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Interfacial aging in composite insulators as a result of partial discharge activity

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Abstract—High voltage outdoor composite insulators used on transmission lines can be subject to degradation due to electrical discharge activity at the core-sheath interface. A methodology is described to explore the effect of de-bonding or loss of adhesion between the sheath and core in composite insulators. The use of planar geometry materials allows interfacial pressure to be varied and facilitates physical and optical imaging of the tracking as it grows and chemical analysis of the samples after aging. The associated electrode geometry allowed the tracking to develop in a constant field, unaffected by the earth electrode. Low pressure between the materials accelerated the growth the tracks. A correlation between partial discharge magnitude and track development is identified. Electrical tree growth was also observed penetrating the epoxy resin, initiated from the interfacial tracks.

Keywords — *pressure, interface, epoxy resin, silicone rubber, tracking, composite insulators, treeing, partial discharge, PD*

I. INTRODUCTION

Composite insulators used in HV transmission lines provide outstanding mechanical and dielectric properties, and have become commodity products, in competition with ceramic and glass insulators [1]. However, issues concerning interfacial degradation have been reported for as long as this type of insulator has been used [2]. A key area of concern is the interface between the pultruded glass-fibre core and the silicone rubber (SiR) sheath, and this makes the quality assurance of design and production critical.

Composite insulators are exposed to various dynamic mechanical loads that involve compression, tension and torsion from installation, maintenance, aeolian vibration, sub-span oscillations and conductor galloping. Unless insulators are appropriately designed, manufactured and installed, the result may be material fatigue, delamination and cracking. In particular the adhesive bond between the core and sheath may be compromised [3],[4],[5]. Such physical aging events can result in regions of low density or even elongated voids. If such low density regions are in areas of high electric fields, enhanced electron mobility will result in high energy electrons and internal discharge activity. This in turn will cause permanent damage at the interface [4]. Deposits of conductive carbon may also result, leading ultimately to interfacial breakdown [6],[7],[8].

II. PREVIOUS TEST REGIMES

Models for interfacial aging remain poorly defined. Several studies have investigated the effect of surface roughness and contact pressure using compression forces to remove air bubbles at interfaces and to investigate the role of adhesives or grease in cable joints [9],[10],[11]. Hasheminezhad and Ildstad [12] proposed a model based on mechanical pressure, surface roughness and the resulting dimensions of interfacial voids. Gu and He [13] investigated interfacial breakdown at XLPE/SiR interfaces. Two electrodes with radii of 2.5 mm were sandwiched between the dielectrics and compressed at 20 kPa. It was observed that a large micro-cavity readily initiated electrical discharges, with associated interfacial tracking and subsequent breakdown.

Anderson et al [14] studied the strength of primer bonding between SiR and epoxy slabs. A wire of 75 μm radius provided field enhancement and samples were aged for 330 hours at 10 kV AC. White powder resulted on the silicone rubber surface, whereas discharge activity caused cracks on the epoxy surface. Kobayashi et al [15] investigated the effects of permittivity and interfacial pressure at epoxy/ethylene propylene rubber and ethylene propylene rubber/LDPE interfaces. Testing used two aluminum foil electrodes, separated by 5 mm in the interface. Electrical tree characteristics varied with the mechanical pressure applied to the samples. At 3 kgf/cm^2 , treeing occurred along the interface, whereas at 15 kgf/cm^2 electrical trees grew into the bulk of the EP slab.

A cylindrical configuration (long-rod) was presented by the authors previously [16]. This report presents an experimental system, using planar insulating materials. A key feature of the design used is that only one electrode is embedded in the interface, so that the field in which the track develops is not principally determined by the track-earth distance. This requires high voltage testing but more closely matches the aging found in composite insulators. SiR and epoxy resin slabs have been subjected to various interfacial pressures, whilst electrically stressed with AC voltages for 96 hours.

III. EXPERIMENTAL

Samples were prepared from 50 x 150 mm plaques of 5 mm thick unfilled epoxy and 3 mm thick unfilled high

temperature vulcanized SiR. A 45 μm diameter stainless steel wire was placed between the dielectrics, which were then pressed together with a force of up to 60 kPa. The wire formed an electrode which enhanced the local electrical field and was found to reproducibly initiate partial discharge activity. The EP was fabricated using Araldite-LY5052 resin and Aradur-HY5052 hardener mixed in the ratio of 100:38 by weight. The mixture was then degassed in a vacuum chamber before being dispensed into a frame over a 1 mm thick polycarbonate sheet. The resulting plaque had a smooth surface finish, with a surface roughness of $\sim 0.3 \mu\text{m}$, whilst the SiR plaques had a surface roughness of $\sim 0.7 \mu\text{m}$. The samples were assembled as follows: the wire and the SiR plaque were cleaned with propanol, whilst the epoxy was rinsed with deionised water. Both plaques were immediately blown dry with warm air to avoid leaving surface stains. The tip of the wire was formed into a circular shape (a crook) of $\sim 1.2 \text{ mm}$ diameter which was then placed between the dielectrics, forming a controlled field enhancement 40 mm from the sample's short edge. This is illustrated in Figure 1. The assembly was orientated with the large planes horizontal. It was supported on a glass plate, with the transparent epoxy resin adjacent to the glass so that images of degradation and light emission could be obtained from the underside, whilst a dead weight could be used to impose controlled pressure from the top.

A photograph of the experimental system and a schematic of the electrode configuration is presented in Figures 1 and 2. The distance between the tip of the wire hook and the ground plate was fixed at 90 mm for all the tests presented here. The gap distances and geometries of external electrodes were designed using FEA to prevent surface discharges. A feature

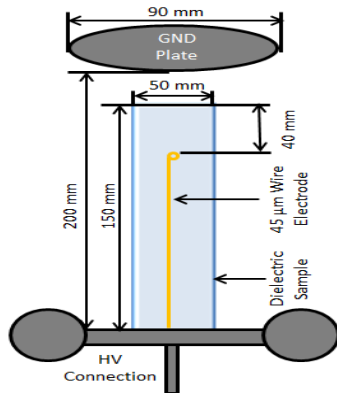


Figure 1. Schematic of the experimental set-up (top view). Not to Scale.

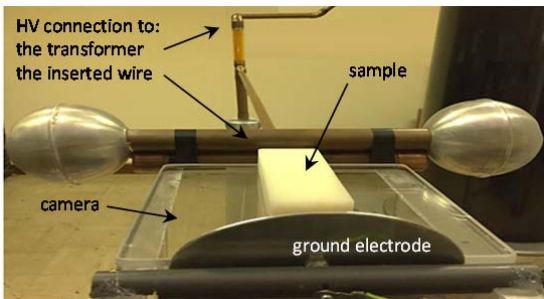


Figure 2. Experimental facility used to investigate interfacial aging in planar insulating samples

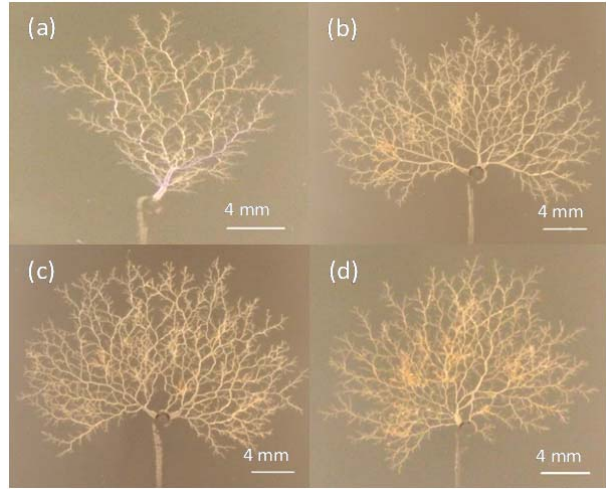


Figure 3. Development of interfacial channels at (a) 0 kPa, (b) 20 kPa, (c) 40 kPa and (d) 60 kPa

TABLE I. PD INCEPTION MAGNITUDES AND VOLTAGES

Pressure (kPa)	Inception magnitude (pC)	Inception voltage (kV)
0	19.61	4.4
20	17.02	4.3
40	13.10	4.8
60	10.84	4.4

of the test geometry is that the earth electrode is planar and always distant from the tracking. As a result damage was not accelerated by field enhancement as the track approached a ground electrode, as is often the case in laboratory tests.

Bricks ($\epsilon_r = 6$ to 8) were used as weights to vary the mechanical pressure on the samples. This ranged from 0 to 60 kPa. To monitor the interfacial activity, partial discharge (PD) magnitudes and the partial discharge inception voltage (PDIV) were recorded using an Omicron MPD600 measurement system. A camera (Canon EOS-1100D) was used to monitor the progression of visible aspects of degradation. AC voltages up to 32 kV were applied to the HV connection (RMS voltage values are exclusively used in this paper).

IV. RESULTS AND DISCUSSION

Figure 3 gives examples of the visible interfacial channels grown at various mechanical pressures. As can be seen, the structure, color and width and length of the tracking pattern are similar for each sample. Table I shows the measured partial discharge inception voltage. The inception voltages are consistent around 4.5 kV, but the PD inception magnitudes decrease when the mechanical pressure is increased (the PD magnitude is halved by increasing the pressure from 0 to 60 kPa). This is thought to be due to voids around the wire being closed up at higher pressures. However, it was observed that when the voltage was increased to 30 kV, PD magnitudes were measured of 65 pC at 0 kPa, and 103 pC at 60 kPa, yet at pressures of 20 and 40 kPa, PD magnitudes were recorded above 450 pC: an observation not yet explained.

Figure 4 shows recorded PD activity with the growth in width and length of the interfacial channel pattern. The

maximum magnitudes were selected and are reported for each second of each test. Correlating visual observations of growth with PD suggests that the maximum PD values in a time period are related to growth in length of the channels, whilst periods of high fluctuations in PD values are related to branching and filling of the area between the main branches.

In Figure 4, the development of PD magnitudes has been categorized into three growth phases, and Table II summarizes the characteristics of each phase, for each sample. These phases are described as follows:

Phase 1: Early growth, characterized by a rapid increase of PD magnitude. Rapid growth in length and width of the fine white observable pattern is seen.

Phase 2: A slower growth in length and width of the tree structure is seen. PDs show a significant fluctuation of maximum magnitudes in each minute. Development of branching is seen between the main channels and an increment in the density of channels is evident.

Phase 3: PDs are no longer growing in magnitude, but show a marked fluctuation in time. Within the damaged region, darkened regions, probably carbon deposits, form in the vicinity ($\sim 190 \mu\text{m}$) of the electrode. The outline of the pattern continues to grow, at a slow constant rate, dependent upon the applied pressure.

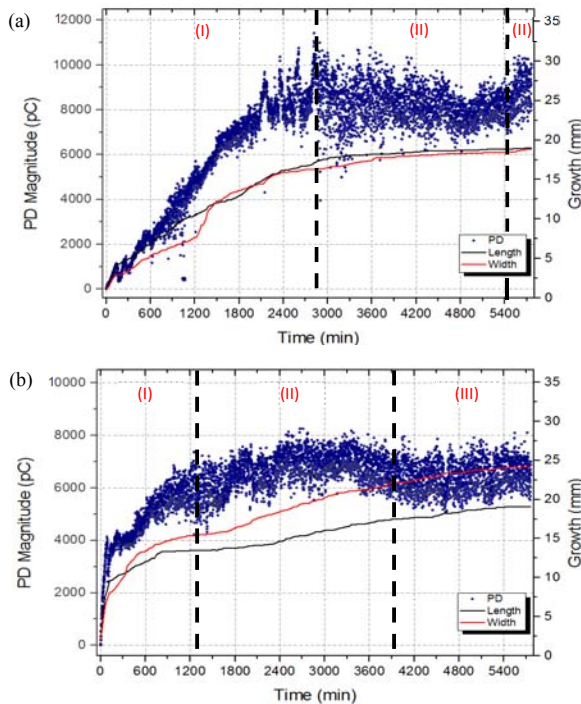


Figure 4. PD magnitudes and interfacial channel growth against time, at (a) 0 kPa and (b) 60 kPa

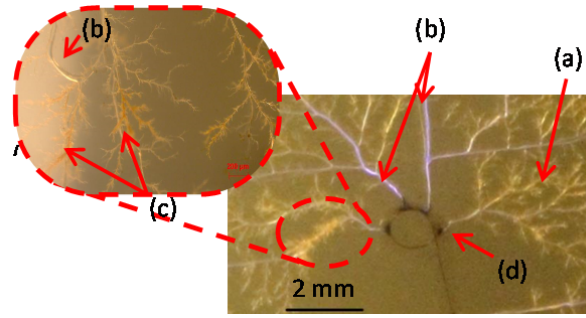


Figure 5. Microscopy of the cross-section from the test at 40 kPa. (a) interfacial channels, (b) main branches, (c) electrical trees and (d) carbon conductive deposits. Active discharges in (b) color the branches purple.

In the final phase, the track grew $\sim 70 \mu\text{m}$ in length. This took: 2 hours at 0 kPa; 5 hours at 20 kPa; 7 hours at 40 kPa; and 6 hours at 60 kPa. This illustrates that a reduction in pressure accelerates the tracking progress.

A key feature of the tracks is whether they are growing in the interface, or in either of the bulk materials. The distinctive interfacial branches are shown in Figure 5. In the geometry tested, tracks developed as trees into the epoxy resin, although this was not seen in the silicone rubber. This is consistent with reports reviewed previously [14],[15]. Figure 6 shows polished cross-sections of the epoxy resin plaques that were observed under an optical microscope. Each sample shows the characteristics and dimensions of the trees which propagated into the bulk of the epoxy. Higher pressures appear to encourage growth of electrical trees into the epoxy resin as reported by Kobayashi et al [15]. This is likely to be due to a reduced tendency to grow within a pressurized interface. At 0 kPa the main channels at the

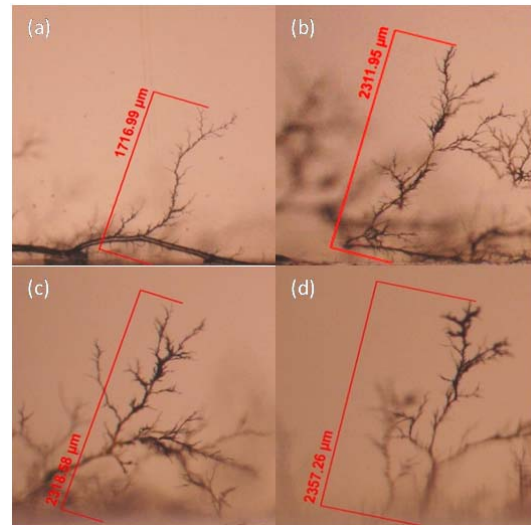


Figure 6. Comparison of the largest electrical trees that grew into the EP plaques (a) 0 kPa, (b) 20 kPa, (c) 40 kPa and (d) 60 kPa.

TABLE II. DEVELOPMENT OF INTERFACIAL CHANNELS ACCORDING TO PD PATTERNS

Pressure (kPa)	Phase 1				Phase 2				Phase 3			
	0	20	40	60	0	20	40	60	0	20	40	60
Length (mm)	17.5	15.1	14.4	13.4	18.8	17.6	18.5	17.4	18.9	18.6	19.5	19
Width (mm)	16.4	24.1	22.4	15.3	18.6	25.6	26.4	22.1	18.8	26	27.9	24.1
Max PD (nC)	11.8	8	9.5	7.4	11.4	8.9	12.3	9.3	11.5	9.7	11.8	8.4
Duration (mins)	2980	1335	650	1248	2594	2777	2981	2699	186	1648	2129	1813

interface are wider and in the epoxy small amounts of carbon deposits can be seen at the walls of the hollow channels and also at the tips of the branches. The carbon deposits are more prevalent on the samples at higher applied pressures, and generally, channels become darker and more branched over time. Figure 7(a) shows channel characteristics for the samples at 60 kPa, where the channels appear black. Figure 7(b) shows that the tip of the electrical trees consist of carbon deposits. Unlike on the epoxy plaques studied, growth of channels on or in the SiR slab was barely discerned.

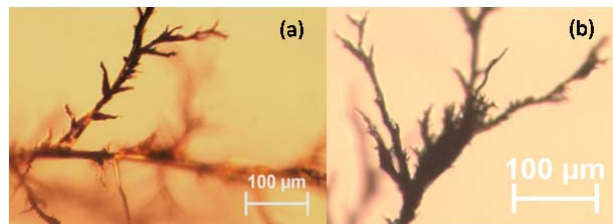


Figure 4. The structure of the branches developed in the epoxy at 60 kPa.
 (a) the carbon deposits on the walls of the channels,
 (b) the tips of the branches

V. CONCLUSION

The planar geometry of the materials and transparent nature of epoxy resin has allowed direct observation of interfacial damage as it progressed between the epoxy and silicone rubber. The test geometry allowed the track to grow into a field unaffected by the earth electrode, as it does in a real composite insulator. As a result, after a period of rapid growth, uniform growth rates were observed. This is behavior expected in service whilst the tree is much shorter than the insulation length.

A strong correlation is seen between maximum partial discharge magnitude and tracking length, suggesting the largest discharges traverse the full length of the track. It is postulated that smaller discharges are responsible for infill growth within the tracking pattern, and electrical tree growth in the epoxy resin. The surface topography of the plaques, measured after testing, indicated channels that spread at the interface had widths up to 1000 μm . Although less evident, eroded channels were also observed on the silicone rubber interface, near to the electrode.

Once initiated by the artificial defect (the wire electrode), the track is able to propagate at a constant speed in the otherwise uniform field and geometry. In practical applications the electric field distribution along an insulator will control the track propagation. The equilibrium growth rate of the track, established once the front of the track is distant from the field-enhancing electrode, is higher under low pressure conditions. It is concluded that in a weak interface, the internal discharge activity more readily forms hollow and wide interfacial channels, which develop debonded areas and interfacial erosion. In addition, the growth

of electrical trees and the formation of carbon deposits in and on the epoxy resin will further enhance the local field sufficiently to further stimulate tracking paths along the interface.

In service insulators the epoxy resin is highly filled with pultruded glass fibre, and the impact of that on treeing and tracking behavior requires further study.

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