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Applicability of ultrasonic measurements in cable condition monitoring

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Summary

Providing new techniques for condition monitoring of cables in nuclear power plants can improve their ageing management. Ultrasound method is a non-destructive technique which can potentially be applied in measuring cable condition. In this work, XLPE samples were artificially aged, and the condition of the samples were defined with tensile tests and ultrasonic measurements. The ultrasonic measurements were compared to the elongation at break and elastic modulus values obtained from the tensile tests. It was concluded that the elongation at break values decreased only slightly due to ageing and no significant changes could be observed in ultrasonic velocity or elastic modulus values.

The challenges related to producing relevant artificial ageing data for assessing the sensitivity of ultrasonic measurement with XLPE samples were evident. Lower ageing temperatures and longer ageing times are required to avoid heterogenous ageing and thus obtain more representative ageing data.

Other main challenge for adopting ultrasonic measurement for cable condition monitoring is related to its limited accessibility to the cable insulator, real cables can be measured only in locations where the insulator is well accessible. However, ultrasonic approach introduced here can be suitable for analysing the condition of surveillance samples.

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Preface

This work was completed as part of the Finnish Research Programme on Nuclear Power Plant Safety 2019 – 2022 (SAFIR2022) within the SAMPO (Safety criteria and improved ageing management research for polymer components exposed to thermal-radiative environments) project's work package 2 "Improvements in ageing management of polymer components".

Espoo 25.1.2023
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Contents

1. Introduction

Cables are commonly used as part of various instrumentation in nuclear power plants and some of them have safety significance during normal operation and accidental scenarios. It has been evaluated that a single nuclear power plant can contain 1000 – 2000 km of cables [Yamamoto et al. 2009]. Thus, it is important to have proper ageing management programmes for cables to ensure their proper function during the whole lifespan of nuclear power plants. One essential research topic is cable condition monitoring which can reliably measure the cable condition. Generally, a condition monitoring criterion of 50% elongation at break (EaB) have been applied to cables [IAEA-TECDOC-1825]. Although there is a consensus that the 50% EaB value represent quite well the acceptable cable condition, it is problematic since the tensile test itself is a destructive test, requiring deposit samples. Thus, providing techniques based on non-destructive measurements would be beneficial in the condition monitoring perspective.

The nuclear power plant cables are just like any other type of cables when their structures are considered. Figure 1 shows a schematic drawing on a typical cable. The most inner part of the cable is the conductor, and it is typically surrounded by an insulator, which insulates it electrically from its surrounding. Depending on the cable type, there can be a metallic shielding around the insulator. On top of these layers is the cable jacket, which protects the inner layers from environmental stressors. If the functionality of the cable is considered, the condition of the insulator is the most critical one. The condition of the jacket can be considered also important, especially as it is easily accessed by e.g., visual inspection.

Figure 1. Schematic illustration on a cable structure.

Ultrasound inspection have been earlier developed for cable condition monitoring for XLPE material [Rinta-Aho et al. 2021]. The challenges related to the previous work with the ultrasound method have been related to:

1) obtain moderately aged samples and
2) distinguishing unaged or severely aged material from moderately aged material.

The aged XLPE samples seem to maintain their mechanical properties quite well in thermal ageing, until a point where they rapidly decrease. Because of this, usually the obtained samples have mostly maintained their mechanical properties, or the mechanical properties have decreased almost to zero. This causes challenges obtaining moderately aged samples. The other issue is related to the limited measurement data obtained with moderately aged samples. It has not been shown properly that ultrasound method could distinguish moderately aged samples from unaged samples reliably. This work aims to provide more insights to these issues.

2. Goal

The aim of this work is to produce more accurate ageing data for XLPE and analyse the sensitivity of ultrasonic technique towards ageing detection by comparing the measurement results to tensile test results. The applicability of the method in condition monitoring of cables is briefly discussed.

3. Materials and methods

The materials were prepared out of industrial quality XLPE pellets delivered by Borealis Ltd. The pellets were processed by moulding them in 1 mm thick sheets. The larger sheets were then cut to tensile test samples and ultrasonic samples (50*50 mm sheets).

Previous experience has shown that obtaining moderately aged samples is challenging. The mechanical properties of XLPE tend to decrease rapidly after some initial ageing period. This is believed to be due the consumption of antioxidants from the material. After all of the antioxidants have been consumed from the material, the degradation of the polymer chains can progress without restrictions and the mechanical properties decrease rapidly. An example of this kind of behaviour can be seen in Figure 2, where XLPE samples were aged at 130°C.

To resolve this issue, the ageing temperature was decreased to 110 °C and the ageing was performed in two separate batches. The second ageing batch was put in the oven 8 weeks after the first one. It was planned that when a rapid decrease in mechanical properties is observed in the first ageing batch, additional sampling points could be introduced by obtaining samples from the second batch.

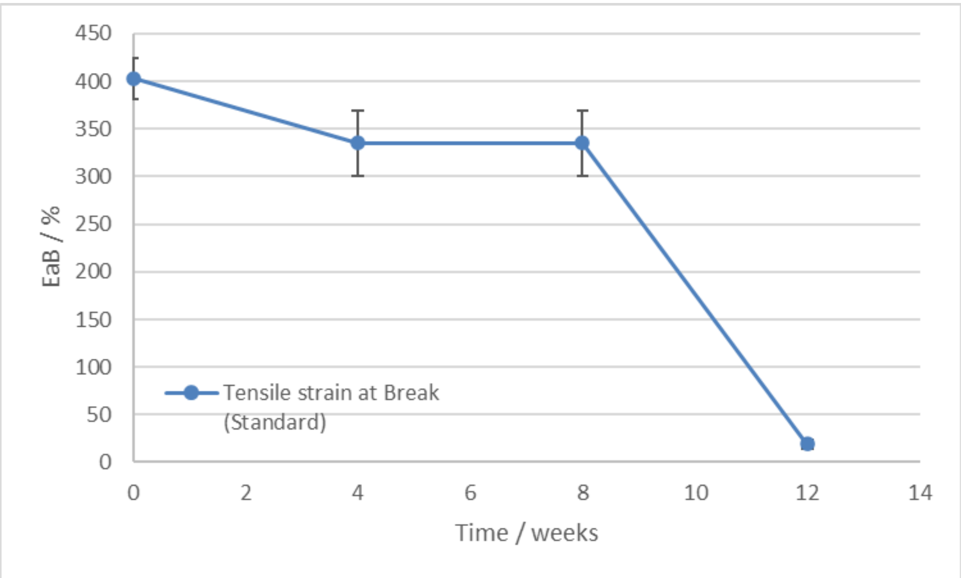

Figure 2. Rapid decrease in elongation at break of XLPE sample when aged at 130 °C.

The tensile tests were performed according to ISO 527. Five individual samples were tested per ageing condition. Instron 5500K8810/4505H2190 machine with 100 N load cell and pneumatic grips was used as the test equipment. Bluehill software (version 4.25) was used as a measurement software and data analysis.

Traditional pulse-echo method was applied in ultrasound measurements. The approach is based on sending a short sound pulse to the specimen and arrival time of the echo (time of flight) is measured. When the thickness of the sample and the time of flight are known, sound velocity can be calculated.

A test arrangement specially developed for measuring ultrasound velocity on polymeric samples was applied (see Figure 3). The sample was inserted in the measurement jig, which had a digital micrometre (Mitutoyo MCD-1” SXF) integrated for thickness measurement. A contact transducer (GE 5 MHz .25B with a nominal frequency of 5 MHz) with an acrylic delay line (22 mm) was used. The signals were recorded using Dynaray Lite (sampling rate 100 MHz) ultrasound inspection system.

Figure 3. Measurement setup (left) and close-up of the delay line - transducer setup (right).

The arrival time difference between delay line - sample echo (front wall echo) and the second back wall echo was used as the measurement parameter. This procedure doubled the sound path reducing relative measurement error by half and increasing the overall sound velocity measurement accuracy.

The recorded ultrasound signal was analysed using Matlab. The time-of-flight was determined as the distance between the local maxima of the signal envelope. The envelopes were determined using Matlab inbuilt function “envelope()”.

4. Results and discussion

The comparison between the tensile test data and ultrasonic measurements are shown in Figure 4. Up to 18 weeks, no changes in mechanical properties was observed. At week 21, a decrease in elongation at break (ca. 120%) can be observed and the elongation stays at constant level until the final week 31. The scatter is rather high after 21 weeks in the measured samples. It was noticed that 2 out of 5 tested tensile samples were aged more severely compared to the other 3 in this ageing condition and the same applied for samples tested at 24 and 31 weeks. Indeed, even the sheet samples on which ultrasonic measurements were performed, seemed to age unevenly (see Figure 5), especially the sample aged for 24 weeks. Due this heterogenous ageing of the samples, the heterogeneously aged tensile samples were left out from the data analysis and the data was re-plotted as shown in Figure 6. In the updated figure, a decrease in elongation values can be observed, but at clearly smaller magnitude (ca. 50%), indicating only a slight ageing.

The elastic modulus is also affected by the heterogenous ageing, but the change was considered to be within the error margins. Generally, it seems that there is no significant change in the elastic modulus value during the ageing period.

The measured ultrasonic velocities seem to stay roughly constant, indicating that the method is not as sensitive as elongation at break to detect ageing. Only one data point seems to display ca. 10% higher sound velocity at 24 weeks. This higher measured sound velocity value can be assumed to be due to heterogenous ageing of the sample. It can be expected that the ultrasonic velocities measured from this sample can vary depending on the measurement site, i.e., darker or lighter areas seen in Figure 5. Otherwise, the ultrasonic results seem to be aligned with the elastic modulus data too as no significant changes were observed in neither one.

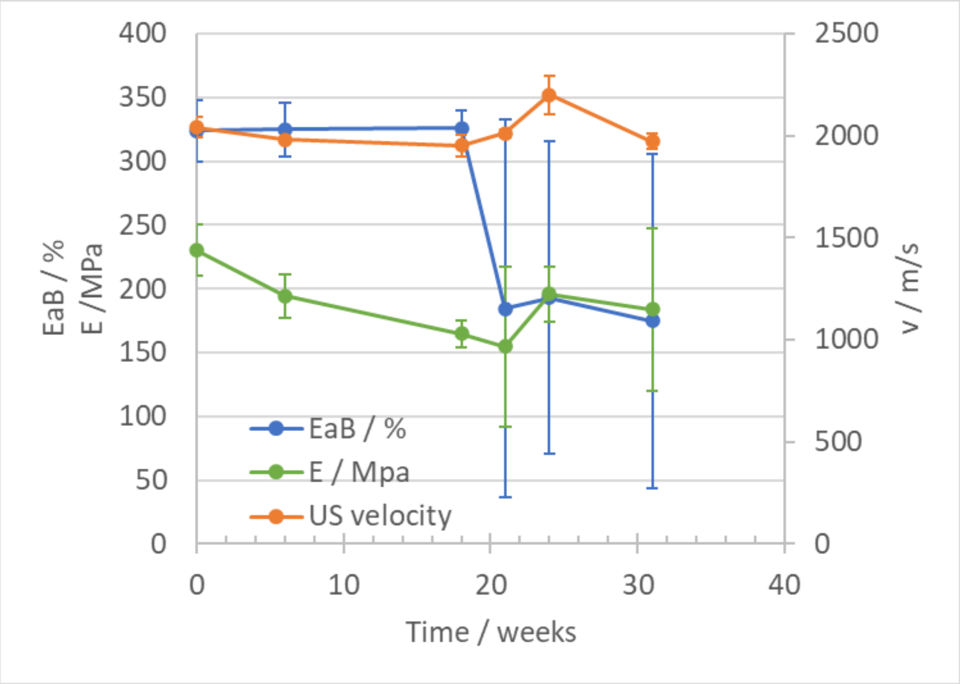

Figure 4. Elongation at break, elastic modulus and ultrasonic velocity values measured as a function of ageing time.

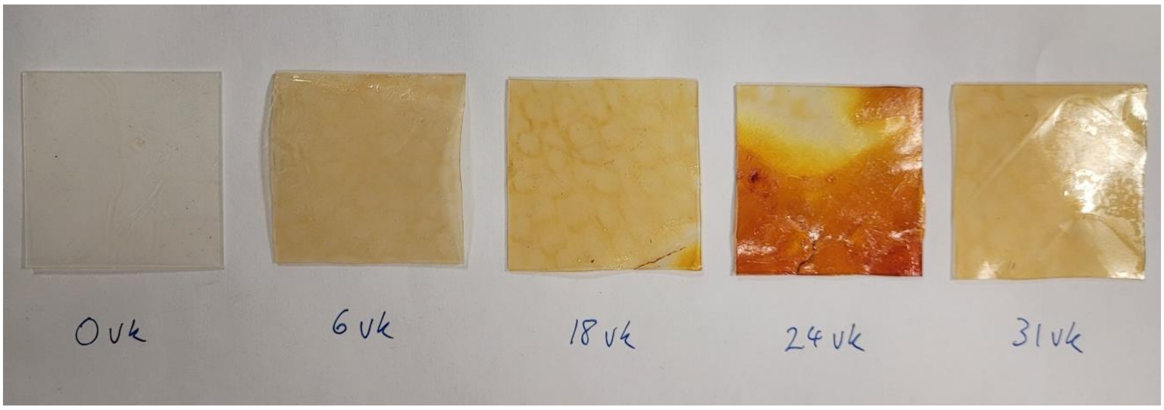

Figure 5. Ultrasonic samples thermally aged from 0 to 31 weeks.

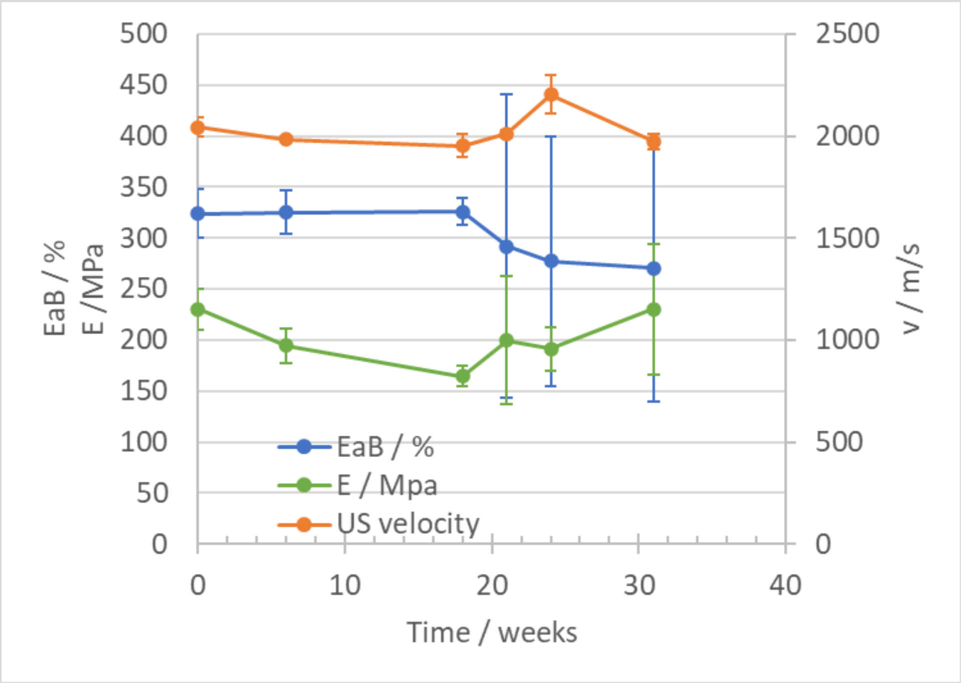

Figure 6. Re-plotted tensile test data.

Based on the presented ageing data, it was not possible to evaluate the sensitivity of the ultrasonic measurement with the aged XLPE samples. For now, it only seems that ultrasonic method can distinguish severely and homogenously aged sample from an unaged sample. Challenges are related to obtaining moderately aged samples and avoiding heterogenous ageing of the XLPE samples in thermal ageing. It is suspected that 110 °C is too high temperature for these types of XLPE samples to obtain representative samples for sensitivity analysis. However, decreasing the ageing temperatures to 80-90 °C would result in significantly longer ageing times and multiply the required number of samples. Performing ageing treatments with a large test matrix which is found to be challenging within this type of framework as it would result in several years of project duration.

Another challenge related to ultrasonic measurements is that their applicability in cable insulator measurements is currently rather limited. Measurements at the ends of the cable where insulator is well accessible is possible for now. Destructive sample preparation is otherwise required, although the required sample size is small, ca. 2 mm. Although it is anticipated that in the measurement of surveillance samples, ultrasonic method might have potential as it consumes only a small amount of the sample, thus saving precious materials.

Despite these challenges, several improvements to the measurement approach have been made with polymers. The most important developments include:

- Construction of the test jig
- Optimization of the thickness measurement
- Standardizing the measurement procedure

These developments have enabled decreasing the scatter in the results improving reliability and repeatability of the measurements.

5. Summary

The use of ultrasonic technique as condition monitoring method for cables have been further developed. Additional artificial ageing data was produced to evaluate the sensitivity of the method to detect ageing. Producing moderately aged XLPE samples was shown to be challenging and thus the sensitivity analysis could not be performed properly. Based on the obtained results, it could be only concluded that ultrasonic method is not sensitive enough to distinguish slightly aged samples from unaged samples.

The challenges related to developing ultrasonic technique further to perform measurements with real cable geometry were briefly discussed. It was concluded that additional artificial ageing times is required to perform representative sensitivity analysis. Although advances have been made in developing the measurement approach, it would be still limited to locations where the cable insulator is well accessible. A potential application seems to be tests performed with surveillance samples as the ultrasonic method consumes only a small portion of the sample.

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