

EFFECTS OF IONIC SOLUTIONS TO WATER TREEING ON XLPE CABLE FOR 22 kV DISTRIBUTION SYSTEM

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Abstract

Underground cables are subjected to ionic moisture conditions after installation and being in long-term services. Moisture causes the degradation of XLPE insulated underground cables by accelerating the occurrence of water treeing. This study is an investigation of the results on the effects of ionic solutions on the occurrence of water treeing on 22 kV XLPE cable for the distribution system of the Provincial Electricity Authority of Thailand. Two ionic solutions, potassium sulfate (K_2SO_4) and iron(II)sulfate ($FeSO_4$), have been used in this study. The experiment has been done with 1000 h and 2000 h testing periods at 3 temperature conditions, room temperature, 50°C and 70°C. The experimental results show that the most expansion of the water treeing size occurred on the tested samples after tested at the temperature of 50°C with the K_2SO_4 ionic solution. In the case of testing with the $FeSO_4$ solution, the most expansion of the water treeing size occurred on the tested samples after tested at the temperature of 70°C. Furthermore, Fourier transform infrared spectroscopy has been used to analyze the trend of the chemical structure changes by considering the absorbance of the infrared spectrum of the C=C bond and the C=O bond. The chemical structure changes agree with the occurrence of water treeing as well.

Keywords: Water treeing, XLPE insulating material, ionic solution, temperature, underground cable, FTIR

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Introduction

In Thailand, water treeing has been the main problem with XLPE underground cables for the electrical distribution system. The main component of water treeing includes moisture that can initiate through a small point or a weak point of XLPE cable. Water treeing is a small defect point that is shaped like a tree and grows in the direction of the electric field. The type of water treeing includes the vented type and bow-tie type, as shown in the publications by Faremo *et al.* (2012); Malik *et al.* (2012); Thomas and Saha (2012); Orton (2013); and Saniyyati *et al.* (2014). In this paper, we have considered the vented type. Many researchers have studied water treeing; Wang *et al.* (2013) have demonstrated the propagation of water treeing by pinholes on a piece of XLPE insulating material. They found the propagation of water treeing increased with a high temperature. Zhou *et al.* (2015) also found that the propagation of water treeing increased at a low temperature. The occurrence of water treeing indicates chemical degradation of the XLPE insulating material. The degree of chemical degradation can be detected by using Fast Fourier Transform Spectroscopy (FTIR). The changes in 3 functional groups of chemical bonding, the C-H bonding, C=C bonding, and

C=O bonding indicate the chemical degradation (Li *et al.*, 2011; Hussain *et al.*, 2012).

Aron and Mosch (2011) and Javakrishnana *et al.* (2016) have studied the penetration of ionic solutions through the XLPE structure which induces the initiation of water treeing under a partial discharge condition. Fabiani *et al.* (2012) and Mauseth *et al.* (2012) have proved that the damaging phenomenon of water treeing took place on the XLPE insulating layer of 115 kV underground cable because of continued exposure to moisture and electrical stress. Qureshi *et al.* (2008) have compared the resistance to the occurrence of water treeing on 15 kV XLPE cable from 4 regional manufacturers. All the manufacturers produced 15 kV XLPE cable according to the international standard controls. The cable samples have been tested under high electric field stress in an aqueous ionic solution at a temperature of 30°C. After 120 days, they have obtained various results for their tested cables.

In Thailand, however, the characteristics of water treeing have not yet been well studied on the underground cables of the distribution system. For this reason, we have studied the

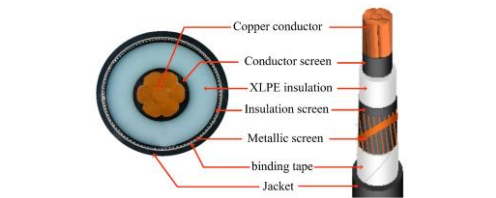


Figure 1. 22 kV XLPE insulated underground cables

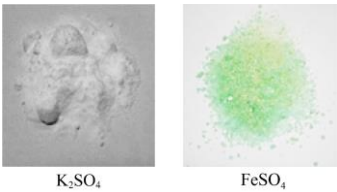


Figure 2. The solid forms of K₂SO₄ and FeSO₄

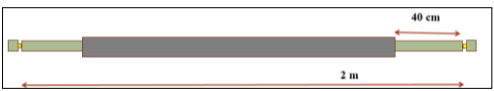


Figure 3. A sample of XLPE insulated underground cable

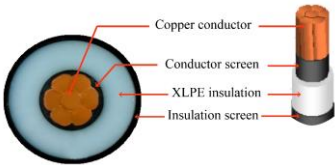


Figure 4. Cross- section of XLPE insulated underground cable with the remaining insulation screen, XLPE insulator, conductor screen, and copper conductor

occurrence of water treeing on the XLPE underground cables of the Provincial Electricity Authority (PEA) distribution system with various ionic solutions and temperatures. Two types of ionic solutions at 3 different temperatures, i.e., room temperature, 50°C and 70°C, have been used. The water treeing density as a function of the testing period has also been analyzed and elucidated.

The rest of the paper has organized as follows: materials and method comprising the materials, preparation, measurement of water treeing, FTIR method, and procedure of the experiment are detailed in the second section. The third section depicts the experimental results and discussion on the effect of the ionic solution, the effect of the pH of the ionic solution, and the FTIR spectrum results. Finally, there is our conclusion.

Materials and Method

Materials

Numbers of single core 22 kV XLPE commercial cables with a cross-section of 50 mm², as shown in Figure 1 (Bangkok Cable, 2018), have been used in this experiment. The K₂SO₄ and the FeSO₄ ionic solutions have been used to represent the environmental conditions, as shown in Figure 2.

Test Sample Preparation

For the experiment, the XLPE cable has been cut into 2 m in lengths due to the limitations of the test chamber, as shown in Figure 3. To accelerate the occurrence of water treeing, the XLPE cable cover has been peeled off to leave the remaining insulation screen, the XLPE insulation layer, the conductor

screen, and the copper conductor, as shown in Figure 4. Then, pinholes have made in the XLPE insulation layer, as shown in Figure 5, based on the method proposed by Wahab *et al.* (2017) and Zhou *et al.* (2017). After that, 40 cm of the insulation screen has removed to increase the electric field stress between the insulation screen and the copper conductor.

The two ionic solutions, i.e., K₂SO₄ and FeSO₄, have been used. A K₂SO₄ material is a non-flammable white crystalline salt which is soluble in water. This chemical compound is commonly used in fertilizers, providing both potassium and sulfur. A FeSO₄ material is mainly used as a precursor to other iron compounds. It is an oxidizing agent and is useful for the reduction of chromate in cement to less toxic Cr(III) compounds. To prepare the ionic solution with a concentration of 0.1 mol/L, deionized water has used to solute 1359.15 g of K₂SO₄ powder and 1184.88 g of FeSO₄ powder. The volume of the ionic solution in each test chamber has 78 L. These two ionic materials represented the underground environmental conditions. The pH value of the ionic solutions has measured before the test, and the measurement results are shown in Table 1.

After the test period, water treeing observation has performed on all the tested cables. Before the water treeing observation, the XLPE insulation has sliced into 400 µm–600 µm in thickness with a microtome, as shown in Figure 6. However, the occurrence of water treeing on the sliced XLPE insulation sheet has no observed due to the invisibility of water treeing. Therefore, the sliced XLPE insulation sheets have been stained with methylene blue and the ratio of staining is shown in Figure 7. For the staining process, as

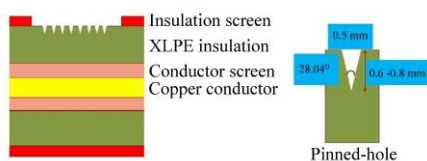


Figure 5. Size of pinhole in the XLPE insulation



Figure 6. Microtome for XLPE slicing

shown in Figure 8, numbers of the sliced XLPE insulation sheets have been immersed in 80°C of boiled methylene blue solution for 2 h, and after that have been allowed to rest for 5-6 h. Finally, the stained, sliced XLPE insulation sheets have been dried for 2 h.

Measuring of Water Treeing

A stereomicroscope (model BX51M, Olympus Corp., Tokyo, Japan) has been used for measuring the morphology. The axes (x-y) have been assumed in cross-section, as shown in Figure 9. The measured position has been started at the tip of the pinhole belonging to the y-axis, as shown in Figure 10. The length of the water treeing has been defined to be L.

FTIR Method

The chemical structure may be changed during the experimental period. To detect whether the chemical structure had changed, FTIR spectroscopy (model Tensor 27

Hyperion, Bruker Corp., Billerica, MA, USA) had been used to analyze the chemical structure changes in the tested XLPE cable, as shown in Figure 11. FTIR is a well-known technique used to identify chemical structure change of organic, polymeric, and inorganic materials. The FTIR analysis method uses infrared light to scan the tested sample to observe changes in the chemical structure (RTI Laboratories, 2018). The magnitude of the infrared light absorbance of molecules is the main factor for identifying the chemical changes. There are three wave ranges of infrared absorption have been used. The first wave range is the higher-energy near-infrared, approximately 14000-4000 cm⁻¹ which can excite

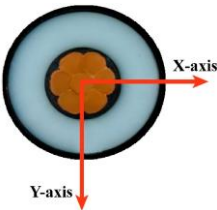


Figure 9. The assumed axes of cross-section of XLPE cable

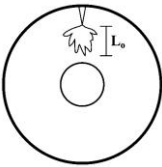


Figure 10. Position for water treeing measurement

Table 1. pH values of ionic solutions

Temperature	pH	
	K ₂ SO ₄	FeSO ₄
Room	6.84	2.63
50°C	7.24	2.40
70°C	7.52	2.15

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

Figure 7. The ratio for XLPE staining



Figure 8. The sliced-XLPE during staining



Figure 11. The FT-IR microscopy (Tensor 27 Hyperion)

overtone or harmonic vibrations. The second wave range is the mid-infrared, approximately $4000\text{--}400\text{ cm}^{-1}$ which has been used to study the fundamental vibrations and associated rotational-vibrational structure. The third wave range is the far-infrared, approximately $400\text{--}10\text{ cm}^{-1}$ (Wikipedia, 2018). In our research, the mid-infrared wave range has been used to analyze the chemical changes in the XLPE insulating material. The sliced sheets of XLPE insulation has exhibited chemical degradation using FTIR at the wave number of $400\text{--}4000\text{ cm}^{-1}$. For each sample, 64 FTIR measurements have been performed on the area of the water treeing occurrence. The change of two chemical bondings has been considered. The first chemical bond to be considered is the C=O bond which

is the representation of the oxidation reaction. The oxidation reaction occurs on XLPE insulating material when it is subjected to an applied voltage and a heat for a long time. The oxidation reaction is the loss of an electron of hydrogen (H) during a reaction by a molecule, atom, or ion. An oxidation reaction occurs when the oxidation state of the molecule, atom, or ion is increased (ThoughtCo, 2018a). For molecules of the XLPE insulating material, the oxidation reaction causes some C-H bonds to change to C=O bonds, as shown in Figure 12. The second chemical bond to be considered is the C=C bond which is the representation of the combustion reaction. The combustion reaction occurs on XLPE insulating material when subjected to an applied voltage and a heat for a long time. The combustion reaction is a significant class of the chemical reaction, commonly referred to as “burning.” Combustion usually occurs when a hydrocarbon reacts with oxygen to produce carbon dioxide and water (ThoughtCo, 2018b). For molecules of the XLPE insulating material, the combustion reaction causes some C-H bonds to change to C=C bonds, as shown in Figure 13. From the FTIR measurement results, the high amplitude of the C=O bond and the C=C bond indicates the high degradation of the XLPE insulating material. The wavelength of the C=C bond is $1600\text{--}1650\text{ cm}^{-1}$ and the wavelength of the C=O bond is $1750\text{--}1780\text{ cm}^{-1}$ (Boonraksa, 2014).

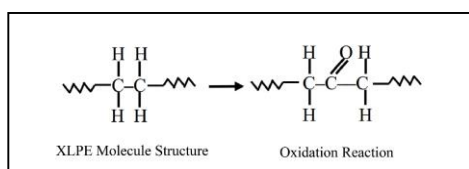


Figure 12. The changing of the C-H bond to be a C=O bond for the oxidation reaction

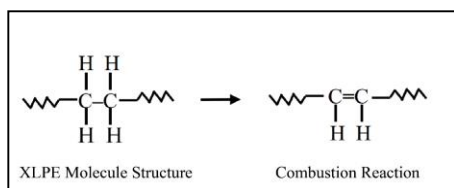


Figure 13. The changing of the C-H bond to be a C= C bond for the carbonization reaction

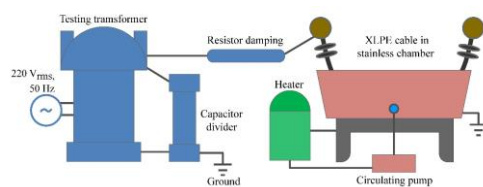


Figure 14. The experimental setup diagram

The Experimental Procedures

The experimental setup is shown in Figures 14 and 15. A voltage of 24 kV, 50 Hz has been applied to the test samples during the testing period. The K_2SO_4 and FeSO_4 ionic solutions have been used. The testing was conducted at room temperature, 50°C , and 70°C with the testing periods being 1000 h and 2000 h. As illustrated in Figure 14, a 100 k Ω resistor has been used as the damping resistor to limit the testing current during the testing periods. A capacitor voltage divider has been used for the voltage measurement. In this experiment, the experimental variables have been separated into 3 variables, as shown in Table 2. Furthermore, a flowchart for the testing procedure is shown in Figure16.

Results and Discussion

After finishing the testing periods, both the occurrence and the propagation of water treeing on the tested samples have been observed with a stereo microscope. The morphology of the water treeing propagation after the testing using K_2SO_4 and $FeSO_4$ ionic solutions is shown in Figures 17 and 18, shown for 1000 h of the test period and in Figures 19 and 20, for 2000 h of the test period. Furthermore, the average of the maximum expansion size of the water treeing is shown in Tables 3 and 4.

Effect of Ionic Solution to Water Treeing Propagation

As illustrated in Tables 3 and 4, the greatest expansion size of the water treeing has occurred at 50°C for 1000 h of the test period in the K_2SO_4 ionic solution. The maximum size of 119.92 μm and the minimum size of 73.62 μm have been measured. For the 2000 h of the test period, the propagation trend of water treeing is similar to the 1000 h of the test period. The greatest expansion size of the water treeing had been occurred at 50°C. The maximum size of 158.85 μm and the minimum size of 89.29 μm have been measured. However,



Figure 15. The actual test arrangement

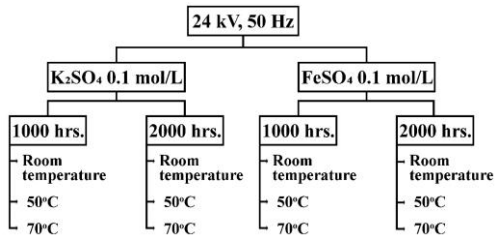


Figure 16. Flowchart of the testing procedure

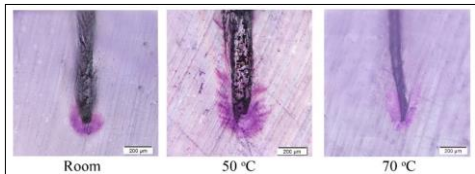


Figure 17. The physical character of water treeing in K_2SO_4 ionic solution after 1000 h of the test period

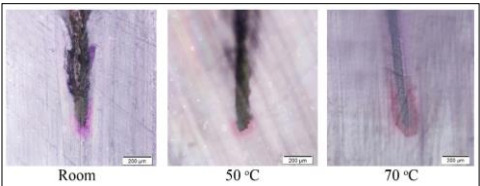


Figure 18. The physical character of water treeing in $FeSO_4$ ionic solution after 1000 h of the test period

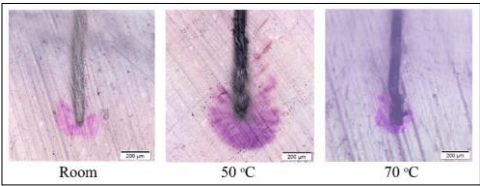


Figure 19. The physical character of water treeing in K_2SO_4 ionic solution after 2000 h of the test period

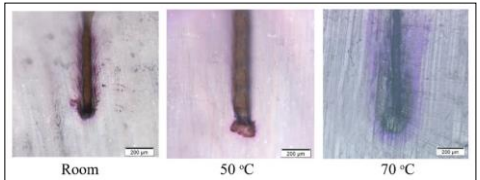


Figure 20. The physical character of water treeing in $FeSO_4$ ionic solution after 2000 h of the test period

the propagation trend of the water treeing in the 2000 h of the test period is greater than the 1000 h of the test period.

In the case of the testing with a FeSO_4 ionic solution for the 1000 h of the test period, the greatest expansion size of the water treeing has been occurred at 70°C. The maximum size of 148.17 μm and the minimum size of 46.58 μm have been measured. The propagation trend of the water treeing is similar to the results of the investigation by Wang *et al.* (2013). For the 2000 h of the test period, the propagation trend of the water treeing similars to the 1000 h of

the test period. The greatest expansion size of the water treeing has occurred at 70°C. The maximum size of 204.23 μm and the minimum size of 70.80 μm have measured. Moreover, the trend of the water treeing expansion size is more extensive than in the 1000 h of the test period.

The maximum expansion size of the water treeing in the testing periods with the FeSO_4 ionic solution is 204.23 μm . Moreover, the maximum expansion size of the water treeing in the testing periods with the K_2SO_4 ionic solution is 158.85 μm . For the testing periods with the FeSO_4 ionic solution, the larger size of the water treeing has been measured for longer than that of the testing period with the K_2SO_4 ionic solution.

Table 2. Variables of water treeing testing

Variables	Parameter
Independent	Voltage (24 kV, 50 Hz) and Ionic solution 0.1 mol/L (K_2SO_4 , FeSO_4)
Dependent	Length of water treeing
Controlled	Temperature (Room, 50°C, 70°C) and testing period (1000 h, 2000 h)

Table 3. Size of water treeing in K_2SO_4 and FeSO_4 ionic solutions at 1000 h of the testing period

Ionic solution	Temperature	Size of water treeing (μm)
K_2SO_4	Room	86.26
	50°C	119.92
	70°C	73.62
FeSO_4	Room	46.58
	50°C	58.15
	70°C	148.17

Table 4. Size of water treeing in K_2SO_4 and FeSO_4 ionic solutions at 2000 h of the testing period

Ionic solution	Temperature	Size of water treeing (μm)
K_2SO_4	Room	89.29
	50°C	158.85
	70°C	91.42
FeSO_4	Room	70.80
	50°C	102.96
	70°C	204.23

Effect of pH of Ionic Solution on Water Treeing Propagation

In the case of the FeSO_4 ionic solution, as shown in Table 1, the lowest pH value w has been measured at 70°C when compared with the other temperatures. In addition, the greatest expansion size of the water treeing has been occurred on the sample which has been tested with the FeSO_4 ionic solution at 70°C.

In the case of the K_2SO_4 ionic solution, the lowest pH value has been measured at 50°C when compared with the other temperatures. However, the greatest expansion size of the water treeing did not belong to the lowest pH value of the K_2SO_4 . The explanation may be due to the role of the temperature on the expansion of the water treeing having a more significant effect on the properties of the XLPE cable during the testing periods than on the pH level.

Infrared Spectrum from FTIR Analysis Results

The chemical structure changes due to the occurrence of water treeing has been analysed via the chemical structure of the XLPE insulation. The occurrence of water treeing indicates the deterioration of the XLPE insulating material. The degree of deterioration of the XLPE insulating material due to water treeing has been examined by the level of the oxidation reaction and the carbonation reaction

in the region of the occurrence of water treeing. Both reactions indicate the aging of the XLPE insulation as well.

The absorbance infrared spectrums obtained from the slices of tested XLPE insulating material showing the occurrence of water treeing by using FTIR spectroscopy. The results are shown in Figure 21 to Figure 24.

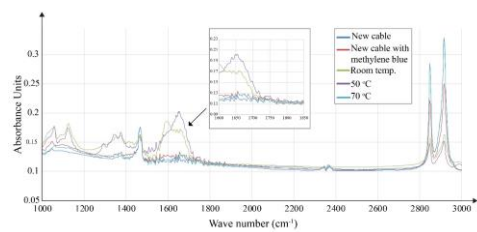


Figure 21. The relationship between the absorbance and wave number of water treeing in K₂SO₄ ionic solution after 1000 h of the test period

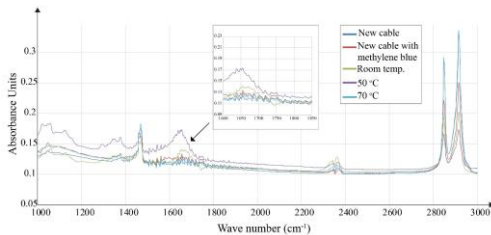


Figure 22. The relationship between the absorbance and wave number of water treeing in K₂SO₄ ionic solution after 2000 h of the test period

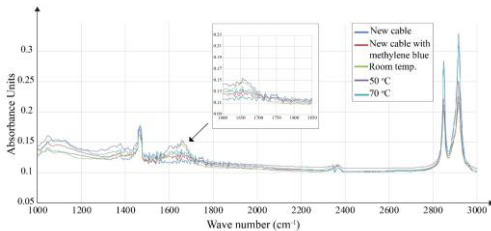


Figure 23. The relationship between the absorbance and wave number of water treeing in FeSO₄ ionic solution after 1000 h of the test period

As seen in the infrared spectrum results, the higher amplitude of the absorbance of the C=C and C=O bonds has been measured from the aged XLPE insulating material when compared with new XLPE insulating material. The infrared spectrum result shows that the degradation of the XLPE cable occurred after finished of the testing periods. However, the accuracy of the

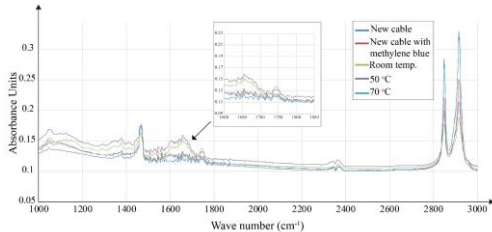


Figure 24. The relationship between the absorbance and wave number of water treeing in FeSO₄ ionic solution after 2000 h of the test period

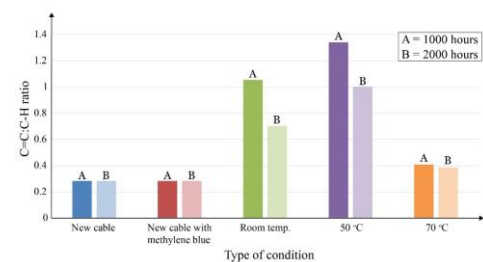


Figure 25. The C= C: C- H ratio of XLPE insulated cable after being tested with the K₂SO₄ ionic solution

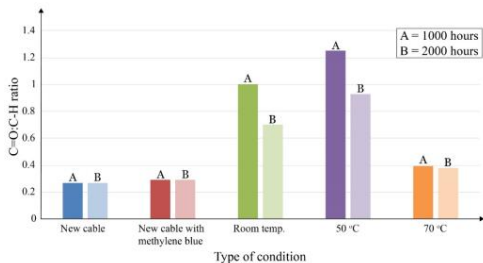


Figure 26. The C= O: C- H ratio of XLPE insulated cable after being tested with the K₂SO₄ ionic solution

FTIR analysis result depends on the thickness of the sliced XLPE insulating material. The absorbance amplitude ratio of the C=C bond to the C-H bond and the absorbance amplitude ratio of the C=O bond to the C-H bond have been used as the degradation index for the XLPE insulated cable to indicate the degree of the XLPE insulating material's degradation. In the case of the XLPE insulated cable with tested in the K_2SO_4 ionic solution, the C=C:C-H ratio is shown in Figure 25 and the C=O:C-H ratio is shown in Figure 26. In the case of the XLPE insulated cable tested in the $FeSO_4$ ionic solution, the C=C:C-H ratio is shown in Figure 27 and the C=O:C-H ratio is shown in Figure 28.

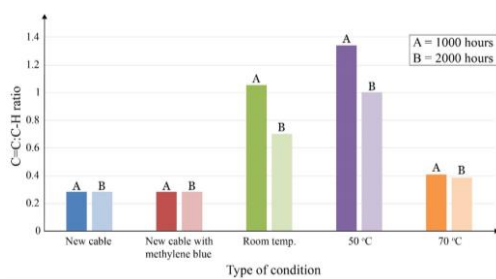


Figure 27. The C=C: C-H ratio of XLPE insulated cable after being tested with the $FeSO_4$ ionic solution

As seen in Figure 21 to Figure 24, in the 1000 and 2000 h of the testing periods, the absorbance amplitudes of the two considered chemical bonds, the C=C bond and C=O bond, on the tested XLPE insulated cable are higher than the absorbance amplitudes on the new XLPE insulated cable. To confirm the degradation index, a comparison of the absorbance amplitude ratio at the considered wave number of the C=C:C-H ratio and C=O:C-H ratio has been performed. Figure 25 to Figure 28 illustrate the C=C:C-H ratio and the C=O:C-H ratio of the tested XLPE insulated cable compared with the new XLPE insulated cable. Moreover, the C=C:C-H ratio and the C=O:C-H ratio of the tested XLPE insulated cable at different temperatures agree with the size of the water treeing, as shown in Tables 3 and 4.

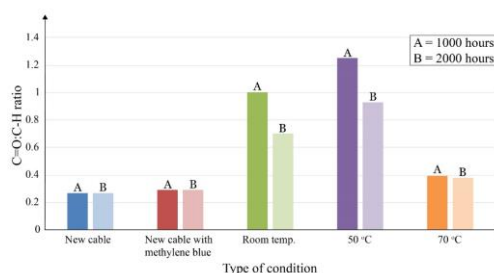


Figure 28. The C=O: C-H ratio of XLPE insulated cable after being tested with the $FeSO_4$ ionic solution

Conclusions

The propagation of water treeing on 22 KV XLPE cable with K_2SO_4 and $FeSO_4$ ionic solutions has been studied. After the ending of the test periods, the vented type of water treeing had occurred around the tip of the pinhole in the XLPE insulating layer. For the K_2SO_4 ionic solution, in both the 1000 and 2000 h of the testing periods, the greatest expansion of the water treeing size occurred in the tested samples at the temperature of 50°C. However, for the other temperatures, the expansion of the water treeing has showed no significant difference. For the $FeSO_4$ ionic solution, in the 1000 and 2000 h of the test periods, the greatest expansion of the water treeing size occurred in the tested samples at the temperature of 70°C, and the shortest expansion of the water treeing size occurred in the tested samples at room temperature. The study results show that the $FeSO_4$ ionic solution has a greater effect on the propagation of water treeing than the K_2SO_4 ionic solution. The explanation may be due to the $FeSO_4$ ionic solution having more acidity than the K_2SO_4 ionic solution. The experimental results confirmed that the acidity of the ionic solution influences the expansion of water treeing. From the FTIR analysis results, the occurrence of the carbonization and oxidation reactions can be detected by using the C=C bond and C=O bond. Both reactions occurred on the

tested XLPE cable sample more than on the new XLPE cable.

Acknowledgements

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