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Contribution to the achievement of SDGs
by Furukawa Electric Group

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Development of a Cross-Linked Polyethylene Insulation Material for DC Cables

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ABSTRACT We have developed an insulating material whose main component is cross-linked polyethylene (XLPE) that can be applied to extra-high voltage DC cables. The actual DC cable was manufactured with the material by utilizing the supply chain built after optimizing the stable supply and handling of raw materials. As a result of conducting various in-house and outside evaluations on the cable, it was confirmed that all the characteristics were satisfied. We have already completed a long-term energization test of a DC 525 kV class cable system, and we believe that we can make a major contribution to the expansion of renewable energy in the future.

1. INTRODUCTION

DC power transmission technology is useful for long-distance, large capacity power transmission because it has less power loss in current paths and higher system stability than AC power transmission. However, since AC to DC and DC to AC converters require more space than transformer equipment between AC, they are mainly applied to projects with sufficiently large transmission distances and transmission capacities.

Renewable energies such as solar and wind power, which are expected to become more widespread in the future, often require large installation areas for facilities. In the case of generating power on a large scale, it is thought that deployment will take place in areas with relatively low population densities and in offshore areas. Therefore, it is expected that the distance between the location of renewable energy power sources and demand areas will become longer. At the same time, it is thought that the interconnection between electric power companies and between regional power grids will need to be more and more dense in the future. In order to realize the above, the introduction of large-capacity grid connection lines is being considered. As a result, it is thought that the usefulness of DC power transmission technology, which excels at long-distance power transmission, will continue to attract attention in the future.

We have been providing oil impregnated paper insulated (OF) cables for DC for some time, but it is becoming difficult to maintain this business from the perspective of business continuity, including environmental characteristics and technology transfer. The production of the OF cable has been withdrawn several years ago. On the other hand, as DC cables, types that use solid insulating materials such as XLPE has become the main stream at present, and we have been working hard to develop XLPE insulated cables for DC. And this time, we have determined the final composition of the solid insulating material that can be used for DC applications, optimized the supply chain and conditions, etc., and finalized it. The details of the process and the performance of the completed DC cable are reported below.

2. XLPE IMPROVEMENT / MODIFICATION POLICY AND METHOD

Insulating materials for DC cables were developed based on the following policies.

- The base material is XLPE, which has many achievements in conventional AC cables.
- The material will be processed by cable manufacturing equipment that can be adjusted from equipment that has conventionally manufactured AC cables.
- Allowable conductor operating temperature is 90°C.
- In order to avoid problems such as poor dispersion in the base material, the modification for the DC conversion does not use fillers or low molecular-weight components, but modifies and denatures the XLPE itself.
- Specifically, a polar group is introduced to function as a charge trapping site.
- We are conscious of the stability of the supply chain and emphasize the availability and handling of raw materials.

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As a method for modifying and denaturing XLPE, we decided to investigate the polar group modification technology of polyethylene. While predicting the electrical performance of the modified material using the latest quantum chemical calculation method, we conducted experiments on numerous compounds of chemical components and repeated material evaluation tests such as the required properties as a DC insulation material described from chapter 3 onward. As a result, we were able to obtain a good insulating material for the DC cable. The evaluation results are shown below.

3. ELECTRICAL PROPERTIES REQUIRED FOR DC INSULATING MATERIALS AND THEIR EVALUATION RESULTS

Insulating materials used for DC cables are required to have different properties from those for AC cables. In particular, space charge characteristics can be mentioned as one of the required characteristics unique to direct current systems. In this report, we focus on this space charge characteristics, introduce two evaluation methods, and report on the performance of the developed material in each method.

3.1 Current Integration Charge (Q(t)) Method

When an insulator is sandwiched between electrodes and held in direct current electric field, charges (electrons, holes) are three-dimensionally injected into the insulator from the electrodes. These injected charges are called space charges. If these space charges move or accumulate in the insulator along over a charging time, their distribution and density changes, causing local changes in the electric field strength inside the insulator, and in the worst case, dielectric breakdown may be occurring in an abnormal amplified electric field. Therefore, it is important for direct-current insulating materials not to accumulate space charges, not to vary with time, and as a result not to favor a local electric field amplification.

This report introduces two methods for measuring the space charge characteristic. The first method is the Q(t) method.

Figure 1 is a conceptual diagram of Q(t) measurement. This is a simple measurement method in which a step type DC voltage shown in Figure 2 is applied between electrodes sandwiching the sample, and the amount of charge injected into the sample over time is measured.

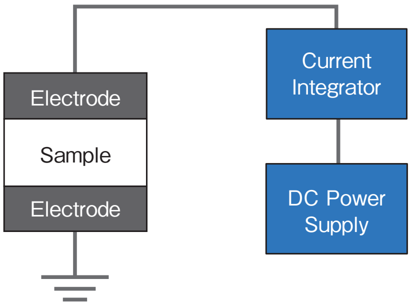

Figure 1 Conceptual diagram of a Q(t) measurement.

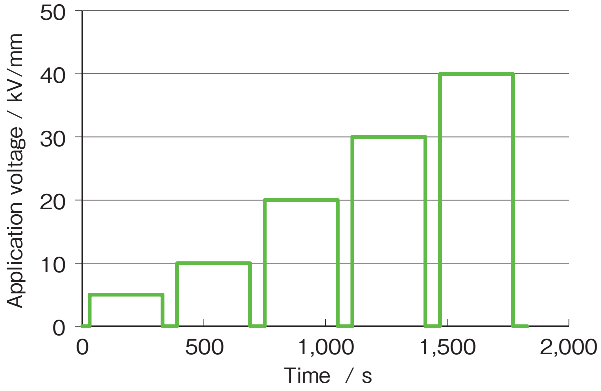

Figure 2 DC electric field applied on a sample.

Figure 3 and 4 show the measurement results of Q(t) at the maximum cable operating temperature of 90°C for sheet samples of the XLPE that we use for normal AC cables and the developed DC XLPE. It can be seen that the integration charge on the vertical axis increases as the application time increases and the applied electric field strength increases. Also, in the case of AC-XLPE, significant accumulation of integration charge is observed from around 20 kV/mm of electric field. On the other hand, the developed DC-XLPE does not show significant accumulation of integration charge even at 30 kV/mm, and has relatively good characteristics.

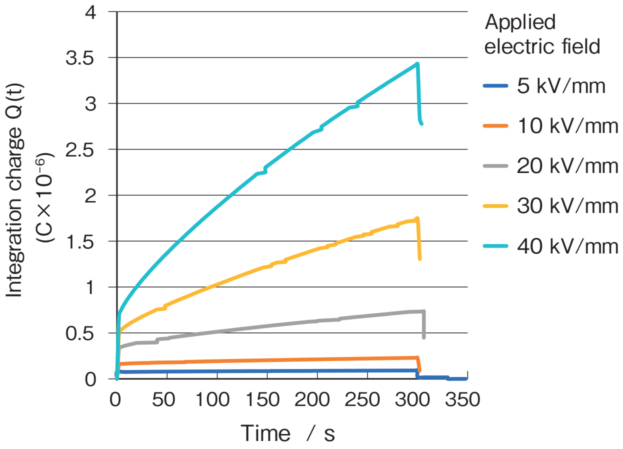

Figure 3 Q(t) measurement results for an AC-XLPE sample at 90°C.

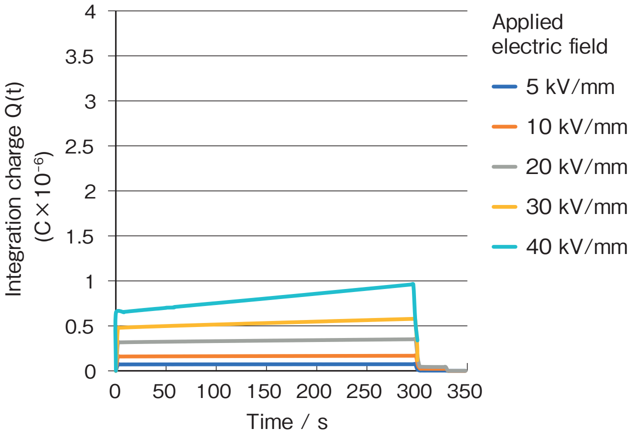

Figure 4 Q(t) measurement results for a DC-XLPE sample at 90°C.

In order to express the easiness of the charge accumulation, the ratio of electric charge immediately after charging and 300 seconds after charging is defined and used as the electric charge ratio. It can be said that the smaller the electric charge ratio, the better the DC performance.

Figure 5 plots the relationship between the electric charge ratio and the DC electric field. It can be seen that the developed DC-XLPE sample has less space charge accumulation than the AC-XLPE sample in the electric field region, that is, the developed product has improved DC characteristics.

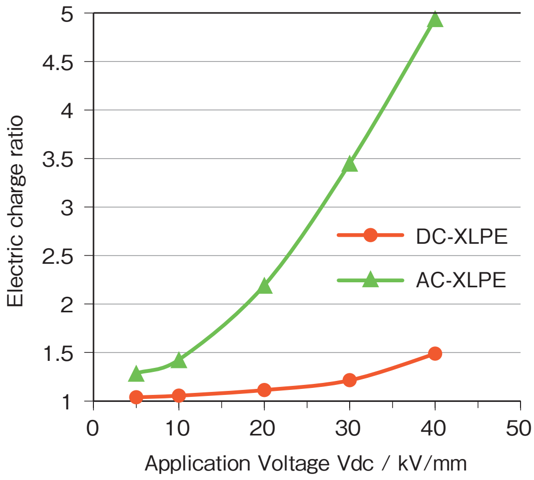

Figure 5 Relationship between the DC electric field and the electric charge ratio.

3.2 Pulsed Electro-Acoustic (PEA) Method

3.2.1 Measurement results for sheet samples

The second evaluation method for space charge characteristics is the PEA method. This is also the same as the Q(t) method with respect that a DC electric field is applied to the samples sandwiched between the electrodes, but it is different with respect that a pulse voltage is applied between the electrodes and the pressure wave generated inside the sample is detected at that time. When the space charge accumulates in the sample, the location receives force from the pulsed electric field and vibrates, generating a pressure wave. By measuring this pressure wave and measuring its delay and magnitude, it is possible to capture the position of the space charges in the thickness direction and the amount of accumulation of the space charges. Compared to Q(t) method, this method is superior because it can provide information on the position and the amount of space charges in the thickness direction of the sample and the charge distribution in the sample.

Figure 6 shows a conceptual diagram of a PEA measurement.

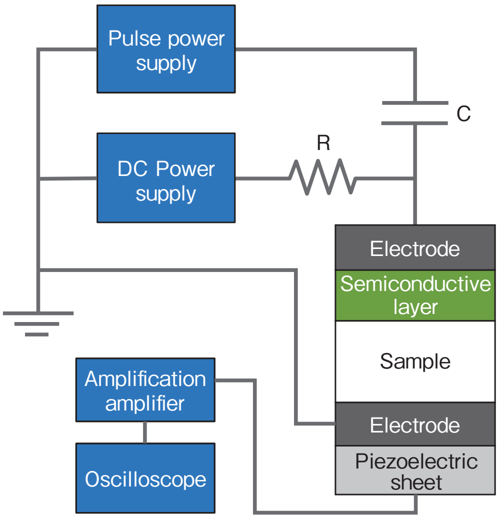

Figure 6 Conceptual diagram of a PEA measurement.

Using a sheet-shaped sample, PEA measurement was performed under the following conditions.

- Sample: Cross-linked sheet formed to a thickness of 0.1 to 0.5 mm
- Temperature: Heating with a heater (90°C)
- Applied electric field: –30kV/mm

As part of results, here we introduce the measurement results at 90°C, which is the maximum operating temperature of the developed product. In addition, the ground electrode is placed at the position where the sample thickness is 0 mm%, and the high voltage electrode is placed at the position where the sample thickness is 100 mm%.

Figure 7 and 8 show the PEA measurement results of an AC-XLPE sheet. In spite of the short time of only 7 hours, it is observed that the accumulation of positive charges gradually progresses in the vicinity of the electrode over time. This injected charge is a space charge, and if the measurement is continued for a long time, it is expected to accumulate and develop into a disturbance in the local electric field distribution (Figure 8 shows that the measurement time is too short for the electric field distribution to be significantly affected yet).

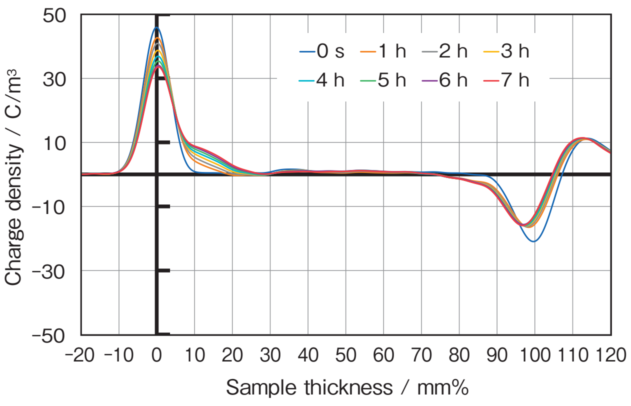

Figure 7 PEA measurement results of AC-XLPE sheets: Distribution of charge density along the thickness direction at 90°C.

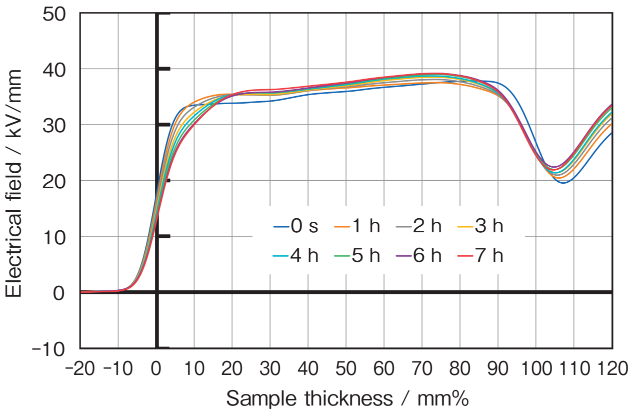

Figure 8 PEA measurement results of AC-XLPE sheets: Distribution of electric field along the thickness direction at 90°C.

On the other hand, the DC-XLPE sheet in Figure 9 does not seem to change from 1 hour to 5hours.

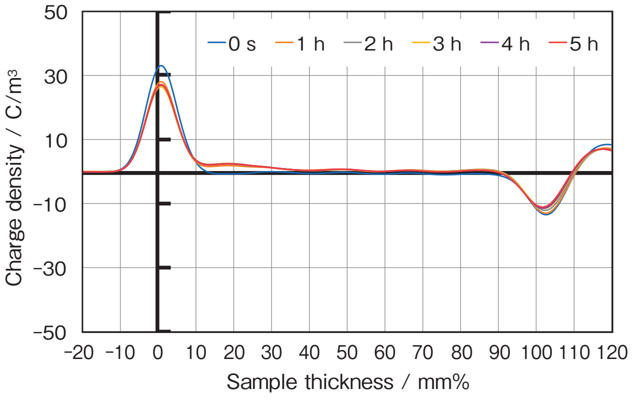

Figure 9 PEA measurement results of DC-XLPE sheets: Distribution of charge density along the thickness direction at 90°C (short time).

Therefore, we decided to extend the measurement time and observe the amount of space charge accumulated in the DC-XLPE sheet over a longer period of time.

Figure 10 and 11 are the results. The developed product did not show any remarkable change in charge density distribution even after 7 days of continuous DC application, and we believe that we were able to confirm its excellent DC characteristics.

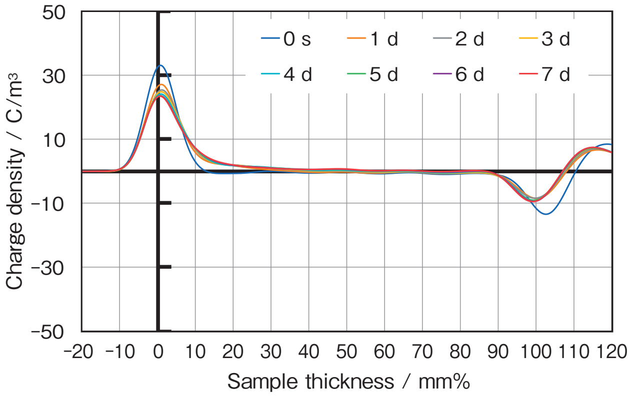

Figure 10 PEA measurement results of DC-XLPE sheets: Distribution of charge density along the thickness direction at 90°C (long time).

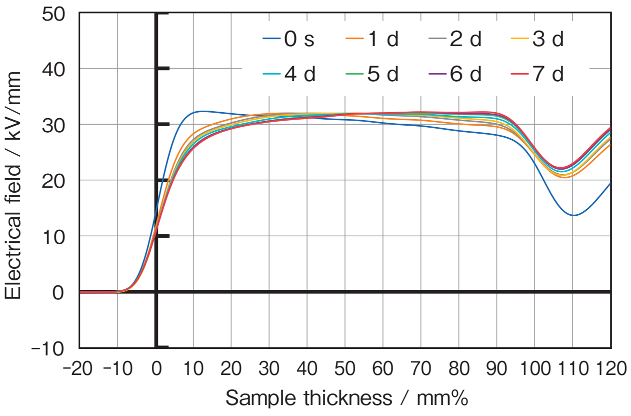

Figure 11 PEA measurement results of DC-XLPE sheets: Distribution of electric field along the thickness direction at 90°C (long time).

3.2.2 Measurement results for a miniature cable manufactured with the developed DC-XLPE

As the next step, we decided to manufacture a miniature cable (a small prototype cable) using the developed DC-XLPE as an insulation layer and conduct PEA measurements (Figure 12).

Figure 12 Cross-section of a miniature cable (the copper strands in the center are falling out).

Test condition:

- Cable outer diameter: 5 to 10 mm
- Structure: Stranded copper wire / conductor screen / insulation layer / insulation screen
- Insulation layer thickness: Around 1 mm
- Temperature: Combing conductor energization and heater heating (90°C)
- Applied voltage: −27kV (high voltage side: conductor screen, Ground side: insulation screen)

From Figure 13 and 14, it was observed that a small negative charge was accumulated near the ground electrode in the early stage, but it disappeared with time, and after 730 hours (approximately one month), a very well-defined curve was obtained.

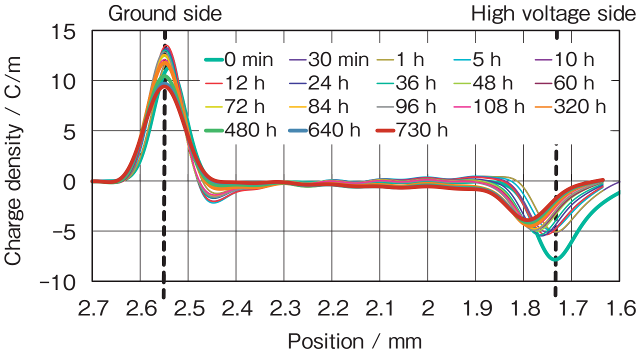

Figure 13 **PEA measurement results of a miniature cable using a DC-XLPE insulation: Distribution of the charge density along the thickness direction at 90°C.**

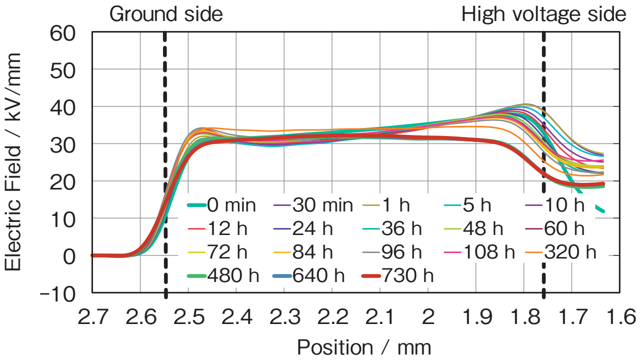

Figure 14 **PEA measurement results of miniature cable using a DC-XLPE insulation: Distribution of the electric field along the thickness direction at 90°C.**

Figure 15, shown below, plots the value obtained by dividing the maximum local electric field in the entire thickness for each measurement time by the initial maximum electric field value which is called the electric field enhancement factor. If the electric enhancement factor exceeds 1 and gradually increases, it means that a position where more electric field stress is applied to the inside of the cable as it is used, it can be said that the cable cannot be relieved even if it withstands the initial test after construction.

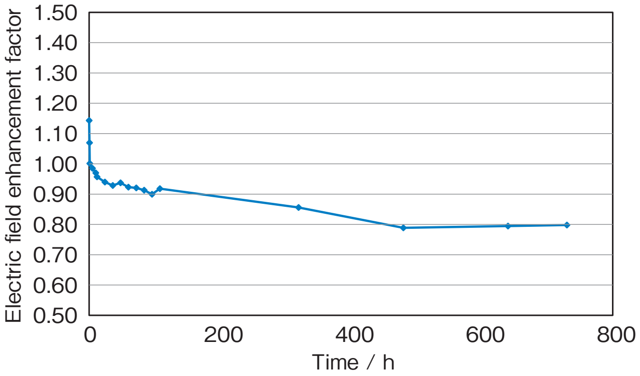

Figure 15 **Time variation of the electric field enhancement factor of a miniature cable using DC-XLPE insulation at 90°C.**

Looking at Figure 15, it can be seen that the electric field enhancement factor of the cable using the developed DC-XLPE settles down in a short period of time and becomes almost flat after 500 hours. From these results, we believe that we have confirmed that the DC-XLPE insulation developed this time has excellent long-term DC characteristics.

4. OTHER IMPORTANT ELECTRICAL PERFORMANCE RESULTS

In addition to this, we would like to introduce some evaluation tests for the material that should be noted for DC cables.

4.1 Volume Resistivity

The measurement results of the volume resistivity at high temperature in accordance with the following measurement condition are shown below.

- Sample structure: A miniature cable with an insulation thickness of about 1 mm
- Measurement electric field: –10 to –40kV/mm
- Measurement temperature: 90°C (heating with a heater)

As for DC-XLPE insulation, there are several existing products on the market from manufacturers of insulating and semiconductive materials for power cables. Three of them were obtained and compared (commercial products 1, 2, 3).

As a result, our DC-XLPE insulation is superior to our AC-XLPE insulation and the commercially available DC-XLPE insulation in the entire measured electrical field range, and has an excellent volume resistivity within the practical electric field design range for power cables (Figure 16).

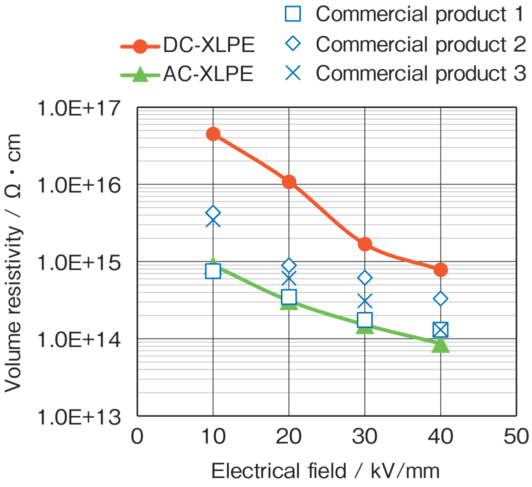

Figure 16 **Comparison of the volume resistivity between the developed DC-XLPE insulation and the other commercially available products.**

4.2 Dielectric Breakdown Characteristic

Regarding dielectric breakdown characteristics, we compared the performance of the developed product with that of other companies' commercial DC-XLPE insulations under two conditions, DC and impulse. The test conditions are as follows.

DC dielectric breakdown test:

- Sample structure: A miniature cable with an insulation thickness of about 1 mm
- Voltage boost method: –70 kV/min -> –5 kV/min step boost
- Measurement temperature: 90°C

Impulse dielectric breakdown test:

- Sample structure: A miniature cable with an insulation thickness of about 1 mm
- Voltage boost method: –100 kV × three times -> –5 kV/min × step up three times
- Measurement temperature: 90°C

Due to variations in measured values, it is difficult to determine superiority or inferiority, however, the product developed by our company is considered to be at least as good as the commercially available product. Therefore, it is considered that the sufficient performance of our developed product has been confirmed (Figure 17).

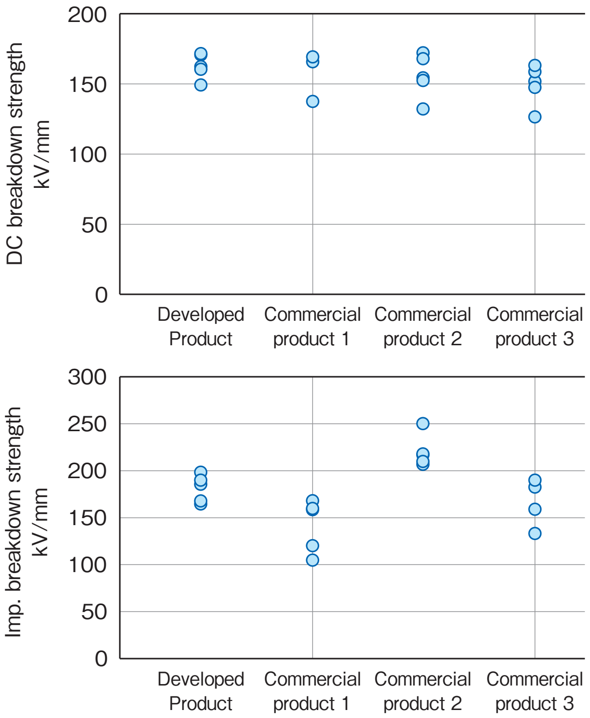

Figure 17 Summary of results from the top: DC breakdown test and the bottom: impulse breakdown test.

4.3 Mechanical Strength (Tensile Strength Test)

If the cable is too rigid, it will adversely affect the installation and connection workability. Therefore, as a representative evaluation of mechanical properties, we will also compare the developed DC-XLPE insulating material and the conventional AC-XLPE insulating material in the tensile strength test. The test conditions are as follows.

- Sample structure: 1 mm thick sheet was formed and punched according to JIS No.3 dumbbell shape.
- Tensile speed: 200 mm/min

As shown below, the mechanical properties of the conventional AC-XLPE insulating material and the developed DC-XLPE insulating material are almost the same, and it is possible to obtain the same handleability as the conventional AC cable (Figure 18).

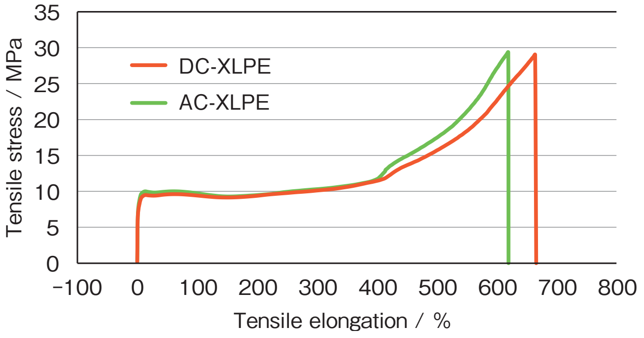

Figure 18 Comparison of stress-strain curves at room temperature.

In addition, after going through various customer-requested tests, in-house tests, and reference tests, we were able to complete a high-performance DC insulation material that satisfies all of these requirements.

5. LONG-TERM ENERGIZATION TEST OF DC 525 kV CLASS CABLE SYSTEM

Although the content overlaps with the news release from our company on April 30, 2021, we will introduce it again.

An actual cable was manufactured using the DC insulation material developed in this report, and a test line including a cable system consisting of various components such as connection parts was constructed and subjected to the following long term energization test.

We conducted a pre-qualification test of the DC 525 kV cable system in accordance with testing recommendations based on CIGRE Technical Brochure No.496. As an extra-high voltage submarine cable, the test was carried out in the “the Next-Generation Offshore DC Power Transmission System development project” of the New Energy and Industrial Technology Development Organization (NEDO) from years 2015 to 2019, while land cable was conducted by a third party. The tests were completed without any problems. We believe that these results have demonstrated the high reliability of our DC cables (Figure 19)[2].

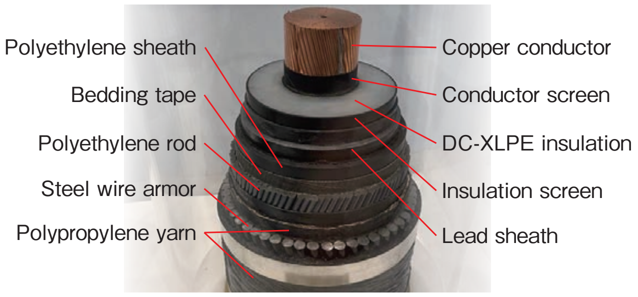

Figure 19 DC 525 kV 1800 mm^2 submarine cable tested for long term energization.

6. CONCLUSION

We have developed the following insulating material that can be applied to extra-high voltage DC cables.

- It was confirmed by two evaluation methods (Q(t) method and PEA method) that the DC characteristics were excellent.
- Compared with the commercially available DC-XLPE insulations, the developed product was equal or superior in all properties, especially in volume resistivity.
- Consideration has also been given to the availability of raw materials, and a stable supply chain has already been established.
- A power cable was manufactured using the developed insulation material, and a long-term energization test was conducted on a DC 525 kV class cable system, and the test was successfully completed.

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