The samples were subjected to pressures of: 20, 100 and 300 kPa. The experimental set-up can be seen in Figure 2-14.
This project investigated the distribution of carbonised areas, tracking patterns and emission of light intensity due to discharge activity. This process occurred in three distinct stages: an initial stage with weak light, an intermediate stage where the channel was wider and the light increased in brightness, and a final stage before breakdown occurred, where the brightest light emission was detected. It was also observed that the area of tracking propagation decreased with the increment of mechanical pressure applied to the samples.

Gu and He [140] using the same experimental apparatus as [134] investigated, the interfacial breakdown between slabs of XLPE and transparent SiR (40 mm x 25 mm and 1 mm thick) that compress two circular wire-electrodes with a radius of 2.5 mm, the fixed electrodes of 10 µm thickness separated by 5 mm from each other to stress the samples under AC voltage. The samples were divided into samples with cavities and those without. The cavities’ dimensions were 0.2, 2.5 and 5 mm. In each case, at the XLPE/SiR interface, the samples were compressed to a fixed 20 kPa. The intensity of the light discharge was used to monitor the influence of the cavity size in the breakdown at the XLPE/SiR interface. It was observed that the light discharge activity was proportional to the dimension of the cavity, so when the cavity increased in size, the electrical discharge activity initiated and developed rapidly; thus decreasing the dielectric strength, and with the consequent likelihood of initiating interfacial tracking. It was also observed that the electrical discharge formed carbon deposits around the electrodes due to the thermal hot spots and molecular degradation of the polymers. Over time, the carbon paths developed at the interface sufficiently to bridge the gap between the electrodes, resulting in a breakdown. Nonetheless, the authors stated that they were not able to identify and monitor the interfacial tracking initiation and development by only processing the discharge light emitted from the electrical discharge activity.

Zhang et al. [141] investigated electrical breakdown and leakage current within interfaces formed by soft-hard and soft-soft interfaces. A soft-soft interface consists of EPDM/SiR, whereas the soft-hard interface was made of fibre reinforced EP and SiR. The dimensions of the slabs were 100 x 50 mm and 2 mm thick. The electrodes were
made of aluminium foil (0.2 mm thick) separated by 2 mm, as Figure 2-15 (a) shows. The tip of the electrodes were shaped as semicircles with a radius tip of 10 mm. Figure 2-15 (b) shows the experimental set-up used to compress the samples. After the application of an adhesive solution, the electrodes were glued between the slabs. The experimental results showed that better adhesion between the EPDM/SiR slabs resulted in lower leakage current magnitudes than at the EP/SiR interface. On the other hand, the breakdown voltage for EPDM/SiR was 36.9 kV and was 38.8 kV for EP/SiR, under AC stress.

![Figure 2-15. (a) electrode configuration to investigate interfacial breakdown, (b) set-up to glue the samples [141]](image)

The values presented here for voltage breakdown are surprisingly high, considering the fact that the tips of the electrodes are only separated by 2 mm. Perhaps this is a result of the adhesive that was applied to the interface. Unfortunately, authors do not provide information about how the connections were designed to avoid regions of high electrical stress.

Anderson et al. [142] studied the importance of the primer bonding at the interface between SiR and epoxy. This focused on the interfacial mechanical strength between these two polymers. It used an electrode wire of 75 µm radius, which provided field enhancement, samples were aged electrically for 330 hours at 10 kV AC. The design of the test arrangement can be seen in Figure 2-16. The experimental results showed that the electrical stress caused surface cracks on the epoxy slab, whereas the SiR slab presented white powder on the surface but less damage in the bulk. It was also
noticed that the interfacial mechanical strength between epoxy and SiR were not reduced, which indicated that small interfacial defects will not put the mechanical integrity of the epoxy and silicon rubber joints at risk.

Figure 2-16. Test arrangement to investigate ageing at the epoxy/SiR interface [142]
Jarvid et al. [143] also used a wire of 10 and 20 µm as an electrode to investigate electrical tree inception in a low-density polyethylene (LDPE) and XLPE. Figure 2-17 (a) shows the wire-plane configuration. This study proposes an alternative geometry to study electrical tree inception. Figure 2-17 (b) shows the development of several electrical trees on the wire. The authors claim that using a wire as electrode allows inception of multiple trees, as the area for inception is large, whilst the inception of a tree using a more traditional needle is limited to the tip. In addition, the use of a wire is beneficial for monitoring tree development. However, due to the diameter of the wire it is difficult to manipulate, and as a result kinks are formed on the sample preparation. Kinks produce localised enhancement of the field in only certain areas, which affects the tests results.

From the work of Jarvid et al. [143], the idea of the using a thicker wire than 20 µm as a HV electrode was considered, so it could be easier to manipulate and avoid kinks whilst assembling the sample. Chapter 4 — Materials used and sample preparation; shows how a 45 µm wire was implemented as an electrode in the present project.
Kobayashi et al. [132] investigated the effect of permittivity and interfacial pressure at an epoxy/ethylene propylene rubber (EP/EPR) and an EPR/LDPE interface. Testing used two aluminium foil electrodes, separated by 5 mm in the interface, as Figure 2-18 (a) shows. The experimental results show that the EPR/LDPE configuration has more tree growth in the LDPE than the EPR slab, when the voltage was increased from 7 and 13 kV with a fixed mechanical pressure of 7.7 kgf/cm².

On the other hand, at the epoxy/EPR interface the tree development characteristics vary with the mechanical pressure applied to the samples. At 3 kgf/cm² treeing spreads along the interface, whereas at 15 kgf/cm² the electrical tree grew into the bulk of the epoxy slab, as Figure 2-18 (b) shows.
Bolliger and Boggs [119] evaluated the chemistry of interfacial tracking, using materials of different combinations, such as XLPE/EPR, XLPE/SiR, EPR/EPR, and EPR/SiR samples. Figure 2-19 shows the shape and electrode configuration that was used in this approach. The electrodes consist of brass shim stock, separated by 10 mm. The thickness of the electrodes (0.127 mm) allows a good union between the slabs tested, avoiding the intrusion of air at the interface.

The outcome of this study shows that the presence of oxygen at the interface and the heat from electrical discharges facilitates the formation of hydroxyl / carbonyl groups and free radicals, which were formed at these interfaces, and play an important role in the development of carbon tracks between the solid dielectrics. The intensity of the discharge activity, UV photon energy and the bombardment of electrons on the polymer surfaces are also initiators of molecular degradation processes, which may enhance the formation of carbonaceous deposits. It was also observed that these ageing events resulted in significant eroded areas on the surface of the polymers during interfacial tracking development. Section 2.3.3 provided a detailed description on the interfacial oxidation and free radical formation process within polymers.

Kamer and Ieda [1] investigated interfacial degradation by inserting a needle at the interface of the composite structure to produce high local electrical stress. It was observed that the breakdown strength was reduced and tracking paths in the fibre-glass reinforced epoxy were formed, as Figure 2-20 shows.
The authors also show the effect of interfaces on the electrical strength of both SiR and CEP (cycloaliphatic epoxy resin) materials, in dry and wet conditions, (after water saturation); the increased humidity also degrades the material properties. Unfortunately there is no further information available about the tracking path development or the experimental set-up, or about of the size of the samples.

Figure 2-20. Shows the formation of tracking paths in fibre-glass reinforced epoxy [1]

2.5.1 **Electrical stress analysis**

This section presents an analysis of the electric field magnitude and distribution that traditional small-scale test regimes employed to study interfacial tracking. The characteristics of the electrode configuration and the influence of the inter-electrode distances are also discussed to identify the electric field magnitude that enable tracking growth along the interface of two different polymers.

The electric field magnitudes were computed using Finite Element Analysis (FEA) with COMSOL software. The information provided from the tests regimes, e.g. electrode size, inter-electrode distances and dielectrics properties (permittivity of each material), were used to build 2D models with the intention to replicate the conditions of the tests. In the FEA models it was assumed that the tips of the electrodes were symmetrical in a pin-to-pin geometry, which was placed between two different insulating materials as provided by each test. It was also assumed that no air was trapped around the tip of the electrodes for simplicity of the models. The models presented in this section only display the electric field distribution at the tip of the electrodes and the models do not intend to evaluate whether the morphology of track
structure becomes conductive or not as it develops. The details on how the models were built, including the meshing procedure in order to obtain accurate results of the models are discussed in Section 3.4.1.

The reviewed tests regimes do not offer information about the inception voltage to initiate tracking growth, hence for the FEA models presented in this section, the voltage on the HV pin was set at 10 kV RMS, to compare the electric field magnitudes among the tests.

- **Characteristics of electric field distribution**

Champion et al. [144] proposed a Field Driven Tree Growth (FDTG) model to evaluate the growth characteristics of electrical trees that divides the electric field distribution into the following three regions:

A. initially the tree grows depending on the maximum field at the pin-tip
B. tree growth is reduced at a constant field
C. final runaway stage is due to the increased field as the tree grows and the distance between the tree tip and ground electrode distance is reduced

This behaviour is represented as a U-shape: that is the maximum electric field is at the tip of the HV and the earthed electrode (region A and C respectively). The reduction of the electric field gradually decreased to become constant (in region B) [144].

Figure 2-21 shows the FEA results of the models developed in this study, presented as a line plotted along the interface between the tips of the electrodes. This allows visualization of the three regions of the electric field distribution, in this case belonging to the proposed electrode arrangement by Bolliger and Boggs [119].

It can be noticed that when the inter-electrode distance is set to 10 mm, the highest electric field magnitude (19.9 kV/mm) located in region A is capable of initiating interfacial tracking growth. Also, a constant field that is < 1 kV/mm between the electrodes (region B) which extends for 2.6 mm at the end of region A is the longest inter-electrode distance among the tests presented in this analysis, in which the lowest
electric field magnitude recorded was 0.52 kV/mm. Thereafter the field increases rapidly in region C, which influences the growth rate as the tracks develop.

Figure 2-21. Computed electric field magnitude of experimental test proposed by Bolliger and Boggs [119]. It also shows the division of the three regions of the electric field distribution.

Figure 2-22 shows the field at the interface of the test proposed by Zhang et al. [141], which is the smallest inter-electrode distance (2 mm) of the tests presented in this section. The computed maximum electric field magnitude reached up to 24.5 kV/mm in region A. This value is low despite the short distance between the electrodes because of the large diameter of the electrodes (0.2 mm). Moreover, there is no region in which the track grows under a constant field.
Figure 2-22. Electric field magnitude of experimental test developed by Zhang et al. [141]. Two regions of electric field distribution are observed; and there is no constant field at this inter-electrode distance.

Figure 2-23 displays a comparison of the electric field distribution between the tests [119] and [141]. This comparison was possible to carry out because the maximum electric field magnitudes of both tests were quite similar. This is due to the similarity of geometries, especially the diameter of the electrodes (for tests [119] 0.127 mm and for tests [141] 0.2 mm).

On the other hand, it can be observed that the electric field distribution has a strong relationship that depends on the small gap between electrodes that controls the local field. It is also clear that as a track develops it will experience a rapid rate of change during the experiment as the track grows.
Figure 2-23. Comparison of the electric field magnitudes and distribution between the tests [119] and [141], the similarity of the thickness of the electrodes resulted in a similar maximum field magnitude.

Figure 2-24 displays a comparison of the electric field magnitude and distribution between the tests [138] and [134] inter-electrode distance of 4 and 10 mm respectively. It can be seen that the three regions (A, B and C) in both tests are clear. The inter-electrode distance of 10 mm resulted in a minimum field magnitude of 0.31 kV/mm in a larger region of a constant field between the electrodes, when compared to the inter-electrode distance of 4 mm the minimum field magnitude almost reached the double field (0.74 kV/mm) in region B. On the other hand, the maximum electric field magnitude is almost the double for tests [134] than test [141], this is due to the different diameters of the electrode 2 µm and 0.2 mm respectively.
Figure 2-24. Comparison of the electric field magnitudes and distribution between the tests [134] and [138]

Figure 2-25 displays a comparison of the electric field magnitudes between the tests [132] and [140], both tests are at the same inter-electrode distance 5 mm, reaching 387 and 206 kV/mm respectively. This confirms that the electric field magnitude at the HV electrode has a strong relationship to the thickness of the electrodes, since the finer electrode enhances the electric field magnitude higher at the tip of the electrodes. Moreover, both tests resulted in a similar area of a constant field between the electrodes, with a minimum field magnitude of about 0.60 kV/mm. It can also show that increasing the inter-electrode distance will result in a large area of a constant field between the electrodes.
Figure 2-25. Computed electric field magnitudes of the test developed by authors Kobayashi et al. [132] and Gu and He [140], when the diameter of the tip of the electrode is 1 and 2mm respectively

Table 2-4 summarises the information presented in this section. This highlights the region of the inter-electrode distance which experiences a constant field. The importance of a larger region of a constant field is that the track can propagate at normal rate unaffected by the high field generated as it grows in closer proximity to the earthed electrode.
Table 2-4. Computed values of the electric field at different inter-electrode distances

<table>
<thead>
<tr>
<th>Experimental test proposed by</th>
<th>Inter-electrode distance (mm)</th>
<th>Electrode diameter (mm)</th>
<th>Max electric field magnitude (kV/mm)</th>
<th>Min electric field magnitude (kV/mm)</th>
<th>Region of a constant field &lt; 1 kV/mm (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhang et al. [141]</td>
<td>2</td>
<td>0.2</td>
<td>24.55</td>
<td>2.90</td>
<td>0</td>
</tr>
<tr>
<td>Fournier and Lamarre [138]</td>
<td>4</td>
<td>0.004</td>
<td>405.20</td>
<td>0.74</td>
<td>0.19</td>
</tr>
<tr>
<td>Gu and He [140]</td>
<td>5</td>
<td>0.010</td>
<td>206.60</td>
<td>0.65</td>
<td>0.39</td>
</tr>
<tr>
<td>Kobayashi et al. [132]</td>
<td>5</td>
<td>0.005</td>
<td>387.49</td>
<td>0.60</td>
<td>0.32</td>
</tr>
<tr>
<td>Bolliger and Boggs [119]</td>
<td>10</td>
<td>0.127</td>
<td>19.94</td>
<td>0.52</td>
<td>2.6</td>
</tr>
<tr>
<td>Du and Gu [134]</td>
<td>10</td>
<td>0.002</td>
<td>789.70</td>
<td>0.31</td>
<td>0.51</td>
</tr>
</tbody>
</table>

The computed values of the electric field magnitudes displayed in Table 2-4, indicates that the maximum field is influenced by the diameter of the electrode tip. Hence the finer the tip is, the higher the field magnitude is, e.g. test by Du and Gu [134]. Whilst increasing the diameter of the tip of the electrode, the electric field magnitude resulted in the lowest field, regardless the inter-electrode distance, e.g. test by Zhang et al. [141]. Moreover, for both tests with inter-electrode separations at 10 mm, the lowest electric field was reached in region B; so the electric field in this region depends on inter-electrode distance, the shorter gap distance will result in a higher field. Thus, it can be concluded that the electrode arrangement that is offered by traditional test designs results in an unrealistic electrical stresses that affect large composite structures. Consequently, small scale samples are not suitable to investigate interfacial tracking growth in a composite insulator.

2.5.2 Summary of this review

This section provided information of laboratory test methods to research interfacial degradation using small size samples. However, the tests facilities do not offer much information about the inception voltage that enables tracking growth, the structure of their experimental facilities, or how they reduce the electrical stress at the HV connections, or at the electrodes. Nevertheless, from the review of previous tests

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regimes, it was observed that interfacial ageing mechanisms remain poorly defined. The investigations about interfacial degradation are mainly focused on breakdown tests and are carried out on small scale samples.

The FEA models built in this research project helped to define the electric field distribution and magnitudes of each test; it also identifies how small inter-electrode distance can influence the interfacial track development. The results presented in this section show that the electric field magnitude is high at the tips of both electrodes. The dimension of any region of constant field is dependent on the inter-electrode distance, larger inter-electrode distances resulting in a larger area of a constant field between the electrodes. The major problem of a small inter-electrode configuration is that the region of a constant field between electrodes is too small, and the high field at the earthed electrode will dominate the rate of track growth as it develops, leading to the runaway stage. These conditions do not reflect the track development in a real situation on large scale HV composite insulators, in which the distance between the electrodes (conductor and tower) is of the order of meters. So far, traditional test regimes are too small to investigate the inception or development of interfacial tracking in realistic electric stresses. Therefore, there is a need to develop an experimental structure with larger samples to provide enough space for the tracking to grow in a constant field unaffected by the proximity of the earth electrode. The following Chapter describes the development of an experimental rig to facilitate larger scale tests in controlled conditions.
Development of experiment design

3.1 Introduction

This Chapter describes the initial development of experimental techniques and apparatus to investigate the mechanism of degradation in composite insulators. Two experimental facilities are presented, and used to investigate the following: (a) the development of interfacial tracking in long cylindrical structures, (b) investigating the effects of loss of adhesion between the sheath and core in composite insulators using planar insulating materials.

The stages gone through in implementing the electrical connections and electrode configurations are presented here. This also requires 3D FEA models of the electrode geometries that have been implemented to prevent surface discharges. Therefore, extensive efforts had been invested in developing two experimental facilities which simultaneously facilitate the imaging of interfacial degradation and partial discharge measurement, with a sensitivity level of \( \sim 3 \) pC. The problems encountered and steps taken to eliminate those challenges have been highlighted in the sections that follow.

3.2 Development of experimental methods

As reviewed in Chapter 2 — Section 2.5, short term tests are typically conducted to study interfacial degradation as a breakdown process, and this usually employs mm-size samples. It was evident that difficulties were encountered in analysis of the progression in interfacial degradation or developing interfacial tracking growth
models. The major problem in the previous tests as described in the literature was the formation of tracks within a small distance between the electrodes [119],[132],[134],[140]. This was because when the conductive interfacial tracks grow, the front edge of the track reduces the effective insulation gap to the opposite electrode, thus increasing the local field and increasing the rate of the track propagation. These conditions and the resulting runaway process do not represent track development in composite insulator in service, at least until the track is perhaps one third of the length of the insulator (which may be metres in length) [2],[23].

Therefore, the main aim of this project was to investigate the interfacial ageing in large test samples (cm-size), also to study the formation and development of interfacial tracking in more realistic conditions. To contribute to the evaluation of the interfacial degradation in composite insulators, two well-controlled experiment facilities involving a cylindrical and a planar experimental system were developed for this study. The cylindrical system with long-rods was developed to replicate the geometrical characteristics of commercial composite insulators used in industry, with an objective of investigating the growth of interfacial tracking and its dependence on electric field enhancement. This was controlled by separating the electrodes by a distance of up to 1000 mm from each other. The main challenge encountered while investigating the cylindrical configuration was that the silicone tubing used to sleeve the core could not be readily adjusted (i.e. hoop stress cannot readily be controlled or measured). This called for the development of an experimental set-up using planar samples, where the mechanical pressure could be increased to achieve a good union between the insulating components. Therefore, the planar experimental system was developed to investigate the role of interfacial pressure between the core and the sheath materials.

Moreover, commercial samples were also investigated for both configurations as described above, with an aim to compare the results from laboratory prepared samples and the commercial samples.
3.3 Test components and test circuit

The components used in the experimental apparatus and their descriptions are listed below. Figure 3-1 shows the circuit diagram used in both experiments, which consists of:

![Circuit diagram](image)

**Figure 3-1. Circuit diagram for testing interfacial degradation in planar and cylindrical samples**

- **a) VARIAC transformer**
  VARIAC transformer energises the circuit. The AC supply boosts the voltage up to 170 kV RMS at 50 Hz.

- **b) Voltage divider**
  It was possible to read accurately the applied voltage between the electrodes through the digital oscilloscope, using a high-voltage capacitance divider in a ratio of 10000:1.

- **c) Ballast resistor**
  A 10 kΩ ballast resistor was placed in the circuit to reduce high current in the case of flash-over or breakdown events.
d) **PD detector**

A commercial Omicron-MPD600 PD detector was used for data acquisition, the detector converted the discharged current signals into digital PD pulses. In addition, Omicron provided a software that enabled the PD events to be visualised, recorded and stored in the computer for post-analysis.

e) **Coupling capacitor**

A 500 pF capacitor was used in the circuit as a coupling capacitor, which was connected in series with the Omicron-MPD600 to detect high frequency currents that are expressed as digital PD pulses, known as apparent charges.

f) **Optical camera**

A camera (Canon EOS-1100D) was used to monitor the progress of the visual aspects of degradation. The camera included software, which allowed the operation of the camera remotely via the computer to adjust the focus, exposure time and take pictures at certain intervals.

g) **Light source**

To enable the visualization of the tracking growth whilst testing – a halogen light source (SCHOTT - KL 1500), which has a dual-light pipe gooseneck lamp of 150 W, with each light of the pipe gooseneck being directed at each lateral side of the samples. This facilitated a uniform illumination (with no shadows) at the tip of the electrode and the area to monitor tracking development.

The combination of images and PD magnitudes were used to establish a relationship between PD magnitudes and the interfacial channel growth (explained in Chapter 5). The light source and the optical camera were earthed to protect them from damage caused by flash-over or breakdown events.
3.4 Development and experimental description

The schematic diagrams of the cylindrical and flat experimental set-ups are illustrated in Figure 3-2.

(a) The cylindrical system: consists of two metal end-fittings (120H x 120W mm), which were separated by a vertical 900 mm insulated rod, with two commercial 8 inch corona rings attached on each end fitting and placed 50 mm above the base of the end fittings, for stress control. This was to effectively reduce surface discharge activities between the sample and the HV connection. The design and the arrangement of the components are shown in Figure 3-2 (a). The cylindrical samples consisted of Polyvinyl-Chloride (PVC) and Polyethylene (PE) heat-shrink tube forming a circumferentially layered structure. A hypodermic needle was placed at the interface within the polymeric structure to enhance the local electrical field magnitude and initiate partial discharge activity. This facility

(b) the flat system, in which external weights were applied to planar samples to vary the interfacial pressure of the samples (not in scale)
provided flexibility in studying both the sheath and core materials. Therefore, once the method had been proven, epoxy resin was used for the core material and silicone rubber for the sheath, in order to replicate the characteristics of commercial composite insulators used in service.

**b) The flat system:** the structure is illustrated in Figure 3-2 (b), and consisted of a wire as the electrode compressed between two planar insulating materials of 150 x 50 mm, which are positioned horizontally on a glass plate. These components were mounted over a translucent rectangular acrylic box (40L x 25H x 20W cm) to support them. A camera was placed underneath the samples to monitor the samples, and because the lower materials were transparent, the growth of tracks could be observed. At the same time building bricks ( \( \varepsilon_r = 6 \) to 8) were used as weights to vary the mechanical pressure on the samples. The interfacial pressure was determined using the equation below (3-1).

\[
P = \frac{F}{A} \quad \text{(3-1)}
\]

\[
F = m \times a \quad \text{(3-2)}
\]

where: \( F \) is the force, \( A \) is the area of the sample, \( m \) is the applied mass and \( a \) is the acceleration of gravity.

The maximum mechanical pressure applied over the samples was 60 kPa, this pressure is below the maximum compressive strength of the materials used in this project. In addition, the shapes and volumes of solid materials are fixed. Hence they are considered incompressible to a certain extent, this depends on the molecular mobility of the polymer chains, e.g. it is easier to change the shape of silicone rubber under small compressive loads due to its flexibility [111],[112]. Section 2.3.2 provided details about the mechanical strength properties of each material, and also the deformation of polymers subjected to compressive / tensile stress.
3.4.1 FEA models of experimental structures

Experimental structures were modelled in COMSOL multiphysics, the aim of these models were initially built to develop the experimental facilities used in this project to investigate interfacial tracking. Therefore, the models helped to identify areas of high electrical stress at the HV and ground connections. It was also used to investigate the electric field magnitude at the tip of the electrode that enabled interfacial tracking growth.

For this investigation, electrostatic physics was applied to these models, in which the main factor for computing the electric field is to define each material’s relative permittivity. In that way, the software can differentiate between domains. The details of the components, structures, and meshing procedures in the following sections provide information on how the models were developed in order to achieve acceptable computed results.

- Model structures

2D and 3D structures with real dimensions of each component were formed to simulate the conditions of the experimental facilities. The models consisted of the following elements: epoxy resin for the central core, silicone rubber for the sheath, and aluminium for the end fitting and corona ring. The properties of the materials used in this project are disclosed in Table 3-1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Relative permittivity ($\varepsilon_r$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal defect, electrodes and ring</td>
<td>Aluminium</td>
<td>1</td>
</tr>
<tr>
<td>Core rod</td>
<td>Epoxy resin</td>
<td>4</td>
</tr>
<tr>
<td>Sheath</td>
<td>Silicone rubber</td>
<td>3.5</td>
</tr>
<tr>
<td>Surrounding Air</td>
<td>Air</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3-1. Properties of the materials used for building the FEA models [110],[113]
Moreover, the components were surrounded by air. This is necessary to complete the computation of the model [145]. Figure 3-3 shows the full structure of the experimental set-up that was placed in a sphere of 2400 mm radius, which was used to establish a boundary condition between the experimental structure and the surrounding air. The external layer (500 mm thick) of the sphere was defined as the infinite element domain. This served to create a boundary that helps as though the model components were surrounded by air that is infinitely expanded, and is beneficial in increasing the accuracy of the model [145].

![Figure 3-3](image.png)

Figure 3-3. FEA model of the cylindrical system was placed in an air sphere of 2400 mm radius. The external infinite element domain consist in a layer thickness of 500 mm.
• **Boundary conditions**

The boundary conditions in the model were defined to differentiate the HV and the earthed electrode. Hence, the ground electrode was assigned to 0 V, whilst the HV electrode was set to the electric potential. The assigned voltage was varied as it was done in the experimental tests to identify the maximum electric field magnitude and its position. The variation of the applied voltage would change the electric field magnitude, while the electric field distribution across the experimental structure would remain the same.

• **Meshing specifications**

In order to compute the model, each component of the geometry needed to be meshed. This meant that the geometry was automatically divided into small triangular elements (for 2D geometries) or tetrahedral elements (for 3D geometries). Using partial differential equations, the software automatically generated a coarse mesh of the geometry of the model. This type of mesh was not enough to obtain the best solution of the model. Therefore, the geometry of the model had to be sub-divided in sections for mesh refinement, because a custom mesh is required for the narrow regions (the corona ring) or in the micro-meter size structures (tip of the wire).

The sensitivity in the quality of the meshed components in the models presented in this research project was guided by the *Minimum Element Quality*, which requires a value close or above to 0.1 for the model to have a good quality mesh. If the minimum element quality is below 0.01, it is considered as a low quality mesh, this could lead to problems when solving the model [146],[147]. To improve the mesh quality it is required to reduce the minimum mesh size or/and the minimum curvature, this was applied to the micro-meter structures and narrow regions of the model. For example, Figure 3-4 shows how the mesh quality was improved in the narrow regions in the commercial corona ring that required a customised mesh. The Mesh Statistics window in Figure 3-4 (a) shows that the *Extra Fine* mesh applied to the model resulted in a minimum element quality of 0.009. To improve the mesh quality of the model, the
minimum mesh size was reduced to 0.7 mm and the curvature factor to 0.02 mm, the minimum element quality increased to 0.030; the minimum element quality did not reach 0.1 in this case, but the curve of element quality histogram was significantly improved as the red circle in Figure 3-4 (b) displays.

Figure 3-4. Mesh Statistics windows served to assess the mesh quality of the corona ring when (a) Extra Fine mesh was applied to the model and (b) the minimum mesh size and the curvature factor was reduced to improve the minimum element quality
3.4.2 Development of the cylindrical set-up

In the initial experiments, two insulating materials used for the sheath were transparent PE heat-shrink tubing (< 2 mm thick) and unfilled epoxy resin (3 mm layer), which were used to sleeve the hollow PVC rods, aiming to mimic the cylindrical structure of composite insulators. The reason for using these dielectrics was because a translucent PE sheath allowed visual monitoring of the development of tracking in the test, whilst the white surface of the PVC rods facilitated a good visual contrast and ready carbonisation (PVC carbonises easily under PD) to monitor tracking growth.

- Defining the vertical position of the corona ring

The aim of these simulations was to define an optimal position for the corona ring in its vertical axis, to reduce the electrical stress at the base of the HV end fitting because corona discharge was initiated in this region when the sample and the metal wire were attached to the HV end fitting. A commercial 8 inch corona ring was used in this project for stress control at the HV metal end fitting. The dimensions used to form the 3D model of the commercial corona ring are: a tube diameter of 16 mm and an external diameter of 210.6 mm of the ring.

Figure 3-5 illustrates how the components were arranged, with the base of the HV end fitting as point 0 and the ring was shifted in its vertical axis, in this simulation the metal defect in the long-rod sample is not included. A parametric sweep function was used in the variation of the position of the ring vertically from 0 to 100 mm in steps of 10 mm. For this simulation, the voltage magnitude at the HV electrode and corona ring was set at 100 kV, which was the maximum voltage applied in this experimental structure before corona discharge was observed to initiate at the HV connections.
Figure 3-5. Diagram of the cylindrical system with the components, also showing the variation of the position of the ring in its vertical axis. The long-rod sample does not contain a metal defect.

Figure 3-6 shows the computed values of the maximum electric field at the base of the HV end fitting, when the ring was varied in its vertical position. It was found out that the lowest electric field magnitude was when the ring was at a distance of 40 and 50 mm from the base of the HV end fitting.

Figure 3-6. Electric field magnitudes when the position of the corona ring was varied in the vertical axis.
It was also observed when the ring was moved above 50 mm, the electric field strength at the HV end fitting increased. Therefore, it is not recommended to place the ring higher than 50 mm in the vertical axis.

• Development and initial observations

The test configuration is shown in Figure 3-7 (a). A 100 cm PVC rod was positioned vertically and two metallic end fittings were fixed at each end of the rod. The samples were assembled with a hypodermic needle between the PVC rod and the heat shrink sheath. The length of the needle was initially varied, and it was observed that when the length of the metal defect was 50 or 100 mm, the discharge activity had relatively low PD magnitudes of about 400 pC at 140 kV. Whereas a longer needle up to 150 mm, produced PD magnitudes reaching 40 nC at 140.

![Figure 3-7. Shows (a) a photograph of the initial cylindrical set-up and insulating materials used, (b) 3D FEA model of the cylindrical structure and the field intensity when the conductive defect is 150 mm long](image)

Clearly, the effect of needle length depends upon the electrode and stress relieving hardware geometry; the general arrangement is shown in Figure 3-8. Initial experimental observations indicated that not only the length of the metal defects had to be long enough to provide stress enhancement (i.e. be out of the region protected...
by the stress relief toroids), but also the distance between the tip of the needle electrode and earthed electrode had to be reduced to generate interfacial tracks (Chapter 5 provides results and observations about the separation of the tip and earth electrode). In addition to the investigation into the effect of length of the needle, 3D FEA models predict the maximum electric field. Thus FEA models presented in this Chapter illustrate the work in this research to understand how to avoid surface discharge at the HV connection and the sample, as seen in Figure 3-7 (b), and yet provide sufficient fields to promote tracking at the interface.

Moreover, improvements were identified to the manufacturing and assembly processes of the samples through visual observation of the sheath. For instance, when the heat-shrink tubing was used to sleeve the PVC rod, it was noticed that the shrink tubing did not bond evenly with the rod when heat was applied to shrink it; leaving air trapped at the interface and air bubbles along the rod, especially around the body of the needle. Consequently, it formed streamer discharges, with PD magnitudes reaching 60 nC at 40 kV. The intensity of this activity eventually punctured the sheath. Since heat-shrink tubing left air trapped between the components, it was considered that a mechanism capable of evenly tensioning the elastomer sheath used to sleeve the rod would be needed. The development of this mechanism is presented in Section 4.6.2
A second test was carried out with a hypodermic needle embedded between the PVC rod for core and epoxy resin for the sheath. In this case epoxy resin was moulded around the PVC rod using cylindrical Polymethyl Methacrylate (PMMA) tube as a mould. This configuration resulted in the growth of an interfacial track 22 mm long on the PVC rod, when the separation of the tip of the needle to the GND electrode was 85 cm [54]. This configuration required an applied voltage of above 140 kV to see a rapid increment of PD magnitudes that reached 40 nC. On the other hand, voltages above 140 kV caused electrical stress at the electrode extension (see Figure 3-8) attached to the PVC rod with silicone glue. In further tests such electrode extensions were embedded into the resin to eliminate surface discharge along this extension (see Section 4.8 for more details about this). Tests conducted with PVC rods for the core, embedded in the epoxy resin with a hypodermic needle at the interface, provided information on degradation characteristics at those interfaces. The initial experimental work with PVC rods was important to facilitate the development of experimental procedures with a cylindrical structure. However, the aim of this project was to investigate interfacial degradation at controlled silicone rubber/epoxy interfaces, and in commercial rods.

The following conclusions can be drawn from the initial cylindrical experimental tests described above:

- If a silicone rubber tube is used to sleeve the core, then the electrode used had to be very fine wire (45 μm), to allow good union between dielectrics and prevent large airgaps.
- If epoxy resin was used to form the core of the samples, then a hypodermic needle could also be used as an electrode, since it was possible to place the needle at the surface of the epoxy, this is done by casting the needle into resin when the rods are fabricated.
- It was observed that there was no need for a corona ring on the earthed electrode since this was far enough away from the high voltage electrode so as not to result in PD.
• The position of the metal defect (needle/wire) should be more than 150 mm above the HV corona ring. This provided a sufficiently enhanced electric field to produce high discharge activity at the tip of the electrode.

• An electrode extension was used to attach to the metal defect to increase its length above 150 mm and avoid surface discharge, which is described in Section 4.8.

• The distance between the tip of the needle/wire and the earthed electrode has to be reduced to the minimum of 200 mm to generate tracking, with an applied voltage up to 50 kV avoiding discharge activity at the HV connections.

The following adjustments were later made to improve the cylindrical system: the earth end-fitting was replaced with a circular aluminium plate of 150 mm diameter, as shown in Figure 3-9. An electrode extension was formed to increase the length of the cylindrical sample (see Section 3.9 for further details). Finally, a 45 μm stainless steel wire was used as electrode when the rod was sleeved with silicone rubber tube, to ensure good union between the components.

The major advantages developed in the cylindrical experimental configuration are:

• Any dimension of the sample in length between the electrodes and sample diameter can be used. The electrode extension allowed the length of the sample to be increased by up to one meter

• The position of the metallic defect can be placed at any distance along the sample.

• Cylindrical samples configurations can be assembled using various insulating materials.

• Configuration of electrodes could be needle to plate or edge of the wire to plate, depending on the materials used to form the sample.
Figure 3-9. Final design of the cylindrical experimental facility used to investigate interfacial ageing in cylindrical long-rod samples. It also shows a composite rod attached to the extension connection. The electrode separation is 90 cm.
3.4.3 Development of the flat system

As explained in the introduction (Section 3.2), the flat system was developed as a complementary facility, to investigate interfacial ageing due to the loss of adhesion between the core and the sheath in composite insulators. Therefore, silicone rubber and epoxy resin plaques of 50 x 150 mm have been subjected to various interfacial pressures, from 0 to 60 kPa.

In the initial experiments, two hypodermic needles were placed between the dielectric plaques to enhance the local electric field magnitude. The main problem encountered carrying out this experiment resulted from the diameter (815 µm) of the needle body, this does not allow for complete contact between the plaques. Thus, even when high pressure is applied for bonding, air can be trapped around the body of the hypodermic needles (as displayed in Figure 3-10).

The distance between the needle tips was 80 mm and the samples were tested with an applied voltage of up to 50 kV for approximately 5 hours, during which time a maximum PD magnitude of 20 nC was recorded. The pressure applied to the plaques was 60 kPa, which did not fully remove the air around the needle. The intensity of the electrical discharge did not produce interfacial tracking growth. On the contrary, several flash-over/flash-under appeared frequently and very fast, until breakdown (BD) occurred at 50 kV.

Figure 3-10. Epoxy and silicone rubber plaques of 50 x 150 mm compressing two hypodermic needles used as electrodes. Where air is trapped, is visible as a lighter shade in the rectangular sample around the needles.
Furthermore, several weak points were observed in the experimental flat system. These needed be addressed to obtain well-controlled experimental facility. The issues were as follows:

- Corona discharge inception between the HV connection external to the plaques and the sample was at 5 kV.
- A 45 μm diameter wire electrode allowed better union of the plaques (smaller or no air gaps) so this should be employed rather than the hypodermic needles.
- It is also a requirement that as the camera was earthed; the minimum distance of the camera lens has to be 150 mm away from the energised sample, to avoid influencing the field in the sample and to avoid flash-over and damage to the camera.

IEC 60270 standard [101] highlights the importance of reducing the electrical disturbances to minimum, in order to detect partial discharge inception voltage (PDIV) of the sample under investigation. PDIV is defined by the first rapid increment of the partial discharge magnitude detected, which is above the background noise when the applied voltage was increased. So, during the test at the increment of voltage, PD magnitudes increased at certain voltages. The first detected increment of PD magnitude that exceeded the background noise was considered the inception voltage, which initiates the PD activity in the sample under test.
Therefore, adjustments were carried out to eliminate the background noise (corona discharge) at the HV electrode. Figure 3-11 shows various connections that were implemented to reduce corona discharge at the HV electrode, which was monitored using a UV viewer. It also shows two nylon plaques of 50 x 150 mm and 20 mm thick, which were used to avoid direct contact to the ceramic weights and to distribute the applied pressure uniformly on the planar samples.

![Diagram showing various connections to reduce corona discharge at the HV electrode](image)

Figure 3-11. Three attempts to eliminate corona discharge at the HV connection. On the right side the corona discharge activity that each connection produced can be seen.
The attempts shown in Figure 3-11 to eliminate the corona discharge activity on the HV connection were not successful, so 3D FEA models were used to design the HV connection. Figure 3-12 shows the model, which consisted of two spheres with dimensions of 100 mm diameter at the ends of a copper pipe (29 mm diameter and measuring 260 mm long to form the HV connection) and an oval earthed plate (90 x 150 mm) separated by 150 and 200 mm from the HV copper pipe.

The FEA models also assisted in finding out if the electric field at the connections exceeded the critical strength (3 kV/mm) for corona inception. It was observed that increasing the electrode distance helped to avoid surface discharge at the connections. Figure 3-13 shows the comparison of maximum electric field magnitudes at the applied voltage of 32 kV RMS. For example, when the electrode distance is 200 mm, the maximum field is 1.78 kV/mm. When the electrode gap is 150 mm the maximum field is 2.01 kV/mm, which is still lower than the threshold value for corona inception. Thus, the new HV connection provided an effective stress control relief device to prevent external surface discharges between the metal defect (wire or needle), the test sample and the HV connection.
From the FEA models presented here and the experimental observations, it was noticed that the electrical stress in the connections can be controlled as a function of the gap distance between electrodes. For this reason the electrode separation was set to 200 mm in order to reduce the electrical stress between the HV and earthed electrodes.

Figure 3-13. 3D FEA models of the implemented experimental structure and the electric field distribution when the electrode gap distance is (a) 200 mm and (b) 150 mm. For both models, the maximum field magnitude is lower than the threshold value for corona inception in air. (1.8 and 2.0kV/mm respectively)

Figure 3-14 (a) shows a schematic diagram of the flat system implemented, where the distance between the tip of the wire and the earthed plate was fixed at 90 mm for all the tests presented in this thesis, whilst the distance between the HV and the earthed electrode was set to 200 mm. In addition, the 3D FEA models were used to identify the field magnitude of 42 kV/mm at the tip of the wire electrode when a voltage of 32 kV was applied, as shown in Figure 3-14 (b).
Figure 3-14. Experimental set-up showing (top view) and (b) 3D FEA model shows the complete experimental set-up, including the field magnitude of 42 kV/mm at the tip of the wire when a voltage of 32 kV is applied, the field magnitudes are in kV/mm.

Figure 3-15 shows a photograph of the final design of the experimental apparatus, used to investigate interfacial ageing in planar insulating materials. The HV connection consisted of a copper pipe (15 mm diameter) that was connected to two perpendicular copper pipes with a 29 mm diameter and a 260 mm length forming a T-shape. The wire embedded within the sample was connected at this joint by passing between the perpendicular pipes. Two aluminium spheres with a 100 mm diameter were attached to the end of the upper 29 mm diameter copper pipe. The earthed plate consisted of an oval aluminium plate of 90 x 150 mm.

Figure 3-15. Experimental facility used to investigate interfacial ageing in planar insulating samples.
For the implemented experimental set-up described above, the background noise at 0 kV was 3.2 pC when the electrodes were separated by 200 mm from each other. Figure 3-16 shows that in the planar experimental set-up (without a wire in the sample) the discharge activity initiates at the HV connections when the voltage was increased to 56 kV, the PD magnitude measured was 6.7 pC.

![Figure 3-16. PD activity and magnitudes of the planar experimental set-up when the voltage was increased at 56 KV](image.png)

### 3.4.4 PD data acquisition and imaging software

In this project, two devices were used to assess the growth of interfacial channels. Omicron MPD600 PD detector was used to monitor partial discharge magnitudes and the partial discharge inception voltage, whilst an optical camera was used to monitor visible degradation. The procedures of how the data was taken, recorded, and analysed are disclosed as follows:

**a) PD magnitudes acquisition**

The PD magnitudes used in this project are values provided by the commercial Omicron MPD600 PD detector. This filters the PD pulses in the frequency (i.e. bandwidth 30 to 400 kHz) specified by the IEC-60270 standard [101]. Therefore, the
output PD pulses measured are below the maximum cut-off frequency given by the IEC standard. Figure 3-17 shows the visualization and control window of the Omicron PD measurement software, where PD events can be visualised, quantified, and recorded with the aid of the Omicron software. The visualization area displays:

(i) the number of PD pulses per cycle (N)

(ii) the voltage phase angle of PD events occurred (\( \phi \))

(iii) the PD magnitudes of both polarities, showing \( Q_{\text{peak}} \) (absolute charge) and \( Q_{\text{IEC}} \) (apparent charge) values

On the right side of the window of the software is the control area with control tabs for changing settings, record options, and the ability to produce files/reports.

It is noteworthy that the \( Q_{\text{peak}} \) magnitudes are proportional to \( Q_{\text{IEC}} \) magnitudes, both of which are determined by the charge calibration that was injected to the system (50 pC) before the beginning of each experimental test [101].
In addition, $Q_{\text{peak}}$ magnitudes and the wave of the voltage are relevant in the analysis of phase-resolved voltage and phase-resolved PD magnitude models [148]. Whereas, $Q_{\text{IEC}}$ values are used to quantify the PD magnitudes in a macro view. In this project the waveform of the voltage was not used to monitor interfacial degradation. Therefore, $Q_{\text{IEC}}$ magnitudes were used in this study to detect partial discharge inception voltage and monitor PD magnitudes as an indicator of tracking development. Omicron software provides an MS-Excel report of the $Q_{\text{IEC}}$ magnitudes that can be quickly accessed [149], for example to plot a trend line of the PD magnitudes for post-analysis of 96 hours of information recorded.

**b) Measurements of channels**

The maximum in length and width of the tracking regions were assessed using camera images obtained at 30-minute intervals, using digital imaging software. Figure 3-18 illustrates how the measurements were done. The images contained 4272 x 2848 pixels, which is equivalent to an area of 52 x 78 mm. The pixels of the channels that grew were measured and then converted into millimetres using a scale of the area that was taken. The image containing the formation of channels was measured in length, width. The length (Y axis) and width (X axis) were measured by drawing a rectangle of the area that the growth of the channels occurred, as the diagram below shows:

![Diagram](image.png)

Figure 3-18. How measurements of the length and width were assessed upon growth of the channels
3.5 Chapter summary

This Chapter provides a description of the development and implementation of two experimental arrangements and their capabilities, with the aim to study interfacial ageing in between polymers and their mechanism of failure. Both experimental facilities presented here allowed visual monitoring of the interface track growth and record PD activity, with a minimum PD background noise of $\sim 3$ pC, this facilitates the detection of inception voltages of the samples under investigation.

3D FEA model of both systems helped to investigate the electric field distribution around the components and assisted in establishing the electrode designs and separations to avoid surface discharge at the connections. The main advantage presented in these experimental configurations is that the distance between electrodes can be varied, so electrode extensions were implemented to samples to study the interfacial degradation as a function of the electric field intensity. The experimental set-ups developed in this project facilitated the development of novel experiments described in Chapter 4. The results of those tests are disclosed in Chapter 5.
Chapter 4

Materials used and sample preparation

4.1 Introduction

This Chapter presents the final methodology developed for the purpose of fabricating samples to mimic the structure of composite insulators that are used in overhead transmission lines. This is to aid investigation of the interfacial ageing at the core-to-sheath interface that may occur within composite insulators due to internal defects. The objective of this Chapter is to describe a standard procedure for fabrication of samples with similar chemical and physical characteristics, to achieve reproducible test results. The limitations and difficulties encountered in these processes are also disclosed, so that these procedures can be implemented for future investigations of interfacial ageing of insulating materials.

4.2 Structures and materials used

Building on the knowledge developed in Chapter 3, two types of samples were prepared for this investigation. One was formed as planar slabs and the other in a cylindrical shape. The geometries and dimensions can be seen in Figure 4-1. Both samples were prepared using unfilled Epoxy resin (EP) and unfilled high temperature vulcanized Silicone Rubber (SiR) as the main materials for this study. In the planar and cylindrical samples, EP is used to form and mimic the solid core, whilst the SiR is placed over the epoxy plaque as Figure 4-1 (a) illustrates, or was sleeve to the epoxy rod as Figure 4-1 (b) illustrates.
The planar samples are used to examine the effect of de-bonding or loss of adhesion of the sheath in composite insulators. On the other hand, cylindrical samples were formed to replicate the internal degradation that occurs at the core-to-sheath interface under electrical stress in a more typical geometry.

The next section describes the preparation of the epoxy resin material. The SiR material was purchased as either a translucent sheet of SiR of 3 mm thickness or a translucent tube of 22 mm internal diameter and 3 mm thickness (Polymax), as received from a commercial supplier.

### 4.3 Preparing epoxy resin

The core of commercial composite insulators is manufactured with glass-fibres embedded with an organic resin, such as epoxy resin (EP). In this project unfilled epoxy resin is used to mimic and form the solid core, as the process to fabricate samples in different sizes and shapes is then simple. Since EP is translucent, it allows visual monitoring of the test as tracking develops. Under electrical discharge activity epoxy resins are likely to form carbonaceous or other residues, which are part of the investigation in this study.

The epoxy resin used here is a thermoset polymer, which consists of the mixture of an epoxide resin, such as Diglycidyl Ether-Bisphenol-A (DGEBA) and cured with a polyamine agent, known as hardener. In this study, the commercial cold curing epoxy resin Araldite-LY5052 and Aradur-HY5052 hardener (Huntsman) is used. The reason for using this specific resin is because it has been used in previous laboratory studies.
[150]–[156]. Its behaviour under electrical stress is therefore known within our research group. However, these investigations have previously been on the mm to micron-scale and are limited to a needle-to-plane configuration. In this project, the epoxy specimens are fabricated in cm-scale and have a 45 µm stainless steel wire as an electrode. The following four steps make the process to manufacture the epoxy resin solid dielectric:

a. *Preparation of epoxy/hardener mixture*
   First, a mixture of epoxy and hardener is prepared in the ratio of 100:38 (by weight) in a beaker, as per the instructions given by the manufacturer (Huntsman). After the desired amount of mixture is produced, the product is stirred, first manually with a stirring bar, then with the help of a magnetic-stirring bar mixer, where the material is placed in a magnetic electric stirrer for about 2 minutes, to mix the compound further.

b. *Degassing of compound*
   De-gassing of the compound is done in order to remove the air in the mixture formed during stirring. This is achieved by placing the compound in a vacuum chamber. The vacuuming process is as follows: the first 15 minutes are in intervals of 1 minute to avoid spilling of the mixture, as foaming will cause it to rise to the brim of the beaker. The vacuuming intervals are then increased to every 5 minutes, as the number of air-bubbles decrease. This process can take up to 60 minutes, until the air-bubbles of the compound are completely eliminated.

c. *Moulding*
   Once the air-bubbles are removed, the product is ready to dispense into moulds of either planar or cylindrical shape, to be cured at room temperature for 24 hours. Section 4.4 and 4.5 provides detailed information about how the resin was cast into planar and cylindrical moulds.
d. Curing

In the final stage, the material is placed in the oven at 100 °C for 4 hours to post-cure, as per the data sheet. The insulating material was left in the oven for 4 hours more once the oven was switched off to slowly cool the epoxy to ensure complete reproducible curing and avoid thermal shock.

The above describes the basic steps to prepare the epoxy resin. The next section defines how to form the solid dielectric with a flat and smooth surface. Since the preparation of the moulds is very important to achieve a suitable sample for experimental testing, the use of polythene gloves is recommended throughout this process.

4.4 Casting planar samples

For preparation of epoxy resin plaques, the epoxy compound obtained from the above process is poured into a rectangular PTFE mould with dimensions 150 x 255 mm as shown in Figure 4-2. This contains 175 grams of the EP compound to form slabs of 5 mm thick. The base of the mould consists of a 2 mm thick polycarbonate sheet. Care is taken to ensure the polycarbonate sheet surface is kept pristine and free of scratches, so after the product is cured, it will result in a flat and smooth epoxy plaque, with a surface roughness of ~1.5 μm. This surface is then used for testing (see Chapter 6 – Section 6.2.3 for more details about surface roughness measurements).
After 24 hours when the epoxy block is cured at ambient temperature, the PTFE frame is carefully removed with a Stanley cutter knife by inserting the sharp tip of the knife at the edges between the PTFE frame and the resin plaque, so separating the frame carefully without breaking its corners, the resulting demoulded plaque is shown in Figure 4-3.

The polycarbonate sheet is also removed from the base just before placing the epoxy plaque to post-cure in the oven. The resulting resin plaque is placed on a nylon tray with the base facing upwards, and then placed in the oven for post-curing.

After the epoxy plaque has cooled down, it is wrapped immediately with polyethylene cling film to protect its surface from scratches. The 150 x 255 mm EP slab was marked (see Figure 4-4) where it should be cut to separate 5 pieces of 50 x 150 mm with a band saw. The cling film was removed from the epoxy plaques only to assemble the specimens for the tests. Section 4.6 discloses the details of the assembling process.
4.5 Casting cylindrical samples

The cylindrical samples were produced by casting it into acrylic tubes of 20 mm internal diameter. They were then used to investigate the development of interfacial tracking in a cylindrical structure. Figure 4-5 shows the acrylic cylinder mould of 150 mm length. Each tube holds 30 grams of the epoxy compound. The edges of the acrylic tubes were smoothed and then wiped with propanol to remove loose particles. The base of each tube was glued to a PTFE lid with hot silicone sealant to prevent the epoxy compound leaking from the base.
After the curing process, the epoxy cylinder was cut in half with a band saw, as Figure 4-6 shows. The flat side of the half-rods was polished until scratches and lines, produced during cutting, were removed. Thereafter, it was rinsed with deionised water and blow dried with warm air. The acrylic mould was carefully removed from the half-rods to avoid scratches on the surface of the cylinder when demoulded. The half rods were positioned with the base facing downwards on a nylon tray, and then it was placed in the oven for post-cure and drying. After the epoxy half-rods cooled down, the samples were protected with cling film until they were needed to assemble the components. Epoxy samples were kept in a wooden draw at room temperature and humidity for about 4 to 12 days before testing. It is known that epoxy resin absorbs a certain amount of moisture under ambient conditions. The amount of moisture uptake affects when the epoxy resin remains stable, such as glass transition temperature and reduced mechanical properties [1],[66],[157]. For future investigations, it is suggested to monitor the amount of moisture taken up by epoxy samples, and to store fabricated epoxy samples in desiccators to reduce/control the moisture absorption. The next section describes the assembly process in detail.

Figure 4-6. 22 x 150 mm long epoxy rod cut in half inside the acrylic mould. The flat surface is polished and rinsed with deionised water. The acrylic mould is removed before placing the sample in the oven for post-curing.
4.6 Assembling process

This section describes the detailed procedure on how the dielectrics and the electrode were assembled to form the test sample ready to be electrically stressed.

In the planar samples, a 45 µm stainless steel wire was used as an electrode, sandwiched between the two dielectrics. In the cylindrical sample, two different electrodes were used: a hypodermic needle and a wire. Polyethylene gloves were worn at all times during sample preparation. This helped eliminate the presence of, or addition of other substances between the materials used.

4.6.1 Assembling planar samples

Figure 4-7 shows the planar dielectrics which consist of one epoxy and one SiR plaque of 50 x 150 mm. To assemble these samples the following steps were undertaken:

- The edges and corners of the epoxy slabs were smoothed with a file, and then rinsed with deionised water. The SiR slab and the wire were wiped with propanol; the slabs were dried immediately; by blow drying with warm air to avoid leaving surface stains.

- The tip of the wire was formed into a circular shape (a hoop) by wrapping the fine wire round a piece of copper wire of 120 µm. As a result, the wire kept a circular shape and the extra wire was cut just at the edge, resulting in a circular tip of ~1.2 mm diameter, as Figure 4-8 shows.

- A mark was made on the external side of the epoxy plaque, as a reference point to replicate the exact point where the tip of the wire needed to be positioned (see Figure 4-7). Thus, the wire was placed first on the epoxy plaque at distance of 40 mm from the opposite side as Figure 4-9 shows. Then the SiR slab was placed over the EP slab to sandwich the wire.

- Figure 4-9 shows the trapped air between the slabs that was formed at the first moment of placing the components together. Air was removed by pressing the SiR plaque against the Epoxy plaque manually until all observable trapped air at the interface was removed.
The samples, now ready for the test, were mounted on a transparent rectangular acrylic box (40L x 25H x 20W cm), which supported the samples whilst ceramic weights were positioned on top to vary the mechanical pressure on the sample. The test configuration and components were illustrated in Section 3.4 — Figure 3-2 (b).

Reference point to place the tip of the wire

(a)

(b)

Figure 4-7. 150 x 50 mm dielectric plaques, where (a) Epoxy and (b) Silicone rubber

Figure 4-8. (a) shows a 120 μm copper wire, around which was wrapped the 45 μm stainless steel wire to form thinner wire into the electrode tip. (b) how and where the wire was cut to form a circular tip
4.6.2 **Assembling cylindrical samples**

To form a cylindrical sample, a 150 mm long SiR translucent tubing of 22 mm internal diameter and 3 mm thickness is used to sleeve the half Epoxy rod that was shown in Figure 4.6. Between these dielectrics a 45 μm stainless steel wire is used as an electrode. The cylindrical configuration includes a sectioned polyoxymethylene (POM) Acetal® rod (see Figure 4-10), which is used to push the SiR tube and the Epoxy half rod together. The sectioned POM rod includes three nylon bolts that are used to tension the SiR tube and adjust the components by tightening the bolts. The assembling procedure is described as follows:

a) A 150 mm long piece of SiR tube is cleaned with propanol and blow dried with warm air immediately to avoid leaving surface stains. A 200 mm long piece of electrode wire was cleaned with propanol and placed in a clean nylon tray.

b) A mark on the external surface of the SiR tube was made to indicate the positioning of the tip of the wire, which indicates the separation to the ground plate.

c) The wire used as electrode was introduced inside the SiR tube, with the aid of a thick wire (2 mm diameter), which was first introduced in the SiR tube, then the
fine wire was attached to the thick wire, which is then used to pull the fine wire inside the SiR tube.

d) The sectioned epoxy rod is placed inside the SiR tube, making sure the wire electrode is between the SiR tube and the epoxy rod, as the diagram shows in Figure 4-11.

e) The tip of the wire that was bent into a circular shape of ~1.2 mm diameter is placed at the edge of the epoxy rod, as Figure 4-11 shows. Then the wire was placed in the desired position, by pulling carefully until it reached the mark previously made on the external surface.

f) The POM rod was placed under the epoxy rod, in order to adjust the components by tightening the bolts included in the half POM rod, as seen in Figure 4-12.

Figure 4-10. 150 mm sectioned POM rod used to adjust the components by tightening the nylon bolts (M8 – 30 mm)

Figure 4-11. The components used to form the cylindrical configuration, as well as the tip of the wire formed at the edge of the epoxy/SiR interface
4.7 Preparing commercial samples

Commercial rod samples of composite insulators were similarly prepared in a planar and cylindrical configuration; the method to prepare these samples for testing is as follows.

4.7.1 Planar samples

Commercial composite rods consist of pultruded glass-fibre for the core and an extruded silicone rubber sheath of 21 mm diameter, were cut into strips 5 mm thick by 150 mm length. The resulting composite plaques were cast into epoxy resin, as Figure 4-13 shows.
The reason for casting the commercial composite sample into resin was to increase the width of the sample. A sample with a thin width limits the voltage applied, increasing the wide width also facilitates a stable surface to apply mechanical pressure on the top of the sample without an unbalance. The structure of the sample is illustrated in Figure 4-14.

The procedure to cast these samples is very similar to that described in Section 4.4, except that composite plaques were placed into a rectangular-shaped PTFE frame of 150 x 50 mm, over a polycarbonate sheet which formed the base of the mould. The epoxy resin mixture was then dispensed into this mould. After curing and post-curing the resulting plaque was polished with abrasive grinding paper from P80 to P2400 grit. It led to a surface roughness of ~4 μm, on which the interfacial test was conducted. These plaques were assembled in the same way as described in Section 4.6.1 to form the samples for testing.
4.7.2 Cylindrical samples

In the cylindrical commercial samples, hypodermic needles were used as electrodes, while commercial rods were embedded into epoxy resin. As an initial step the lubricant coat was removed from the hypodermic needles by soaking the needles in Silstrip® solution following the process described by Bahadoor et al [151].

Commercial rods of 100 mm length were cut in half lengthways, and polished before being embedded into the epoxy resin; in order to visualise the progression of the test on the polished surface. The reason for casting was to avoid discharge activity at the union of the electrode and the sample. Figure 4-15 shows two different methods that were prepared as follows; (a) where a hypodermic needle was introduced between the rod and the silicone rubber sheath by first creating the hole with another needle and (b) a hypodermic needle was placed on the surface of the elastomer sheath and embedded in epoxy resin.

Figure 4-15. Diagram of how the commercial samples were prepared for testing, where a hypodermic needle was placed: (a) within the commercial product at the pultruded glass fibre composite/silicone rubber interface and (b) at the interface between the silicone rubber and the laboratory cast epoxy resin. Not to scale.
Both configurations were embedded into the epoxy resin, using an acrylic tube mould of Ø 22 mm (as Figure 4-5 shows) for casting the epoxy mixture. The distance of the needle’s tip was 70 mm from the sample’s edge (see Figure 4-15 (a)).

After the resulting rod assembly was cured, it was de-moulded as follows: two grooves of ~1.5 mm deep were cut with a hand saw along the acrylic mould. A flat screw driver was used to go along these grooves to crack and remove the acrylic tube. The final rod/assembly was rinsed with water and dried.

Finally the rods were placed in a nylon tray, and then the tray placed in the oven at 100 °C for 4 hours to post-cure. Figure 4-16 shows the resulting rods ready for the test.

4.8 Electrode extensions

The cylindrical samples were elongated by cylindrical extensions to enlarge the gap between the electrodes. Three different lengths of extensions were used; 25, 55 and 75 cm. These extensions consisted of a PVC tube of 15 mm diameter. The PVC tube also had a 575 µm diameter wire passing through the tube and embedded in resin: one end connects to the HV electrode, whereas the other end of the wire was inserted into
the hollow body of the hypodermic needle of ~800 µm internal diameter, which was embedded in the sample as Figure 4-17 (a) shows. To avoid surface discharge, this connection was embedded using hot silicone glue as Figure 4-17 (b) shows.

![Figure 4-17. The connection that allowed the length of the cylindrical samples to be extended, (a) the red arrows show the direction by which the 575 µm wire is inserted in the hollow body of the connection; (b) after the wire from the sample was inserted, this connection was embedded in hot silicone glue.](image)

### 4.9 Chapter summary

This Chapter explains the procedures undertaken and the processes to make samples with consistent characteristics. Some recommendations can be made from this work. Since a large amount of epoxy resin was needed to fabricate these large samples, the compound was prepared in three beakers, so it would not cure too fast, and would be easier to de-gas. In order to prepare the cylindrical samples, it is recommended to use epoxy rods no longer than 15 cm, as longer samples increased the likelihood that air-bubbles would be trapped along the cylinder. In addition it is recommended to ensure the edges of the mould joints are sealed properly as the compound may leak or allow air to ingress into the compound thus forming air-bubbles.

The main challenge in these procedures was remoulding the commercial sample for inclusion in the planar and cylindrical moulds. It was important that the surface of the epoxy sample was scratch-free. Thus, the surfaces of both epoxy samples were very carefully treated to avoid scratches or contaminants. Moreover, the epoxy samples
were fabricated in batches of fives for planar and four for cylindrical samples, and stored in a clean wooden drawer at room temperature for between 4 to 12 days, prior to testing. They would be wrapped in cling film covering all surfaces for this time to keep them clean. Finally, it is recommended that an examination should be done to the tip of the electrode wire hoop using a microscope to ensure it is properly formed. Any edges, scratches, kinks or other defects could lead to anomalously high fields and facilitate the growth of tracks from that point, not at the intended hoop tip.

This chapter has documented how planar and cylindrical samples have been fabricated to allow reproducible measurements on laboratory-prepared materials, and commercial composite insulations. This work has been a major part of the research project and provides a solid foundation for the measurements reported in Chapter 5.
Interfacial tracking results

5.1 Introduction

This chapter presents experimental results from cylindrical and planar samples. The description of the components and sample preparation was described in detail in Chapter 4. Experimental results are divided into two main sections i.e. cylindrical and planar samples. Experimental work on cylindrical configuration allowed investigation of the interfacial degradation as a function of electric field intensity, this was achieved by (i) varying the separation between the tip of the wire electrode and the earth plate varied in four steps: 120, 100, 80, and 60 mm, and (ii) varying the electrode separation up to one meter. In the planar system, the loss of mechanical pressure between epoxy resin and silicone rubber plaques was investigated. The effect of the surface roughness of the samples’ interface was also investigated. 2D and 3D FEA models allowed for the computation of the electric field intensity in both experimental systems and are used to understand the required electric field that initiates interfacial tracking.

Moreover, to ensure the reproducibility of results, a unified test procedure was used throughout the experiments. Although the length tracks and partial discharge magnitudes differ slightly when comparing between samples, it is still possible to identify a typical behaviour that helped develop a model of the interfacial degradation discussed in Section 7.4. AC voltages reported in this chapter are RMS values unless otherwise stated.
5.2 Tests results for cylindrical samples

The initial tests aimed to investigate the inception field level as a function of separation of the electrode tip and the earthed electrode. Different separation between the earthed electrode plate and the wire tip were tested, varying from 60 to 120 mm. Samples were electrically stressed at 37 kV for 1440 minutes. Table 5.1 shows that the partial discharge inception voltage increases when the separation of the tip of the electrode and the earthed electrode is larger. The PDIV indicates the apparent charge magnitude that initiates discharge activity in the sample that was stressed. It was useful to detect the PDIV because it allowed comparison of the level of electrical stress to the other samples. It was also possible to observe the inception voltage increased when the separation distance between the electrodes was varied, meaning that a higher voltage (electrical stress) was required to stress the cylindrical sample when the distance between the electrodes increased.

Table 5-1. Partial discharge inception voltage

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Electrode separation (mm)</th>
<th>PDIV (pC)</th>
<th>Inception voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC-60</td>
<td>60</td>
<td>9.80</td>
<td>4.5</td>
</tr>
<tr>
<td>IC-80</td>
<td>80</td>
<td>16.25</td>
<td>5.4</td>
</tr>
<tr>
<td>IC-100</td>
<td>100</td>
<td>36.45</td>
<td>11.3</td>
</tr>
<tr>
<td>IC-120</td>
<td>120</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Interfacial degradation was only seen when the separation from the tip to the earthed electrode was at 100 mm. When the separation of tip and the earthed electrode was set to 60 mm, interfacial channels grew fast in length, up to 36.5 mm in 1020 minutes. The characteristics of the long track can be seen in Figure 5-1 and the test was stopped to avoid breakdown. It was also observed that at 80 mm separation, interfacial channels also grew fast, reaching 29.4 mm in length. The opposite happened when the separation was set at 100 mm – the interfacial track only grew 10 mm in length. When the separation of the tip to the earthed electrode was at 120 mm, at this electrode separation, the electric field was not enhanced enough to start the formation of interfacial tracking even after 2800 minutes of electrical stress at 37 kV.
This behaviour is due to the influence of the 8 inch diameter commercial corona ring at the HV electrode. So, when the separation of the tip and the earthed electrode was at 120 mm, the electric field enhancement at the HV connection was not enough to stress the cylindrical sample.

After observing the required separation between the wire tip and the ground electrode was above 120 mm to stress the sample, it was decided to fix the separation between the tip of the wire to the ground electrode to 90 mm. The reason is that at 100 mm, the initiation of interfacial channel is too slow and at 80 mm the distance may become shorter and the growth of track can be influenced as the channel extends in length.

5.2.1 Electrode separations

Further test were undertaken with various separations between the HV and the earthed electrode. Figure 5-2 shows a schematic diagram that illustrates how the distance of the earthed electrode from the HV end fitting (NB this is not the same as the hoop electrode-plane electrode separation distance) was varied from 20 to 100 cm. These tests served to identify the level of interfacial degradation at different insulator lengths. The results presented in this section made it possible to identify the threats posed to the reliability of composite insulator in service, at varying operating voltages.
Table 5-2 shows the recorded PDIV of ten samples tested, it can be observed that the inception voltages had a strong relationship with the electrodes separation. For example, when the electrodes were 20 cm apart, the voltage required to initiate partial discharge activity was approximately 10 kV whereas, when the separation between the electrodes was 1 meter, the discharge activity started at about 1.9 kV. One of the reasons why the values of the inception voltage are higher when the earthed electrode was set apart at 20 and 40 cm was because the corona ring reduced the discharge activity at this electrode separation. On the other hand the inception voltage is lower with longer electrode separation because the corona ring causes no field reduction effect when the earthed electrode was set above 60 cm, so partial discharge activity is more easily initiated at lower voltages in such cases.
Table 5-2. PD inception magnitudes and applied voltage

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Electrode distances (cm)</th>
<th>Inception magnitude (pC)</th>
<th>Inception voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C20-A</td>
<td>20</td>
<td>38.20</td>
<td>9.58</td>
</tr>
<tr>
<td>C20-B</td>
<td>20</td>
<td>41.12</td>
<td>10.38</td>
</tr>
<tr>
<td>C40-A</td>
<td>40</td>
<td>55.08</td>
<td>7.11</td>
</tr>
<tr>
<td>C40-B</td>
<td>40</td>
<td>37.47</td>
<td>4.99</td>
</tr>
<tr>
<td>C60-A</td>
<td>60</td>
<td>17.25</td>
<td>4.40</td>
</tr>
<tr>
<td>C60-B</td>
<td>60</td>
<td>16.66</td>
<td>5.45</td>
</tr>
<tr>
<td>C80-A</td>
<td>80</td>
<td>22.80</td>
<td>3.89</td>
</tr>
<tr>
<td>C80-B</td>
<td>80</td>
<td>19.64</td>
<td>3.38</td>
</tr>
<tr>
<td>C100-A</td>
<td>100</td>
<td>24.35</td>
<td>1.3</td>
</tr>
<tr>
<td>C100-B</td>
<td>100</td>
<td>20.19</td>
<td>1.9</td>
</tr>
</tbody>
</table>

The maximum PD magnitudes are displayed in Figure 5-3, where is shown the increment of these PD magnitudes when the voltages were raised from 20 to 37 kV at different electrodes’ separations. It was observed that when voltages above 35 kV were applied PD magnitudes varied in time. But from 35 kV upwards there were no fluctuations of PD magnitudes, as these were always increasing and at 37 kV the PD magnitude increased rapidly as shown in Figure 5-3. It can also be observed from the graph that at electrode separations from 20 to 60 cm, the maximum PD magnitudes were 186 pC at 25 kV, whereas at electrode separations 80 and 100 cm PD magnitudes were between 600 to 700 pC. This indicates the corona ring reduced the discharge activity in the electrode separation up to 60 cm. Finally, it was observed that at 37 kV the PD magnitudes keep increasing over time with an electrode separation at 100 cm.
FEA models to investigate the electric field magnitudes and distributions

3D FEA models were built to investigate the electric field magnitudes and identify the position of the maximum field in the large cylindrical structure. The FEA models in this section do not include the air trapped around the tip of the electrode. The average voltages tabulated in 5-2 were used in the models, when the earthed electrode distance was varied as it was done in the tests. Table 5-3 displays the computed maximum electric field magnitudes at discharge inception (located at the tip of the wire), as Figure 5-7 depicts.
The computed values of the electric field magnitudes displayed in Table 5-3 indicate that the electrode separations at 20 and 40 cm exceeded the critical electric field magnitude in air (3 kV/mm) at the core-to-sheath interface [20]. For the other electrode separations the calculated electric field magnitude indicates values lower than those expected to start electrical discharge activity. Thus, the maximum field is controlled by the location of the tip of the wire in the larger assembly. When the tip of the wire is out of the area in which the field is managed by the corona ring, the field magnitude is much higher.

Moreover, Table 5-4 presents the electric field magnitudes encountered at the tip of the electrode at different voltages and different electrode separations, which are investigated in this experimental work.

<table>
<thead>
<tr>
<th>Electrode distances (cm)</th>
<th>Applied voltage (kV rms)</th>
<th>Max electric field (kV/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>10</td>
<td>4.07</td>
</tr>
<tr>
<td>40</td>
<td>6.1</td>
<td>3.27</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
<td>2.73</td>
</tr>
<tr>
<td>80</td>
<td>3.6</td>
<td>1.94</td>
</tr>
<tr>
<td>100</td>
<td>1.6</td>
<td>0.88</td>
</tr>
</tbody>
</table>
Table 5-4. Computed values of the electric field at different voltages encountered at the tip of the wire electrode

<table>
<thead>
<tr>
<th>Electrode distances (cm)</th>
<th>Max Electric Field at 35 kV (kV/mm)</th>
<th>Max Electric Field at 37 kV (kV/mm)</th>
<th>Max Electric Field at 43 kV (kV/mm)</th>
<th>Max Electric Field at 50 kV (kV/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>14.2</td>
<td>15.1</td>
<td>17.5</td>
<td>20.3</td>
</tr>
<tr>
<td>40</td>
<td>18.7</td>
<td>19.8</td>
<td>23.1</td>
<td>26.8</td>
</tr>
<tr>
<td>60</td>
<td>18.75</td>
<td>19.9</td>
<td>23.2</td>
<td>26.9</td>
</tr>
<tr>
<td>80</td>
<td>18.8</td>
<td>20.2</td>
<td>23.4</td>
<td>27.3</td>
</tr>
<tr>
<td>100</td>
<td>19.2</td>
<td>20.3</td>
<td>23.6</td>
<td>27.5</td>
</tr>
</tbody>
</table>

As observed in Table 5-4, when the sample is stressed at 35 kV, an increase of about 35 % is observed in the electric field magnitude for electrode separations 20 and 100 cm. When the electric field is considered as a function of applied voltage in all samples from 35 - 50 kV, a 43 % increase is observed in the electric field. Therefore, it is expected that a higher internal degradation will occur at voltages above 35 kV.

Figure 5-4 shows an enlarged view of the 3D model of the experimental set-up and the electric field magnitude along the core/sheath interface, when the separation of the electrodes was 20 cm. The green line connotes the electric field distribution 400 µm inside the silicone rubber sheath, whilst the blue line is the electric field distribution at 400 µm inside the epoxy resin core, which shows lower electric field magnitudes compared to electric field magnitudes and distribution inside the silicone rubber sheath.

Figure 5-4 also depicts the influence of the corona ring in the electric field enhancement, as at 80 mm away from the HV electrode is below 3 kV/mm, but after the corona ring, the electric field increases rapidly.
Figure 5-4. Electric field magnitude and distribution 400 µm inside the epoxy resin and the silicone rubber, when the separation between the electrodes is 20 cm. The image above the plot uses the 3D structure of the sample and electrode configuration in an FEA reconstruction.

Figure 5-5 shows the electric field that causes a 45 µm wire at the epoxy/silicone rubber interface. The line distribution of the electric field was taken at 400 µm inside the epoxy resin and the silicone rubber when the electrode separation was 1 meter and the applied voltage set at 37 kV. It can be seen from the plot that the corona ring reduces the electric field enhancement below 2 kV/mm for about 500 mm. Figure 5-6 shows an enlarged view of the electric field magnitude at the core/sheath interface, at the tip of the electrode and the earthed plate. From this graph, it is observed that the electric field is high only on the HV electrode and the earth electrode does not influence the development of interfacial channels. The electric field at the tip of the wire reaches 20 kV/mm, and then decreases rapidly to 0.5 kV/mm at 10 mm from the electrode wire tip (Figure 5-6 (b)). Whilst when the electrode separation is 20 cm the electric field at 10 mm from the electrode wire tip is 0.4 kV/mm.
Figure 5-5. The electric field magnitude at the core/sheath interface, from the tip of the electrode to the earth plate, (b) the magnified area

Figure 5-6. Electric field intensity 400 µm inside the epoxy resin and the silicone rubber, when the electrode distance is 1 meter and the applied voltage is 37kV
Figure 5-7 depicts the electric field at the epoxy resin/silicone rubber interface and silicone rubber/air interface. It can be observed that the maximum electric field is at the tip of the electrode and the intensity is more significant in the silicone rubber.

Figure 5-7. The electric field magnitudes and distribution in a cross-section of the internal structure, as seen the field enhancement at the tip of the wire that is positioned between an epoxy rod and silicon rubber sheath. This is the simulation when the electrodes are separated 100 cm and with an applied voltage of 37 kV
5.2.2 Influence of the separation between the electrodes

This section presents the track initiation and development when the electrode separation was increased from 20 to 100 cm, whilst the separation between the tip of the electrode wire and the earthed electrode plate was fixed at 90 mm. Partial discharge magnitude and the measurement of the lengths of the tracks were used to quantify the intensity of the internal degradation. The voltage applied to the samples in the experiments reported in this section was 37 kV.

Figure 5-8 shows the partial discharge magnitudes of these tests at 20, 40, 60, 80 and 100 cm over a period. As seen, sample C20-A at 20 cm electrode separation has the lowest PD magnitude recorded; this is due to the influence of the corona ring placed at the high voltage electrode which reduced the electrical stress. Also, sample C40-A at electrode separation 40 cm was also affected by the corona ring, thereby making it one of the lowest PD magnitude recorded among all the tests. However, sample C100-A at electrode separation 100 cm has the maximum PD magnitude, and it was least influenced by the corona ring.

![Figure 5-8. Partial Discharge (PD) activity over time of tests at electrode distance from 20 to 100 cm](image-url)
It can also be observed that when the separation was at 20 cm (C20-A), the maximum PD recorded was 9200 pC and when the separation of the electrodes is 100 cm (C100-A) the maximum discharge magnitude reached 24600 pC. It is evident from Figure 5-8 that a direct relationship exists between discharge activity and electrode separations, i.e. as the electrode separations is larger, the electrical discharge activity becomes stronger and vice-versa.

Figure 5-9 provides information on the growth in length of interfacial channels when the distance of the HV end fitting and earthed electrode was varied from 20 to 100 cm. Sample C100-A experienced the fastest development of interfacial channels over all the samples presented in this section, the formation of dark branches near the tip of the electrode were the main findings in these tests. Figure 5-10 (a) shows that the channels grew to 17.7 mm at 510 minutes, and the maximum PD reached 11574 pC. At 690 minutes, channels grew to 19.31 mm, maximum PD reached 15207 pC. The main observation at this time was the initial formation of dark tracks near the tip of the electrode; this is related to carbonaceous deposits within the tracks, which would enhanced the local field at their development [158]. Figure 5-10 (b) shows the areas more clearly where these carbonized channels were formed.
Chapter 5

Interfacial tracking results

After 1110 minutes channels grew up to 23 mm in length and the maximum PD magnitude reached 17207 pC. The development of a new branch at the tip of the electrode had grown rapidly, and the characteristics of this branch can be seen in the red circle displayed in Figure 5-10 (c). The formation of the new branches is associated with conducting tracks that enhance the local field and increased the discharge activity [158]. After carbonisation close to the metal hoop the discharge activity is originated from the carbonized tracks rather than at the tip of the wire hoop electrode. This was evident in the continued increment of maximum PD magnitudes over time and rapid channel growth in length.

Figure 5-10. Development of interfacial channels sample C100-A with electrode distance at 100 cm. (a) 510 minutes, (b) 690 minutes, formation of dark channels near the tip of the electrode is circled in red, (c) 1110 minutes, a new branch is formed at the tip of the electrode, (d) formation of interfacial channels of 29.71 mm in length after 2880 minutes
Overall, a positive relationship exists between electrode separation, growth in length of interfacial channels and the increment of PD magnitudes; as the intensity of the discharge activity promotes the growth of larger interfacial channels. The results presented in this section shows that the maximum PD magnitude has a strong relationship with the growth of channel in length. Table 5-5 summarises the information on the maximum PD recorded and the length of the interfacial channels of the tests presented in this section.

Table 5-5. Experimental results at different electrode distances and voltages

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Electrode distances (cm)</th>
<th>Max length of channels (mm)</th>
<th>Max PD recorded (pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C20-A</td>
<td>20</td>
<td>21.42</td>
<td>9200</td>
</tr>
<tr>
<td>C40-A</td>
<td>40</td>
<td>20.31</td>
<td>12800</td>
</tr>
<tr>
<td>C60-A</td>
<td>60</td>
<td>22</td>
<td>15500</td>
</tr>
<tr>
<td>C80-A</td>
<td>80</td>
<td>23.89</td>
<td>18700</td>
</tr>
<tr>
<td>C100-A</td>
<td>100</td>
<td>29.71</td>
<td>24600</td>
</tr>
</tbody>
</table>

5.2.3 Influence of the applied voltage and separation between the electrodes

This section provides information about the influence of the applied voltage magnitude and the interfacial track development. This test was also useful to establish / suggest safe voltage limits, to avoid breakdown or to damage equipment. The tests were initially set to 37 kV as maximum applied voltage; above this voltage three samples failed due to the intensity of the discharge activity that punctured the sheath of the samples tested in the first ~40 minutes after the initiation of the test, thereby resulting in a breakdown. Therefore, in the tests described subsequently, the increase of the voltage magnitude to 43 kV was only when the PD magnitudes became almost
constant and the track reached about 75% of the total length of the average track growth (20 mm).

Four samples with the earthed electrode separated from the HV fitting by between 20 and 80 cm were initially stressed at 37 kV. At this voltage magnitude, it was observed that the PD magnitudes increased consistently but slowly until PD magnitudes became almost constant. Figure 5-11 shows in the first 900 minutes of the four tests, PD magnitudes were less than 10000 pC. This resulted in the growth of channels \(~17\) mm in length at this time as Figure 5-12 shows. To encourage the growth of interfacial channels, the voltage magnitude was increased to 43 kV, normally after the 900 minutes of initiating the test. In each case after the voltage magnitude was increased the PD magnitudes increased rapidly, encouraging the growth of channels in length rapidly (Figure 5-11 and Figure 5-12). For instance, when the electrode separation was 20 cm (sample C20-B) and the initial applied voltage was set to 37 kV, the max PD recorded was 6704 pC. Thereafter, when the voltage was raised to 43 kV after 960 minutes, PD magnitudes increased and reached 13346 pC in the last 1920 minutes of the test; Figure 5.11 (a) shows this increment.

For the sample C40-B with the electrode separation of 40 cm and the applied voltage of 37 kV, the max PD recorded was 11922 pC. When the voltage was raised to 43 kV after 960 minutes, PD magnitudes increased to a max PD magnitude of 21318 pC in the last 1920 minutes (see Figure 5.11 (b)). At the electrode separation of 60 cm (sample C60-B) and the applied voltage of 37 kV, the max PD recorded was 9856 pC. When the voltage was raised to 43 kV after 990 minutes, PD magnitudes increased reached a max PD magnitude of 22681 pC in the last 1890 minutes of the test. Finally, at the electrode separation of 80 cm (sample C80-B) and the applied voltage of 37 kV, the maximum PD recorded was 13700 pC. When the voltage was raised to 43 kV after 1590 minutes, PD magnitudes increased and reached a maximum PD magnitude of 24200 pC in the last 1290 minutes of the test.
Figure 5-11. PD activity of: (a) sample C20-B - electrode distance at 20cm with the voltage increased after 960 min, (b) sample C40-B - electrode distance at 40cm, voltage increased after 960 min, (c) sample C60-B - electrode distance at 60cm, voltage increased after 990 min, (d) sample C80-B - electrode distance at 80 cm and voltage increased after 1590 min

Figure 5-12 displays the maximum growth in length of the interfacial channels for the four tests exposed to 2880 minutes of electrical stress. It was observed that the increment of voltage influenced the interfacial degradation, as at a higher voltage the partial discharge activity became stronger and consequently the growth of channel in length increased.

The incremental growth in length of the channels after the voltage was increased to 43 kV was as follows: for the sample C20-B, it grew 9 mm, for the sample C40-B the length of interfacial channels increased 7.23 mm, whilst the increase was 12.37 mm for the sample C60-B.

However, for sample C80-B with the electrode separation of 80 cm, the length of interfacial channels increased by only 1.24 mm after the voltage increase; the growth in length was less pronounced at 43 kV for all tested samples. It is assumed that
channels did not have enough time to develop, because the voltage was increased after more than half of the test time. It was observed that the internal degradation depends on the applied voltage. At a higher voltage, electrical stress increases rapidly and consequently the channel length becomes greater.

![Graph showing interfacial channel growth against time at different increments of voltage](image)

Figure 5-12. Interfacial channel growth against time at different increments of voltage

Sample C60-B illustrates the influence of the applied voltage, as the growth of the channels was more marked that the other samples. Figure 5-13 illustrates the development of the test, the separation of the tip of the electrode to the ground electrode was set to 90 mm and the applied voltage was 37 kV. Figure 5-13 (a) shows the development of the channels that grew to 16.9 mm at minute 990, the max PD recorded was 9856 pC. When the voltage was raised to 43 kV after 1140 minutes, PD activity increased to 15658 pC and the growth of the channels increased rapidly to 18.2 mm, Figure 5-13 (b) and (c) shows these changes. As a result of the voltage increase, the PD magnitudes reached a maximum PD magnitude of 22681 pC in the last 1890 minutes of the test.
Figure 5-13. Sample C60-B: (a) development of the channels at 37 kV at 990 minutes, (b) 1140 minutes was noticed that one of the branches grew at 6.5 µm/minute, (c) 2070 minutes: a new branch grew at the tip of the electrode, (d) interfacial channels at 2880 minutes.

Figure 5-14 shows the growth characteristic of electrical trees in the epoxy rod, the main branch grew 5092 µm in length and 146 µm width. The tips of these channels are black in appearance. It assumed that these dark channels encourage the growth in length of the channels at the interface rapidly.
Finally, sample C100-B with electrode separation at 100 cm was electrically stressed at 32 kV, ensuring that this electrode separation would be enough to cause significant PD activity and internal degradation. However PD activity and the development of interfacial channels were observed to be smaller (Figure 5-15) than the other samples presented above. Therefore, it is noteworthy that the electrode separation can result in a fast partial discharge inception voltage to initiate the growth of interfacial channels, but if a voltage above 32 kV is applied to the sample, the growth of channels will result in larger channels at the core/sheath interface.
Comparison with samples C20-B, C40-B, C60-B, C80-B and C100-B confirms that PD magnitudes are influenced by the applied voltage and the separation between the electrodes, but the increment of voltage showed a greater encouragement on the development of interfacial channels. Jointly, the increment of voltage up to 43 kV and the electrode separation shows that tracking degradation at the epoxy resin/silicone rubber is strongly influenced by both the applied voltage and the electric field intensity. Table 5-6 summarizes this information.

Table 5-6. Maximum PD magnitudes and growth in length of the channels at different electrodes distances

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Electrode separation (cm)</th>
<th>Max length of channels (mm)</th>
<th>Max PD recorded (pC)</th>
<th>Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C20-B</td>
<td>20</td>
<td>22.51</td>
<td>13346</td>
<td>37/43</td>
</tr>
<tr>
<td>C40-B</td>
<td>40</td>
<td>26.05</td>
<td>21318</td>
<td>37/43</td>
</tr>
<tr>
<td>C60-B</td>
<td>60</td>
<td>29.36</td>
<td>22681</td>
<td>37/43</td>
</tr>
<tr>
<td>C80-B</td>
<td>80</td>
<td>20.52</td>
<td>24200</td>
<td>37/43</td>
</tr>
<tr>
<td>C100-B</td>
<td>100</td>
<td>19.20</td>
<td>10925</td>
<td>32</td>
</tr>
</tbody>
</table>
5.2.4 Results of tests with commercial rods

This section presents the experimental tests performed using commercial rods to investigate their interfacial degradation. These experimental tests aim to understand the internal degradation that occurs in commercial composite insulators in service. Detailed information of the sample preparation was provided in Chapter 4.

Measurement of the intensity of the degradation processes in these tests was carried out by analysing the partial discharge activity and the light emitted from the discharges, as the colour of the samples were not translucent. The construction of sample GRP-C6 and GRP-C7 made it possible to measure the growth of the channels as the sample was embedded into the transparent epoxy resin (see Section 4.7.2 for further details); the electrode separation in these tests were fixed at 90 cm.

The maximum PD magnitudes when the voltage was increased is displayed in Figure 5-16, it was observed that above 25 kV PD magnitudes are proportional to the applied voltage. From 30 kV upwards the PD magnitudes were consistent, and were always increasing.

![Figure 5-16. PD magnitudes when the voltage was increased up to 37 kV in commercial samples](image-url)
Sample GRP-C1, was the first test with commercial rods with an applied voltage of up to 37 kV. Figure 5-16 shows the PD magnitudes, there is a moderate increment over time. Figure 5-17 shows the image captured when the camera was placed on the side of the sample, which was then realised not to be the best place to monitor the progression of these tests as the light emitted from the discharges cannot be fully quantified. This test lasted 3270 minutes, and a maximum PD magnitude 7889 pC was recorded as shown in Figure 5-18.

Figure 5-17. Electrical discharge activity in sample GRP-C1, (a) and (b) shows the brightest light emitted from the discharge at 3270 minutes

Figure 5-18. PD magnitudes against time of sample GRP-C1
Figure 5-19 shows the PD magnitudes from sample GRP-C2, which was electrically stressed for 9720 minutes. PD magnitudes showed a continued increment up to about 4690 minutes of the test, thereafter the magnitudes stopped increasing. As a result, the light emitted from the discharge intensity at minute 4600 was also reduced, this made it very difficult to capture during the test.

Figure 5-20 shows a comparison between samples GRP-C1 and GRP-C2 that were initially tested to investigate the voltage limit in commercial samples. Comparing the PD development observed in sample GRP-C1 at 37 kV and that of sample GRP-C2 at 35 kV for 3270 minutes, it can be seen that the PD trend is quite similar but for sample GRP-C2, a higher magnitude of about 10500 pC was attained whilst sample GRP-C1 reached 7990 pC.
Figure 5-20. Comparison of PD development between sample GRP-C1 and GRP-C2, following a similar PD pattern.

Figure 5-21 shows the PD magnitudes and the increment of voltage that was applied to sample GRP-C3. Figure 5-22 (a) shows the light emitted from the PD activity, which was very poor during the test. The light from the electrical discharges became brighter when the voltage was increased in minute 6570 from 35 to 43 kV. Figure 5-22 (b) shows the amount of degradation after 13290 minutes of applied electrical stress at 43 kV.

Figure 5-21. PD magnitudes and increment of voltage that was applied to sample GRP-C3.
Figure 5-22. Sample GRP-C3 shows (a) light emitted from the PD activity, (b) the resulted degradation as dark areas after 13290 minutes of applied electrical stress at 43 kV.

Figure 5-23 shows a comparison of samples GRP-C2 and GRP-C3 at 35 kV. It can be seen that these two tests initially do not follow the same pattern, but both samples reached a stable PD level after 3000 minutes of testing. A significant difference between the PD magnitudes for samples GRP-C3 and GRP-C2 was observed with both samples attaining a maximum PD of 21400 pC and 12600 pC respectively at 6540 minutes of testing.

Figure 5-23. Comparison of sample GRP-C2 and GRP-C3 at 35 kV, both tests were plotted at 6540 minutes for comparison.
Figure 5-24 shows the comparison of PD magnitudes between samples GRP-C1, GRP-C2 and GRP-C3. It is noteworthy that 37 kV was applied to sample GRP-C1, yet it can be seen that sample GRP-C3 had a very different PD development and higher magnitudes at 35 kV. The reason for the difference in the PD magnitudes between samples is not clear. It is probably due to factors associated with sample assembly, e.g. (i) air could be trapped around the tip of the needle electrode when it was placed at the rod/sheath interface or (ii) the tip of the needle could be bent when it was introduced at the interface.

Nevertheless, there is barely any difference in voltage between 35 and 37 kV on analysing the samples under the optical microscope. In both tests tracking development was weak. Conversely, a strong tracking and treeing formation was seen in sample GRP-C4 that was tested at 43 kV, in which the PD patterns are completely different.

![Graph showing PD magnitudes for samples GRP-C1, GRP-C2, and GRP-C3.](image)

*Figure 5-24. Samples GRP-C1, GRP-C2 and GRP-C3; tests were plotted at 3270 minutes for this comparison*

Figure 5-25 shows the PD magnitudes of sample GRP-C4, tested at 43 kV, in the initial stage of the test the maximum PD recorded was 18762 pC, thereafter the discharge activity decreases significantly to PD magnitudes about 9600 pC.
Figure 5-25. PD magnitudes of sample GRP-C4

Figure 5-26 (a) and (b) shows the strongest light emission captured from the discharge activity that was recorded at 330 minutes of the test, which correlates to the highest PD magnitude. Figure 5-26 (c) shows the level of degradation of sample GRP-C4 after 6600 minutes of electrical stress. Figure 5-30 (a) shows a cross-section of the sample after the test indicates that the tracks preferred to grow into the pultruded glass-fibre core and the sheath of the sample to pierce it; as it will be the shortest path to the earth electrode, for that reason it has been assumed that the light emitted from the electrical discharges were weak. The commercial samples were cast in epoxy resin, so it was difficult to damage / puncture the sheath, whereas the samples fabricated by the author the silicone tube used as sheath was easier to pierce by high discharge activity, thus the voltage was limited to 43 kV (see Section 5.2.3) because of the weak sheath of the lab-fabricated samples.
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Figure 5-27 shows the PD magnitudes of sample GRP-C5, where the applied voltage was 50 kV, encouraged the growth of fast tracks at the core to sheath interface as shown in Figure 5-28 (a) and (b). However, after 420 minutes of the test, the discharge activity was reduced over time due to the growth of tracks that no longer propagates along the interface, and a reduction of the light intensity of the electrical discharges was observed as shown in Figure 5-28 (c). Figure 5-30 (b) shows a cross-section of the sample after the test shows that the tracks preferred to grow into the pultruded glass-fibre core of the sample.

Figure 5-26. Progress of the test of sample GRP-C4 (a) maximum light emitted from the electrical discharge intensity at 330 minutes (b) light from the PD activity was difficult to visualise at 610 minutes, (c) damaged area at the end of the test.
Figure 5-28. PD magnitudes of sample GRP-C5 exposed to 2750 minutes of electrical stress at 50 kV.

Figure 5-27. Shows sample GRP-C5. (a) and (b) the intensity of the discharge activity reached the full length of the commercial rod section, in both images at 210 minutes (c) minute 2750 at the final stage of the tests where the light from the discharges was reduced due to tracks that did not grow along the interface, but in the bulk of the pultruded glass-fibre core
Figure 5-29 displays the comparison of PD magnitudes between samples GRP-C4 and GRP-C5 as the PD trend became very similar at 2750 minutes. The similarity in the trends is believed to be a function of the voltage levels set at 43 and 50 kV respectively. However, sample GRP-C5 had a higher magnitude at the beginning of the test reaching 28830 pC, whilst sample GRP-C4 reached 18763 pC.

![Graph showing PD magnitudes of samples GRP-C4 and GRP-C5](image)

Figure 5-29. PD magnitudes of samples GRP-C4 and GRP-C5, tests were plotted up to 2750 minutes for this comparison

Figure 5-30 displays polished cross-sections of the sample GRP-C4 and GRP-C5 after testing. Optical images from the microscope show that the development of dark tracks are visible in the silicone rubber, but the growth of electrical trees is more pronounced in the bulk of the pultruded glass-fibre core. These two samples had the worse degradation among all the samples; this is clearly related to the applied voltage that was set at 43 and 50 kV respectively. Sample GRP-C5 was tested for half the time of GRP-C4, but it resulted in a greater growth of electrical trees in the core. Moreover, PD magnitudes and patterns are different compared to previous commercial samples (GRP-C1, GRP-C2 and GRP-C3) suggesting the decrease of PD magnitudes at the final stage of the test, which is related to the growth of electrical trees in the bulk of the composite structure.
Sample GRP-C6 was prepared with the hypodermic needle on top of the silicone rubber to monitor from a different perspective the process of interfacial degradation. The development of this test is summarised as follows:

Figure 5-30. Cross-section of the plaques show electrical tree growth in sample (a) GRP-C4 after 6600 minutes of electrical stress at 43 kV and (b) GRP-C5 after 2750 minutes of electrical stress at 50 kV.
• The track grew 6.16 mm in length over the first 150 minutes at the epoxy resin/silicone rubber interface, as Figure 5-31 (a) shows. The light from the discharges was observed but there was no sign of any track growth for a period of 420 minutes.

• At 450 minutes little branches of the track came out of the epoxy resin/silicone rubber interface reaching about 12.5 mm in length, as seen in Figure 5-31 (b). Although, the track growth at the interface was more noticeable at 480 minutes.

• Figure 5-31 (c) shows the final dimension of the track that reached 13.26 mm in length; this also includes the area where the track grew beneath the sheath. This hidden track is ~6 mm long and the image is from after the sample was exposed to 750 minutes of electrical stress.

A camera placed on the side helped to visualise the area where the tracks penetrated the silicone rubber and also the growth of the tracks in the epoxy resin (see Figure 5-32).
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Figure 5-33 shows the recorded PD magnitudes, which helped to identify the period when the tracks grew under the silicone rubber. PD magnitudes decreased in minute 210, which is the time when the tracks visually stop growing at the interface, but it developed within the pultruded glass-fibre and appeared again to grow in the epoxy resin at minute 450 when the PD magnitudes increased again. These test results are the supporting evidence for the first time of the assumptions that the decrease of PD magnitudes is directly related to the growth of electrical trees in the bulk of the composite structure.

Figure 5-32. Shows the growth of the tracks seen in the epoxy resin and the area where the tracks appear again from beneath the sheath are in the dotted, white circle

Figure 5-33. PD magnitudes and interfacial channel growth against time of sample GRP-C6
Sample GRP-C7 was tested at 32 kV, the voltage was reduced as the previous test (sample GRP-C6) was at 50 kV. This was to investigate if the tracks would pierce the silicone rubber and if the growth from beneath the pultruded glass-fibre would occur again at this voltage. Unfortunately, it was not possible to continue with this investigation as the sample failed at minute 1880, after one branch reached a de-bonded area, resulting in streamer discharge. Figure 5-34 shows the de-bonded area at the epoxy resin/silicone rubber interface and the resulted streamer discharge, which increased in strength over time until flash-under occurred and damaged the sample.

Figure 5-34. Sample GRP-C7 (a) the area where epoxy resin did not bond properly to the silicone rubber and streamer discharge intensity is marked in the red dotted figure, (b) streamers approached towards earthed electrode prior to flash-under

Figure 5-35 shows the PD magnitudes and the growth of the interfacial channels before the streamer discharge occurred, maximum PD recorded in this test was 2598 pC, which caused the growth of interfacial channels of 3.49 mm in length and 5.61 mm in width.
Experimental tests with commercial samples allowed the investigation of the mechanisms of degradation that occurred at the interface of composite insulators. PD magnitudes were used to monitor the tests, which indicate two different PD patterns according to the applied voltage. Tests with applied voltage up to 37 kV showed that PD magnitudes tend to increase slowly over time. Whereas when the applied voltage was above 43 kV PD magnitudes increased rapidly, then it decreased over time. This was identified as electrical tree growth in the bulk of the sample. Thus, PD magnitudes in this section served to monitor the intensity of the internal degradation in commercial rods. Table 5-7 summarized the findings in this section.
5.2.5 Discussion of the results in cylindrical samples

In this section, commercial composite rods and lab-fabricated cylindrical samples were exposed to different voltage magnitudes. The influence of the distance between HV and earthed electrode was also investigated to understand the interfacial degradation in a long-rod configuration, as it occurs in a composite insulator. The commercial rods exhibited different PD pattern behaviour and lower discharge inception voltages. The average inception voltage was 2.4 kV in commercial rods; whilst 3.6 kV in the lab samples (when the distance between HV termination and the earth electrode was 80 cm).

It was observed in the lab-fabricated samples that at an applied voltage of 35 kV the PD magnitudes increase continuously over time. Whilst the commercial rods exhibited an increase continuously of PD magnitudes at applied voltages of 30 kV. Moreover, PD magnitudes increased over time faster when compared to the fabricated samples. This difference is due to the glass-fibres embedded in the matrix of the rod, which facilitate the electrons mobility at the fibre epoxy interface, and consequently increase PD activity [5].

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>PD Inception magnitude (pC)</th>
<th>Inception voltage (kV)</th>
<th>Max PD (pC)</th>
<th>Applied voltage (kV)</th>
<th>Duration of the test (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRP-C1</td>
<td>25.65</td>
<td>3.6</td>
<td>7989</td>
<td>37</td>
<td>3270</td>
</tr>
<tr>
<td>GRP-C2</td>
<td>24.80</td>
<td>3.2</td>
<td>12600</td>
<td>35</td>
<td>9720</td>
</tr>
<tr>
<td>GRP-C3</td>
<td>14.34</td>
<td>1.5</td>
<td>27787</td>
<td>35/43</td>
<td>13298</td>
</tr>
<tr>
<td>GRP-C4</td>
<td>13.60</td>
<td>1.6</td>
<td>18763</td>
<td>43</td>
<td>6600</td>
</tr>
<tr>
<td>GRP-C5</td>
<td>27.69</td>
<td>2.1</td>
<td>28831</td>
<td>50</td>
<td>2750</td>
</tr>
<tr>
<td>GRP-C6</td>
<td>20.96</td>
<td>2.4</td>
<td>31963</td>
<td>50</td>
<td>750</td>
</tr>
<tr>
<td>GRP-C7</td>
<td>24.47</td>
<td>2.2</td>
<td>2598</td>
<td>32</td>
<td>1800</td>
</tr>
</tbody>
</table>
The results of this study provide information about (i) the influence of the separation of the HV and earthed electrode on the PD activity, (ii) the influence of the variation of voltage magnitude in the interfacial degradation, and (iii) the relationship with the results of the commercial composite rods and lab-fabricated samples with unfilled epoxies.

(i) Influence of the separation of the HV and earthed electrode on PD activity

The influence of the distance of the HV and earthed electrode was first investigated in the lab-fabricated samples. It was observed when the earth electrode was 20 and 40 cm distant, the PD magnitudes were below 10000 pC for test C20-A, resulting in the small growth of channels in length. On the other hand, larger electrode separation results in higher PD magnitude, which promotes the growth of larger interfacial channels.

Thus, the variation of the electrodes distance allowed the change of the electric field magnitude in which the tracks grew independently from the applied voltage. Table 5-5 displays the maximum growth in length and maximum PD magnitudes.

(ii) Influence of the variation of voltage magnitude in the interfacial degradation

The influence of the increased voltage magnitudes in the interfacial degradation was also studied in the lab-fabricated samples. It was noted that 43 kV is the maximum voltage that can be applied to these samples without premature sheath failure. If the test is initiated at this voltage, the intensity of the discharge activity will puncture the sheath of the sample causing a breakdown. The samples were tested initially with a voltage of 37 kV and then after ~900 minutes the voltage was increased to 43 kV, which then resulted in an increment of the PD activity that encouraged the fast growth of channels, causing a strong level of degradation. The increase of voltage was possible latterly because the track itself modified the field in which it was growing.
Champion and Dodd [159] investigated the relationship between the increment of voltage magnitude and electrical tree growth. They noted a stable rate of growth in lower voltages from 11 to 14 kV; but a faster tree growth was observed when the applied voltage was increased from 15 to 17 kV. They highlighted the reasons for the rapid growth and change in the tree structures was because the increment of voltage affected the development of space charge within the polymeric matrix.

The main characteristic observed in these tests was the development of dark channels near the tip of the electrode. The development of carbonised tracks enhances the local field within the structure of the track as it grows, increasing the discharge activity [158]. A polished cross-section of the sample C60-B shows the growth of electrical trees from these carbonised tracks (see Figure 5-14). The development of trees into the epoxy resin is consistent with the work presented by Andersson et al. [142] and Kobayashi et al. [132].

(iii) Experimental results of the commercial composite rods

Observing the test results of commercial samples, it can be seen that PD patterns changed when the voltage magnitude was increased from 35 to 50 kV. Samples electrically stressed at 35 kV have relatively low degradation when compared to those electrically stressed at 50 kV, where the preference of channels is in the bulk material, resulting in a large growth of electrical trees (see Figure 5-30). These observations were confirmed by analysing the images of the development of sample GRP-C6, PD patterns also indicated the reduction of PD magnitudes to be strongly related to the growth of electrical trees in the pultruded glass-fibre core of the sample (see Figure 5-33).

It was difficult to establish a relationship between the results of the commercial composite rods and lab-fabricated samples. This is mainly because the development of PD magnitudes and interfacial channels were developed in a different manner. For instance, in the lab-fabricated samples it was visually observed that during the formation of carbon tracks and growth of electrical trees into the epoxy rod, the PD
magnitudes increased over time. Whereas in the commercial rods PD magnitudes decreased when electrical trees were developed in the pultruded glass-fibre core. This is an observation that requires more investigation. The comparison between the polished cross-sections of the sample after the tests displayed in Figures 5-14 and 5-30 shows different mechanisms of channel propagation into the core rod of the commercial samples. For example, 5-14 shows that a main channel (146 µm wide and 5092 µm in depth) grew into the epoxy rod; whereas in Figure 5-30 it can be seen that the glass-fibre in the core allowed tracks to propagate along the fibres and into in the bulk of the composite structure. This is consistent with the work reported by Kamer and Ieda [1] where the discharge activity used the glass-fibres as a path so electrical trees were formed along the glass-fibres and developed in the bulk of the composite structure.

Finally, from the results presented in this section, it was learned how effectively the PD activity can be reduced with the aid of a corona ring placed at the HV electrode. It was observed that when the separation between the HV and earthed electrode was 20 cm, it resulted in low PD magnitudes that reduced the growth of channels in length, whereas a larger separation between the HV and earthed electrode (above 60 cm) will result in strong PD activity, and consequently, greater interfacial ageing.

It was also seen from the tests performed at higher voltages (43 and 50 kV) and prolonged durations, interfacial degradation becomes more pronounced. It can therefore be suggested that utilising a corona ring in systems at voltages of 132 kV or lower would be effective towards achieving a reduced electrical stress experienced by composite insulators in polluted environments [160].
5.3 Tests results for planar samples

5.3.1 Introduction

This section presents test results investigating the growth of interfacial tracking when mechanical pressure was varied from 0 to 60 kPa. Please refer to Section 4.6.1 for materials, structure and the assembly of the samples presented in this section.

Four samples (A, B, C and D) were tested at intervals of 20 kPa. These samples were electrically stressed with AC voltages at 32 kV for 96 hours. Two additional tests (E and F) were conducted at 60 kPa, performed at 42 kV, sample E for 17 hours and sample F for 100 hours. Sample E and F are used to discuss the chemistry of tracking presented in Section 6.2. Finally a sample with sectioned parts of commercial rods (GRP-F) is presented at the end of this section. The data was divided according to the maximum PD magnitude and phases of channel growth. RMS voltage values are used in this section to present the results.

Figure 5-36 gives examples of the visible interfacial channels grown at various mechanical pressures. As shown the dimensions (width and length) of the tracking patterns are similar for each set of samples at 0 to 60 kPa from A to D. However, the colour and structure of the channels differed when pressure was applied; the formation of dark channels near the tip of the electrode were more evident. Whereas the samples with no pressure applied were characterized by a single and wider main channel that looked white. It was also observed that the skeletal structure contained fewer branches than the other samples when pressure was applied.
Table 5-8 shows the measured partial discharge inception voltage (PDIV) for each sample. The increment of pressure requires higher voltage magnitude to initiate partial discharge activity, i.e. the required voltage magnitude to initiate electrical discharge is almost double between zero pressure and 60 kPa. This is thought to be due to trapped air around the wire being closed up at higher pressures. As Figure 5-37 shows, PD magnitudes also increase with the increment of pressure except for tests at 40 kPa, it can also be seen that the inception voltages are consistent for tests at 0 kPa and 40 kPa around 2.5 and 3.5 kV respectively.

Figure 5-36. Development of interfacial channels for sample A at: (a) 0 kPa-A, (b) 20 kPa-A, (c) 40 kPa-A and (d) 60 kPa-A

5.3.2 Partial discharge inception voltage in planar samples
Table 5-8. PD inception magnitudes and voltages

<table>
<thead>
<tr>
<th>Test</th>
<th>0 kPa</th>
<th>20 kPa</th>
<th>40 kPa</th>
<th>60 kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Applied voltage (kV)</td>
<td>PD (pC)</td>
<td>Applied voltage (kV)</td>
<td>PD (pC)</td>
</tr>
<tr>
<td>A</td>
<td>2.18</td>
<td>19.34</td>
<td>2.23</td>
<td>25.90</td>
</tr>
<tr>
<td>B</td>
<td>2.98</td>
<td>17.60</td>
<td>3.66</td>
<td>19.96</td>
</tr>
<tr>
<td>C</td>
<td>2.49</td>
<td>18.21</td>
<td>2.56</td>
<td>26.30</td>
</tr>
<tr>
<td>D</td>
<td>2.39</td>
<td>15.10</td>
<td>4.50</td>
<td>25.12</td>
</tr>
<tr>
<td>Average</td>
<td>2.51</td>
<td>17.56</td>
<td>3.24</td>
<td>24.32</td>
</tr>
</tbody>
</table>

Figure 5-37. PD inception magnitudes and voltages at different mechanical pressure

The variation of the applied mechanical pressure to the samples shows different inception voltages to initiate PD activity, as higher voltage magnitudes are required to initiate PD activity at the increment of mechanical pressure [5],[132],[140]. When the inception voltages are compared in each data set, it is possible to identify that inception voltage increases with the increment of mechanical pressure. This is a very consistent behaviour in all the measurements displayed in Table 5-8.
A common behaviour can be observed when no mechanical pressure was applied to the samples, the inception voltage was at \( \sim 2.5 \) kV. When the mechanical pressure was increased to 20 kPa, the inception voltage increased to \( \sim 3.2 \) kV. These measurements had a certain variation when compared and so further tests are needed for consistent data. The increment of pressures 40 and 60 kPa showed that the inception voltage was more consistent at \( \sim 3.5 \) kV. Consequently, discharge inception is proportional to the presence of air at the interface between the wire and the insulating plaques. It is expected that at high pressures this air around the wire is reduced, therefore requiring higher voltage to initiate the discharge activity.

The experimental facility developed in this project allowed to investigate the growth characteristics of interfacial channels, which are used to identify distinct phases of tracking growth, based on PD information and optical images.

- **Electric field at the epoxy/silicone rubber interface**

Figure 5-38 shows the computed electric field magnitude and distribution at the silicone rubber/epoxy resin interface with a variation of air around the 45 \( \mu \)m wire. An average inception voltage of 3 kV RMS was used to investigate the electric field in this system through 2D FEA models. It can be observed that the electric field at the tip of the wire reaches 13.08 kV/mm with no air around the electrode. When the diameter of the air pocket trapped around the tip is 150 \( \mu \)m, the electric field magnitude reached 40.7 kV/mm. The size of the air around the wire was increased up to 550 \( \mu \)m and the electric field at the tip of the wire slightly changed to 42.1 kV/mm.

As seen from the FEA model the presence of air trapped around the tip becomes critical on the surface of the epoxy plaque, as the amount of air around the tip of the electrode enhances the electric field three times in comparison to a scenario with no air around the tip. Even if volume of the air is reduced by increasing the mechanical pressure, the size of this air around the tip of the electrode does not reduce much [125]. FEA models showed that the amount of air is irrelevant in the enhancement of the electric field magnitude.
5.3.3 Development of interfacial channel and PD behaviour

To investigate the growth characteristics of interfacial channels, this section compares samples by PD events and magnitudes. Growth was measured by length and width of channels, with depth also characterised in set of samples A. Rate of growth in depth and width of interfacial channels was related to PD and pressure.

Figure 5-38. Computed electric field magnitudes at the tip of the electrode: (a) 13.08 kV/mm with no air around the tip of the electrode (b) 40.7 kV/mm when the diameter of the air is 150 µm and (c) 42.1 kV/mm when the diameter of the air is 550 µm
This growth was shown to occur in two phases; (i) an initial rapid growth phase, and (ii) a second phase of slower propagation. Measurements of channel growth in length, width, and depth (only samples A provide information of the growth in depth) against maximum PD showed that the rate of growth in length depends on the maximum PD magnitudes and applied pressure. The initial phase of growth was influenced by a high electric field at the tip of the electrode. Once the interfacial channel reached a constant electric field, the rate of growth was reduced. The behaviour is evident from the PD magnitudes over time, which shows a rapid increase in magnitude, followed by a reduction of PD magnitude.

- **Analysis of growth of sample 0 kPa-A**

Figure 5-39 displays the PD magnitudes over time and the growth of channels in length and in width for sample 0kPa-A. The two phases of growth (i) and (ii) can be distinguished from the PD magnitudes.

In the first phase of growth (i), the channels grew to a length of 17.57 mm, a width of 16.40 mm, and a depth of 1.46 mm. After 3120 minutes, a maximum PD of 11220 pC was recorded. In the second phase of growth (ii) (beginning at 3150 minutes), the channels grew by 1.31 mm in length, 2.12 mm in width, and 0.44 mm in depth.

The maximum PD magnitude decayed for a period of 2340 minutes and was focused to the channels close to the tip of the electrode, causing the main channels to thicken and slowing the growth in channel length. It is assumed that PD activity no longer extend through the length of the channels. The red line in Figure 5-39 divides the two phases of growth.
Figure 5-39. Max PD against growth in length and width of the channels over time (sample 0 kPa-A)

Figure 5-40 shows that in sample 0 kPa-A max PD began to increase from 5520 minutes, when a maximum PD of 10810 pC was recorded. (see the red oval). In a period of 240 minutes, the channels grew 0.11 mm in length, 0.30 mm in width, 0.025 mm in depth.
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Figure 5-40. Max PD against the growth in depth of the channels over time (sample 0 kPa-A)

- **Analysis of growth of sample 20 kPa-A**

As in at 0 kPA, two phases of growth can be distinguished from the PD magnitudes. In the first phase of growth (i), the channels grew to a length of 12.21 mm, a width of 17.76 mm, and a depth of 0.59 mm. At 1080 minutes, a maximum PD of 7890 pC was recorded. A similar but less pronounced PD magnitude (7730 pC) remained, until 1710 minutes when the channels grew to a length of 13.65 mm and a width of 19.91 mm. In the second phase of growth (ii) from 1740 minutes, indicated by the red line in Figure 5-41, the channels grew by 2.7 mm in length, 2.23 mm in width, and 1.4 mm in depth (see the blue circle). The maximum PD decayed considerably for 1680 minutes and was focused in the initial channels, thickening and slowing the growth in the length of the channels. A relationship between PD decay and growth in the depth of the channels is proposed.
Figure 5-41. Max PD against growth in length and width of the channels over time (sample 20 kPa-A)

Figure 5-42 shows an increment of max PD from after 3450 minutes, when the maximum PD of 9050 pC was reached. In a period of 2310 minutes, the channels grew 0.86 mm in length, 1.82 mm in width, and 1.01 mm in depth. In the second phase, the rate of growth for depth was higher than that for length. The small growth in channel length indicates that the track propagates in a constant field and its growth is not influenced by the electric field at the tip of the electrode. Whereas the rapid growth of channels in depth in the second phase is associated with the formation of dark channels that enhance the local field and promote the growth of electrical trees into the bulk of the epoxy [132]. These new structures/channels resume the PD activity in the second phase of growth. Therefore, it is proposed that the growth in the depth of the channels increase the PD magnitudes in the second phase, which in turn encourages a small growth in the channel length.
Analysis of growth of sample 40 kPa-A

In the first phase of growth at 40 kPa-A shown in Figure 5-43, the channels grew to a length of 17.25 mm and a width of 18.86 mm, the growth in depth was insignificant. At 870 minutes, a maximum PD of 8537 pC was recorded. A higher PD (88983 pC) had been recorded at 450 minutes. However, even with the variation in PD magnitudes, the growth rates for the length and width of the channels continued to increase. In the second phase of growth (after 900 minutes), the channels by grew 1.6 mm in length, 1.56 mm in width and 1.99 mm in depth.
Figure 5-43 shows an increment of maximum PD from the 3360 minutes, when the max PD of 8851 pC was reached. In a period of 2400 minutes, the channels grew 0.73 mm in length, 0.48mm in width, and 0.80mm in depth. In the second phase, the rate of growth for depth was higher than that for length.
• **Analysis of growth of sample 60 kPa-A**

At 60 kPa-A (Figure 5-45), in the first phase of growth (i) the channels grew to a length of 13.65 mm and a width of 17.20 mm. At 690 minutes, a maximum PD of 10500 pC was recorded. In the second phase of growth (ii), from 720 to 1260 minutes, the decay of max PD magnitudes was less evident. The channels grew 1.62 mm in length and 2.14 in width. During this stage, the growth in depth was difficult to monitor. An interesting observation occurred at 1710 minutes. A high PD value of 12300 pC encouraged growth in length and width, but mostly in width. This rapid enhancement is assumed to be from the rapid increase in the depth of the channels.

![Figure 5-45. Max PD against growth in length and width of the channels over time (sample 60kPa-A)](image)

Figure 5-46 shows an increment of max PD recorded from 1290 minutes, when the maximum PD of 11500 pC was reached. In a period of 4470 minutes, the channels grew 3.46 mm in length, 5.75 mm in width, and 2.51 mm in depth.
The two phases of growth were difficult to identify for most of the samples at 40 and 60 kPa, because a decay of PD magnitudes were insignificant. Perhaps this is due to the formation of carbon deposits at the tip of the electrode, that are more evident in these samples, which is associated to the increment of PD magnitudes as the carbonized tracks extend.

Table 5-9 displays a summary of the final growth of the channels in length of each sample data for comparison. It also provides information of the maximum PD recorded during the test and the time when the maximum PD occurred, so it can be noticed from the maximum PD recorded when PD influenced the growth in length.
Table 5-9. Final growth in length of each sample data, the maximum PD recorded during the test and the time when max PD occurred

<table>
<thead>
<tr>
<th>Test</th>
<th>0 kPa</th>
<th>20 kPa</th>
<th>40 kPa</th>
<th>60 kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Final length (mm)</td>
<td>Max PD (pC)</td>
<td>Time when max PD occurred (min)</td>
<td>Final length (mm)</td>
</tr>
<tr>
<td>A</td>
<td>18.99</td>
<td>11870</td>
<td>2970</td>
<td>17.21</td>
</tr>
<tr>
<td>B</td>
<td>16.80</td>
<td>5823</td>
<td>4680</td>
<td>17.94</td>
</tr>
<tr>
<td>C</td>
<td>20.28</td>
<td>12500</td>
<td>5040</td>
<td>17.27</td>
</tr>
<tr>
<td>D</td>
<td>17.53</td>
<td>7560</td>
<td>960</td>
<td>31.70</td>
</tr>
</tbody>
</table>

From table 5-9, samples A to D can be compared at each mechanical pressure, this comparison helps to understand the phases of growth and the length that the channels grew at the maximum PD magnitudes, which are as follows:

- Comparison for data set at 0 kPa of samples A to D can be seen that the maximum PDs were in the range of 5800 to 12500 pC. Sample 0 kPa-C shows the largest channel, which is proportional to the highest PD magnitude. Maximum PD magnitudes in samples at 0 kPa occurred after the half time of the tests except for sample 0 kPa-D.

- Comparison for data set at 20 kPa of samples A to D can be seen that the maximum PDs were in the range of 8200 to 9000 pC. Sample 20 kPa-D shows the largest channel among the tests, which is proportional to the highest PD magnitude 30000 pC. Maximum PD magnitudes in samples at 20 kPa occurred after the half time of the tests.

- Comparison for data set at 40 kPa of samples A to D can be seen that the channels grew an average of 18.3 mm and maximum PDs were in the range of 8200 to 12300 pC. It is interesting that sample 40 kPa-A and B grew almost the same length but maximum PD magnitude differ by 3000 pC. Maximum PD magnitudes in samples at 40 kPa occurred after the half time of the tests.

- Comparison for data set at 60 kPa of samples A to D can be seen that the maximum PDs were in the range of 9300 to 12300 pC. Sample 60 kPa-D shows...
the largest channel, which is proportional to the highest PD magnitude 17000 pC. Maximum PD magnitudes in samples at 60 kPa occurred before the half time of the tests except for sample 60 kPa-D.

Table 5-10 and 5-11 summarises the dimension of the channels that grew in length and also displays the maximum PD magnitudes in the first phase of growth.

These results present a strong relationship between the maximum PD magnitude and channel length, suggesting that in the first phase of growth the largest discharges traverse the full length of the interfacial track. Whereas the second phase of growth involves the decay of PD magnitudes, which is related to a reduction of tracking growth rate in length. This phase was characterised by the formation of dark channels, and the growth of electrical trees into the bulk of the epoxy plaque.

It is proposed that the formation of dark channels near the tip of the electrode and the growth of electrical trees in the epoxy bulk encouraged the growth of interfacial channels in the second phase.

Table 5-10. First phase of growth based on PD behaviour samples 0 and 20 kPa of samples A to D

<table>
<thead>
<tr>
<th>Test</th>
<th>0 kPa</th>
<th>20 kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time where the 1st phase of growth ends (min)</td>
<td>Max PD in the 1st phase of growth (pC)</td>
</tr>
<tr>
<td>A</td>
<td>3120</td>
<td>11870</td>
</tr>
<tr>
<td>B</td>
<td>660</td>
<td>5145</td>
</tr>
<tr>
<td>C</td>
<td>720</td>
<td>9300</td>
</tr>
<tr>
<td>D</td>
<td>960</td>
<td>7560</td>
</tr>
</tbody>
</table>
Table 5-11. First phase of growth based on PD behaviour samples 40 and 60 kPa of samples A to D

<table>
<thead>
<tr>
<th>Test</th>
<th>40 kPa</th>
<th></th>
<th></th>
<th>60 kPa</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time where the 1st phase of growth ends (min)</td>
<td>Max PD in the 1st phase of growth (pC)</td>
<td>Length at 1st phase of growth (mm)</td>
<td>Increment in final length (mm)</td>
<td>Time where the 1st phase of growth ends (min)</td>
<td>Max PD in the 1st phase of growth (pC)</td>
<td>Length at 1st phase of growth (mm)</td>
</tr>
<tr>
<td>A</td>
<td>1080</td>
<td>8537</td>
<td>17.75</td>
<td>1.83</td>
<td>1020</td>
<td>10500</td>
<td>14.94</td>
</tr>
<tr>
<td>B</td>
<td>1020</td>
<td>10894</td>
<td>15.73</td>
<td>3.86</td>
<td>840</td>
<td>6738</td>
<td>13.35</td>
</tr>
<tr>
<td>C</td>
<td>1170</td>
<td>8515</td>
<td>14.83</td>
<td>3.77</td>
<td>960</td>
<td>10304</td>
<td>13.80</td>
</tr>
<tr>
<td>D</td>
<td>1020</td>
<td>6940</td>
<td>15.41</td>
<td>1.51</td>
<td>1020</td>
<td>13200</td>
<td>18.42</td>
</tr>
</tbody>
</table>

Figure 5-47 shows a decrease in duration of time at the first phase of growth that was seen as mechanical pressure increased.

Figure 5-47. Effect of pressure on initial growth phase duration (data from Table 5-10 and 5-11)

The values displayed in Figure 5-47 are the maximum time taken from each set of data; these values can be seen in Table 5-10 and 5-11.
5.3.4 **Effect of pressure on interfacial channel growth**

Figures 5-48 to 5-51 show the relationship between the applied pressure and the final channel dimensions at minute 5760. With applied pressure, it appears that growth in channel width is favoured relative to growth in length (Figure 5-48). The data sets at 20 and 60 kPa exhibited larger growths in channel width compared to channel length, while the data obtained at 40 kPa, displayed an increase in channel depth (see Figure 5-49). Figure 5-50 shows that the growth of interfacial channel length appears to be slightly invariant with the increment of mechanical pressure.

![Graph showing effect of pressure on channel growth](image)

*Figure 5-48. Effect of pressure on final channel width and length for set of sample A*
Figure 5-49. Effect of pressure on final channel depth for sets of sample A

Figure 5-50 shows that the final growth of interfacial channels in length of four set of samples A to D were influenced by the applied pressure, a slight variation in the growth in length appears when compared between them.

Figure 5-50. Effect of pressure on final channel length. Each point is the average of four set of samples A to D measurements taken at minute 5760 and the error bars represent the standard deviation of the mean
Chapter 5

Interfacial tracking results

Figure 5-51 shows that increasing applied pressure, the overall channel volume increases (sets of sample A).

![Graph](attachment:graph.png)

**Figure 5-51.** Effect of pressure on effective channel volume (the product of the channel length, width and depth), sets of sample A

In Figure 5-52, the maximum PD curves for the first phase of growth are plotted for each pressure. With no applied pressure (0 kPa-A), the PD reaches a maximum value of 12000 pC. As pressure is applied, the magnitude of the maximum PD drops significantly. However, it is still increasing gradually with applied pressure. In addition, the maximum PD curves transition from a slightly linear growth curve PD for 0 kPa-A to an increasingly logarithmic growth curve, with increasing pressure. Figure 5-52 also shows that the discharge activity propagates faster with low PD values when the mechanical pressure is increased.
Sets of sample A, analysed in this section clearly shows a strong relationship between maximum PD behaviour and channel length. For example, sample at 0 kPa-A had the largest magnitude of PD, resulting to be the only sample where the channel length is greater than the channel width. It was also observed that as the mechanical pressure was increased the magnitude of maximum PD decreased (Figure 5-52). The growth in channel length is stifled and compensated by the growth of interfacial channels in width and depth (Figures 5-48 to 5-50).

5.3.5 Result with a commercial sample

This section presents the result of the test of the commercial composite plaque (see Section 4.7.1 for further details). Sample GRP-F was electrically stressed with an applied voltage of 32 kV and mechanical pressure of 20 kPa. It was recorded a PDIV of 19.05 pC at 2.1 kV, which is very consistent with the inception voltage disclosed in table 5-8. Figure 5-53 shows the PD magnitudes of this test, which moderately increased over time; the maximum PD magnitude 21631 pC was recorded. It was
difficult to monitor the progression of the tests, as the development of the interfacial tracks cannot be verified by the light emitted from the discharges. Figure 5-54 shows the level of the interfacial degradation after sample GRP-F was electrically stressed for 18900 minutes.

![Graph showing PD magnitudes](image)

Figure 5-53. PD magnitudes of sample GRP-F exposed to 18900 minutes of electrical stress

The PD magnitudes and patterns are very similar with commercial sample tests (GRP-C1, GRP-C2 and GRP-C3) presented in Section 5.2.4.

![Image of GRP plaque degradation](image)

Figure 5-54. Degradation of the GRP plaque after 18900 minutes of electrical stress at 32 kV
Sample GRP-F was analysed under the optical microscope showing that tracking development was weak. The development of interfacial tracks mainly occurred along the glass-fibre, which allowed the tracks to propagate rapid in length. A weak growth of electrical trees into in the bulk of the composite structure was also observed. Further tests are needed to investigate levels of interfacial degradation at different voltage magnitudes.

5.3.6 PD behaviour and patterns

Figure 5-55 shows a common PD behaviour that was observed in the planar samples presented in this section, which evolve in time as follows:

(i) Initially PD magnitude increases as the track length increases. The applied voltage is high enough to drive PDs the whole tree length.

(ii) PD magnitudes no longer increase as the interfacial channels are long enough for the maximum PD length to be limited by the voltage applied and not the track length, and decay as space charge reaches equilibrium [121].

(iii) PD magnitudes resume to the limit of the system voltage, as carbonisation at the wire electrode allows the PD to extend further (initiated at the carbon track rather than the tip of the wire) and so the interfacial channels starts to grow at the rate of carbonisation growth.
Summary of the results

The flat experimental facility developed in this research project allowed to investigate the growth characteristics of interfacial tracking in detail and identify phases of tracking growth based on PD information and optical images.

- Section 5.3.2 showed that increment of mechanical pressure requires higher voltage to initiate partial discharge activity. The variation of interfacial pressure also influenced interfacial track development, as interfacial channels grew fast in length in samples with no pressure applied (see Table 5-10).
- A strong correlation was seen between maximum partial discharge magnitude and interfacial channel length, suggesting the largest discharges traverse the full length of the track. It is postulated that smaller discharges are responsible for infill growth and electrical tree formation and growth into the epoxy resin.
The electrode geometry allowed the track to develop in a constant field and unaffected by the earth electrode, as discussed in Section 2.5.2.

- PD events and magnitudes served to identify two phases of growth as well as growth characteristics of interfacial channels. The initial phase of growth was influenced by a high electric field at the tip of the electrode; hence the greatest growth occurs within the first phase. The second phase of growth the discharge activity was influenced by carbonized tracks, and the growth of electrical trees into the bulk of the epoxy plaque [17]. These observations were outlined in Section 5.3.3.

- As discussed in Section 5.3.4, higher pressures encouraged the growth of electrical trees into the epoxy resin and higher total volume of growth. It was observed that the formation of carbonized tracks at the tip of the electrode is more severe when higher mechanical pressure is applied to the sample. The reduction of air in the interface, resulting in thermal degradation and carbon deposits.

- The reduction of mechanical pressures lead to a longer initial channel growth (see Table 5-10) and development of wide interfacial channels, allowing the formation of eroded interfacial channels and de-bonded areas. Figures 5-36 showed the characteristic of the interfacial channels.

- Table 5-9 and Figure 5-48 indicated that there was no significant relationship observed between pressure and channel length.
Physical and chemical analysis of interfacial tracking

6.1 Introduction

This Chapter presents the physical and chemical structure of the interfacial erosion/tracking formed on epoxy resin and silicone rubber in planar samples, which were analysed in detail. Cylindrical samples are not analysed in this section. This is because the cylindrical shape has a geometry which is difficult to image, and a surface which is hard to characterise. Firstly, optical imaging is considered, followed by surface roughness and then chemical characteristics of interfacial tracking. Therefore, optical and Laser Scanning Microscopy (LSM) were used to investigate the physical structure of the tracks formed on epoxy resin and silicone rubber plaque. On the other hand, spectroscopic techniques such as: AFM-IR, ATR-FTIR and Raman spectroscopy was utilised to identify nano-chemical maps of interfacial tracking. The resulting journal publication result from this work illustrates the novelty of the AFM-IR technique [161].

6.2 Physical structure of the interfacial tracking

6.2.1 Optical microscopy imaging

After the tests, the samples were analysed under the optical microscope. Carl Zeiss digital microscope was used to obtain the optical images of the aged areas. It was initially observed that the tip of the wire used as the electrode had a mark around it, as Figure 6-1 shows. The dimension of this mark is very similar to the dimensions of most of the samples. It varies from ~360 to ~530 µm when the pressure is increased from 0
to 60 kPa respectively. Figure 6-1(b) shows the cross-sections the samples, 40 x 30 mm (the area where the channels grew). 0 kPa-B was cut and polished to have visual access to the electrical trees that grew in the epoxy plaque.

Figure 6-1. (a) the top view of the surface shows the trapped area next to the wire used as an electrode (b) a cross-section of the epoxy plaque, where the characteristics of the channels can be observed that grew from the electrical discharge at the surface of the epoxy slab and the channels that grew into the bulk of the epoxy resin, for the sample 0 kPa-B

Figure 6-2 shows an optical image of the surface of the epoxy plaque of sample 60 kPa-E. The characteristics of the channels in the first phase of growth are fine and translucent in appearance thus difficult to see/image. Several branches from the tip were formed and this is assumed to be as a result of the amount of air around the wire, this is an observation not clear yet.

Figure 6-2. Optical microscopy images showing the interfacial tracks formed in the epoxy resin plaque after 1000 minutes of electrical stress (sample 60 kPa-F)
After the experiment, the epoxy and silicone plaques were separated to expose them to visual observation under the degraded interface. Figure 6-3 (a) shows the optical image of the channels that grew in the epoxy surface and Figure 6-3 (b) displays an SEM image of the channels that grew into the SiR surface of sample 60 kPa-D.

As seen in Figure 6-3, unlike the epoxy plaques analysed, the formation of channels on the SiR plaque was barely discerned. Therefore, the optical images of the surface of the samples did not provide much information about the dimension (depth) of the channels. Thus, it was decided to investigate the surface topography of the plaques in order to obtain more details about the characteristics of the structure of the channels as discussed in the next section.

6.2.2 The surface topography of the plaques

This section provides information about the method used to characterise the surface roughness of the plaques used in the experimental tests. The waviness profile and surface roughness were measured in each batch of samples fabricated in the lab, in order to identify whether the plaques were suitable for testing.
Moreover, after the experimental tests, the surface topography of the epoxy resin and silicone rubber plaques were analysed. In this way, the physical characteristics and dimensions of the channels formed due to the electrical discharge on the surface of the plaques were measured. The plaques of 150 x 50mm of the epoxy and silicon rubber can be visualised under the optical microscope, and also be used to analyse the topography of the plaques.

Laser Scanning Microscopy – Keyence (VK-X200K) was used to characterise the surface topography of the silicone rubber and epoxy plaques. The main feature of the LSM is characterising surface roughness using laser rather than the reflection of light as the interferometer does to measure the surface roughness, so measurements are more highly accrued, especially when a translucent material such as the epoxy resin is characterised.

Three values were obtained to characterise the topography of the plaques. The first comprised the characterization of the surface roughness on the plaques’ prior tests, whilst the other two parameters helped to analyse the physical structure of the eroded tracks that were formed on the surface of these insulating materials. The parameters used in this analysis are as follows:

i) **Surface roughness, \( Sa \):** provided the average surface roughness by computing the variations of different points (peaks and valleys) across the surface of the epoxy and silicone rubber plaque.

ii) **The maximum profile peak height, \( Rp \):** computed the highest point above the average line along the measured curve.

iii) **The maximum profile valley depth, \( Rv \):** is the lowest profile point below the mean line measured, which was used in this study to determine the depth of the tracks.

To determine the surface topography, LSM software uses equations and parameters described in the international standard ISO 25178. Once the surface is scanned, it will result in a variety of data in the surface topography of the sample, consisting of two parameters: the waviness and roughness.
Waviness is the wide measurement (long wavelength) of the surface, whereas roughness short wavelength) is the local measurement. Large surface measurements can affect the accuracy of the surface roughness measurements, as the waviness of the surface is also taken into account in the computation of the surface roughness, thus an area of 1 x 1 mm was scanned along different parts of the plaque to characterise an average surface roughness. Moreover, to measure the interfacial channels in the surface an area of 15 x 15 mm was scanned.

Moreover, the surface roughness is calculated from the peaks (Rp) and valleys (Rv) of the measured surface, which can be below or above the standard cut-off values determined by the ISO 4287, which are smoothed (standard deviation) by a Gaussian filter. Figure 6-5 illustrates the principle of how the peaks and valleys of the surface topography were assessed. Then LSM software provided surface roughness profile values that are computed on real surface conditions.
6.2.3 Surface roughness characterization

The surface roughness characteristics of epoxy and silicone plaques are displayed in Figure 6-6 and 6-7 respectively. As seen in Figure 6-6, the surface roughness of the epoxy plaque was increased due to high peaks of 27.5 µm. As a result, the surface roughness of this area is 3.65 µm. In other areas of the same plaque, the surface roughness is 0.80 µm.

Figure 6-6. The surface topography of the epoxy plaque. The areas in red are the high peaks of 27.5 µm that affected the calculation of the total surface roughness profile.

Figure 6-7. The surface roughness of silicone rubber plaque.
Figure 6-7 shows the characteristics of the silicone rubber topography. As seen, this material is less smooth than the epoxy plaque. As it presents areas of a greater roughness, there are more areas in red that shows the high peaks. In contrast, the lower valley depth shows a value of $\sim 0.79 \mu m$ with respect to the zero base line. Thus, the calculation of the total surface roughness profile is an average of these values. The main point to consider is that the surface roughness of each plaque will allow the formation of large areas of no contact between the plaques when the epoxy and silicone rubber are placed together.

Three areas were random measured in the plaques (up, middle and low area) to measure the surface topography of the epoxy and silicone rubber plaques. Table 6-1 shows the maximum value measured of the surface roughness between these three points as showed in Figure 6-6.

<table>
<thead>
<tr>
<th>Surface roughness (µm)</th>
<th>Epoxy plaque</th>
<th>Silicone rubber plaque</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.23</td>
<td>1.31</td>
<td></td>
</tr>
<tr>
<td>1.36</td>
<td>1.83</td>
<td></td>
</tr>
<tr>
<td>3.65</td>
<td>1.97</td>
<td></td>
</tr>
<tr>
<td>1.75</td>
<td>2.05</td>
<td></td>
</tr>
<tr>
<td>2.27</td>
<td>1.67</td>
<td></td>
</tr>
<tr>
<td>0.79</td>
<td>2.47</td>
<td></td>
</tr>
<tr>
<td>0.85</td>
<td>2.16</td>
<td></td>
</tr>
<tr>
<td>0.96</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td>1.10</td>
<td>1.64</td>
<td></td>
</tr>
<tr>
<td>1.46</td>
<td>2.08</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>1.54</strong></td>
<td><strong>1.83</strong></td>
</tr>
</tbody>
</table>
6.2.4 The topography of the surface

Figure 6-8 shows the 3D-characterization of the surface roughness of one of the samples. For this analysis, each surface was divided into 6 regions, as displayed in regions that were marked from A to F. Region A is around the tip of the wire and F is the farthest the channel grew.

![Diagram of sample topography](image)

Figure 6-8. Topography of the sample at 40 kPa-A, also indicates how the regions were divided to characterize the surface profile of the samples

Figure 6-9, shows the dimensions of the maximum profile peak (Rp) and maximum profile valley depth (Rv) that were formed in each of the channels at the epoxy resin surface for set of sample A.
Figure 6-10 shows the topography of the epoxy plaque of sample 0 kPa-A and the characteristics of the interfacial tracks formed in the epoxy resin plaque after 5760 minutes of electrical stress at 32 kV. The dimensions of the channels are wide (560 µm) and deep (103.2 µm), close (1900 µm) to the tip of the electrode. It is believed that this measurement was influenced by the deep erosion that occurred on the surface of the epoxy resin due to the poor contact between the plaques as a result of the surface roughness of each plaque. Consequently, the large flat pockets of air are likely to be formed at the interface (as each plaque has different surface roughness, see Table 6-1) allowing high-energy electrons to move faster, which reacted in the epoxy plaque and caused wider eroded channels. This shows that more material is eroded in a rich oxygen interface.

It can also be seen that the deepest valley (117.5 µm) detected was ~700 µm from the tip. The depth of the channels was reduced to 30 µm as the branches grew in length and away from the tip of the electrode. Moreover, the cross-section of the sample at 0 kPa that was examined in the optical microscope, showed wide 51.2 µm and thick hollow channels (Figure 6.1), confirming that the loss of pressure resulted in high discharge activity and consequently deep channels as the sample at 0 kPa-A showed.
Figure 6-10. The topography of the sample at 0 kPa-A, it also shows the dimensions of the channels on the surface of the epoxy resin plaque after the sample was electrically stressed.
6.2.5 **Summary of the physical structure of the tracking**

The planar geometry of the samples analysed by the optical and scan microscope allowed for the observation of the resulted tracks in tree-dimensions. The cross-sections of the areas where the channels grew into the resin were visualised and measured via the optical microscope. Hollow channels ending in dark tips were observed. This information helps to understand changes in the partial discharge patterns, and also gives a better view of the formation of dark channels encourage the growth in the length of the interfacial channels in the final phase of growth. The topography of the plaques allowed us to see the physical characteristics of the interfacial channels, while the measurement of these characteristics helped us to understand that the decay of PDs is due to concentration in areas where the deepest measured channels are. It was also observed that the channels become thinner as they grow as PD will not encourage their growth.
6.3 Chemistry of interfacial tracking

Vibrational spectroscopy techniques such as: AFM-IR, ATR-FTIR and Raman spectroscopy were used in this study to identify functional chemistry groups at the interfacial channels, and detailed nano-chemical maps. The basis of this is that matter interacts with light in the presence of electromagnetic radiation. The strength and nature of reaction depends on frequency. As well as the wavelength of electromagnetic radiation that leads to particles being emitted, absorbed or scattered in a unique way, based on its electromagnetic spectrum.

\[ \text{a) ATR-FTIR principle} \]

Fourier Transform-Infrared (FTIR) spectrometers, provides information about the presence or absence of functional groups, by triggering molecular vibrations through irradiation with infrared light (IR). The radiation frequencies are measured in terms of wavenumbers (cm\(^{-1}\)). FTIR spectrometer (Nicolet 5700 spectrometer, Thermo Electron Corp.) was used to obtain the bulk Infrared spectra from 64 co-averages collected in Attenuated Total Reflection (ATR) mode using a diamond refractive. The spectrum is recorded by a modified reflectance. The ATR-FTIR operates at 4 cm\(^{-1}\) resolution across the 500 – 4000 cm\(^{-1}\) range.

\[ \text{b) Raman Spectroscopy} \]

Raman spectroscopy is complementary to the IR technique; it uses similar principles as the IR but using laser radiation to excite the wavelength of the sample and the measurement of frequencies in Raman is based on the scattering of radiation and not on absorption. Raman spectra were acquired using a Renishaw InVia microscope equipped with a 633 nm laser operating at 0.1 % (approximately 0.5 mW) power. The acquisition time was 20s and spectra are the results of 3 accumulations.
c) **AFM-IR**

Nanoscale infrared analysis (AFM-IR) consists of a tuneable IR source used to illuminate the samples with pulses of 10 ns at 1 KHz. This increases the temperature of the specimen, thereby inducing a transient force on an AFM probe cantilever tip in contact with the surface causing an AFM cantilever oscillation amplitude on a shorter timescale. This hybrid technique includes topographical measurements, IR mapping at a high resolution and can also be performed at a determined wavelength [162]. This has previously been demonstrated to correlate with IR absorbance measured by traditional FTIR spectroscopy[163]. The AFM-IR analysis was completed on a NanoIR2 system (Anasys Instruments) which operates with top-down illumination as seen in Figure 6-11.

![AFM-IR principle of operation](image)

**Figure 6-11.** The AFM-IR principle of operation where the tuneable infrared source is pulsed in order to induce thermal expansion in the specimen. The oscillation signals are then detected by deflection of the AFM probe oscillation
Figure 6-12 shows the optical microscopic images of the two test samples (60 kPa-F and 60 KPA-E) that were assembled with identical geometries and electrically stressed at the same voltage (42 kV) and the same interfacial pressure applied (60kPa), but for a different period of time. The growth characteristics and optical appearance of the interfacial channels were characterised for each test as followed:

- **Sample 60 kPa-F**: The first test energised for 1020 minutes at 42kV. Fine / yellowish channels in the structure were observed, forming about 75% of the overall skeletal tree structure (length and width).
- **Sample 60 kPa-E**: Exposed to 6000 minutes of partial discharge activity, the main channels widened over the period and darkened in colour. In addition, black deposits developed adjacent to and close to the electrode during the test.

As shown in Figure 6-12, the tracking structure of the two tests were very alike, as discussed in Section 5.3.1. It was observed that they had a similar rate of growth. Prior to characterisation, the epoxy and silicone plaques were separated to expose the degraded interface. The results of the chemical analysis are disclosed in the following Sections below:


6.3.1 **FTIR Analysis of Epoxy Surface**

After electrical stressing, epoxy resin and silicone rubber sections of the sample were manually separated and analysed independently. Epoxy specimens were first investigated using conventional bulk FTIR spectroscopy in ATR mode, Figure 6-13. Infrared peaks characteristic of the epoxy resin were analysed before and following the experimental tests. Resulting information is displayed in Table 6-2. For sample 60 kPa-F (after 1020 minutes of electrical aging), white/yellowish channels that were developed at the interface show some spectral changes, indicating that a slight degree of oxidation had taken place, for example: the concentration of the hydroxyl O-H region was observed around 3300 cm\(^{-1}\), increasing the characteristics of C-H signals at 2849 cm\(^{-1}\) and 2920 cm\(^{-1}\); and IR absorbance at 1660 cm\(^{-1}\) was detected, corresponding to the C=O stretch of generated carboxylic acid groups and the C=C stretch of alkene species. On the other hand, sample 60 kPa-E after 6000 minutes of discharge activity, shows an increment in hydroxyl absorbance, and broadening of the carbonyl peak. In addition, a distinct broad peak appeared around 1306 cm\(^{-1}\), which overlapped nitrite/nitrates N-O stretches, as seen in Figure 6-13 (c) [164],[165].

![Figure 6-13. FTIR-ATR peaks of the epoxy samples obtained. (a) Before electrical stress; (b) Sample 60 kPa-F exposed to 1020 minutes at 42 kV, and (c) Sample 60 kPa-E exposed to 6000 minutes at 42 kV.](image-url)
It is known that carboxylic acid, ester and hydroxyl groups are readily generated during degradation (thermal / photo) of the epoxy resin [166], and these degradation mechanisms are likely to be active during exposure to discharge activity. The introduction of ester C=O and hydroxyl O-H bonds is consistent with the auto-oxidation of polymeric materials, and both have previously been observed by infrared analysis of electrical treed epoxy resin and polyethylene specimens [167],[168],[169].

In contrast, the introduction of N-O groups has only been reported for epoxy-amine resins in which the IR absorbance obtained on dark channels agrees with the previous observed for epoxy samples that was exposed to 50 hours of electrical stress in the air [170]. Hepburn et al. noted the oxidation process, including the formation of N-O
groups under ambient humidity. However, distinctive ageing IR signals were not observed when samples were electrical stressed in dry air. This suggests that in this study, enough moisture was present at the interface under ambient humidity for ageing to take place in the same way. It is known that epoxy resins are likely to absorb a certain level of moisture under these conditions and produce water during thermal stress [171]. The presence of N-O bonds could also be as a consequence of bombardment by excited species (for example, NO$^+$($\text{H}_2\text{O}$)$_n$ and NO$_2$$^+$($\text{H}_2\text{O}$)$_n$ ions present under corona discharge activity [105],[172]). However, given that these IR signals are not often reported in electrical treeing for polyethylene samples [173], the oxidative decay and the presence of amine linkages are more likely to be formed.

6.3.2 Raman Spectroscopy of Epoxy Surfaces

Optical microscopy images of the epoxy part of the specimen showed characteristic dark tracks at the surface of the resins, with large dark deposits appearing close to the wire electrode. Such dark channels are commonly associated with conducting disordered graphitic deposits, since these have previously been detected in polyethylene samples following electrical treeing [174],[158]. In the present case however, Raman spectra showed no characteristic D and G bands (ordinarily found at approximately 1360 cm$^{-1}$ and 1575 cm$^{-1}$) for sample 60 kPa-F and 60 kPa-E, even in the extensive dark region formed around the wire electrode (see Figure 6-14). The Raman peaks instead correspond to characteristic vibrational absorbance peaks of the oxidised epoxy resin (note the appearance of several carbonyl peaks, and a strong C=C stretch peak at 1653 cm$^{-1}$, consistent with infrared analysis), Table 6-2. The dark deposits are likely to be amorphous carbon, which generates only weak peaks in both Raman and infrared spectra [175]–[178].
6.3.3 AFM-IR on Epoxy Surfaces

In order to study in greater detail the chemistry of interfacial tracking structures with the aid of the AFM-IR. By using AFM-IR, the sampling volume (related to the amount of material in contact with the tip cantilever) is reduced, thereby greatly increasing lateral...
and surface sensitivity. This is in contrast to the sampling space of ATR-FTIR, which consists of the bulk intact polymer sample, sub-surface trees (deep channels), as well as analysing the tracks.

Firstly, localised IR spectra were measured by placing the probe cantilever in contact with the surface of the specimen, and then increasing the radiation in the range of 900 cm\(^{-1}\) to 1800 cm\(^{-1}\). The oscillation amplitude provoked the increment in temperature of the specimen, the infrared (IR) absorbance was detected and recorded at different probe positions as shown in Figure 6-15. The local AFM-IR spectra of epoxy resin plaques before were electrical stressing showed signals in line with those obtained using bulk ATR-FTIR (black dashed lines, Figure 6-15) following electrical stress. These differences can be seen in Figures 6-15 (b) and 6-15 (c). The most significant difference in the case of the shorter duration sample (after 1020 minutes) was the detection of absorbance at 1752 cm\(^{-1}\) at all measured points of the local AFM-IR spectra, indicating that oxidation occurred along the epoxy resin-to-SiR interface. Moreover, high absorbance was observed at 1284 cm\(^{-1}\) and 1306 cm\(^{-1}\), which can be related to the generation of nitrites as well as nitrates in this area at an early time point. Following normalisation to the aromatic 1505 cm\(^{-1}\) band, the high absorbance associated with N-O bonds showed little variation along the surface and was instead concentrated inside the tracks. On the other hand, the absorbance intensities of carbonyl and carboxylic acid/alkene (C=C) varied significant according to the location of the cantilever tip. Taken together, the normalised spectra could be further divided into specific regions: (i) spectra obtained from various areas of apparently intact resin suggested the formation of C=O and N-O groups, (red spectra, Figure 6-15 (b)); (ii) spectra taken at deep channels at the tip were noted as raised interfacial channels in the height image and displayed relatively high absorbance at 1752 cm\(^{-1}\) (C=O stretch) and at 1248 cm\(^{-1}\) (C-O stretch), displaying a strong formation/concentration of ester groups in the tracks (blue spectra, Figure 6-15 (b)); and (iii) spectra detected from peripheral regions showed a strong absorbance at 1660 cm\(^{-1}\) (unsaturated C=C stretch or carboxylic acid C=O peak) and at 1080 cm\(^{-1}\) — hydroxyl asymmetric degradation (green spectra, Figure 6-15 (b)).
Nanoscale IR mapping was used to further confirm the spatial distribution of formed hydroxyl, carbonyl and alkene groups as seen in Figure 6-16. IR signals associated with ester groups (1248 cm\(^{-1}\) and 1748 cm\(^{-1}\), Figures 6-16 (c) and 6-16 (f), respectively) were most intense in areas where the interfacial degradation was severe and channels were wide as well as deep (marked by arrows outside these channels). These locations matched with high IR amplitude at wavenumbers related to unsaturated bonds as well as carboxylic acid groups (1660 cm\(^{-1}\) and 1080 cm\(^{-1}\), Figures 6-13 (b) and 6-13 (e), respectively). On the other hand, absorbance at 1336 cm\(^{-1}\) and 1456 cm\(^{-1}\) showed little variation across the surface, in agreement with local IR spectra. Since AFM-IR measurements observed IR absorbance indirectly due to thermal expansion, a certain level of correlation to height features may be obtained as a result of change the tip-sample contact area or due to the damaged resin reducing the thermal expansion coefficient. Thus, a scan was done at 1505 cm\(^{-1}\), which corresponds to aromatic groups. This infrared signal was comparatively plain, thereby showing that the IR signals detected previously correspond to chemical differences. Several conclusions can be subsequently obtained from the analysis of the AFM-IR data of Sample 60 kPa-F (1020 mins) concerning the interfacial degradation process. The results show that the detection of polymer ageing using conventional bulk IR spectroscopy is not limited to the visible interfacial tracks formed during discharge activity. The presence of N-O and C=O signals in all the probed areas using the AFM-IR and Raman spectroscopy indicate that the entire epoxy/SiR interface suffer a certain level of oxidation upon electrical stress and applied mechanical pressure. In addition, as the concentration of ester groups is strong within the tracks and only identified at the later stages of the degradation using the ATR-FTIR spectroscopy, this indicated that ester formation occurs during the later stages of oxidation. In contrast, the presence of hydroxyl, carboxylic and alkene groups in areas around the interfacial channels, reveals that these species are a precursor to ester formation as well as visible ageing in the wide and deep interfacial channels. Furthermore, as these IR peaks are the greatest change as detected by ATR-FTIR, this suggests that this is the dominant chemical process occurring in electrical tree channels extending into the bulk at this stage [179].
Figure 6.15. AFM-IR signals corresponding to tip locations marked (insets) on the contact mode height image of epoxy resins (a) Before tracking; (b) Exposed to 1020 minutes of electrical stress (Sample 60 kPa-F) and (c) Exposed to 6000 minutes of electrical stress (Sample 60 kPa-E). AFM-IR spectra are normalised to the 1505 cm\(^{-1}\). The plotted black dashed line is the bulk ATR-FTIR spectrum.
Figure 6-16. AFM-IR images of the epoxy resin surface area 80 x 80 µm, from sample 60 kPa-F exposed to 1020 minutes of electrical stress. (a) Contact mode height image and ratio maps collected at (b) 1080 cm$^{-1}$; (c) 1248 cm$^{-1}$; (d) 1336 cm$^{-1}$; (e) 1456 cm$^{-1}$; (f) 1505 cm$^{-1}$; (g) 1660 cm$^{-1}$, and (h) 1752 cm$^{-1}$.

Figure 6-18 (b) shows the AFM-IR analysis at exposed channels on epoxy specimens following prolonged electrical stress (6000 minutes, Sample 60 kPa-E). The peaks observed in the local spectra are very different to the peaks obtained using bulk ATR-FTIR in showing a relatively enhanced carbonyl absorbance, though this is far less evident than observed in Sample 60 kPa-F (aged for 1020 mins). Furthermore, a reduced absorbance across the 1200 cm$^{-1}$ - 1450 cm$^{-1}$ region was seen, which correspond to N-O, C-H and C-O bonds. It should also be noted that the whole IR signal was attenuated in comparison to Sample 60 kPa-F (Figure 6-16(a)) and IR spectra became broad and poorly defined along the surface. This is due to a loss of functionality, related with a breakdown in structure and the release of volatiles corresponding to advanced ageing of the polymer [118],[119]. In addition, during IR mapping, weak signals were observed in the interfacial channels of all the scanned wavenumbers. This suggests further localised breakdown, which is in line with the proposed formation of amorphous carbon deposits within the tracks (Figure 6-17).

In order to observe the differences in absorbance, ratio maps were obtained in a similar manner to the normalisation procedure used for local spectra by dividing the amplitude signal by the absorbance measured at 1505 cm$^{-1}$ (associated with aromatic rings) as illustrated in Figure 6-18. Ratio images were measured at 1752 cm$^{-1}$ and 1505 cm$^{-1}$.
cm$^{-1}$, which confirmed that ester carbonyl absorbance was enhanced relative to aromatic groups within the tracks, whereas images generated using maps gathered at 1660 cm$^{-1}$/1505 cm$^{-1}$ demonstrated that alkene/carboxylic acid absorbance was very strong around the interfacial channels, consistent with the results obtained from deep channels in Sample 60 kPa-F (Figure 6-16). All other scanned wavenumbers displayed weak IR signals associated with aromatic groups, showing that, O-H, N-O and C-O bonds were affected while aromatic rings remained intact.

![AFM-IR images](image)

Figure 6-17. AFM-IR images of the epoxy resin plaque/surface (area 80 x 80 µm), IR maps obtained by pulsed IR illumination of Sample 60 kPa-E (exposed to 6000 minutes of electrical stress) (a) Contact mode height image and ratio maps collected at (b) 1080 cm$^{-1}$; (c) 1248 cm$^{-1}$; (d) 1336 cm$^{-1}$; (e) 1456 cm$^{-1}$; (f) 1505 cm$^{-1}$; (g) 1660 cm$^{-1}$, and (h) 1752 cm$^{-1}$

60 kPa-F broad signal at 1660 cm$^{-1}$ has been linked to the formation of alkene groups, since the formation of unsaturated low molecular weight species during interfacial tracking on an epoxy resin has been previously confirmed using mass spectroscopy to analyse tracking on epoxy samples [119]. Two mechanisms for alkene formation are considered: the first is hydrogen abstraction corresponding to alkyl radicals and the second is the Norrish-type two mechanisms, which involves hydrogen abstraction from an excited carbonyl species due to di-radical intermediate to generate a ketone and alkene. Bolliger and Boggs indicated that the second mechanism is more likely as the expected quantum yield of a di-radical intermediate is low [119]. The IR absorbance detected in this project confirm the observation made by Bolliger and Boggs as no
Chapter 6  
Physical and chemical analysis of interfacial tracking

locally high carbonyl absorbance was detected coinciding at 1660 cm\(^{-1}\) and no ketone IR signal (around 1710 cm\(^{-1}\)) was observed.

![Figure 6-18](image)

Figure 6-18. Shows AFM-IR images of the epoxy resin surface (area 80 x 80 µm). Exposed to 6000 minutes of electrical stress (Sample 60 kPa-E) obtained from IR maps. (a) Contact mode height image and ratio maps measured at (b) 1080 cm\(^{-1}\)/1505 cm\(^{-1}\); (c) 1248 cm\(^{-1}\) to 1505 cm\(^{-1}\); (d) 1336 cm\(^{-1}\) to 1505 cm\(^{-1}\); (e) 1660 cm\(^{-1}\) to 1505 cm\(^{-1}\), and (f) 1752 cm\(^{-1}\) to 1505 cm\(^{-1}\).

Finally, to confirm that electrical stress generates chemical changes across the interface rather than being confined to channels, a cross-section of the epoxy surface from Sample 60 kPa-E after 6000 minutes of electrical ageing was prepared by microtoming and analysed with AFM-IR spectroscopy. Due to the roughness of this area, ratio images were measured to the IR signal at 1505 cm\(^{-1}\). The IR absorbance detected showed significant differences with increased intensities at the epoxy/SiR interface for alkene, hydroxyl, carbonyl and nitrate/nitrite absorbance. However, absorbance corresponding to O-H and C-O groups was found highest with the first few microns, whilst absorbance at 1336 cm\(^{-1}\) (nitrates), 1660 cm\(^{-1}\) (alkenes), and 1752 cm\(^{-1}\) (carbonyls) were highest at increased depths as shown in Figure 6-19. This may suggest that C=C, C=O, and N=O bonds occur during the oxidation process and are subsequently eliminated from the interface upon prolonged oxidation.
This is consistent with the relatively weak IR signals observed at these frequencies in the AFM-IR ratio images of Sample 60 kPa-E compared to Sample 60 kPa-F. Understanding the reason for this requires further investigation as tip effects cannot be ruled out at the edge of these unsupported specimens.

![AFM-IR images](image)

Figure 6-19. AFM-IR images of a microtomed cross-section area 30 x 15 µm from Sample 60 kPa-E exposed to 6000 minutes of discharge activity. (a) Contact mode height image and IR maps measured at: (b) 1080 cm\(^{-1}\) to 1505 cm\(^{-1}\); (c) 1248 cm\(^{-1}\) to 1505 cm\(^{-1}\); (d) 1336 cm\(^{-1}\) to 1505 cm\(^{-1}\); (e) 1660 cm\(^{-1}\) to 1505 cm\(^{-1}\), and (f) 1752 cm\(^{-1}\) to 1505 cm\(^{-1}\)

### 6.3.4 ATR-FTIR of Silicone Rubber

The observations and analyses of silicone rubber plaque showed visible white tracks on the surface with no tracking penetration into the bulk of SiR, observed. The bulk ATR-IR spectra of the SiR sample remained unaffected following 1020 and 6000 minutes of exposure to discharge activity as seen in Figure 6-20 and Table 6-2. This is in line with previous studies on interfacial ageing on SiR. Observed degraded species mainly consisted of SiO\(_2\) and short chain silicones as identified using mass spectroscopy [119]. In addition, these species can easily migrate into the SiR during intense electrical stress due to its elastic properties. The generation of a broad carboxylic acid IR absorbance at
1674 cm\(^{-1}\) was observed which was accompanied by weak IR signals of hydroxyl compound. Altogether, this points towards oxidation decay.

![FTIR-ATR signals of SiR samples](image)

**Figure 6-20.** FTIR-ATR signals of SiR samples (a) Before experimental test; (b) Exposed to 1020 minutes of electrical stress, and (c) Exposed to 6000 minutes of electrical stress

### 6.3.5 AFM-IR of Silicone Rubber

AFM-IR images of the silicone rubber surface of Sample 60 kPa-E following 6000 minutes of electrical stress, showed less clearly defined surface tracks on silicone rubber compared to the tracks found on the epoxy resin plaque, as shown in Figure 6-21. This is in line with reported electron and optical microscopy of silicone rubber samples after interfacial tracking, where partial recovery of channels has been observed [180],[181]. This can be associated with the elasticity of SiR as well as its local plasticization by short chain ageing products.
Table 6-3. IR amplitude peaks and functional groups for silicon rubber plaques

<table>
<thead>
<tr>
<th>Wavenumber</th>
<th>Functional groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>788 cm$^{-1}$</td>
<td>Si-CH$_3$ asym. rock + Si-C asym. Stretch</td>
</tr>
<tr>
<td>1009 cm$^{-1}$</td>
<td>Si-O-Si sym. Stretch</td>
</tr>
<tr>
<td>1070 cm$^{-1}$</td>
<td>Si-O-Si asym. Rock</td>
</tr>
<tr>
<td>1258 cm$^{-1}$</td>
<td>Si-CH$_3$ sym. Bend</td>
</tr>
<tr>
<td>1412 cm$^{-1}$</td>
<td>Si-CH$_3$ asym. Bend</td>
</tr>
<tr>
<td>1446 cm$^{-1}$</td>
<td>CH$_2$ scissoring</td>
</tr>
<tr>
<td>1674 cm$^{-1}$</td>
<td>Carboxylic acid C=O stretch</td>
</tr>
<tr>
<td>2907 cm$^{-1}$</td>
<td>CH$_2$ sym. Stretch</td>
</tr>
<tr>
<td>2958 cm$^{-1}$</td>
<td>CH$_2$ asym. Stretch</td>
</tr>
<tr>
<td>3340 cm$^{-1}$</td>
<td>Hydroxyl O-H stretch</td>
</tr>
</tbody>
</table>

Figure 6-21. AFM-IR absorbance, corresponding to the tip locations marked (insets) on the contact mode height image of epoxy resins after (a) Exposed to 1020 minutes of electrical stress (Sample 60 kPa-F) and (b) Exposed to 6000 minutes of electrical stress (Sample 60 kPa-E). AFM-IR spectra are normalised at 1048 cm$^{-1}$ peak. The plotted black dashed line is the bulk ATR-FTIR spectrum.
Local AFM-IR spectra were found to differ significantly from the bulk ATR-FTIR spectra, showing that chemical differences were once again more concentrated at the interface. Using the AFM-IR technique it was noticed that the Si-O-Si infrared signals at 1009 cm\(^{-1}\) and 1070 cm\(^{-1}\) were replaced by a broad signal at 1126 cm\(^{-1}\) along the epoxy/SiR interface, which corresponds to the generation of Si-O-C bonds and can be associated with the release of SiO\(_2\) as well as short chains of silica species [119]. For spectra obtained within the central track only, the peak at 1126 cm\(^{-1}\) disappeared, indicating further local Si-O bond breakage, which was confirmed by IR mapping. This coincided with increased absorbance at 1240 cm\(^{-1}\), showing that C-O-C bonds were generated at a later degradation stage. This is in line with the observed development of carbon deposits, which are related to the formation of graphitic deposits as previously reported regarding the formation of electrical trees in SiR [182]. Moreover, the spatial distribution of these products was further confirmed by ratio images, as Figure 6-22 shows.

Figure 6-22. AFM-IR images of the silicone rubber plaque (area 80 x 80 µm), from sample 60 kPa-E exposed to 6000 minutes of electrical stress. (a) Simple contact mode height image and ratio maps collected at (b) 1048 cm\(^{-1}\); (c) 1126 cm\(^{-1}\); (d) 1156 cm\(^{-1}\); (e) 1240 cm\(^{-1}\); (f) 1276 cm\(^{-1}\); (g) 1404 cm\(^{-1}\); (h) 1440 cm\(^{-1}\), and (i) 1636 cm\(^{-1}\).
6.3.6 Summary of the chemistry of interfacial tracking

In this section different spectroscopy techniques were used to identify the chemistry of interfacial tracking. AFM-IR has provided detailed images with submicron resolution of interfacial tracking and associated chemical and physical damage inflicted by partial discharge activity in the region between the epoxy resin and silicone rubber plaque. The AFM probe with resolutions on the scale of ~50 nm, this ensures that the spectra signals can be obtained within the interfacial channels and at specific locations in great detail, minimising signals from elsewhere. For example, in a channel that can be 100 µm wide, the spectra of 2000 different points can be obtained and is able to generate chemical map images that can be taken from the intended locations.

The strongest signal at 1752 cm\(^{-1}\) is related to the C=O stretch bonds; the peak at 1248 cm\(^{-1}\) (C-O stretch) was also taken as an indication of a large of concentration of esters within the channel. Peak at 1660 cm\(^{-1}\) was observed just outside of the channels, this could indicate a mechanism by which channels are able to widen. It was also observed that C=O and N=O bond formation occurs away from the channels (intact areas).

On the other hand, the traditional FTIR chemical analysis technique captured the spectra signal in a wider area that exceeded a channel width, this is not sufficient to study the chemical degradation of the tracking in detail, but to rather capture the bulk of the material and fail to distinguish the characteristics of the interfacial channels which are highly inhomogeneous along the track channel structure. Thus, when the plaques were analysed with the FTIR, the local spectra showed that the oxidation of epoxy resin occurs along the whole interface between silicone rubber and epoxy resin.

The silicone rubber bulk ATR-FTIR spectra remained unchanged after electrical ageing, whereas local AFM-IR analysis revealed the formation of Si-O-C bonds along the interface as well as C-O-C bonds in the interfacial channels. Raman spectroscopy was used to identify the chemistry of conducting carbon deposits found in the dark tracks formed near the tip of the electrode.
Chapter 7

Growth models for interfacial ageing

7.1 Introduction

Observations from experimental work described in previous Chapters (5 and 6), topography on the plaques and the chemical analysis of interfacial tracking provide information to develop a theoretical interfacial degradation model. The model presented in this Chapter will help to identify the initiation and phases of the channel propagation. The aim of this model is to understand the interfacial degradation process and identify the development of partial discharge magnitudes and patterns which might be used for asset management and prognostics.

7.2 Interfacial ageing process

The interfacial degradation process at the epoxy/silicone rubber interface can be summarised as: electron avalanche at the tip of the wire electrode, where high-energy electrons gain enough kinetic energy by charges that are capable to ionize the trapped air around the tip of the electrode, resulting in streamer discharge [5],[17],[123],[124]. This type of discharge activity is originated in large areas of poor contact that exist at the epoxy/silicone interface, because there is no chemical bonding between the plaques, resulting in low density regions. The main reason for areas of poor contact is that each material has different surface roughness (as discussed in Section 6.2.3). It is unavoidable that air is trapped at the interface, especially around the wire electrode. In these regions of poor union, electron avalanches can take place (due the gas...
ionization) as electrons can move freely within the trapped air or weak interface and can be accelerated and gain high energy [183],[184],[185].

The application of mechanical pressure between the silicone rubber and the epoxy resin plaque reduces trapped air at the interface [125]. Low interfacial pressure allows the high-energy electrons to move faster along the low density regions at a weak interface. Therefore, fast electrons are generated in the trapped air at the tip of the HV wire electrode, as Figure 7-1 shows; leading to discharges in gas from the avalanches that are capable of initiating the partial discharge activity at the silicone rubber/epoxy resin interface [183].

![Direction of the electric field](image)

Figure 7-1. Schematic of a cross-section of the silicone rubber/epoxy resin interface at low interfacial pressure, showing electron mobility at the tip of the wire electrode labelled ‘E’, generating a high electric field region. The air trapped around the tip of the electrode is labelled ‘A’ (not to scale)

The repetitive partial discharges cause degradation between the solids upon impact of these electrons associated UV radiation and thermal damage in the polymers. The influence of electron bombardment and charged particles originated in an oxygen rich environment accelerates the rupturing of the polymer chains. This resulted in eroded material at the epoxy/silicone interface, as discussed in Section 2.3.3.

Furthermore, oxidation at the interface initiated at the oxygen trapped around the tip of the electrode, which is influenced by electron impact and the UV photon energy in this region. Is thought to cause photo-oxidation at the epoxy/silicone rubber interface
This type of degradation causes the formation of hydroxyl and carbonyl groups (carboxylic acids and esters) in the in epoxy plaque, resulting in oxidized hydrocarbon chains [166]. Section 6.3 provided further details about the chemistry of the interfacial oxidation process.

7.3 Electric field at the epoxy/silicone rubber interface

FEA models in this research project helped to identify the electric field magnitude and distribution at the silicone rubber/epoxy resin interface around the wire at its tip. As seen in Figure 7-2 the electric field at the tip of the wire reaches 434 kV/mm on the surface of the epoxy resin when the applied voltage was set to 32 kV, which is the same voltage that was applied to the planar samples (see Section 5.3 for further details). In Section 5.3 it was also discussed that the amount of air around the tip of the electrode enhances the electric field three times in comparison to a scenario with no air around the tip (due to the relative permittivity of epoxy). Consequently, the presence of air becomes critical on the surface of the epoxy plaque. Even if volume of the air is reduced by increasing the mechanical pressure, the size of this air pocket trapped around the tip of the electrode does not reduce significantly [125].
Finally, FEA models showed that the amount of air is irrelevant in the enhancement of the electric field as long as the pocket is long enough (~100 μm) to sustain discharges. Section 5.3.2 provided information about the influence of air at the interface and comparison of the electric field magnitudes with air and no air around the tip of the electrode.

### 7.4 Interfacial tracking inception

Figure 7-3 depicts a schematic diagram of how the first channel was formed, which is an eroded area close to the tip of the electrode. The structure of the initial channel appears as fine-white, tubule channels, which is an extended discharge area where electrons and ions are recombined and inducing luminescence (see Figure 7-9) [183]. These tubules channels extend over time in the direction of the electric field,
promoting the gas discharge within the interfacial channels that are visible as luminous discharge. The initial channel grew in the first 10 minutes an average of 1.8 mm on samples at 0 kPa and 2.3 mm on samples at 60 kPa.

Eroded channels were more evident on the epoxy plaque whilst the silicone rubber was relatively undamaged compared with the epoxy resin, because it is comparatively stable both thermally and against UV created by electron avalanches [5]. This is because the bonds in silicone have more strength than in epoxy, so high electron energy and the continue discharges are generally not enough to break them [87]. This is the very reason silicone is used as a sheath material to protect the epoxy from the natural elements and surface discharges in this application [34],[100]. For these fundamental reasons, after the initiation process the track growth is primarily in the epoxy side of the sample.

7.5 Growth and propagation of interfacial tracking

The interfacial tracking manifestly has different characteristics, stages and phases of growth. This is because the growth of channels within the materials may vary and have preferences of growth according to the material properties (thermal stability,
permittivity or elastic modulus). In addition, the divergent field at the tip of the electrode allowed track expansion in length, width and depth [5]. Two phases of interfacial channel growth was identified in the experimental work presented in Section 5.3. Distinctive PD patterns were presented in Figure 5-39 to 5-46 and this allowed identification of the two phases of interfacial channel growth. In addition, the physical characteristics of interfacial channels are a result of long exposure to PD activity, which showed four distinctive stages of channel degradation. The first two physical characteristics of growth are evident in the first phase of growth. These are described in detail in the next section.

7.5.1 Physical characteristics of interfacial channels

Interfacial channels show four distinct characteristics in their development; these characteristics were observed in all experimental tests that were carried out using planar samples. The following diagrams intend to illustrate these events:

(i) An initial stage in which PD magnitudes increase rapidly, generating high-energy electrons moving through existing voids at the wire surface, resulting in a first fine channel at the tip of the electrode (labelled B in Figure 7-4).

(ii) The growth of the interfacial channels spreads across the interface in a two-dimensional treeing pattern (labelled C in Figure 7-4).

(iii) The channels widen. The formation of dark and yellow coloured channels becomes more evident, related to the second phase of the PD activity (labelled B and C in Figure 7-4).

(iv) Carbonized deposits (labelled F) at the tip of the electrode are formed as a result of continued discharge activity in the resin; the formation of electrical trees (labelled D) in the bulk of the epoxy resin in the vicinity of the electrode was observed initiating from the track channel surfaces.
In addition, in the last stage as interfacial ageing progresses over time, it was observed that the formation of eroded interfacial channels and/or carbonized interfacial tracks is clearly dependent on the interfacial pressure. The following observations allow the identification of different mechanisms that caused the formation of wide hollow channels or the formation of carbon layers in these channels.

**a) Eroded interfacial channels**

As the discharge activity continues at the epoxy/silicone rubber interface, gaseous products (ozone and ions of oxygen) react in the epoxy plaque that caused wider eroded channels. The volatile species produced during epoxy erosion can permeate through the free volume within the glassy epoxy resin [188]. Figures 6-8 and 6-9 in Section 6.2.4 show characteristics and dimensions of the hollow channels that were visible on the epoxy surface, which is material
eroded. Figure 6-9 shows deep channels on the epoxy plaque that were formed when no mechanical pressure was applied to the sample. This shows that more material is eroded in a rich oxygen interface.

**b) Carbonized interfacial tracks**

High intensity of the discharge activity causes the formation of carbonized channels near the tip of the electrode. A few carbonized deposits can be seen on the walls of the hollow channels and also at the tip of the electrical trees that grew in the bulk of the epoxy resin. The carbonaceous deposits are more prevalent on the samples at higher applied pressures as seen in Figures 5-36 and Figure 6-12 discussed in Section 5.3.1 and 6.3 respectively. This is likely to be a direct result of a lack of oxygen present during the ageing process, thus degraded carbon is left as a residue rather than forming gaseous CO and CO$_2$ [189]. Therefore, the chemical markers that were visualized under the optical microscope (the surface of the epoxy resin slab in Figure 7-5) might be attributed to the gas decomposition products from the epoxy, that are defused in that area; and what is left on the surface of each plaque are only residuals of the erosion [188]. Generally, the first channels to become darker are those nearest to the tip of the electrode where the field is highest.

Figure 7-5 shows carbonized channels at the tip of the electrode and a cavity formed on the epoxy resin plaque due to erosion degradation of depth 103 µm and ~50 µm in width at the tip of the wire electrode hoop (sample 60 kPa-D).
The optical images of interfacial channel formation and physical analysis of the plaques served to develop a theoretical model of interfacial channel growth, as well as identifying the characteristics of interfacial tracking in a much greater detail. Figure 7-6 shows a cross section diagram with the growth characteristics of the interfacial channels.

Figure 7-5. The surface of the epoxy resin plaque and the characteristic of the channels observed under an optical microscope

A. Position of the tip of the wire electrode
B. Main channel
C. Interfacial channel growing just beneath the surface
D. Electrical tree in the epoxy resin
E. Carbonized deposits
7.5.2 Phases of tracking growth

As discussed in section 5.3.3, interfacial tracking growth occur in two phases: (i) an initial rapid growth phase, where channels grew according to the max electrical stress at the tip of the electrode (area A) and (ii) a second phase of slower propagation, the channel growth is now influenced by carbonized branches adjacent to the electrode (area B).

Figure 7-7. Schematic diagram of the two phases of channel growth. Phase I: an initial rapid growth of interfacial channels. Phase II: a second phase of slower channel propagation influenced by carbonized branches which effectively extend the electrode.
A. First phase of growth

In the first phase of growth the field enhancement at the tip of the electrode promoted the growth of interfacial channels, which are clear/white tubules channels. The initial phase is distinctive by a rapid growth of the interfacial channels in length and rapid increment of PD magnitudes over time, for further details see Section 5.3.3.

The air trapped at the tip of the electrode and at the interface also supported the rapid growth of the channels. A critical time of this phase was observed in all samples when the applied pressure was above 20 kPa, for a period of around 1020 minutes (Table 5-10 and 5-11 in Section 5.3.3). For samples with no pressure applied the initial phase of growth can last between 660 to 3120 minutes (Table 5-10). In this phase of growth, it was noted that channel growth continues preferentially at the epoxy/silicone rubber interface since it is the weak point (being held together by weak intermolecular forces rather than covalent bonds), and large areas of poor contact are expected to exist between the plaques along the interface. Moreover at the time of increase in PD magnitudes the growth of channels was observed to spread across the interface in a two-dimensional treeing pattern (length and width), as discussed in Section 5.3.4.

B. Second phase of growth

In the second phase of growth the interfacial channels grew in a constant field, which was not influenced by the electric field at the electrode, so the rate of channel growth was reduced. Moreover, the second phase is characterised by the decay of PD magnitudes and the reduction of the rate of growth of channels in length. In this phase it was observed that when the mechanical pressure was above 20 kPa, interfacial channels changed in colour and structure; generally channels become darker and more branched over time. This is assumed to be as a result of: (i) less oxygen trapped at the interface, (ii) long exposure time of the electrical stress applied to the samples and (iii) an indirect interaction of the gas discharge decomposition, which occurred in the interfacial channels that were formed on the epoxy plaque. These ageing mechanisms form a carbonized layer on the walls of the main interfacial channels (see Figure 7-8).
Chapter 7

Growth models for interfacial ageing

(a)) [158] and a formation of carbonaceous deposits at the tip of the electrode, as Figure 7-8 (b) shows.

![Figure 7-8. Test at 60 kPa-D, showing the structure of the branches developed in the epoxy plaque. (a) shows the carbon deposits on the walls of the channels, (b) shows the characteristics of the tips of the branches](image)

As observed in Section 5.2.4 and 5.3.3, PD magnitudes tend to decay after prolonged discharge activity, which is related to the development of dark channels and growth of electrical trees in the bulk of the solid dielectric. Champion and Dodd [158] observed that the formation of a carbonized layer on the main channels caused a decay in PD magnitudes. This is because carbonaceous deposits caused multiple and isolated discharges in different segments within the channels. So the movement of electrons and charges took place between shorter distances.

Hikita et al. [189] noted two different PD patterns, the first was characterised by a rapid increase in PD magnitudes, influenced by oxygen presented in a void. The second pattern of PD magnitudes decayed. Hikita et al. indicated that this reduction of PD magnitudes and a variation of PD patterns were due to gas decomposition within the tubules channels; so when trapped oxygen in voids is decomposed, it changes into gas products such as CO and CO\textsubscript{2}. This characteristic degradation was only seen in the second phase of channel growth, and depends on: (i) the time of exposure to electrical stress, (ii) applied mechanical pressure and (iii) the material conditions such as moisture intake [190],[191]. As discussed in section 5.3.1 samples at 40 and 60 kPa showed that the decay of PD magnitudes was less evident. The hypothesis proposed
by this research is that interfaces under greatest pressure contain less oxygen, thus less erosion at the interface occurs resulting in fine interfacial channels but the formation of more carbonized interfacial tracks.

In the final stages of testing, a growth in length of the carbonaceous tracks around the tip of the electrode was more evident as interfacial channels became thicker, which is shown in Figure 7-9. The development of carbonised tracks near the tip of the electrode enhanced the local field within the structure of the track as it grew, increasing the discharge activity [158], which encourages the growth of electrical trees in the epoxy plaque [132].

The growth of these new structures in the epoxy are black in colour at the tree tips (see Figure 7-8 (b)) and visually appeared to be composed of carbonized branches, which act as a separate segment for PD activity [158]. Indeed experimental work presented in this research identified a new increment of the PD magnitudes as a result of the growth of tree structures in the epoxy plaque (see Figure 5-55 in Section 5.3.6). So, this evidence shows that these conductive electrical trees enhanced the local field, acting as an extension of the HV electrode.

![Figure 7-9](image_url)

Figure 7-9. Test at 40 kPa-C showing (a) active discharges in the main channels, (b) clear/white interfacial branches, (c) carbonized track at the tip of the electrode and (d) electrical trees
7.6 Discussion

The development of interfacial channels and partial discharge patterns disclosed in the experimental results (see Section 5.3) agrees with the proposed theoretical model. A strong relationship was seen between the maximum partial discharge magnitude and tracking length, suggesting that the largest discharges traverse the full length of the track. It is postulated that the smaller PD magnitudes are responsible for the growth of electrical trees in the bulk of the resin near the tip of the electrode. It was observed that the growth of electrical trees and formation of carbonized tracks at the tip of the electrode is more severe when higher mechanical pressure is applied to the sample, probably because of a lack of oxygen in the interface, resulting in thermal degradation products of solid carbon, rather than gaseous CO and CO₂. Polished cross-sections of the epoxy resin plaques that were observed under an optical microscope, allowed observation of small amounts of carbonaceous deposits at the walls of the tubules channels and also at the tips of the branches. The carbon deposits are more prevalent on the samples at higher applied pressures.

The characteristics of growth were identified from PD patterns, as discussed in Section 5.3.3. Experimental tests in planar samples presented a common PD behaviour, which is described in Section 5.3.6. The rate of growth of tracks in early stages is controlled by discharge-driven erosion. However, once discharge length is limited by the driving voltage rather than the tree channel length, growth is controlled by carbonisation rates within the channels. This implies small scale lab testing does not replicate service conditions because in the former voltages are high enough to drive discharges from electrode to electrode.

The electric field at the tip of the electrode was computed in COMSOL multiphysics. The 2D model presented in Figure 5-38 shows that the electric field magnitude reached 40.7 kV/mm at an applied voltage of 3 kV RMS, this was the average inception voltage that was obtained in the experimental work presented in Section 5.3. This predicted field is more than enough to initiate partial discharge activity at the tip of the wire electrode and encourage interfacial channel growth. Figure 7-2 shows an electric field magnitude that reached 434 kV/mm when the voltage was increased to
32 kV RMS. However, Rowland et al. [192] used a full 3D model of an electrical tree. This predicted an electric field of 2000 kV/mm at the tree inception in a solid dielectric material, if space charge injection is ignored. Clearly all these computed values are moderated by space charge injection, so the commutations are not expected to yield accurate values but for academic purposes FEA models are useful to understand the mechanisms of degradation at high electric fields.

Finally, the model of interfacial degradation proposed in this chapter is based on evidence from experimental work, FEA models and analysis of the surface topography of the epoxy and silicone rubber plaques. The predicted electric field magnitude at the tip of the electrode presented in this study allowed us to predict the local field that produced tracking growth. This information helps to understand the mechanisms of interfacial ageing in composite insulators in service.
Chapter 8

Discussion, conclusions and future work

8.1 Introduction

This Chapter discusses the limitations and difficulties encountered in the development of the two experimental facilities developed, sample preparation, and tests results. Conclusions are given based on experimental work that shows evidence of the conditions required to cause interfacial degradation. The required voltage, the electric field enhancement, and also the critical size of the internal conductive defect, which initiates interfacial degradation, were determined. The study has provided test procedures in order assess interfaces in HV insulation systems. At the end of the section, recommendations are suggested for future investigations.

8.2 Discussions

The experimental facilities and sample preparation presented in this project were progressively improved, these and the challenges were summarised at the end of each respective chapter. The designs, measurements, and procedures were recorded, so future studies can build the same experimental structures and fabricate samples in a similar way as presented in this thesis in order to obtain reproducible results.

The two experimental facilities presented in this project allowed a detailed investigation of interfacial degradation. Experimental work on cylindrical configuration allowed for investigating the interfacial degradation as a function of electric field. This
was achieved by changing the separation between the tip of the wire to the earth electrode.

Test results in the cylindrical system indicate that the development of interfacial channels require field enhancement. It was observed that the corona ring reduced the electric field of the wire hoop employed for this purpose, thus when the separation between the earthed plate and the tip of the electrode is 100 mm, the interfacial channels do not grow in length but rather grow in width. The decrease in the field magnitude causes a decrease in the growth rate in length of the channels, even stopping the growth in length. It was seen when the length of the conductive defect at the HV electrode was 80 mm, it did not cause damage in the internal structure of the composite insulator, as the corona ring that is attached to the HV end-fitting reduced the electric field in the presence of any conductive defect. However, the length of the conductive defect becomes critical in an insulating system if the internal defect is above the corona ring, for example at 140 mm, the electric field at the tip is enhanced enough to initiate partial discharge activity: in which case the channels will grow in length rapidly.

This, in the context of insulators in service means if an internal defect is below the corona ring it will not cause failure. If the same defect is above the corona ring’s region to influence, it may enhance the electric field to cause partial discharge activity at the interface. For insulator design, the seal at the end-fitting should be carefully considered as degradation of the seal allows moisture ingress to the core. This is a problem when moisture penetration increases in length above the corona ring, the field will then be high enough to initiate electrical discharges. Therefore, the position of the ring at the HV end is also critical, as it may help to attenuate discharge activity in the presence of conductive defects close to the HV end.

The flexibility of the cylindrical system allows samples of any dimension to be tested, so electrode separation was also investigated with samples up to one meter length. Table 2-1 provides the dimensions of composite insulators at different voltage rates. When the separation exceeds one meter and the applied voltage is above 50 kV, the electric field is enhanced to initiate interfacial degradation in the presence of
delamination, de-bonding or any other conductive defect within the insulator structure or even pollution on the surface of the insulator.

In the planar system, the loss of mechanical pressure between epoxy resin and silicone rubber plaques was investigated. Findings in this project suggest that the reduction of mechanical pressure allows electron mobility in these regions.

Great care is required when the insulator is formed in order to produce a strong/perfect bonding between the core and the sheath and to avoid air trapped at the core/sheath interface or regions of high electron mobility. Care is also needed to avoid bending the insulator while installing the insulators in transmission towers for the same reason. Moreover insulators may be subjected to cracks, delamination or de-bonding of the sheath which is critical, especially at the HV metal end-connection.

This study shows that the presence of air at the interface is critical. An air gap of 350 µm around the wire was modelled FEA models and shows that the e-field is increased three times in the presence of air while the volume of air is irrelevant once it has reached 10’s of µm in length. 2D and 3D FEA models allowed for the computation of the electric field intensity in both systems and is used as an indicator to understand the required electric field that initiates interfacial tracking, as discussed in Section 5.3.

The growth characteristics of interfacial channels are similar in both planar and cylindrical systems. Firstly, the development of a very fine channel at the interface occurs, which later becomes the main channel due to the intensity of the electrical discharges. Then the main channel becomes wide and yellowish over time because of erosion, identified visually as hollow channels on the surface of the epoxy resin plaque. The dimensions of these channels in width and depth are given in detail in Section 5.3. Finally, electrical tree formation was also seen as typical dark channel growth into the resin. The channel characteristics were analysed in detail in planar samples, as the exploration of these channels was difficult to appreciate in the cylindrical system. On the other hand, PD patterns differ between cylindrical and planar samples, the reason in not yet clear. PD patterns in planar samples show very similar trends in all tests, but in some planar tests at the same pressure, PD magnitudes initially increase very
rapidly. This is assumed to be due to the surface roughness of the sample or contamination whilst assembling the sample that can influence rapid increments in PD magnitudes.

The use of an electrode extension allowed undertaking experiments up to one meter in length. However, in the planar system, samples were limited to 50 x 150 mm because the bigger the sample, the more weight is required to achieve higher pressure. For example, the mechanical force that was applied to the sample was limited to 60 kPa, because in order to achieve that pressure, it is necessary to apply ~45 kg on top of the sample, which the present experimental apparatus cannot sustain.

Finally the recorded PD data of the long-term test was split into three hour long files. Initially files above 6 hours of PD data were not possible to open.

8.3 Conclusions

The major contribution of this project was the design and development of two experimental structures, as well as a method for the consistent fabrication of two-layer sample structures. These provided a solid foundation to study the inception and growth of interfacial tracking in long cylindrical and planar samples. The latter allowed the physical and chemical analysis of the morphological structure of the tracks. With the information from the chemical and physical structure of tracking, the PD magnitudes and FEA models documented in this study helped to identify the growth characteristics of interfacial degradation, and also to develop a growth model of tracking, which is presented in Chapter 7. The outcomes of this work served to increase the knowledge and understanding of degradation mechanisms that occur in HV composite insulators in service. The results of this investigation can also contribute to the establishment of test procedures and guidelines for assessing/improving the designs of interfaces in HV insulation systems.
Extensive efforts had been invested in the design and implantation of the two experimental structures to improve the sensitivity of PD detection in both experimental systems to ~3 pC in order to accurately detect partial discharge inception voltage and obtain PD measurements with a minimum PD background noise of ~3 pC.

Both experimental facilities allowed the usage of PD magnitudes and optical images to monitor the progression of visible aspects of degradation. A key feature of the test structures is that it provides a large region of a constant field, where the interfacial tracking can propagate at normal rate unaffected by the high field at the earthed electrode.

Interfacial tracking in cylindrical samples was successfully developed to mimic the structure of composite insulators. This served to monitor for the first time the development and growth characteristics of interfacial tracking in such structures. Section 5.2 showed the influence of different electrode distances in the interfacial degradation. It was shown that the corona ring at the HV end fitting can effectively reduce track propagation by reducing the field in the vicinity of a defect.

Cylindrical samples also allowed to separate the distance of the HV and earthed electrode from 20 to 100 cm. The variation of the electrodes distance served to study the change of the electric field magnitude, which is independent to the applied voltage. In the geometry studied, the optimum location was up to 40 cm from the HV termination; the experimental results showed that at this electrode separation distance the corona ring reduced discharge activity, and in turn, the smallest growth of channels in length was observed (20.3 mm). It was found that when the electrode distance was at 60 cm or above, the PD magnitudes at the tip of the wire were more pronounced (see Figure 5-8). This was due to the higher electric field in which the tracks grew. It was also observed that tracks can grow when the field at the metal defect reached 15 kV/mm (Table 5-4). In conclusion, if the development of a conducting defect within the long composite structure can reach a field magnitude of 15 kV/mm, tracking growth will compromise the structure of the insulator.
The use of the planar samples allowed to monitor and measure tracking growth in length, width, and depth. Whilst in cylindrical samples, it was only possible to monitor and measure the growth of the tracks in length. The growth of the tracks in width was limited, since the camera placed in front of the sample could only capture a limited area due to the cylindrical geometry of the sample. The growth of the tracks in depth was not possible to measure. Thus, observations and tests results of tracking development in planar samples were used to develop a growth model of the interfacial tracking behaviour in a composite structure. The average inception voltage in cylindrical samples was 3.6 kV (Table 5-2 in Section 5.2.1), whereas in planar samples, it was 3.0 kV (Table 5-8 in Section 5.3.2).

The growth characteristics and development of tracking were similar in both planar and cylindrical samples. Thus, observations and tests results of planar samples allowed to identify in detail the growth characteristics and phases of tracking growth and also to model the tracking behaviour that occurred at the interfaces of composite insulators. Section 7.5.1 describes four distinct stages of interfacial channel growth that were identified in planar samples, which were also identified in cylindrical samples. Moreover, the preference growth and physical damage was seen to be into the epoxy rather than the silicone in all the samples.

The investigation concerning the effect of interfacial pressure reduction can be divided into: samples with pressure and no pressure, as discussed in Section 5.3.2. The common experimental observation of this test was that when mechanical pressure was applied, dark channels were the most common characteristic in all the samples tested. Whilst samples with no mechanical pressure applied were characterized by clear and wider channels. Tests in planar samples also allowed the identification of tracking growth characteristics based on a PD pattern, in which (i) initially PD magnitude increases as the track length increases, this is known as the first phase of growth that lasts 1020 minutes in the specific tests reported; (ii) the second phase of growth involves the reduction of PD magnitudes, which is related with the reduction of tracking growth rate in length, formation of dark channels, and the growth of electrical trees into the bulk of the epoxy plaque; and (iii) PD magnitudes resume an increase in
size and frequency. This pattern is due to the voltage limiting discharges within tracks to a certain length. Therefore at the start, as the track grows the discharges are track-length limited. However once the track is a long as the longest discharge, the discharge cannot lengthen the track until carbonisation occurs at the tip of the wire electrode. This then effectively increases the reach of the discharge and the track can resume growth, Section 5.3.6 outlines these changes.

Thus, a strong relationship was found between partial discharge magnitude and track length (Section 5.3.3). Observations show preferential erosion and carbonisation of the epoxy over the silicone, and the growth of these channels into the epoxy plaque requires a further analysis. Moreover, similar characteristic of tracking growth was seen in commercial composite insulators, the growth of electrical trees in the resin and within the pultruded glass-fibres.

The results of the chemistry of tracking (Section 6.3) and the interfacial model of growth proposed (Chapter 7) in this study help to understand the interfacial ageing mechanisms and have a wider view about the degradation process. Since for many years, interfacial ageing in composite insulators was seen under conventional assumptions, such as the formation of long carbon conductive paths that enhance the electric field and cause breakdown, this project confirms that carbon deposits increases PD magnitudes. This research project showed that the development of interfacial tracking has different growth characteristics, which is slightly different at the growth of large tracks along the interface, which has been reported in composite insulators in service [2]. This type of degradation may be as a result of multi-stresses that insulators in service are exposed to as well as internal factors that may cause internal discharge activity [7],[73]. For example, moisture ingress at the core or problems with the primer that is used to bond the core and the sheath [21]. It could also be the mechanical stress that the insulator is subjected to, which may accelerate the growth of long tracks [27],[28]. Pollution on the surface of the insulator can also enhance the electric field, causing partial discharge within the insulator structure and subsequently, the growth of long interfacial tracks [3],[20],[73],[98].
The experimental apparatuses developed in this project are flexible and allow the investigation of different types of aging mechanisms involving humidity control environment, moisture ingress at the interface or the increment of temperature. This allows for investigation of mechanisms that influence interfacial tracking growth and produce the subsequent models of degradation. Therefore this is only the beginning in obtaining a deeper insight into understanding degradation and predicting failure in composite insulating systems.

8.4 Future work

The work for future research is suggested as follows:

As disclosed in Section 4.6, the formation of the cylindrical samples contained a sectioned polyoxymethylene rod that includes three nylon bolts to tension the silicone tube and the epoxy half rod together by tightening the bolts. No unified pressure was applied to the bolts of the samples. For future studies, it is suggested that a precision torque wrench should be used to tighten the bolts with the same pressure to all samples.

The growth of trees in the resin was related to the decrease in PD magnitude in planar samples, but this behaviour in PD magnitudes was not observed clearly in cylindrical samples. It is assumed that the tree had more space to grow in the half epoxy cylinder of ~10 mm, the tree grew 5 mm into the half epoxy cylinder, Whereas the tree grew 2.7 mm into the epoxy plaque that was 5 mm thick. It was found that the discharge activity became stronger as the tree grew into the epoxy. It is assumed for that reason PD magnitudes always increased over time. A future investigation is suggested to increase the thickness of the epoxy plaque to 10 mm to identify if PD patterns would be varied with the growth of larger trees into the resin or if it is due to the geometry of the sample.
Epoxy plaques and cylinders fabricated for this study were stored under an ambient humidity for 4 to 12 days before testing. It is known that epoxy resin absorbs moisture under ambient conditions [66],[157]; this may influence the test results. For future work, it is suggested to store the fabricated epoxy samples in desiccators to control the moisture absorption in epoxy samples, and by doing so, the reliability of the results can be validated.

For future work it is important to focus on the events that took place when the interfacial channels were initiated, this can help to improve the model with more details. In addition, it is necessary to validate the proposed hypothesis with more evidence that a lack of oxygen at the interface results in thermal degradation products, e.g. solid carbonized tracks, rather than gas decomposition products from the epoxy, that was defused in the bulk of the materials, as discussed in Chapter 7. The flat system developed in this project is suitable to investigate these details.

Furthermore, the inception process can be studied in detail by controlling the void around the tip of the wire electrode to obtain more accurate inception magnitudes. Whereas the gas decomposition from the formation of carbonized tracks can be measured and captured by casting tubes in the epoxy plaque. These gases can also be extracted from the silicone rubber plaque with the aid of a hypodermic needle for later analysis.

To investigate interfacial tracking initiation, imaging needs to be improved. In some samples the image processing of track growth was difficult to undertake, especially identification of early growth of the channels. The camera should use a macro lens in order to capture more details of the tracking inception, branches, and formation of carbon deposits.

The illumination in the lab should be better controlled, that will help to capture clearer images especially in cylindrical tests. As there are areas in the pictures that are difficult to measure as illumination is too bright, making it difficult to see details of the small branches. The lab room can also be totally dark, so the light emitted from discharge activity can be detected at different exposure time.
In this project the materials were placed together by simple contact, future work can investigate the use of different primers between the slabs at the interface. It can be also interesting to study the use of silicone grease around the tip to reduce electro mobility and increase dielectric strength. In this project, the degradation of epoxy resin was investigated. Future work can look into degradation characteristics of other insulating materials, such as polyethylene instead of the epoxy.

Insulators that are hanging in transmission towers to support the lines are subject to great tension, thus they may be subject cracks or delamination. Future work can investigate the effects of tracking growth when a sample is bended to different degrees.

Experimental work could also be undertaken in a chamber where oxygen can be replaced by a different gas, such as nitrogen, to investigate whether interfacial degradation behaves in the same way in an oxygen depleted environment. Furthermore, experimental work should be undertaken in a controlled environment, where the room humidity can be eliminated.

The main achievement of this project is the sensitivity of PD detection in both experimental systems, the experimental facilities provide PD background noise of ∼3 pC, which can allow studies of PD inception voltages and PD patterns resolved in phase/voltage to detect and differentiate between different phases channel growth in cylindrical, planar and commercial samples.
References


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Appendix: List of Publications

