The Ionic Solutions Effects to Degradation on XLPE Insulated Underground Cable with Environmental Model

N. Promvichai, T. Boonraksa, and B. Marungsri*

Abstract— *Water treeing has been studied for a long time ago. It is the cause of aging in Cross-Link Polyethylene (XLPE) insulated underground cable. The failure was mostly associated with the presence of ionic solutions in water treeing. The characteristics of ionic solutions that catalyzed the pre-breakdown in XLPE cable have not known well. Six of the ionic solutions, i.e.NaCl, Na_2SO_4, K_2SO_4, $Cu(NO_3)_2$, $CuSO_4$, and $FeSO_4$, having a concentration of 0.1 mol/L were used in this study. The experiment was carried out under three different temperatures of ionic solutions; room temperature, 50^oC, and 70^oC. A single core 22 kV XLPE cable in the distribution system of Provincial Electricity Authority (PEA) of Thailand has applied the voltage in the laboratory at 24 kV 50 Hz for testing. The effects of pH and conductivity of ionic solutions to the expansion of water treeing were elucidated. The experimental results showed that the fast propagation and most extended size of water treeing occurred at room temperature in $CuSO_4$ ionic solution. For all ionic solutions, the trend of water treeing propagation was not different between 1000 hours and 3000 hours testing period. However, the parameters of water treeing testing should be more for analyzing.*

Keywords— **Water treeing, Ionic solution, pH, Conductivity, Underground cable, XLPE.**

1. INTRODUCTION

Water treeing has been the main effect to degradation of cross-linked polyethylene insulated underground cable (XLPE cable) [1]. In Thailand, XLPE cables were increasingly used in underground power distribution system. However, wet and hot of the underground environment in Thailand may initiate the degradation on XLPE cables. Water treeing occurs when a voltage is applied to the XLPE cable with the place that moisture present [2]. Moreover, water treeing may fast growing up when the XLPE insulation degenerated until it completely breakdown [3].

Many researched papers described the phenomena of water treeing, but it has been not knowing well. Reference [4] proposed the testing of water treeing in chemical solution with temperatures. Their results showed that fast propagation of water treeing grew at low temperature but as in [5] said that fast propagation of water treeing grew at high temperature. Moreover, as in [6] told that slow propagation of water treeing did not grow at low or high temperature, but it grew slowest between low and high temperature. Maybe the published papers of their experiments were tested in short times and fewer conditions.

Some research papers showed the trend of water treeing size was long as more time as in [7,8]. There have two types of water treeing including the vented type and the bow-tie type. Both water treeing types grew to belong to the electric field as in [9]. For the vented type, the direction of water treeing propagation started at the pinned-hold tip of XLPE insulator to a copper conductor. Some XLPE cable, water treeing propagation starts from copper conductor to pinned-hold tip of the XLPE insulator as in [10]. For the bow-tie type, the direction of water treeing started inside of insulator void and grew opposite direction from the void that belongs to electric field. Usually, the water treeing starts from XLPE insulator to the copper conductor of XLPE cable. However, there still are others water treeing types such as water treeing can grow after electric treeing occurred as in [11,12], and electric treeing can grow after water treeing occurred.

In Thailand, water treeing in the XLPE cable for distribution system has been not studied well yet. Therefore, this paper was studied to clarify the effects of ionic solution in temperatures on XLPE cable for Provincial Electricity Authority (PEA) distribution system in Thailand. The experiment was conducted by the parameters of ionic solutions including pH and conductivity. The organizations of the paper are as follows; Simulation which includes the equation of the electric field, modeling of underground cable, simulation procedure is given in the second section. Simulation results and discussion are given in the third section. Next, the experiment preparation includes sample preparation, experimental setup, the condition of the experiment are illustrated in the fourth section. The experimental results were explained in the fifth section. The discussion which includes the effect of the ionic solution temperature, the effect of ionic solution type, pH and conductivity to the propagation of water treeing, is given in the sixth section. Finally, the Conclusion of this paper is given.

N. Promvichai and B. Marungsri are with the School of Electrical Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand.

T. Boonraksa is with the School of Electrical Engineering, Rajamangala University of Technology Rattanakosin, Nakhon Pathom 30000, Thailand.

*Corresponding author: B. Marungsri; E-mail: bmshvee@sut.ac.th, narupon.promvichai.sutee@hotmail.com.

2. SIMULATION

The simulation was conducted by assuming the crack started from the insulation screen to XLPE insulation layer. The pinned-hole shape was used to represent the crack of XLPE insulation. The electric field stress at the tip of pinned- hole initiated water treeing.

For the study of the roles of the ionic solutions, the simulation was done by assuming an XLPE cable immersed in the ionic solution which having the difference in conductivity and pH. The dimensions of XLPE cable is illustrated in Fig. 1. The role of the ionic solution to accelerate the expansion of water treeing was evaluated by electric field stress at the tip pinned-hole. This is the preliminary study for the propagation of water treeing. Highest electric field stress may lead to the fastest propagation of water treeing. However, it was not easy to simulate water treeing because many parameters must concern.

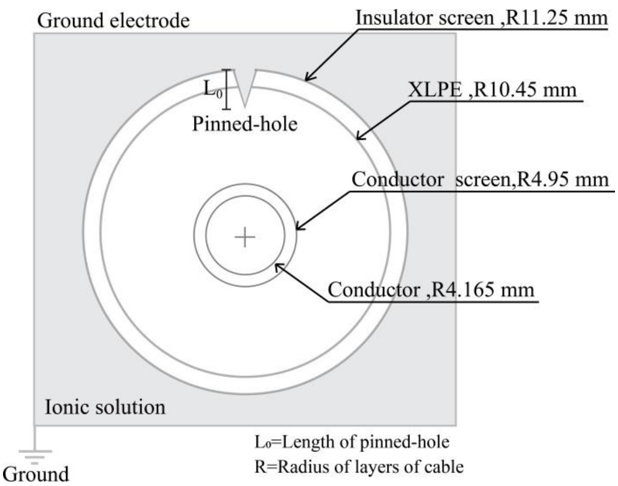

Fig.1. Underground cable model for simulation.

The Electric Field Equation

To determining electric field stress, ANSYS Maxwell 2D software was used to the electric field stress. The software was used as a tool to solve the electric field problem based on finite element analysis (FEA) method [13,14]. The equation for the electric field stress is shown in Equation (1).

$$\nabla^2 \vec{E} = -\mu\sigma \frac{\partial}{\partial t}\vec{E} - \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \qquad (1)$$

where ε is the dielectric constant of media, μ and σ are the magnetic permeability and the conductivity of conductors, respectively.

Underground Cable Model

The vented type water treeing with pinned-hole length L_0 (0.1 mm, 0.5 mm, 1.0 mm, and 1.5 mm) was considered in the simulation. The cross-section model of underground cable was shown in Fig. 1.

The dielectric constant and the conductivity of underground cable components are shown in Table 1. Furthermore, the dielectric constant and the conductivity of the ionic solution are shown in Table 2-3. The measuring of the dielectric constant (Relative permittivity) and conductivity (Bulk conductivity) was described in [15].

Table 1. Electric properties of the underground cable and ground

List	Dielectric constant	Conductivity (S/m)
Semiconductor	100	2×10^{-3}
XLPE	2.3	1×10^{-17}
Conductor	1	5.8×10^{7}
Ground	1	2×10^{6}
Vacuum	1	0

Table 2. Dielectric constant of the ionic solutions at room temperature, 50°C, and 70°C

List	Temperatures		
	Room	50°C	70°C
NaCl	30.23	0.02	1.88×10^{-3}
Na_2SO_4	56.96	3.28×10^{-4}	4.52×10^{-3}
K_2SO_4	80.97	0.01	1.98×10^{-3}
$Cu(NO_3)_2$	77.66	7.83	3.72
$CuSO_4$	24.5	5.64	5.22
$FeSO_4$	46.19	15.56	7.74

Table 3. Conductivity (S/m) of the ionic solutions at room temperature, 50°C, and 70°C

List	Temperatures		
	Room	50°C	70°C
NaCl	1.049	0.676	1.77×10^{-3}
Na_2SO_4	1.405	0.848	1.771×10^{-3}
K_2SO_4	1.609	0.739	1.762×10^{-3}
$Cu(NO_3)_2$	1.391	0.130	1.778×10^{-3}
$CuSO_4$	0.535	0.136	1.769×10^{-3}
$FeSO_4$	1.036	0.558	1.774×10^{-3}

Simulation Procedures

Assume that the voltage was applied to the copper conductor and XLPE cable immersed in the ionic solution. The boundary conditions of the simulation chamber include applied voltage 24 kV, 50 Hz at the copper conductor and applied voltage 0 kV at the ground electrode as shown in Fig. 2. The simulation conditions are shown in Table 4.

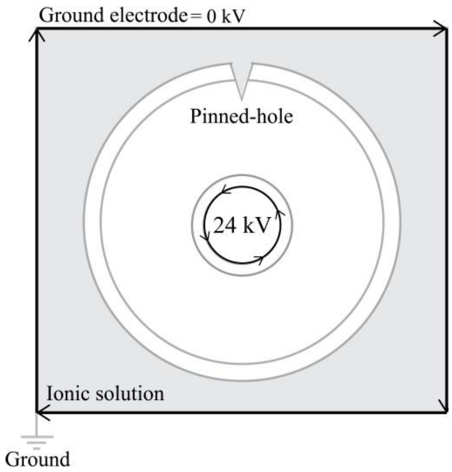

Fig.2. Boundary conditions of the chamber and XLPE cable.

Table 4. Conditions of simulation procedure

Parameter	Value
Voltage (V)	24 kV, 50 Hz
Radius of water treeing (r_0)	0.1mm, 0.5 mm, 1.0 mm, and 1.5 mm
Ionic solutions	NaCl, Na_2SO_4, K_2SO_4, $Cu(NO_3)_2$, $CuSO_4$, and $FeSO_4$

3. SIMULATION RESULTS AND DISCUSSION

As illustrated in Fig. 3, the maximum of electric field stress 10 kV/mm at 0.5 mm of the pinned-hole tip was obtained from the simulation results at room temperature and 50°C. The maximum of electric field stress is not over than the rated maximum of the electric field strength of XLPE underground cable [16]. Therefore, the breakdown of XLPE cable may not occur for all of the pinned-hole sizes when testing in the real experimental. Next, in order to accelerate the occurrence of water treeing, the pinned-hole size 0.5 mm was selected to use in the experiment. However, this pinned-hole size (0.5 mm) initiated a small size of water treeing; it is difficult to observe. Therefore, the pinned-hole size was a shift to 0.6-0.8 mm.

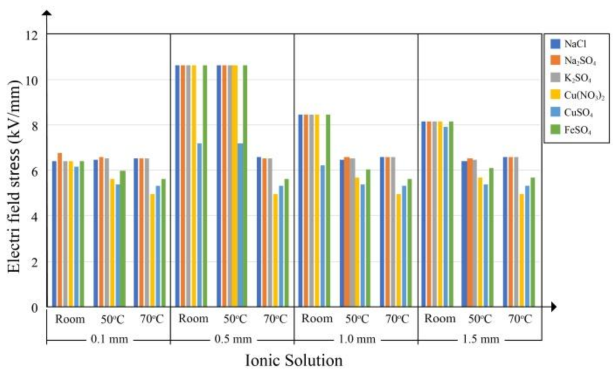

Fig.3. Electric field stress of XLPE cable in different size of pinned-hole.

4. EXPERIMENTAL

Sample Preparation

A single core–XLPE cable for 22 kV distribution system in Thailand. Reference [17] showed the constructions of this cable including conductor (circular compact stranded annealed copper), conductor screen (semi-conductive cross-linked polyethylene compound), insulation (cross-linked polyethylene compound), metallic screen (copper wires with copper contact tape), binding tape (polyester or spun bond tape), and sheath (black polyvinyl chloride: PVC). The cross-section area of the cable is 50 mm^2 with 5.5 mm thickness of the insulation layer. The cable was cut in 2 m length. Then, it was peeled cover out by remaining of the conductor, conductor screen, insulation, and insulation screen as shown in Fig. 4.

Reference [18]-[20] showed the acceleration of degradation of XLPE cable with the making of damage point by steel needles. The steel needles were used for the making of pinned-hole in XLPE insulator as shown in Fig. 5.

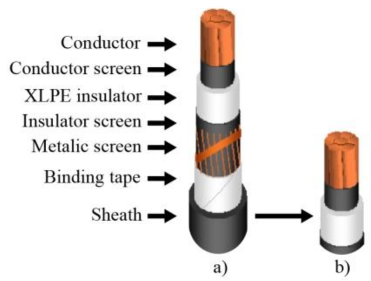

Fig.4. 22 kV XLPE underground cable with includes a) full XLPE cable b) XLPE cable for testing.

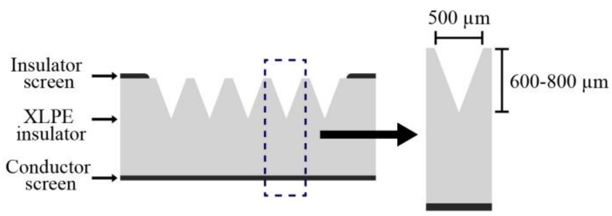

Fig.5. Pinned-hole dimension for XLPE insulated cable.

Experimental Setup

Fig. 6 showed an experimental setup to study the propagation of water treeing in XLPE cable. The testing circuit to applying voltage on XLPE cable showed in Fig. 7.

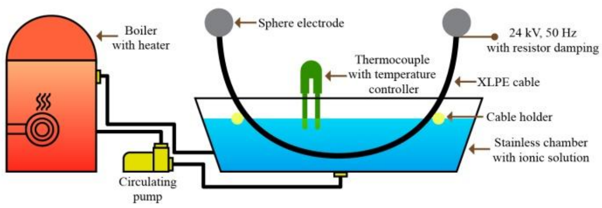

Fig.6. A schematic of experimental setup.

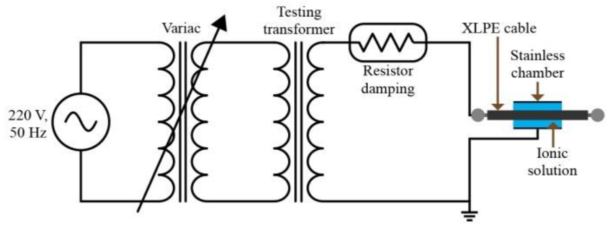

Fig.7. Circuit diagram to apply the testing voltage.

The Experimental Conditions

The conditions for study water treeing in XLPE cable are as follows.

1) Applied voltage: 24 kV
2) Applied Frequency: 50 Hz
3) Ionic solutions: 0.1 mol/L (NaCl, Na_2SO_4, K_2SO_4, $Cu(NO_3)_2$, $CuSO_4$, and $FeSO_4$)
4) Temperatures: Room temperature, 50^{o}C, and 70^{o}C.

5. EXPERIMENTAL RESULTS

After tested for 1000 hours and 3000 hours, XLPE cable was sliced by a microtome to become a thickness of 400 – 600 µm to observe the occurrence of water treeing. Then the slices were stained with methylene blue solution at 80^{o}C for 2 hours. After that, the slices were dried for 3 hours. The proportion of solution for staining is shown in Fig. 8.

Methylene blue		NaOH		Deionized water		Sliced-XLPE
1 g	:	1.5 g	:	250 mL	:	2.5 g

Fig.8. The proportion of solution for staining.

The occurrence of water treeing was observed by a stereomicroscope (Olympus BX51M). The measuring position of water treeing showed in Fig. 9 (R_0=Length of Water Treeing). The vented type was observed. The morphologies of water treeing are shown in Fig. 10-15 for the 1000 hours Testing Period, and Fig. 16-21 for 3000 hours of testing period, respectively (a = room temperature, b = 50^{o}C, and c = 70^{o}C). The averages of the maximum size of water treeing are shown in Table 5 for the 1000 hours Testing Period and Table 6 for the 3000 hours Testing Period, respectively.

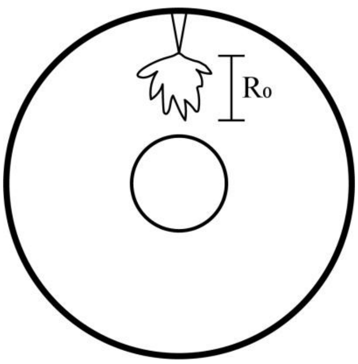

Fig.9. Measuring direction of the vented type water treeing.

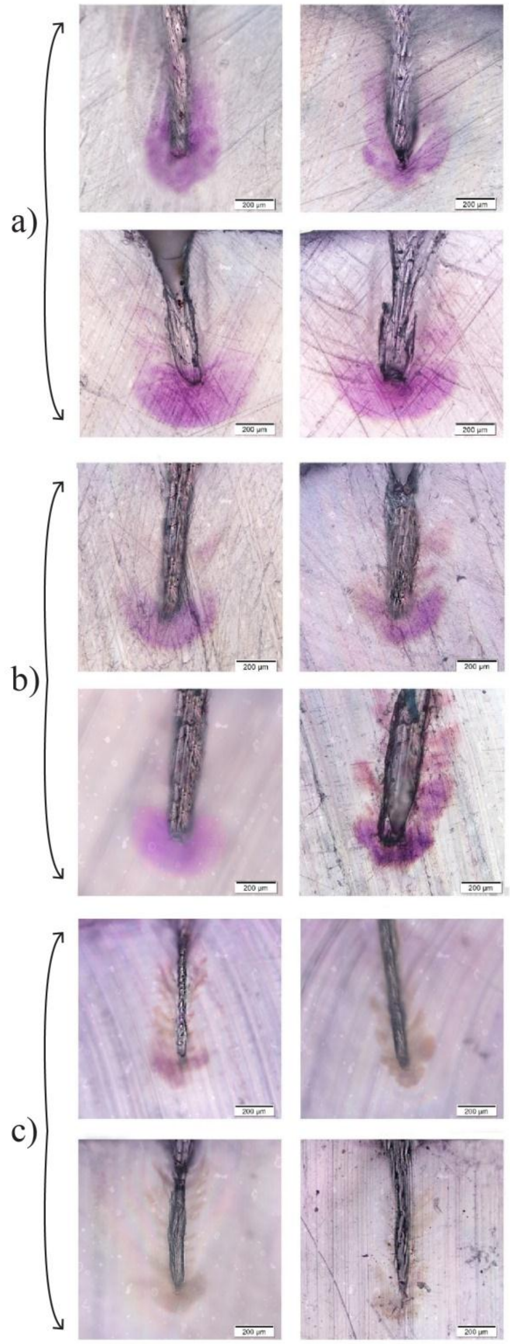

Fig.10. Morphology of the Vented Type in NaCl for 1000 hours Testing Period at (a) Room Temperature, (b) 50^{o}C, (c) 70^{o}C.

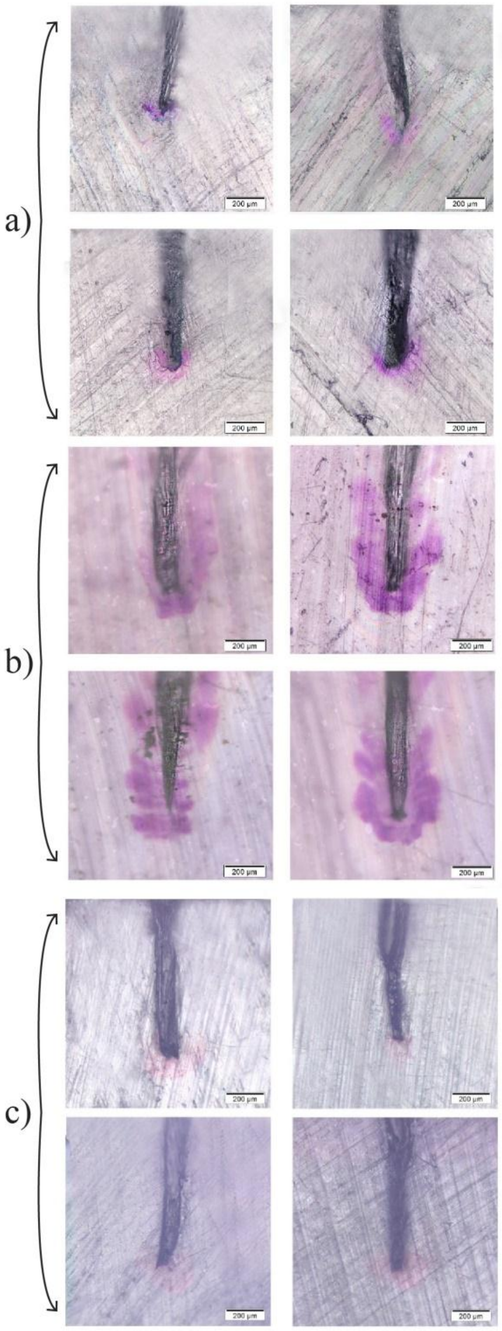

Fig.11. Morphology of the Vented Type in Na_2SO_4 for 1000 hours of Testing Period at (a) Room Temperature, (b) 50°C, and (c) 70°C.

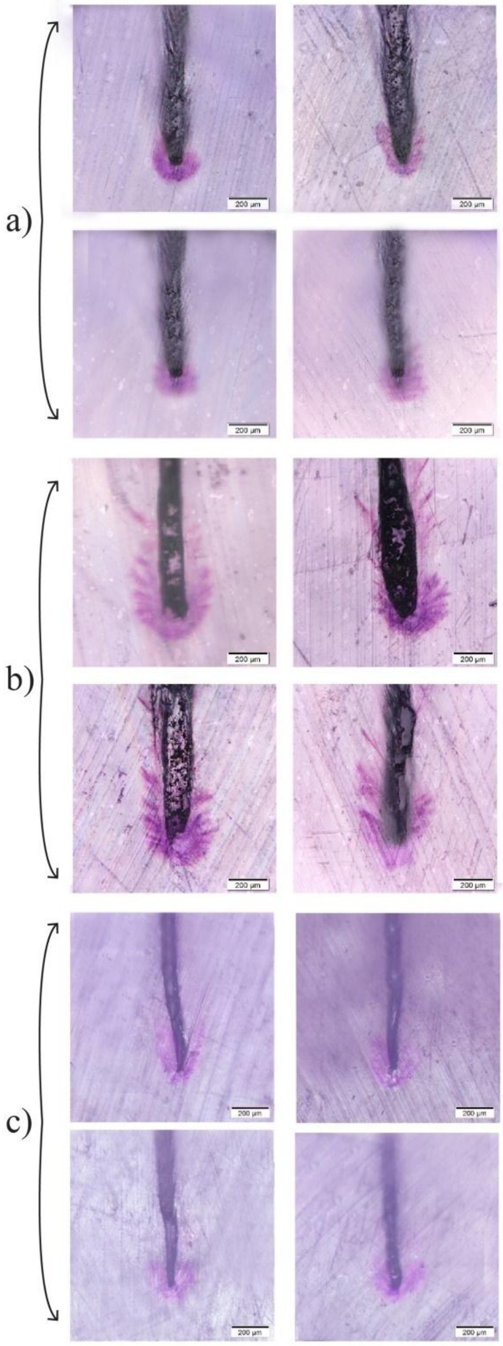

Fig.12. Morphology of the Vented Type in K_2SO_4 for 1000 hours of Testing Period at (a) Room Temperature, (b) 50°C, and (c) 70°C.

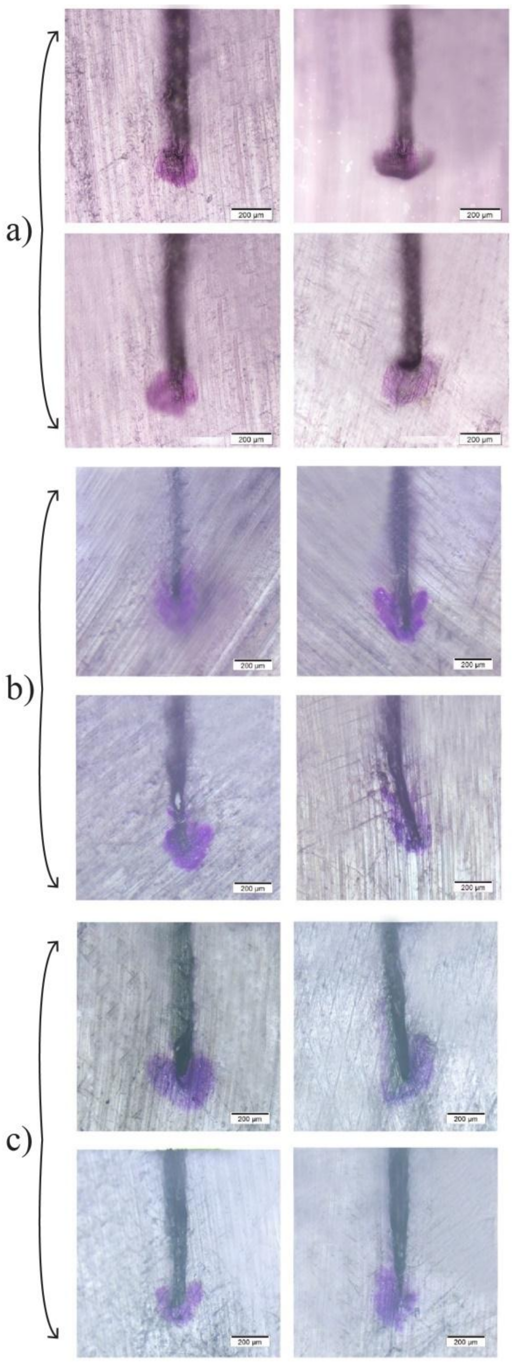

Fig.13. Morphology of the Vented Type in $Cu(NO_3)_2$ for 1000 hours of Testing Period at (a) Room Temperature, (b) 50°C, and (c) 70°C.

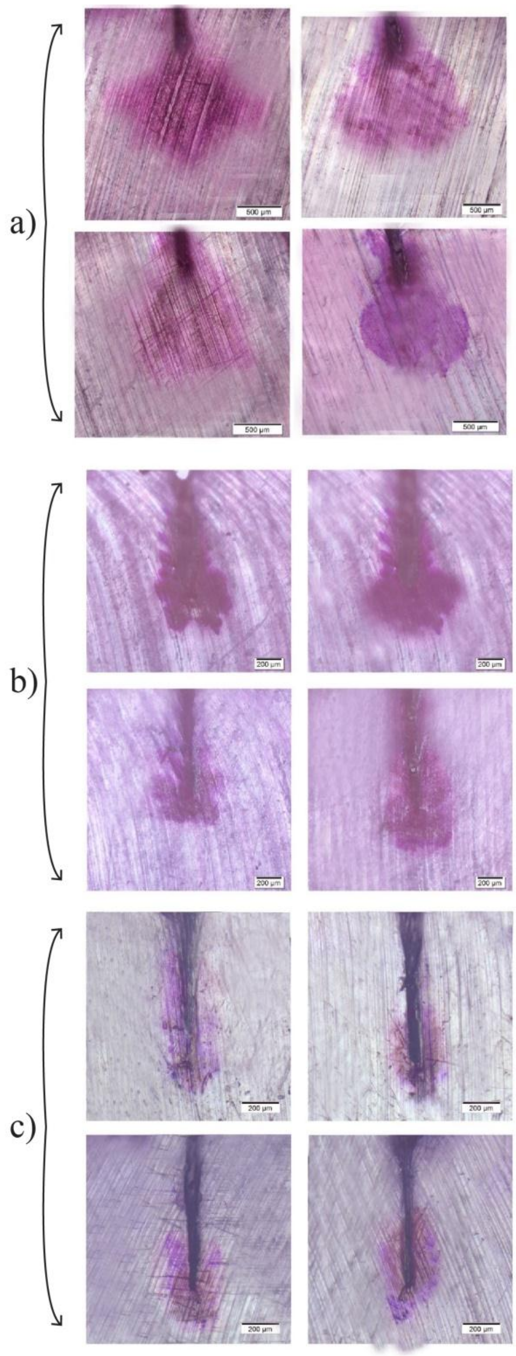

Fig.14. Morphology of the Vented Type in $CuSO_4$ for 1000 hours of Testing Period at (a) Room Temperature, (b) 50°C, and (c) 70°C.

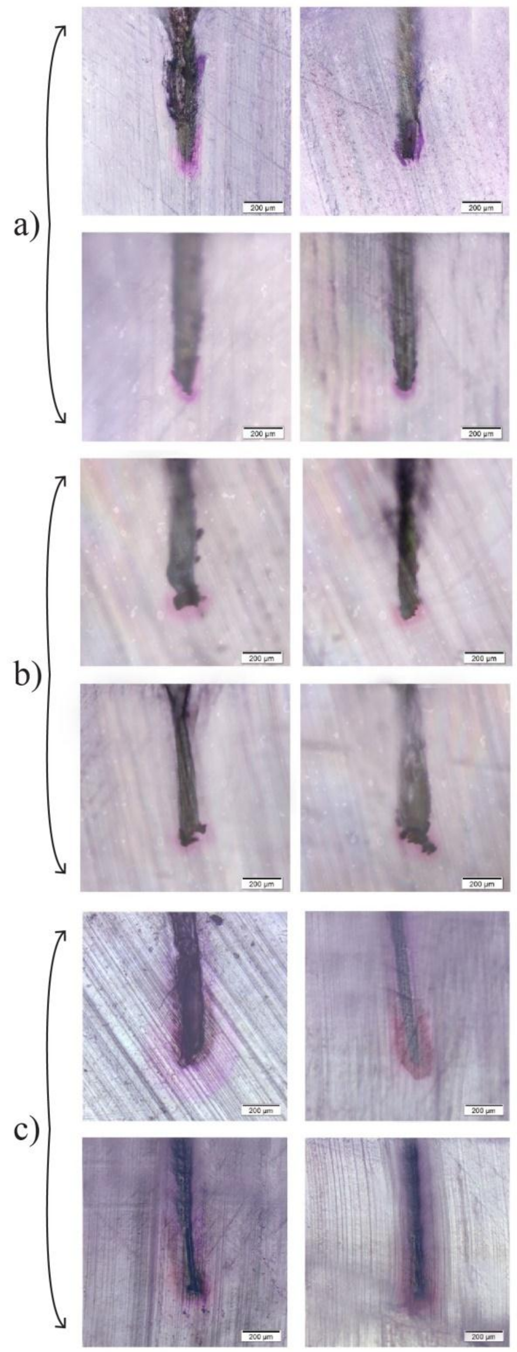

Fig.15. Morphology of the Vented Type in $FeSO_4$ for 1000 hours of Testing Period at (a) Room Temperature, (b) 50°C, and (c) 70°C.

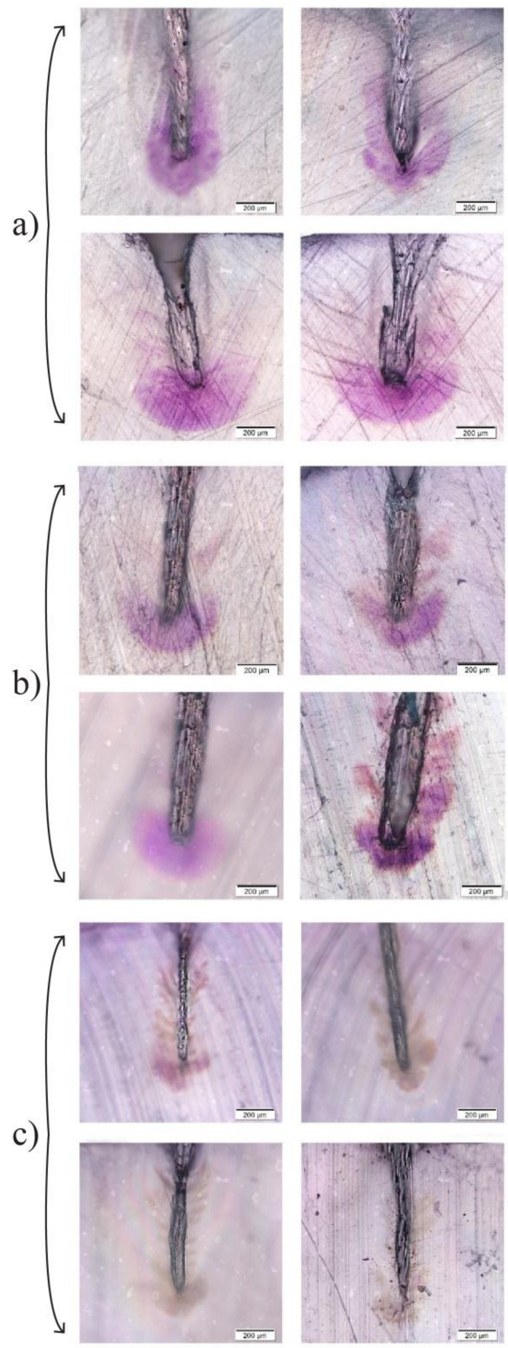

Fig.16. Morphology of the Vented Type in NaCl for 3000 hours of Testing Period at (a) Room Temperature, (b) 50°C, and (c) 70°C.

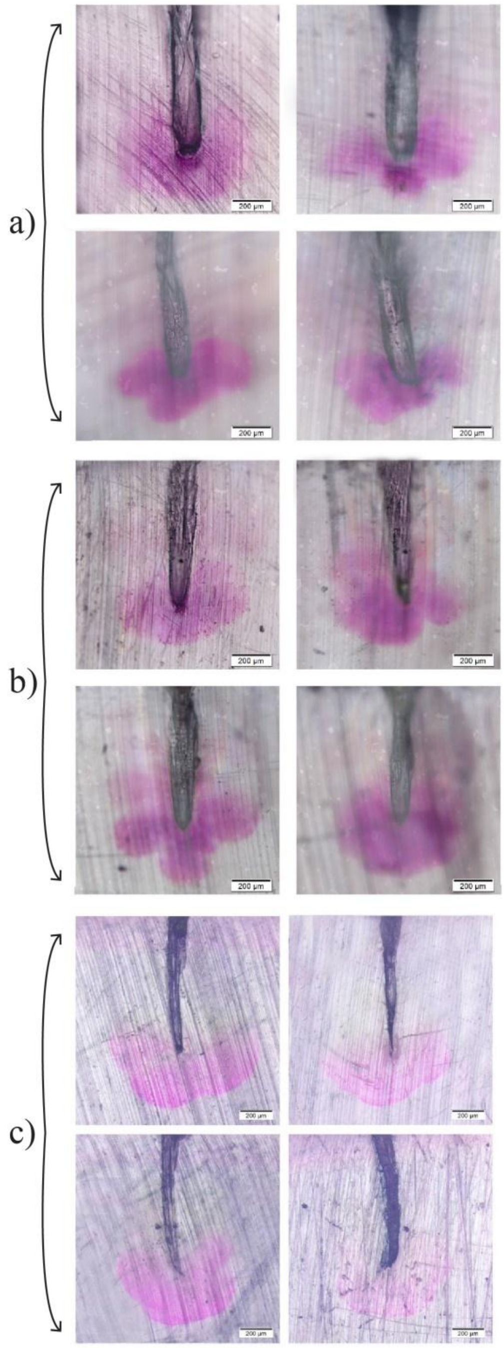

Fig.17. Morphology of the Vented Type in Na_2SO_4 for 3000 hours of Testing Period at (a) Room Temperature, (b) 50^{o}C, and (c) 70^{o}C.

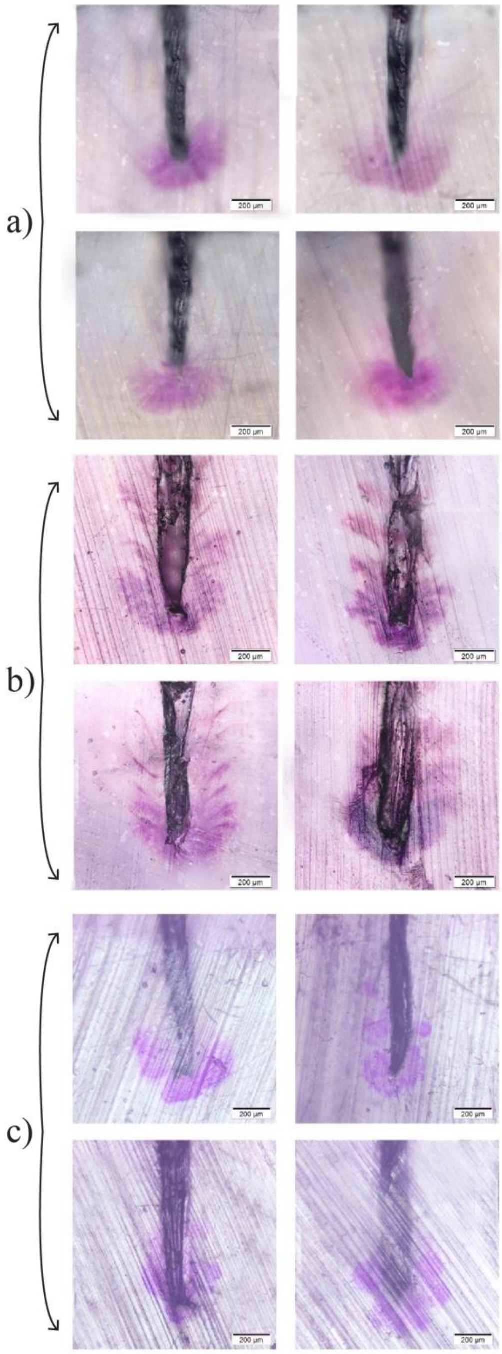

Fig.18. Morphology of the Vented Type in K_2SO_4 for 3000 hours of Testing Period at (a) Room Temperature, (b) 50^{o}C, and (c) 70^{o}C.

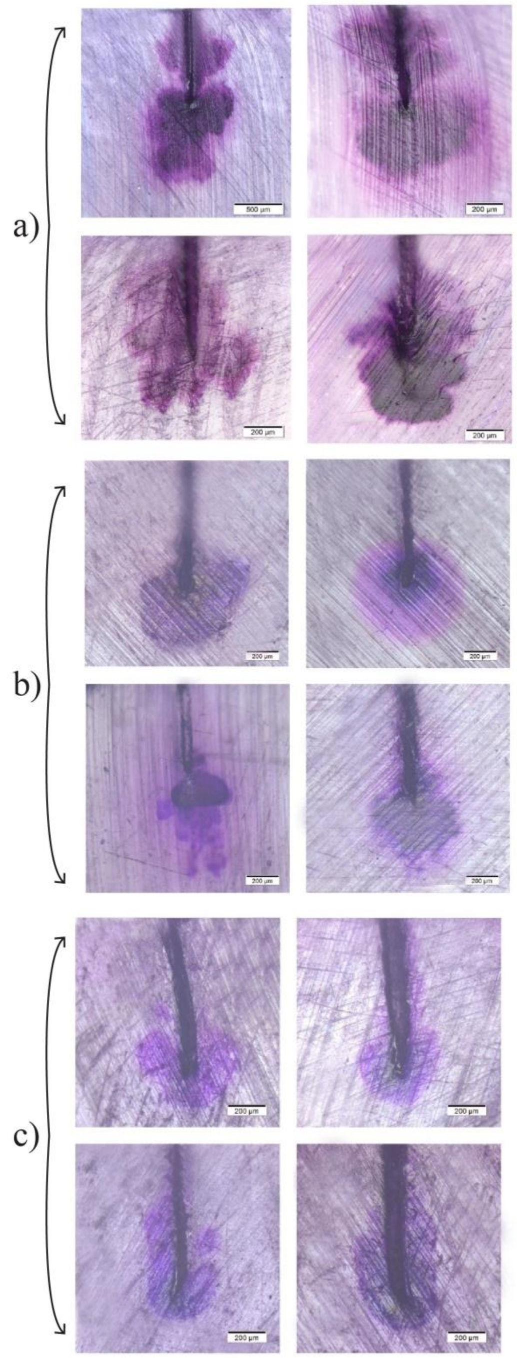

Fig.19. Morphology of the Vented Type in $Cu(NO_3)_2$ for 3000 hours of Testing Period at (a) Room Temperature, (b) 50^{o}C, and (c) 70^{o}C.

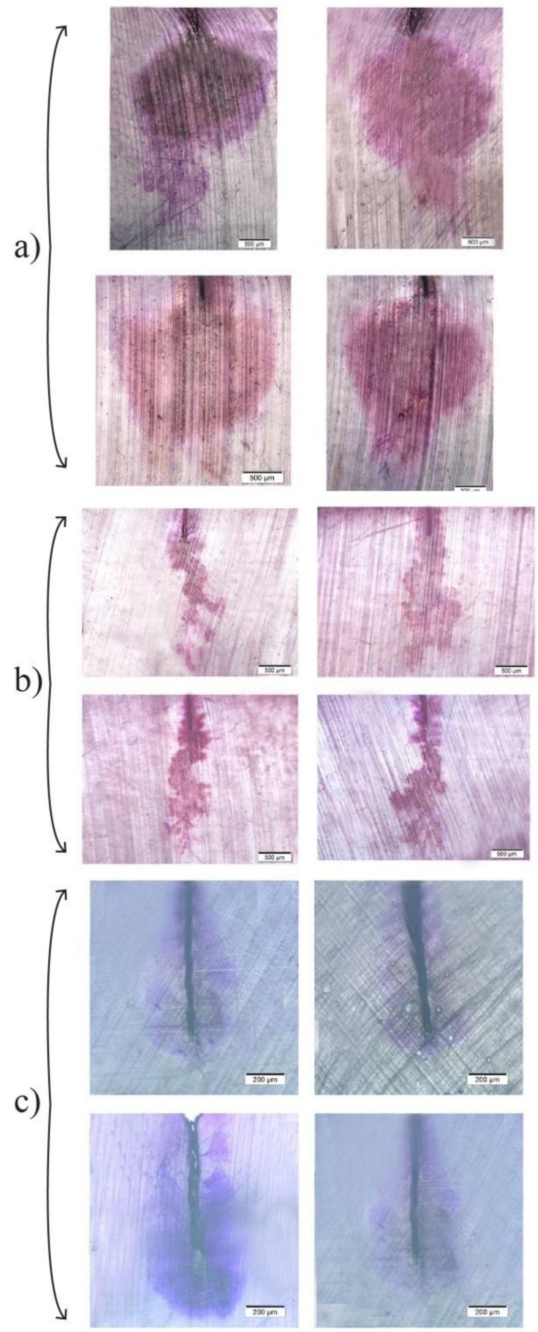

Fig.20. Morphology of the Vented Type in $CuSO_4$ for 3000 hours of Testing Period at (a) Room Temperature, (b) 50^{o}C, and (c) 70^{o}C.

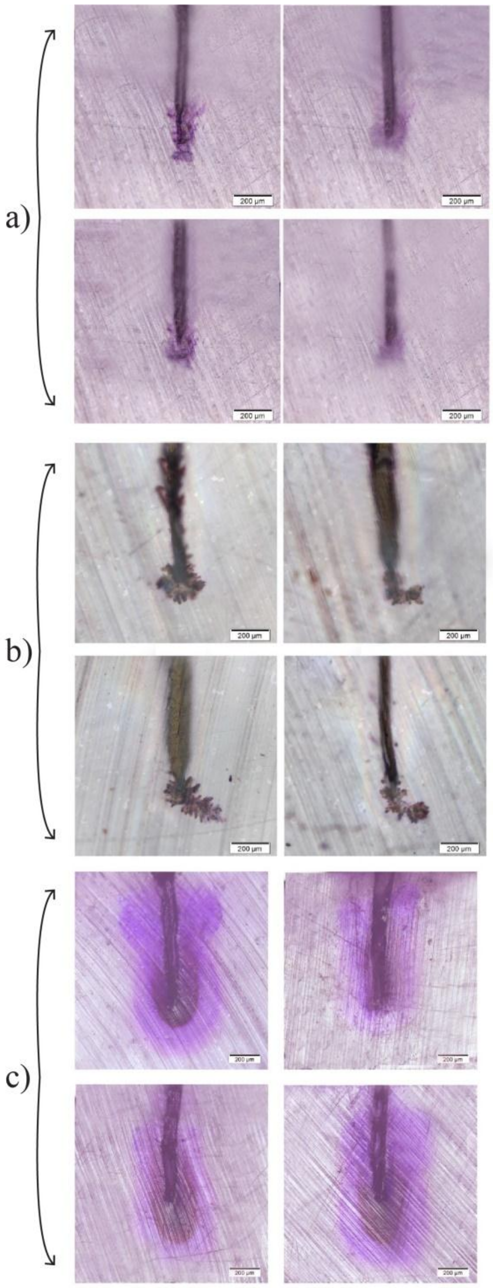

Fig.21. Morphology of the Vented Type in $FeSO_4$ for 3000 hours of Testing Period at (a) Room Temperature, (b) 50°C, and (c) 70°C.

Table 5. The Average of Maximum Size of Water Treeing for 1000 hours of Testing Period

Ionic Solutions	Size (µm)		
	Temperature		
	Room	50°C	70°C
NaCl	174.37	174.71	119.24
Na_2SO_4	67.90	193.48	143.04
K_2SO_4	86.26	119.92	79.62
$Cu(NO_3)_2$	136.62	116.29	139.89
$CuSO_4$	1271.44	266.34	239.15
$FeSO_4$	46.58	58.15	148.17

Table 6. The Average of Maximum Size of Water Treeing for 3000 hours of Testing Period

Ionic Solutions	Size (µm)		
	Temperature		
	Room	50°C	70°C
NaCl	286.01	289.54	278.20
Na_2SO_4	223.84	291.99	316.80
K_2SO_4	201.62	168.06	158.40
$Cu(NO_3)_2$	535.61	453.64	185.95
$CuSO_4$	2878.01	1989.70	262.36
$FeSO_4$	96.40	150.15	238.56

Table 7. The pH of Ionic Solutions at Room Temperature

Time	Ionic Solution					
	$^*S_1$	$^*S_2$	$^*S_3$	$^*S_4$	$^*S_5$	$^*S_6$
**P	6.49	7.67	6.84	3.94	4.04	2.63
1	6.44	7.65	6.82	3.91	3.99	2.61
2	6.40	7.62	6.80	3.90	3.85	2.60
3	6.37	7.60	6.79	3.89	3.82	2.58
4	6.34	7.56	6.79	3.87	3.80	2.55
5	6.29	7.51	6.65	3.85	3.73	2.54
6	6.25	7.49	6.51	3.82	3.69	2.51

**P=primary or first time of solution measuring
$^*S_1$ = NaCl, $^*S_2$ = Na_2SO_4, $^*S_3$ = K_2SO_4,
$^*S_4$ = $Cu(NO_3)_2$, $^*S_5$ = $CuSO_4$, and $^*S_6$ = $FeSO_4$

Table 8. The pH of Ionic Solutions at 50°C

Time	Ionic Solution					
	$^*S_1$	$^*S_2$	$^*S_3$	$^*S_4$	$^*S_5$	$^*S_6$
**P	6.74	7.44	7.24	3.43	3.70	2.40
1	6.68	7.42	7.21	3.42	3.66	2.39
2	6.63	7.32	7.21	3.40	3.65	2.36
3	6.57	7.30	7.20	3.39	3.64	2.32
4	6.51	7.28	7.17	3.37	3.61	2.33
5	6.45	7.15	7.15	3.31	3.58	2.30
6	6.42	7.01	7.13	3.31	3.52	2.30

**P=primary or first time of solution measuring
$^*S_1$ = NaCl, $^*S_2$ = Na_2SO_4, $^*S_3$ = K_2SO_4,
$^*S_4$ = $Cu(NO_3)_2$, $^*S_5$ = $CuSO_4$, and $^*S_6$ = $FeSO_4$

Table 9. The pH of Ionic Solutions at 70°C

Time	Ionic Solution					
	*S$_1$	*S$_2$	*S$_3$	*S$_4$	*S$_5$	*S$_6$
**P	6.77	7.23	7.52	2.97	3.37	2.15
1	6.75	7.19	7.51	2.95	3.36	2.06
2	6.72	7.15	7.49	2.95	3.34	2.10
3	6.67	7.12	7.46	2.95	3.34	2.05
4	6.62	7.09	7.45	2.93	3.33	2.07
5	6.59	7.03	7.25	2.92	3.29	2.06
6	6.54	6.91	7.21	2.91	3.25	2.04

**P=primary or first time of solution measuring
*S$_1$ = NaCl, *S$_2$ = Na_2SO_4, *S$_3$ = K_2SO_4,
*S$_4$ = $Cu(NO_3)_2$, *S$_5$ = $CuSO_4$ and *S$_6$ = $FeSO_4$

Table 10. The Conductivity (S/m x10^{-3}) of Ionic Solutions at Room Temperature

Time	Ionic Solution					
	*S$_1$	*S$_2$	*S$_3$	*S$_4$	*S$_5$	*S$_6$
**P	1.40	1.40	1.60	1.39	0.53	1.03
1	1.50	1.50	1.69	1.41	0.81	1.05
2	1.50	1.50	1.72	1.42	0.89	1.10
3	1.53	1.53	1.73	1.62	0.99	1.18
4	1.59	1.59	1.79	1.62	1.02	1.19
5	1.66	1.66	1.83	1.77	1.20	1.22
6	1.77	1.77	2.01	1.82	1.40	1.28

**P=primary or first time of solution measuring
*S$_1$ = NaCl, *S$_2$ = Na_2SO_4, *S$_3$ = K_2SO_4,
*S$_4$ = $Cu(NO_3)_2$, *S$_5$ = $CuSO_4$ and *S$_6$ = $FeSO_4$

Table 11. The Conductivity (S/m x10^{-3}) of Ionic Solutions at 50°C

Time	Ionic Solution					
	*S$_1$	*S$_2$	*S$_3$	*S$_4$	*S$_5$	*S$_6$
**P	0.67	0.84	0.73	0.13	0.13	0.55
1	0.69	0.89	0.75	0.19	0.15	0.59
2	0.71	0.99	0.84	0.19	0.20	0.60
3	0.75	1.09	0.97	0.20	0.31	0.68
4	0.77	1.18	0.99	0.22	0.35	0.70
5	0.78	1.21	1.00	0.32	0.70	0.75
6	0.79	1.29	1.10	0.35	0.86	0.78

**P=primary or first time of solution measuring
*S$_1$ = NaCl, *S$_2$ = Na_2SO_4, *S$_3$ = K_2SO_4,
*S$_4$ = $Cu(NO_3)_2$, *S$_5$ = $CuSO_4$ and *S$_6$ = $FeSO_4$

The concentration of the ionic solution at 0.1 mol/L was used. Due to the long testing period, the concentration of the ionic solution may be changed. So, the electrical parameters of the ionic solution were measured, and the concentration was adjusted every 500 hours for the concentration control. The concentration adjustments were three times for the 1000 hours Testing Period and six times for the 3000 hours Testing Period, The electrical parameters, i.e., conductivity and pH were measured, and the results are shown in Table 7 - Table 12.

Table 12. The Conductivity (S/m x10^{-3}) of Ionic Solutions at 70°C

Time	Ionic Solution					
	*S$_1$	*S$_2$	*S$_3$	*S$_4$	*S$_5$	*S$_6$
**P	1.77	1.77	1.76	1.77	1.76	1.77
1	1.93	1.87	1.77	1.80	1.78	1.79
2	2.00	1.90	1.79	1.81	1.80	1.80
3	2.21	1.98	1.81	1.89	1.83	1.85
4	2.35	2.01	1.85	1.92	1.86	1.88
5	2.51	3.85	1.99	1.97	1.99	1.89
6	2.83	4.02	2.10	2.00	1.96	1.99

**P=primary or first time of solution measuring
*S$_1$ = NaCl, *S$_2$ = Na_2SO_4, *S$_3$ = K_2SO_4,
*S$_4$ = $Cu(NO_3)_2$, *S$_5$ = $CuSO_4$ and *S$_6$ = $FeSO_4$

6. DISCUSSION

The Effect of Ionic Solution Temperatures on the Propagation of Water Treeing

For 1000 hours of the tested period, the difference in the effect of ionic solution temperature on the propagation of water treeing was obtained. Fast propagation of water treeing occurred at 50°C was obtained when using NaCl, Na_2SO_4, and K_2SO_4 solution. In the case of $Cu(NO_3)_2$ solution, no difference in the propagation of water treeing was obtained at room temperature, 50°C, and 70°C. In the case of a $CuSO_4$ solution, fast propagation of water treeing occurred at room temperature. Moreover, in the case of $FeSO_4$, the fast propagation of water treeing occurred at 70°C.

For 3000 hours of the tested period, no evidence different in the effect of ionic solution temperature was obtained. However, In the case of K_2SO_4, $Cu(NO_3)_2$ and $CuSO_4$, the fast propagation of water treeing occurred at room temperature. In the case of NaCl, the fast propagation of water treeing occurred at 50°C. Furthermore, in the case of Na_2SO_4 and $FeSO_4$, the fast propagation of water treeing occurred at 70°C.

The Effect of Ionic Solutions on the Propagation of Water Treeing

Six of ionic solutions with the concentration 0.1 mol/L including NaCl, Na_2SO_4, K_2SO_4, $Cu(NO_3)_2$, $CuSO_4$, and $FeSO_4$ were used in this study for elucidating the effect of the ionic solution to the propagation of water treeing. As shown in Table 5, after the 1000 hours Testing Period, the fastest propagation of water treeing occurred in $CuSO_4$, NaCl, $Cu(NO_3)_2$, K_2SO_4, Na_2SO_4, and $FeSO_4$, respectively. As shown in Table 6, after the 3000 hours Testing Period, the fastest propagation of water treeing occurred in $CuSO_4$, $Cu(NO_3)_2$, $NaSO_4$, NaCl, K_2SO_4, and $FeSO_4$, respectively. Therefore, the $CuSO_4$ solution is the most effect ionic solution to the propagation of water treeing in XLPE cable. For all ionic solutions, A comparison of the average of the maximum size of water treeing after 1000 hours and 3000 hours of testing periods are shown in Fig. 22 and Fig. 23, respectively.

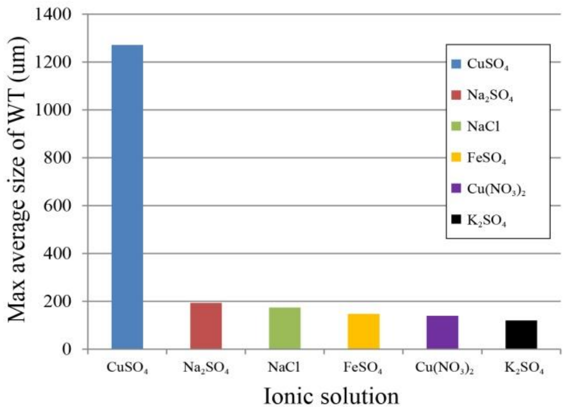

Fig.22. A Comparison of the maximum size of water treeing for the 1000 hours testing period.

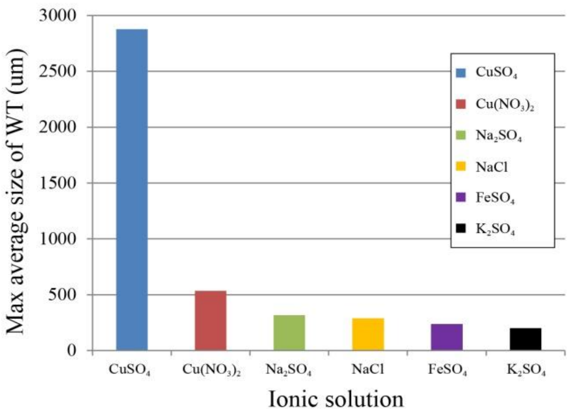

Fig.23. A comparison of the maximum size of water treeing for the 3000 hours testing period.

The effect of the pH Rate on the Propagation of Water Treeing

During the testing period, the ionic solution was checked and was changed every 500 hours to control the ionic solution concentration. For the 1000 hours Testing Period, all of the ionic solutions were changed two times. For the 3000 hours Testing Period, all of the ionic solutions were changed six times. The pH rate was calculated from "The last measuring of pH value (pH_{last})" and "Primary value of pH ($pH_{primary}$)". The pH_{last} is the last measuring of pH value. The $pH_{primary}$ is the original pH value of the ionic solution. The calculation of pH rate was computed with "Grow Rate equation" as shown in Equation (2) by modifying as in [21]. As illustrated in Fig. 24, the pH rate at the 3000 hours Testing Period is more than the pH rate at the 1000 hours Testing Period. For NaCl, Na_2SO_4, and $Cu(NO_3)_2$ solutions, the maximum of the pH rates are 4.75%, 5.78%, and 3.50%, respectively. For K_2SO_4 and $CuSO_4$ solutions, the maximum of the pH rate is 4.82% and 8.66%, respectively. Moreover, the $FeSO_4$ solution, the maximum of the pH rate is 5.12%.

$$pH\ rate = \frac{pH_{last} - pH_{primary}}{pH_{primary}} \times 100\% \qquad (2)$$

As illustrated in Table 5 and Table 6, the maximum expansion of water treeing agrees with the maximum of the pH rate of Na_2SO_4 and $Cu(NO_3)_2$ solution.

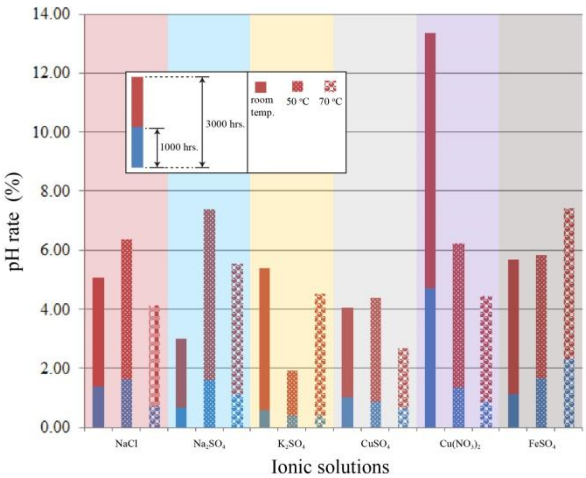

Fig.24. pH Rate for all ionic solutions.

The Effect of Conductivity Rate on the Propagation of Water Treeing

According to all of the ionic solutions were changed every 500 hours for pH rate controlling. Also, the solution conductivity was measured every 500 hours too. Calculation of the conductivity rate is shown in Equation (3) by modifying as in [21]. For the Equation 3, this paper gave the short word of conductivity = "*Con.*". The conductivity rate was calculated from "The last measuring of conductivity value (Con_{last})" and "Primary value of Conductivity ($Con_{primary}$)." The Con_{last} is the last measuring of conductivity value. The $Con_{primary}$ is the original conductivity value of the ionic solution.

$$Con.\ rate = \frac{Con_{last} - Con_{primary}}{Con_{primary}} \times 100\% \qquad (3)$$

As shown in Fig. 25, the highest conductivity rates were calculated from $Cu(NO_3)_2$ (532.35%) and follow with $CuSO_4$ (173.85%) at the 3000 hours Testing Periods, respectively. It means that the fastest propagation of water treeing occurs when testing with $Cu(NO_3)_2$ and $CuSO_4$ solutions more than the other ionic solutions.

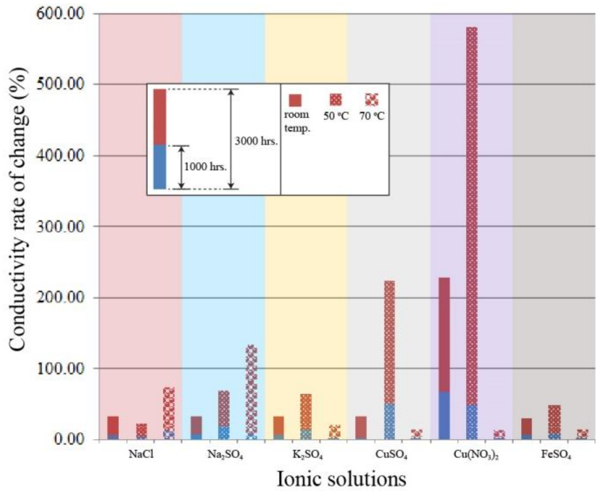

Fig.25. The conductivity rate for all ionic solutions.

The Extra Type of Water Treeing

Mainly the vented type of water treeing was observed after complete the experiment. However, a combination of the other types of water treeing was observed.

The first type, water treeing can be transformed into an electrical treeing, for instance under overvoltage. This type of water treeing was called “combination of water treeing and electrical treeing” as shown in Fig. 26. In this study, the occurrence of a combination of water treeing in the environmental setup of $CuSO_4$ was observed.

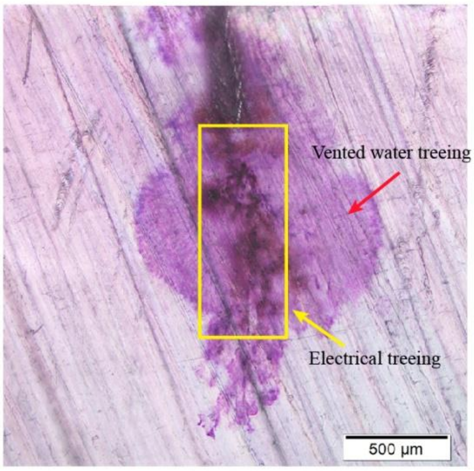

Fig.26. A Combination of Water Treeing and Electrical Treeing

The second type, it seems the palm tree. It called “palm-crack shape water treeing” as shown in Fig. 27. For this study, palm-crack shape water treeing in the environmental setup of $FeSO_4$ was observed.

Last type, the first part intensive clearly water treeing was observed near the tip of pinned-hole, and a second part, dissolved water treeing was observed. It is named “combination of intensive water treeing and dissolve water treeing” as shown in Fig. 28. In this study, a combination of intensive water treeing and dissolve water treeing in the environmental setup of $FeSO_4$ was observed.

Fig.27. Water treeing in palm-crack shape.

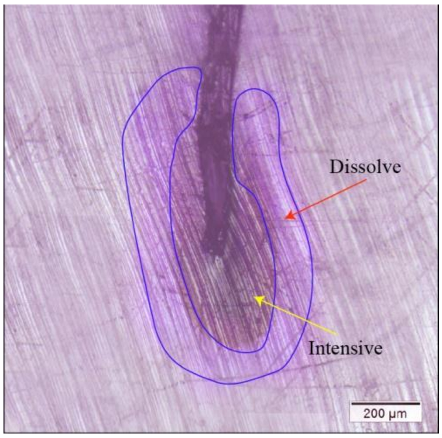

Fig.28. A combination of intensive water treeing and dissolve water treeing

7. CONCLUSION

The propagation of water treeing caused by various ionic solution on XLPE insulated underground cable was studied. The propagation of water treeing depended on pH and conductivity levels of ionic solution. The vented type water treeing was considered to study. Precisely in the 3000 hours testing period, the propagation of water treeing is faster than in the 1000 hours testing period. The CuSO4 ionic solution is the most effective to accelerate the propagation of water treeing in XLPE insulated cable when compared with the other type of ionic solutions in the experiment. The explanation may be due to the high pH rate and high conductivity rate. For the term of ionic solution temperature, no evidence propagation trend of water treeing was observed for all ionic solutions. It was found that fast propagation occurred at a low temperature and also, fast propagation occurred at a high temperature too. In addition, a combination type of water treeing was observed. Therefore, in the underground environment, the ionic solution having high pH level and high conductivity may fast accelerate to gain the damage of XLPE cable.

ACKNOWLEDGMENT

This work was supported by National Research Council of Thailand and High Voltage Insulation Technologies Laboratory of Suranaree University of Technology,

Thailand.

REFERENCES

[1] Kao, Z., Wei, Z., and Wenbiao, T. 2013. Self-healing Phenomenon of Water Tree in the Process of the Accelerated Aging of XLPE Cables. IEEE International Conference on Solid Dielectrics, pp.824-827.

[1] Gang, Y., Hua, L., Fuchang, L., Xiaogang. W., Zeqi, H., Qin, Z., and Jingwei, Cai. 2013. Study on the Dielectric Response Characteristic of XLPE Cables. Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp.81-84.

[2] Takashi, K., Tatsuku, O., Naohiro, H., Kazuhisa, M., and Katsumi, U. 2017. Evaluation of Relationship between Residual Charge Signal and AC Breakdown Strength of Water-tree Degraded 22 to 77 kV Classes XLPE Cables Removed from Service using Pulsed Voltages. IEEE Transactions on Dielectrics and Electrical Insulation, Vol.24, No.1, pp.656-665.

[3] Ogiwara, J., Yonaha, K., Uehara, H., and Kudo, K. 2010. Temperature Characteristics of Water Tree Propagation in a Wide Temperature Range Using XLPE Sheets. Annual Report Conference on Electrical Insulation and Dielectric Phenomena.

[4] Wang, J., Zheng, X., Li, Y., and Wu, J. 2013. The Influence of Temperature on Water Treeing in Polyethylene. IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 20, No. 2, pp.544-549.

[5] Zhou, K., Yang, Mingliang., Huang, M., Li, T., and Tao, W. 2015. The Role of Chain Orientation on the Propagation of Water Trees at Different Temperatures. IEEE 11th International Conference on the Properties and Applications of Dielectric Materials (ICPADM), pp.732-735.

[6] Urbanczyk., A. 2011. Performance of Enhanced Insulation System Designed for Medium Voltage Cables. 8th International Symposium on Advanced Topics in Electrical Engineering (ATEE)

[7] Saniyyati, C.N., Arief, Y.Z., Ahmad, M.H., Piah, M.A.M., Adzis, Z., Suleiman, A.A., and Muhammad, N.A. 2014. Investigation on Propensity Difference of Water Tree Occurrences in Polymeric Insulating Materials. IEEE 8th International Power Engineering and Optimization Conference (PEOCO2014), pp.413-417.

[8] Wenbiao, T., Shuyong, S., Yue, Zhang., Wei, H., Kai, Z., Tianhua, L., and Ming, H. 2016. Study on the Electric-field Characteristics of Water Tree Region on the Dry or Wet Condition in XLPE Cables.

[9] Feremo, H., Selsjord, M., Hvidsten, S., Bengtsson, K., and Ryen, A. 2012. Initiation of Vented Water Trees from the Conductor Screen of MV XLPE Insulated Cables. IEEE International Symposium on Electrical Insulation, pp.386-390.

[10] Ming, H., Kai, Z., Wenbiao, T., Mingliang, Y., and Di, Y. 2014. Transformation Mechanism of Electrical Tree to Water Tree in XLPE Cables. International Conference on Power System Technology (POWERCON), pp.1491-1496.

[11] Kai, Z., Ming, H., Wenbiao, T., Min, H., and Mingliang, Y. 2014. A Possible Water Tree Initiation Mechanism for Service-aged XLPE Cable: Conversion of Electrical Tree to Water Tree. IEEE Transactions on Dielectrics and Electrical Insulation, pp.1854-1861.

[12] Narupon, P., Kelvin, M., Pius, C., Tassanai, S., Terapong, B., and Boonruang, M. 2017. Effects of Ionic Solution in Water Treeing Propagation of XLPE Insulated HV Cable by Using ANSYS MAXWELL 2D. 5th IIAE International Conference on Industrial Application Engineering, Okinawa, Japan, pp.261-266.

[13] ANSYS Maxwell 2D. 2015. ANSYS Maxwell 2D v15. User's Guide. ANSYS Inc, Canonsburg. Available from: http://ansoft-maxwell.narod.ru/english.html, Accessed date: July 5, 2018.

[14] Narupon, P., Terapong, B., and Boonruang, M. 2018. Effect of NaCl Solution and Temperatures on Water Treeing Propagation in XLPE Underground Cable for Medium Voltage. IEECON 2018, Krabi, Thailand, pp.88-91.

[15] Terapong, B. 2014. Characteristics of Water Treeing in XLPE Insulated High Voltage Underground Cable for 22 kV Distribution System. Thailand: Suranaree University of Technology.

[16] Aixuan, Z., Yanbo, W., Xing, Zhang., Junbo, D., and Guanjun, Z. 2015. Insulation Status Diagnosis of XLPE Cable Based on Polarization and Depolarization Current (PDC). IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC).

[17] Kai, Z., Xiantao, T., and Wenbiao, T. 2013. Effect of TIPT Catalyst on Insulation Rejuvenation of Water-Tree Aged Cables. IEEE International Conference on Solid Dielectrics, pp.509-512.

[18] Mingliang, Yang., Kai, Z., Ming, H., Tianhua, L., and Wenbiao, T. 2015. Insight on Micro-structures of Rejuvenated Water-tree Cables by Two Kinds of Injection Liquids. IEEE 11th International Conference on the Properties and Applications of Dielectric Materials (ICPADM), pp.104-107.

[19] Yu, Z., Deyuan, L., Jiandong, W., and Yi, Y. 2018. A Modified Algorithm for the Simulation of Charge Behavior in Water Tree Aged Cross-Linked Polyethylene Cable. IEEE Access, Vol.6, pp.23929-23938.

[20] wikiHow. (2018). How to Calculate Growth Rate. [Online Available: https://www.wikihow.com/Calculate-Growth-Rate]. Last accessed: 10th June 2018.