INCLINED PLANE TESTS OF COMPOSITE, SILICONE RUBBER AND COMPOSITE SILICONE RUBBER COATED MATERIALS

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Abstract: Polymeric HV insulators have been used on distribution and transmission lines for more than 25 years and are increasingly replacing porcelain and glass insulators around the world. Typically, the polymeric insulators consist of composite materials for the core and these provide the structural element of the insulator with the application of silicone elastomers for the outer surface. This paper describes the relative performance of pure composite, silicone rubber and silicone rubber coated composite samples during inclined plane tests. The test is conducted in accordance with the standard BS EN 60587:2007. The correlation between visual observations of damage and the leakage current behaviours of these specimens under constant ac stresses are investigated. In addition, the thermal profile of the sample during the tracking processes is analysed based on thermal images captured by an infrared camera.

1. INTRODUCTION

Polymeric HV insulators have been used on distribution and transmission lines for more than 25 years and are increasingly replacing porcelain and glass insulators around the world [1, 2]. Typically, the polymeric insulators consist of composite materials for the core that provide the structural element of the insulator. Silicone elastomers are used for the outer surface including the sheds. Polymeric insulators are shown to be 90% lower in weight in comparison to the ceramic equivalent, have an excellent ability to withstand vandalism and are capable of being designed with extremely high leakage lengths [3].

The polymer composites used in insulators are made by resin epoxy reinforced with fibre glass mesh. The composites can be made as strong as steel with half the weight. They are reliable, immune to corrosion and chemically resistive. The weak points of polymer composites are that epoxy materials have a low resistance to degradation by electric arcs. The material is typically hydrophilic. This can lead to an increased likelihood tracking and resulting carbonisation on the surface. These problems mean that composites alone are not suitable for use as an insulator at high voltages.

The silicone layer used on as housing of high voltage insulators provides a hydrophobic characteristic which can assist in the reduction of dry bands occurring on the surface. Even when it is lost, silicone rubber materials are capable of recovering to a hydrophobic state after certain period [4, 5]. Compared to epoxy resins, silicone rubbers filled with alumina trihydrate (ATH) are shown to have a good capability in suppressing or delaying tracking and erosion taking place on the surface [4]. The weakness of silicone is a low mechanical strength. Silicone rubbers can also be damaged by UV light and suffer from problems related to algae growth.

The combination of a composite with a silicone rubber allows the provision of both electrical and mechanical strength as is used on a conventional polymeric insulator.

This paper describes the relative performance of pure composite, silicone rubber and silicone rubber coated composite samples during inclined plane tests. The test is conducted in accordance with the standard BS EN 60587:2007 [6]. The correlation between visual observations of damage and the leakage current behaviours of these specimens under constant ac stresses are investigated. In addition, the thermal profile of the sample during the tracking processes is analysed based on thermal images captured by an infrared camera.

The tracking test is a highly aggressive test that allows contaminant to flow down the surface of the specimen. With the formation of a conductive path between two electrodes, dry band arcing rapidly develops on the sample. The test therefore allows the resistance of insulating materials to be assessed. Materials can be resistant in one of two ways. Firstly, if material is hydrophobic, this will help to prevent the formation of the conductive path between the two electrodes. Secondly, if the dry band arcing does take place, the material type partially defines the level of ablation / combustion that will take place in the proximity of the dry band arc.

The work intends to attempt to understand whether the composite structure under the silicone rubber has any impact on tracking performance (it is usual to test just the outer coating in tracking tests). The thermal images captured during the tracking test and used for this purpose.

2. EXPERIMENTAL SETUP

2.1. Test facility and layout

In the tracking tests carried out, samples of pure resin based composites, pure silicone rubber samples and silicone rubber coated composites have been tested. The test is conducted in accordance with the standard BS EN 60587:2007 [6]. A system has been developed that can test up to five specimens simultaneously. An infrared camera is used to capture thermal images during tracking process. Figure 1 illustrates the system setup (just one test sample shown for clarity).
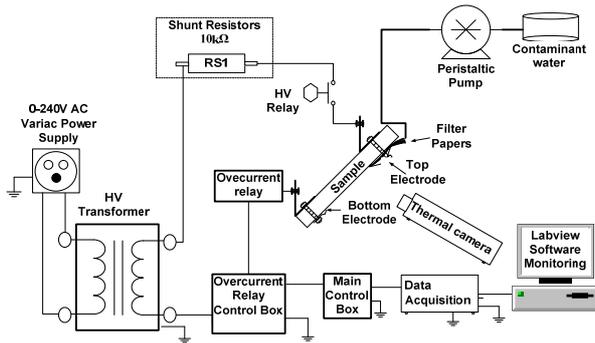

Figure 1: Schematic of the tracking test setup

A transformer (415V/11kV) is used to supply power to the test circuit and the voltage is measured at the output of this transformer using a high voltage probe. Each sample is fed from this supply via a high voltage relay and a resistance, the value of which depends on the test voltage and the flow rate of the contaminant. The current flowing across the sample is measured using a resistive shunt. Overcurrent protection operates should the current exceed 60mA±6mA for 2s to 3s. A peristaltic pump is used to create a water flow across the inclined sample at the flow rate stated in the standard. The current and voltage are monitored using a Labview system that has a 12-bit vertical resolution and a sampling rate of 10kS/sec.

In cases where the thermal profile of the sample surface was monitored, only one sample was tested. A Fluke IR camera was directed at the sample. The camera used a detector with 340 x 240 resolutions. The model Ti55 that being used in the tracking test is capable to measure the temperature up to 620°C. The tracking thermal images were captured every 5 seconds.

2.2. Description Of Samples To Be Tested

The samples to be tested were as shown in Figure 2. All samples are 120mm x 50mm as required by the tracking test standard. They have a thickness of 5mm-12mm. The composite sample has a resin base. The silicone rubber sample is produced using a commercially available silicone rubber mix. The other three samples have a composite base onto which is placed a varying thickness layer of silicone rubber.
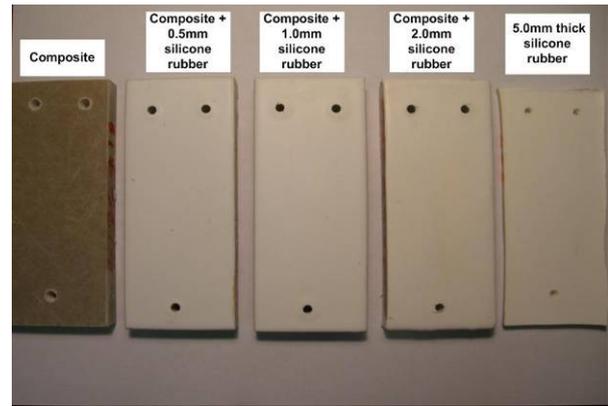

Figure 2: Sample surfaces before the start of the tracking test.

3. OVERVIEW OF TEST RESULTS

The materials described were all subjected to a constant voltage tracking test. A 2.5kV AC voltage stress was applied to each of the samples. The fail criteria was the point at which the overcurrent protection operated. As previously described, the temperature distribution on the surface of the specimen was monitored by infra-red camera. The current flowing across the specimen and the test voltage were collected by the Labview system and the energy dissipation calculated. Measurements of the time to failure, visual observations of the damage, the reduction in mass of the sample and the erosion depth were all taken once the testing was complete.

Figure 3 shows an example of the sample surfaces after completion of the tracking test.
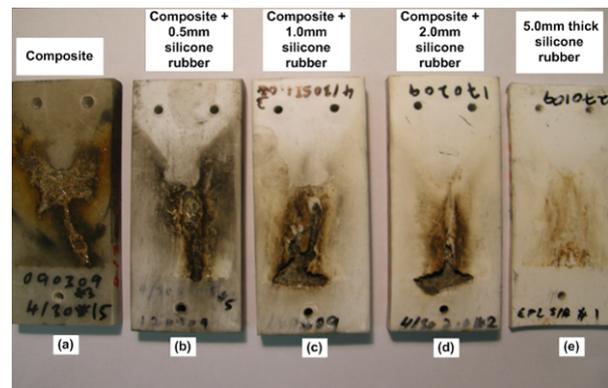
Figure 3: Example sample surfaces after completion of the tracking test.

In terms of the time to failure, the composite samples had the shortest time to failure of less than 1hr. In contrast, the pure silicone rubber sample survived for over 20 hours without failure. For the samples made by coating the composite with a silicone, the time to failure was increased as the thickness of the silicone rubber coating increased. The relevant data is shown in Table 1. These data represent average results that were collected from three samples of each type.

Table 1: Overview of time to failure, residue production and erosion depth observed in each sample type.

Sample	Average time to failure (minute)	Average mass of residue produced (gram)	Average maximum erosion depth (mm)
Pure composite	46	0.02	0.60
0.5mm silicone rubber coated	270	0.10	2.21
1.0mm silicone rubber coated	790	0.39	4.01
2.0mm silicone rubber coated	1029	0.64	4.98
Pure silicone rubber	>1200	0.02	0.86

From this data, certain basic conclusions can be reached that are in line with tests carried on similar materials by other researchers.

For the composite sample, the arcs that are developed on the surface of the sample rapidly carbonise the sample surface protecting it from further damage. The carbonisation increases the electric field across the remainder of the sound insulation surface, increasing the likelihood of further damage. As a result, the composite sample fails rapidly once the voltage is applied and a relatively small erosion depth is observed.

The silicone rubber sample does not fail after twenty hours but a more significant level or erosion occurs. This occurs as silicone rubber is merely ablated by the arcs / changed into other non-conductive compounds. It does not carbonise as is the case with an epoxy.

For the samples that consist of silicone rubber laid onto the composite sample, the time to failure increases as the depth of silicone rubber increases. This is not surprising since once the silicone rubber layer is breached, carbonisation of the underlying composite surface will take place and this will increase the electric field across the sample. Of more interest is the erosion depth that is measured on the combination samples. While the depth of penetration was only 0.6mm on average into the composite samples, this increases to 1.71mm (2.21mm minus the 0.5mm thickness of the silicone coat) for the 0.5mm coated sample). This phenomena will be discussed in more detail when details of the thermal testing are described.

4. DETAILED DATA ANALYSIS

4.1. Thermal and leakage current analysis

Figure 4 shows an example of the observations made by the infrared camera in both the IR (a) and the visible (b) spectrum. The images shows a case where the heated contaminant channel can be easily observed as can a location of particularly high temperature where a discharge is taking place. Using the post processing software available in the camera, the maximum, average and minimum temperature of a selected portion of the sample surface can be found. For this work, a measurement window was placed between the tip of the HV electrode and the edge of the LV electrode. The window width was about 30mm as shown in Figure 4a.
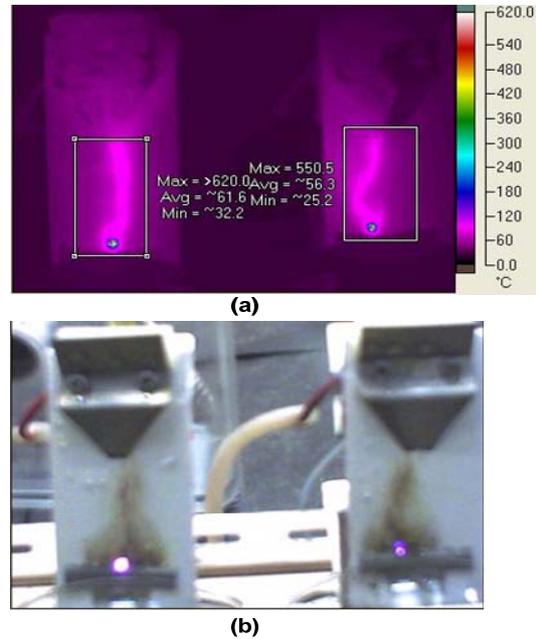

Figure 4: Tracking processes on samples. (a) captured by infrared camera. (b) actual visual image.

Figure 5 shows the maximum temperatures observed on the various sample types.

For the polyester resin sample in Figure 5(a), the maximum surface temperature was maintained at between 80°C and 150°C for most of the tracking test duration. A very high temperature value (>620°C) is shown only during the time of failure (when the flames are actually seen on the sample). Evaporation of the test contaminant will clearly lead to evaporation of the liquid from the specimen at a temperature of around 100°C. The increased temperatures observed are, however, not significantly above this and owing to the significant degradation observed indicate that the material must decompose at reasonably low temperatures. This is a finding confirmed in [7]. In the first ten minutes or so of the test, the temperatures observed do not go past the boiling point of the contaminant. This therefore suggests that damage only begins after this time since a higher temperature would be observed from any discharge.

In the case of the pure silicone rubber sample, the maximum surface temperature is seen to increase in an almost linear manner as time increases. Much higher temperatures are observed on the silicone rubber sample.
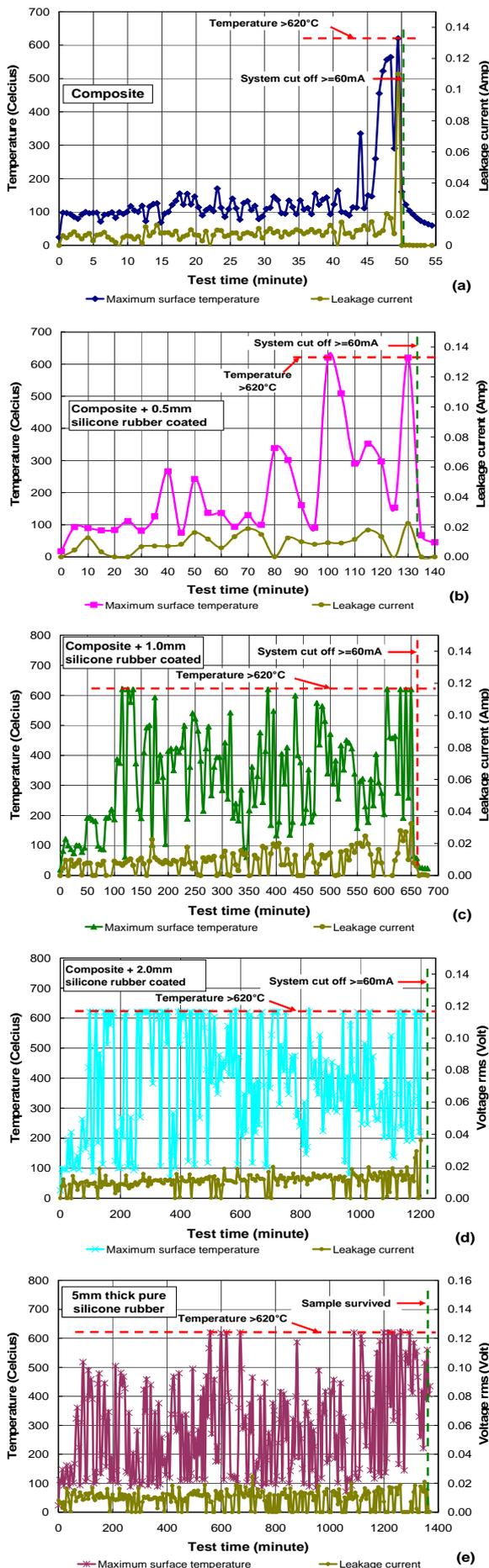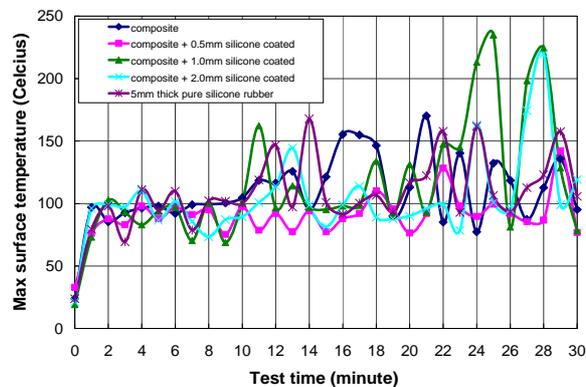
**Figure 5:** Maximum surface temperature data observed on the various samples during the tracking process.

Again, there is an initial period when the surface temperature is shown not to exceed 100°C such as can be seen in Figure 6 (which is a close up view of the initial 30 minutes of each test). This temperature should also be associated solely with the evaporation of water from the sample surface. In this region, no damage will be observed on the sample such can be seen in Figure 8. The figure shows the visual observation of various samples during initial 5 minute tracking test processes. The general lack of arcing activity correlates with the temperature not rising above 100°C. Figure 7 shows the leakage current plot that corresponds to the surface temperature data in Figure 6. The current shown is the RMS value. The current waveforms pattern shown in this figure indicate no direct correlation between surface temperature and RMS current.

For the samples that are coated with silicone rubber, higher surface temperatures shown to exist. with temperatures of above 620°C (the maximum limit of the camera) often being measured. This level of temperature is not seen on samples of either individual component. This elevated temperature was seen with the highest frequency on the sample coated with 2mm of silicone. It is thought that these high temperatures develop when the silicone layer is ablated to such an extent that decomposition of the underlying composite begins to take place. The pit formed by the ablation of the silicone rubber coating confines the arcing activity to one particular location on the sample leading to intense localised arcing and high temperatures being observed.

As with the plain silicone sample, a period of around 30 minutes after the start of the test is generally observed when the surface temperature values are shown to be less than the boiling point of the contaminant (approx. 100°C). In this region, we can therefore state that no significant arcing is taking place on the sample. As no variation of this time period is seen as a function of the thickness of the silicone rubber coating, it may therefore be concluded that the different thickness layers have no impact in delaying the hydrophobicity loss of the sample surface and the initiation of arcing.

Figure 6: Maximum surface temperature data observed on the various types of sample during the initial 30 minutes of the tracking process.
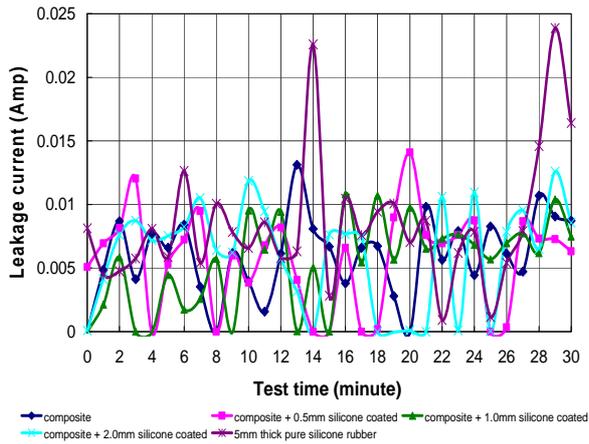
Figure 7: Leakage current observed on the various type samples during the first 30 minutes of the tracking process.
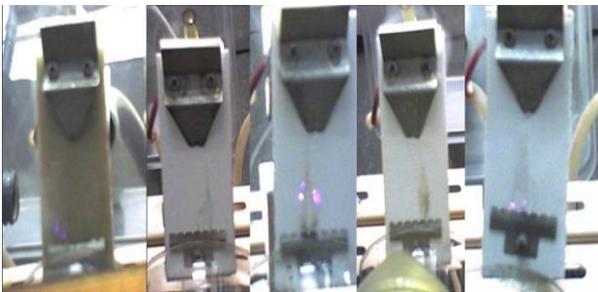

Figure 8: Visual observation of various samples during the initial 5 minutes of the tracking test process. (Composite, composite plus 0.5mm silicone coated, composite plus 1.0mm silicone coated, composite plus 2.0mm silicone coated, 5mm thick pure silicone coated samples shown).

Figure 9 shows the actual leakage current waveforms captured over 5 cycles at 5 minutes, 10 minutes and 25 minutes from the start of the test for the 0.5mm silicone coated composite sample. The first and the third leakage current patterns in 9(a) and 9(c) show sinusoidal-like or triangle-like currents with a time lag to onset of current in each half cycle. This is caused by a dry band arc taking place on the sample surface. The pattern in 9(b) shows a purely sinusoidal component which indicates that the current is passing through the electrolyte solution. These patterns are characterised on the basis of the methods detailed in [8]. Future work will include further analysis of the current waveforms captured during these tests in an attempt to correlate the exact correlation of current waveform and surface temperature.

5. CONCLUSION

Tracking test measurements have been carried out on samples of pure composite, pure silicone coated rubber and silicone rubber coated composite. An increasing level of silicone rubber coating is seen to lead to an increase in the time to failure. More surprisingly, the combination of the silicone rubber coating and the composite seems to increase the maximum erosion

depth that is observed in the samples. This correlates with more intense arcing activity that is detected using an infra-red camera where temperatures of over 620°C are observed. There does, however, appear to be no relationship between the thickness of the silicone coat and the time at which tracking damage is initiated (this determined by the point where the surface temperature of the sample first rises above 100°C).
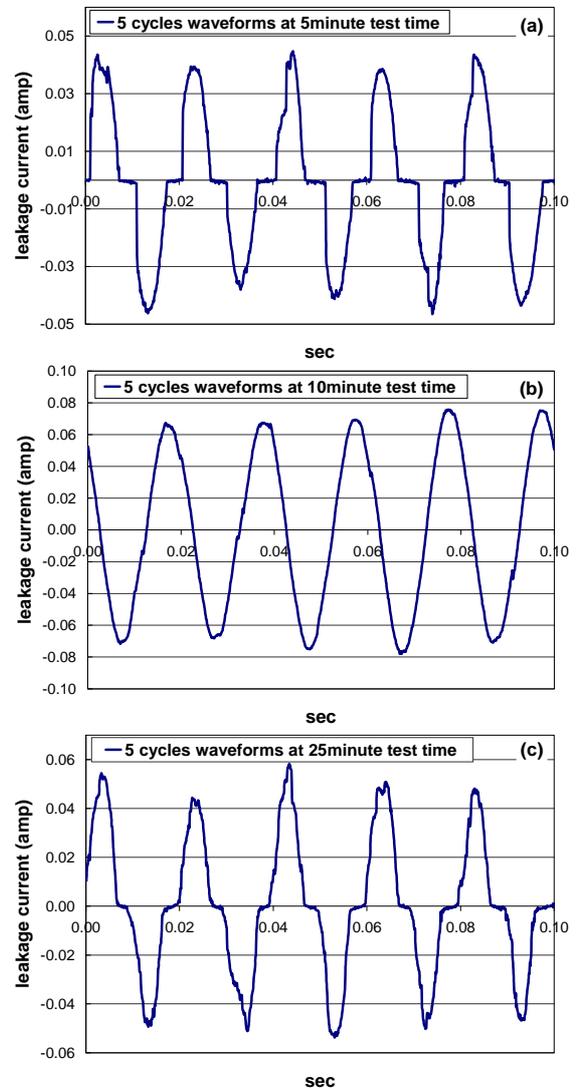
Figure 9: Leakage current observed on various type samples surface during 30minute tracking process.

6. REFERENCES

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