The Effect of pH and Temperature on the Propagation of Water Treeing in XLPE Insulated Underground Cable

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ABSTRACT

Water treeing has become the major problem in XLPE insulated underground cable caused by the moisture penetration. Even though some studies have been done on this problem, it is still not clear how the moisture can damage the XLPE insulated cable under certain operating conditions quickly. This work has studied the effect of pH and temperature of the ionic solutions to the degradation of the XLPE insulation. The study focused on the XLPE cable used in the 22 kV underground distribution systems in Thailand. The ionic solutions involved a 0.1 mol/l of NaCl and $CuSO_4$ solutions for degrading the XLPE cable at ambient and 50°C in 1000 hours and 4000 hours with the electric stress of 22 kV 50 Hz continuously. $CuSO_4$ and NaCl revealed a pH of 4.04 to 3.70 and 6.49 to 6.74 from ambient to 50°C respectively. The higher strength of acidity resulted in $CuSO_4$ at 50°C was observed to be more effective in the propagation of water treeing across the XLPE insulation. The propagation of water treeing across the XLPE was strongly dependent on the pH level. Temperature above ambient was concluded to be detrimental for XLPE insulation when a $CuSO_4$ ionic solution exists over an extended period due to the significant propagation of water treeing.

Keywords: Water treeing Propagation, Ionic Solution, pH, Temperature, XLPE Power Cable.

1. INTRODUCTION

For many years, the Cross-Linked Polyethylene (XLPE) insulation has been accepted to have excellent electrical properties that make it suitable for use in underground cables. XLPE has been mostly employed as an insulator especially in underground distribution power cables, for example, in 22 kV distribution networks over several provinces in Thailand. Despite its excellence in electrical properties, it faces "environmental problem" which relates to the ingress of moisture or other ionic solutions that reduce the performance of XLPE insulation in high electric fields. Moisture or other ionic solutions can penetrate into XLPE insulation through small cracks and weak points. Then, the applied voltage acts as an external force (electric fields) to enable this ingress through small cracks [1]. The penetrated solutions form tracks or tree-like structure in XLPE insulation known as water treeing which distort the polymeric materials due to partial discharges progressing through layers under electric stress in extremely non-uniform fields [2]. Several studies [3-6], have proved that the damaging phenomenon of water treeing takes place inside the XLPE insulation with continued exposure to moisture and electrical stress. Furthermore, the water treeing is considered as a major source in the aging of polymeric cable insulation through thermal degradation, partial discharges, aggression by environment and losses [7].

The study of the inception and extent of the growth of water treeing to electrical treeing have been examined and analyzed in [8]. Water treeing is normally grouped into two types which are vented type and bow-tie. Firstly, vented type treeing is defined as the type of water treeing growing from insulation boundaries to another side of the insulation as shown in Fig. 1, mainly vented type treeing grows toward the electric field line. Another type is bow-tied treeing, see Fig. 2, and is defined as the water treeing growing inside of insulation volume. Bow-tied treeing grows in the opposite direction from the electric field line [9].

Several published research papers illustrated the fast growing of water treeing propagation at high temperature [12], whereas others research papers revealed that propagation of water treeing grew fast at low temperature [13]. However, in all the above researcher's works, the parameters of the ionic solution were not considered. In this study, both the effect of pH and temperature of the ionic solutions to XLPE cable are examined. This study, NaCl and $CuSO_4$ ionic solutions were used for testing because there have many types and properties of the ionic solution (salt solution) in the underground systems in Thailand. $CuSO_4$ solution usually occurs when

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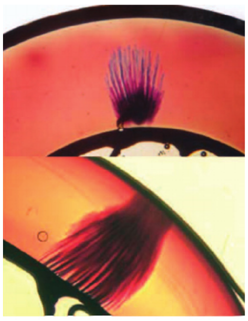


Fig.1: *Type Treeing [10].*

Fig.2: *Bow-Tied Treeing [11].*

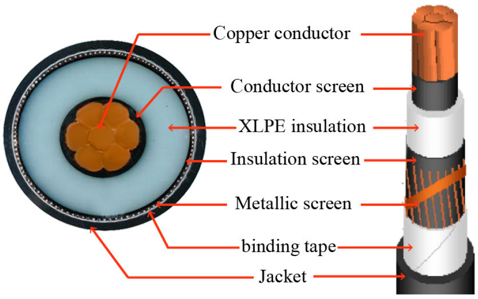


Fig.3: *Single Core 12/20(24) kV XLPE Underground Cable [14].*

there is water entering the underground cable and reacting with the copper conductor. Therefore, NaCl and $CuSO_4$ ionic solutions were chosen for testing. Also, the different properties of both ionic solutions are shown in Table 1-3.

2. EXPERIMENTAL SETUP

2.1 Sample Preparation

The new (unused) single core (XLPE) medium voltage underground cable of 50 mm^2 12/20(24) kV was used in this experiment (see Fig. 3). The cable was cut into pieces of 200 cm length. Since the water treeing occurs in XLPE insulation, to fasten their occurrence, only critical layers were left for the experiment (see Fig. 4). The essential layers were XLPE insulation, conductor screen and the copper conductor as shown in Fig. 4.

From the layers of interest of XLPE cable, few pin-holes were made to initiate the formation of water treeing (if not pinned, the experiment may operate over an extended period without initiating a water

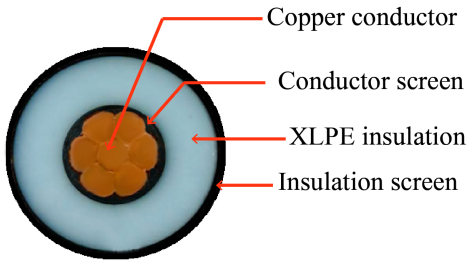


Fig.4: *Layers of Interest in 12/20(24) kV XLPE Cable.*

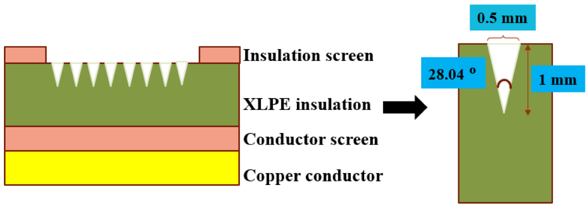


Fig.5: *Setup of Pin-Holes in XLPE Cable.*

treeing). For each XLPE cable, four sections for pinning were made. The number of pin-holes and their dimensions are shown in Fig. 5.

For dimension controlling of pin-holes setup in XLPE cable, there are two steps. Firstly, the Vernier caliper was used to measure the radius of the pin (0.5 mm). Finally, the washer was put on the pin that near the pin-tip but the length of pin-tip left to be 1 mm. So, when the pin was impaled on the XLPE insulation, the washer will prevent and control the length of pin-tip to be 1 mm. However, the length of pin-tip may be incorrect around 1±0.1 mm. To ensure that the size of pin-holes is prescribed, the researchers used a microscope to measure the size of pin-holes. This pin-holes setup was only a defected point for testing of vented type treeing.

For bow-tied treeing, the defect point occurred from some mistake point of the production in the factory. The defect point of bow-tied treeing cannot make in XLPE insulator. Therefore, bow-tied treeing may occur in the XLPE insulator.

2.2 Experimental Procedure

The arrangement and setup of the experiment are shown in Fig. 6-7. Two test chambers, one for NaCl and the other one for a $CuSO_4$ ionic solution, having 0.1 mol/l were used (see Fig. 7). In Fig. 7, the left test chamber contained NaCl ionic solution kept at 50°C circulated continuously with an electric pump. The continuous electric stress of 24 kV 50 Hz was applied throughout the test. Moreover, the left test chamber contained several cables which were stressed for 1000 hours and 4000 hours. On the right of Fig. 7, a $CuSO_4$ ionic solution was used with the above procedures. In the case of ambient temperature, the

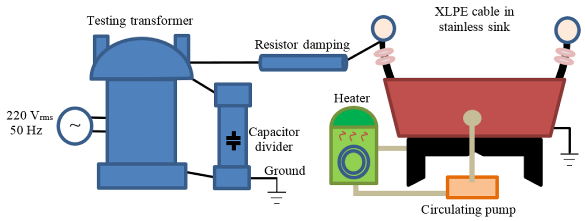


Fig.6: *Arrangement of the Test Chamber.*

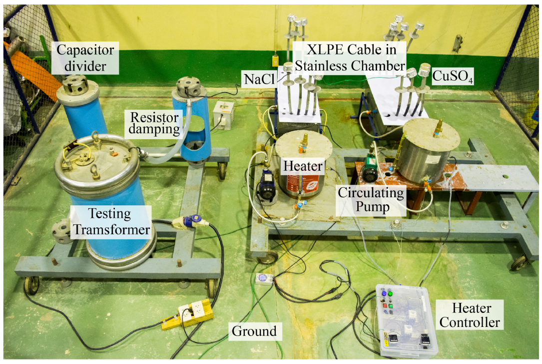


Fig.7: *Setup of the Experiment.*

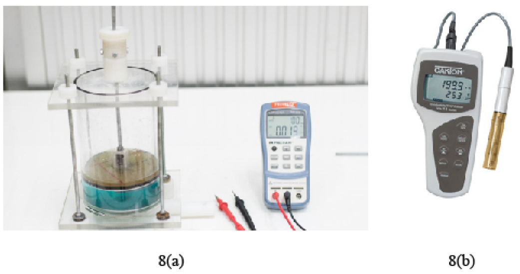


Fig.8: *a) Measuring Capacitance b) Bulky Conductivity.*

heat was not equipped.

2.3 Ionic Solutions

In a 0.1 mol/l of NaCl and $CuSO_4$, bulk conductivity and relative permittivity were obtained by using equipment shown in Fig. 8 at ambient and 50°C. The values of bulk conductivity (S/m) were measured directly with equipment in Fig. 8(b). Amounts of relative permittivity were obtained through measurement of the capacitance of the ionic solution at ambient and 50°C. Based on the capacitance of the capacitor, the relative permittivity of the ionic solution was calculated as shown in (1) [15].

$$\varepsilon_r = \frac{(C \times d)}{(A \times \varepsilon_0)} \tag{1}$$

Where

ε_0 = free permittivity equals to 8.85×10^{-12} F/m.

ε_r = relative permittivity of the ionic solution.

Fig.9: *A Stereo Microscope (Olympus BX51M) [16].*

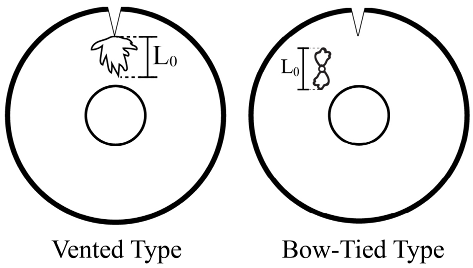


Fig.10: *Measuring the Length of Water Treeing.*

C = measured capacitance of the ionic solution.

d = distance between parallel circular plates of the test cell shown in Fig. 8a (3 cm).

A = cross-section area of the test cell plate (7 cm^2)

For observing the presence of water treeing, the XLPE cable was sliced with layers of interest without cores (see Fig. 4) in a thickness of 400-600 μm by using microtome equipment. The slices were stained with methylene blue solution at 80°C for 2 hours (for getting a precise observation of the water treeing under the microscope) before allowing to dry for about 3 hours. A stereo microscope (Olympus BX51M) shown in Fig. 9 was used to identify and measure the length of the water treeing in the sliced specimen. The length of vented type treeing as well as bow-tied treeing, denoted by L_o, are shown in Fig. 10.

3. EXPERIMENTAL RESULTS

Table 1 and Table 2 show the results of bulk conductivity and relative permittivity of NaCl and $CuSO_4$, respectively in ambient and 50°C. Table 3 shows the pH levels of NaCl and $CuSO_4$ in ambient and 50°C. The pH level of an ionic solution at a specific temperature was measured by using pH meter (pH - Benchtop Meters).

Tables 4, 5, 8, and 9 show the measured length of vented and bow-tied treeing for NaCl ionic solution at ambient and 50°C for 1000 and 4000 hours. Tables 6, 7, 10, and 11 show the length of vented and bow-tied treeing for NaCl ionic solution at ambient and

50°C for 1000 hours and 4000 hours.

Figs. 11-14 are some of the microscopic images of water treeing and their comparison are shown in Figs. 15-18.

Table 1: *Bulk Conductivity and Relative Permittivity of NaCl Solution.*

Temperature	NaCl Solution	
	Bulk Conductivity (S/m)	ε_r
Room	1.049	30.32
50°C	0.676	0.22

Table 2: *Bulk Conductivity and Relative Permittivity of $CuSO_4$ Solution.*

Temperature	$CuSO_4$ Solution	
	Bulk Conductivity (S/m)	ε_r
Room	0.535	24.5
50°C	0.136	5.64

Table 3: *pH of Ionic Solutions at 0.1 mol/l.*

Temperature	pH of Ionic Solutions	
	NaCl	$CuSO_4$
Room	6.49	4.04
50°C	6.74	3.70

Table 4: *Length of Vented Type Treeing with NaCl.*

Temperature at 1000 hrs.	Length of Water Treeing (μm)		
	Max	Min	Average
Room	208.25	189.19	198.72
50°C	127.49	100.23	113.86

Table 5: *Length of Vented Type Treeing with NaCl.*

Temperature at 4000 hrs.	Length of Water Treeing (μm)		
	Max	Min	Average
Room	336.21	326.29	331.25
50°C	280.23	269.03	274.63

Table 6: *Length of Vented Type Treeing with $CuSO_4$.*

Temperature at 1000 hrs.	Length of Water Treeing (μm)		
	Max	Min	Average
Room	1580.32	1535.72	1558.02
50°C	1988.64	1875.44	1932.04

Table 7: *Length of Vented Type Treeing with $CuSO_4$.*

Temperature at 4000 hrs.	Length of Water Treeing (μm)		
	Max	Min	Average
Room	3002.84	2834.58	2918.71
50°C	3311.33	3158.65	3234.99

Table 8: *Length of Bow-Tied Treeing with NaCl.*

Temperature at 1000 hrs.	Length of Water Treeing (μm)		
	Max	Min	Average
Room	140.28	130.36	135.32
50°C	201.11	180.19	190.65

Table 9: *Length of Bow-Tied Treeing with NaCl.*

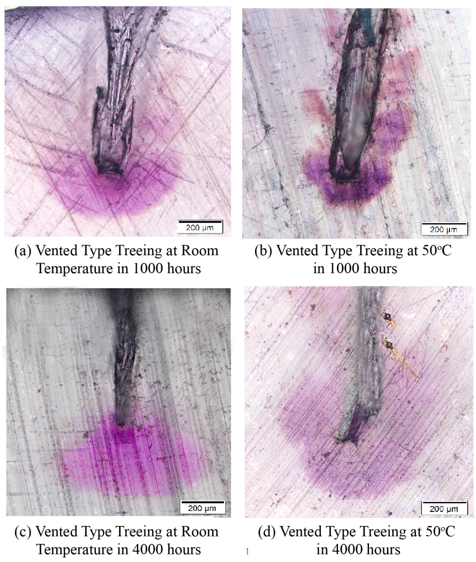
Temperature at 4000 hrs.	Length of Water Treeing (μm)		
	Max	Min	Average
Room	280.71	222.57	251.64
50°C	293.11	251.37	272.24

Table 10: *Length of Bow-Tied Treeing with $CuSO_4$.*

Temperature at 1000 hrs.	Length of Water Treeing (μm)		
	Max	Min	Average
Room	220.31	189.75	205.03
50°C	342.82	328.02	335.42

Table 11: *Length of Bow-Tied Treeing with $CuSO_4$.*

Temperature at 4000 hrs.	Length of Water Treeing (μm)		
	Max	Min	Average
Room	350.03	301.29	325.66
50°C	400.55	380.07	390.31



(a) Vented Type Treeing at Room Temperature in 1000 hours
(b) Vented Type Treeing at 50°C in 1000 hours
(c) Vented Type Treeing at Room Temperature in 4000 hours
(d) Vented Type Treeing at 50°C in 4000 hours

Fig.11: *Vented Type Treeing in NaCl Solution.*

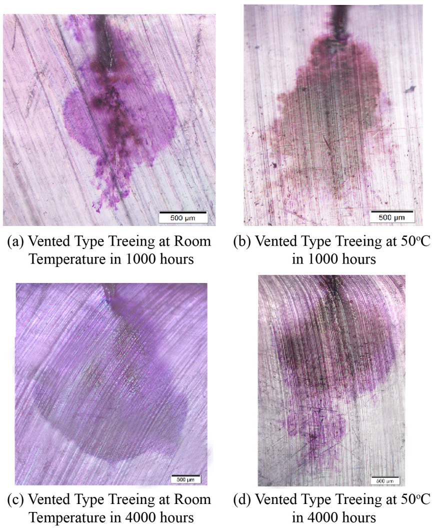


Fig.12: *Vented Type Treeing in $CuSO_4$ Solution.*

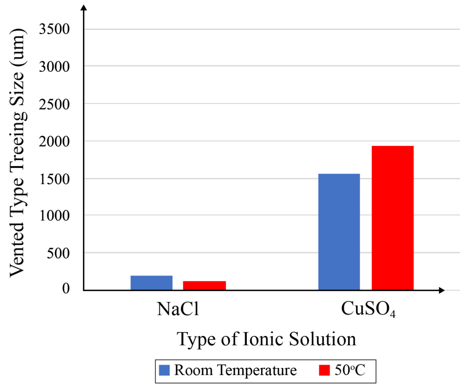


Fig.15: *Vented Type Treeing Size after 1,000 hours of testing period.*

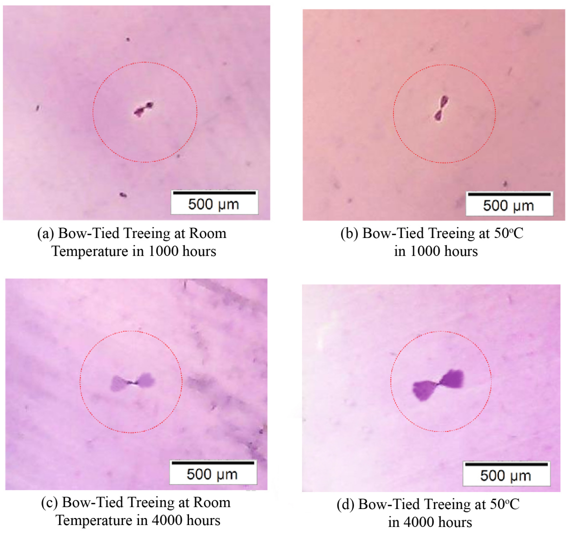


Fig.13: *Bow-Tied Treeing in NaCl Solution.*

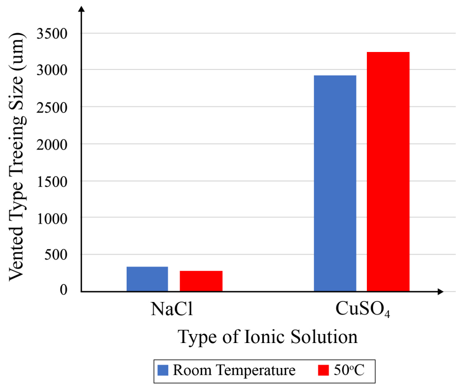


Fig.16: *Vented Type Treeing Size after 4,000 hours of testing period.*

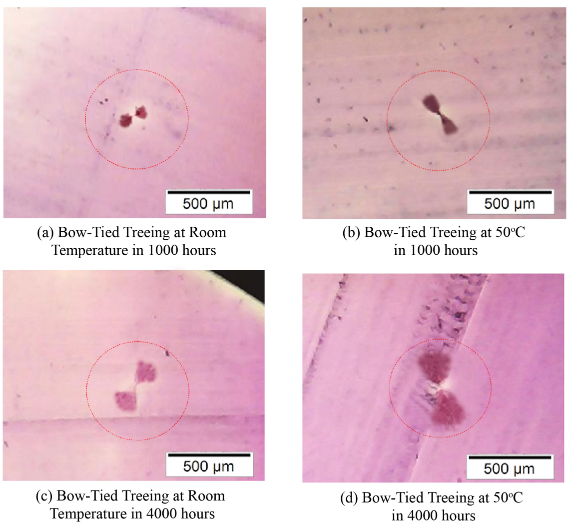


Fig.14: *Bow-Tied Treeing in $CuSO_4$ Solution.*

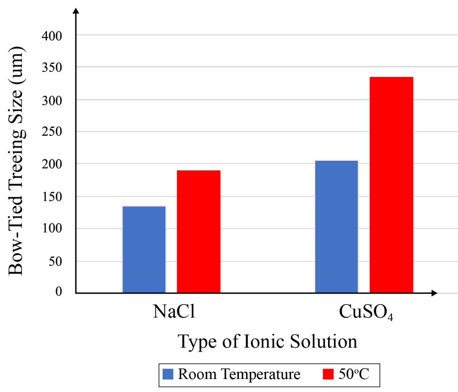


Fig.17: *Bow-Tied Treeing Size after 1,000 hours of testing period.*

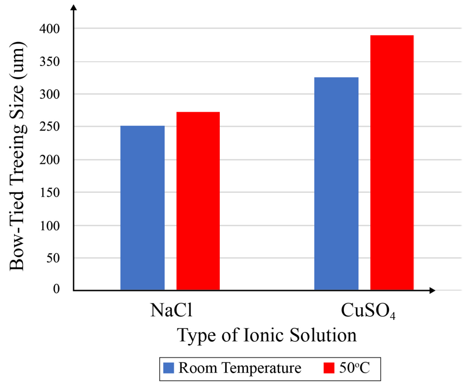


Fig.18: *Bow-Tied Treeing Size after 4,000 hours of testing period.*

4. DISCUSSION

4.1 Effect of Temperature

From Tables 5-6 and Figs. 16-17, it was observed that water treeing propagates faster at room temperature than at 50°C. Similar results were obtained when observations were made in 1000 hours and 4000 hours (see Figs. 16-17). The most resulted in water treeing due to NaCl was vented type treeing. On the other hand, with a $CuSO_4$ solution, water treeing propagated faster at 50°C than room temperature. In the case of a $CuSO_4$ solution, both vented and bow-tied treeing occurred. Also, similar results were obtained when observations were made in 1000 hours and 4000 hours (see Figs. 18-19). Generally, the $CuSO_4$ solution seemed to be more dangerous compared to NaCl at room and 50°C regarding water treeing propagation.

4.2 Effect of pH on XLPE layer

From Table 4, the values of the pH scale of NaCl and $CuSO_4$ are in the range of strong acid to pure water (neutral or pH nearly to 7). NaCl solution was investigated to be more acidic at room temperature (6.49) than at 50°C (6.74). The effect of pH 6.49 was seen to the water treeing length of 208.25 μm (1000 hours) to 336.21 (4000 hours). Moreover, the pH of 6.74 at 50°C resulted in the water treeing length of 127.49 μm (1000 hours) to 280.23 μm (4000 hours). Therefore, NaCl was observed to be more acidic at ambient rather than 50°C.

However, the $CuSO_4$ solution was observed to be less acidic at room temperature (4.04) than at 50°C (3.70). The pH 4.04 resulted in the water treeing length of 1580.25 μm (1000 hours) to 3002.84 μm (4000 hours). Moreover, the pH of 3.70 at 50°C resulted in the water treeing length of 1988.64 μm (1000 hours) to 3311.33 μm (4000 hours).

Therefore, the characteristic of pH lower than 7, termed as acidity [17], was seen to be deleterious to the life of XLPE cable due to the gradual corrosion and accelerated water treeing propagation which results to the insulation failure.

5. CONCLUSION

The effect of temperature and pH of NaCl and $CuSO_4$ ionic solution in 22 kV XLPE power cable was studied. NaCl and $CuSO_4$ were observed to undergo acidity property which is detrimental to XLPE insulation when subjected to a different temperature. The NaCl was found to be dangerous to XLPE insulation at ambient temperature while $CuSO_4$ above ambient temperature. The propagation of water treeing across the XLPE was strongly dependent on the pH level; the lower the pH level, the higher is the propagation of water treeing and vice versa. Temperature above ambient was concluded to be detrimental to XLPE insulation when a $CuSO_4$ ionic solution exists over an extended period due to the significant propagation of water treeing.

6. ACKNOWLEDGEMENT

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