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Research article

A study of expected lifetime of XLPE insulation cables working at elevated temperatures by applying accelerated thermal ageing

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ABSTRACT

Deterioration of cable insulation during its normal operation is a major concern. Usually, electric cables receive less periodic maintenance compared to the other electric components, although they are subjected to several environmental conditions during operation such as high temperature and oxidative atmospheres.

In this study, a standardized accelerated thermal ageing technique was used, with the application of the Arrhenius model. This technique is commonly used in accelerated life testing to establish a lifetime-stress relationship and estimate cable lifetime. Two types of Cross-Linked Polyethylene (XLPE) material working at elevated temperatures between 95 and 105 °C were selected for testing. In such accelerated ageing processes, it is required for the insulation to reach a degradation level, which is considered the end of life for the material under evaluation. The end of life criteria (also called endpoint) is defined as a percentage reduction of elongation at break, which is considered in this study to be 50% retention of elongation at break. Thermal ageing was carried out according to the BS 7870-2 standard, while elongation at break was evaluated at several ageing stages. The uncertainty in the measurement was estimated. The short-term data points determined by ageing treatment is represented graphically in the Arrhenius plot. The extrapolation of such data was used to predict the long-term performance and estimate the cable lifetime. The lifetime for XLPE is expected to be between 40 and 60 years at 90 °C rated operating temperature. Experimental findings of this study show an estimated cable lifetime between 7 and 30 years for rated operating temperatures between 95 and 105 °C.

1. Introduction

Deterioration of cable insulation during its normal operation has been a major concern for utilities. Cross Linked Polyethylene (XLPE) was invented in 1963, in the General Electric Research Laboratory, to create a crosslinked material with better mechanical and thermal properties than Polyethylene, which can stand an operating temperature of 90 °C [1]. There have been attempts to increase the operating temperature of conventional high voltage transmission cables to more than 90 °C, in order to prevent thermal degradation for XLPE dielectric [2]. Efforts were exerted to estimate the insulation lifetime and study the ageing process that may lead to a breakdown. Chemical changes were observed when an XLPE cable with water-barrier design was thermally aged. It was found that crystallinity was increased after the application of thermal stress [3]. Exposing a flame-retardant cross-linked polyethylene (FR-XLPE) to thermal ageing at 100, 135 and 155 °C for 800–2000 h was found to affect its performance progressively. Ageing was found to happen through three stages, in the first stage cross linking increased in the material and caused a reduction in conduction current and the imaginary part of complex permittivity. In the second stage, oxidative degradation resulted and became dominant which resulted in an increase in conduction current and the real and imaginary permittivity. In the last stage, the conduction current stabilized but the complex permittivity continued to increase [4]. Insulation degradation was investigated by applying different stresses, including electrical, thermal, and mechanical stresses. To achieve this, the insulations are exposed to high stresses for a specific time, until a degradation level (endpoint) is reached. Ageing under wet conditions was also considered for particular insulations after it was found that humidity is a main source of water trees in XLPE [7].

Since ageing of insulating materials under normal operating conditions would take long durations, and as it is inconvenient to get aged samples from the field to do the required testing and assessment, accelerated ageing techniques have been implemented by the researchers to simulate the stresses and environmental conditions that the cables are most likely to encounter while in service.

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This work aims to estimate the lifetime of XLPE cable working at elevated temperatures by applying the Arrhenius model on thermally aged samples. This model is commonly used in accelerated life testing to assess the lifetime-stress relationship and estimate the service life of a product. This procedure follows a thermal ageing protocol, according to the British Standard BS 7870-2 [6].

1.1. Arrhenius equation

In 1890, it was generally known that higher temperatures result in an increase in reaction, usually doubling it by an increase of about 10-degree, without any obvious clarification about the reason. This common knowledge has remained until the year of 1899 when Svante Arrhenius, the Swedish chemist, integrated the concepts of Boltzmann distribution law and the activation energy into one of the most significant relationships in physical chemistry as indicated in Eq. (1) [5]:

$$k = A\, e^{\frac{-E_a}{RT}} \tag{1}$$

where k is the rate constant, E_a is the activation energy, R is the gas constant, T is the temperature in Kelvin and A is a frequency factor constant or also known as the pre-exponential factor or Arrhenius factor. The term RT is considered as the average kinetic energy and the exponent E_a/RT will be affected by the ratio of the activation energy E_a to the average kinetic energy RT. A bigger ratio would lead to a reduced rate constant due to the negative sign. As such, this implies that low activation energy and higher temperature produce bigger rate constants, and consequently speeding up the reaction.

1.2. Activation energy

From the perspective of chemistry, it is common knowledge that there is a particular minimum amount of energy possessed by molecules. Chemical reactions occur when such molecules collide, in which their kinetic energy makes the bonds to stretch, bend, and finally break. In case the molecules kinetic energy is low due to their slow motion or collision in an improper direction, no reaction happens and the molecules just bounce off each other. However, a high chance of a chemical reaction to take place is when the molecules collided rapidly in a proper direction with kinetic energy greater than the minimum energy barrier. The minimum amount of energy that is required to activate molecules to initiate a chemical reaction is called the “activation energy”, E_a [7].

The non-exponential form (logarithmic) can also be used to express the Arrhenius Eq. (1) so that it becomes more convenient in interpreting the results. This will result in the following linear equation.

$$ln\, k = ln\left(A\, e^{\frac{-E_a}{RT}}\right) = ln\, A + ln\left(e^{\frac{-E_a}{RT}}\right) \tag{2}$$

$$ln\, k = ln\, A + \frac{-E_a}{RT} = \left(\frac{-E_a}{R}\right)\left(\frac{1}{T}\right) + ln\, A \tag{3}$$

Plotting $ln\, k$ vs. $1/T$ yields a straight line with a slope of $-E_a/R$ (the coefficient of the inverse of T) and a y-intercept of $ln\, A$. Consequently, the activation energy can be determined from the k values found at various temperatures, through graphical representation of $ln\, k$ against $1/T$ as shown in Figure 1.

1.3. Accelerated ageing mechanism of polymer cable

Usually, the electric cable after installation receives less periodic maintenance compared to the other electric components, although it is subjected to several environmental conditions during operation such as high temperature and oxidative atmospheres. As the cable get aged, a degradation of the electrical and mechanical properties of the insulating material will occur causing irreversible changes in the chemical structure

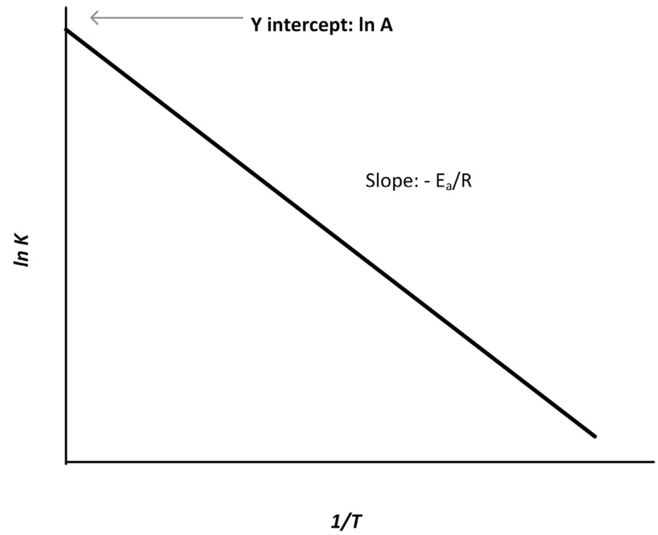

Figure 1. Representation of Arrhenius plot (ln k vs. 1/T).

and hence reducing the service lifetime of the cable. Accordingly, the Arrhenius model is applied to study the time-temperature ageing impacts and assessment of the material lifespan. Arrhenius curve has to be plotted from the straight-line equation using the short-term data, and subsequently an extrapolation is performed to predict the long-term performance.

It is necessary to turn attention to the concept or mechanism of ageing. There are several factors that can determine the ageing of polymeric insulating materials. These include whether the material had been utilized for long timeframes, service environmental conditions, and the polymer system itself. The insulating materials and the external jacket are made up of basic additives and polymers that endow them their particular features, including fire retardant, antioxidant, and thermal stabilizers. The speed of material ageing can be extremely affected due to certain factors such as temperature and radiation. Presence of water vapor as well as oxygen can also participate in ageing process [8].

Physical or chemical processes at the material's molecular level, resulting from environmental service conditions, are some of the causes of ageing. Therefore, in cable materials, the main mechanisms of ageing can be categorized as either physical or chemical. Whereas physical ageing mechanisms impact the compounds' compositions, chemical ageing mechanisms impact the compounds' molecular structures. Tensile strength, elongation at break, and compressive modulus are the most common forms of characteristics related to physical ageing. As such, the insulation criteria for end of life could be defined as some percentage reduction of elongation at break. The tensile tests on materials of cable insulation incorporate measurements that enable the operator to obtain the percentage elongations at break (E-at-B) and relate it to ageing.

2. Experimental work

2.1. Process flowchart

The flowchart in Figure 2 summarizes the experimental process. Further details of the XLPE cable ageing procedure, starting from the selection of material and the ageing process and ending with the interpretation of results, are provided in the following sections.

2.2. Specimens selection and preperation

2.2.1. Description of materials used in thermal ageing

The study has addressed two types of insulating materials which are commonly used for extruded medium voltage and high voltage power cables, which are: Material A and Material B.

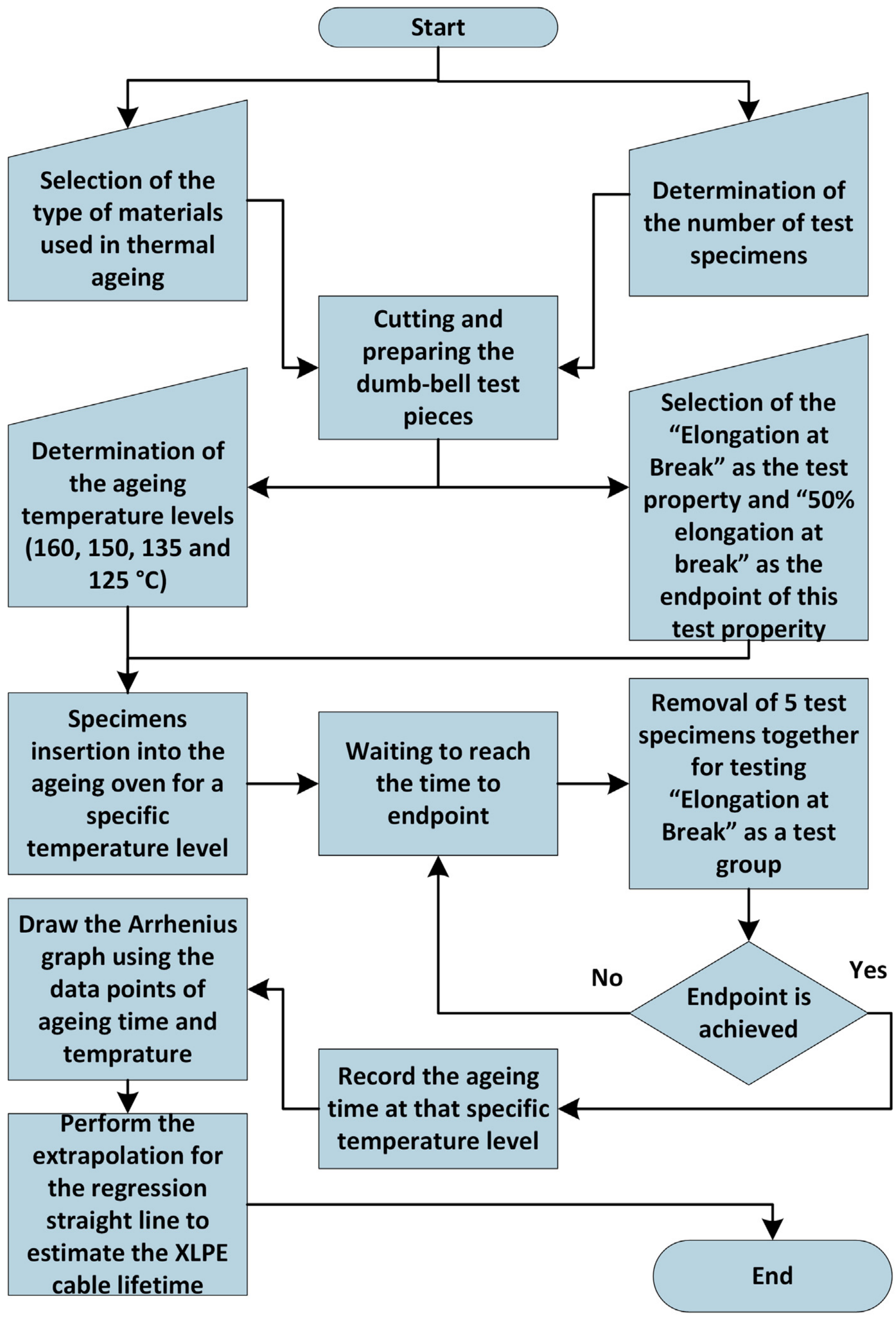

Figure 2. The experimental process flowchart.

Material A is a crosslinkable natural polyethylene compound, specially designed for insulation of power cables. Its applications are intended for insulation of XLPE medium voltage AC cables with rated voltages up to 69 kV ($U_m = 72.5$ kV). Material B is a low density crosslinkable polyethylene compound designed for high voltage (up to 154 kV) power cable insulation requiring a high degree of cleanness. It has an extremely low level of contamination and proper balance of non-staining antioxidant and peroxide, to ensure thermal stability and optimum cure levels.

2.2.2. No. of test specimens

Preparation of test specimens is an extremely significant part in the thermal ageing process. All instructions and procedures necessary in the specimen's preparation must be in accordance with relevant international standards. One of the major factors to show accurate results of accelerated ageing tests is the selection of an adequate number of specimens for each temperature level. In this study, the number of specimens was chosen based on the material behavior under high temperature in accordance with its technical data sheet. Moreover, the high experience of laboratory personnel in ageing processes for such material contributed

Table 1. The number of test specimens for each temperature level.

Ageing temperature level (°C)	Ageing temperature level (°K)	No. of test specimens (samples)	
		Material A	Material B
160	433.15	30	30
150	423.15	30	30
135	408.15	60	60
125	398.15	60	60

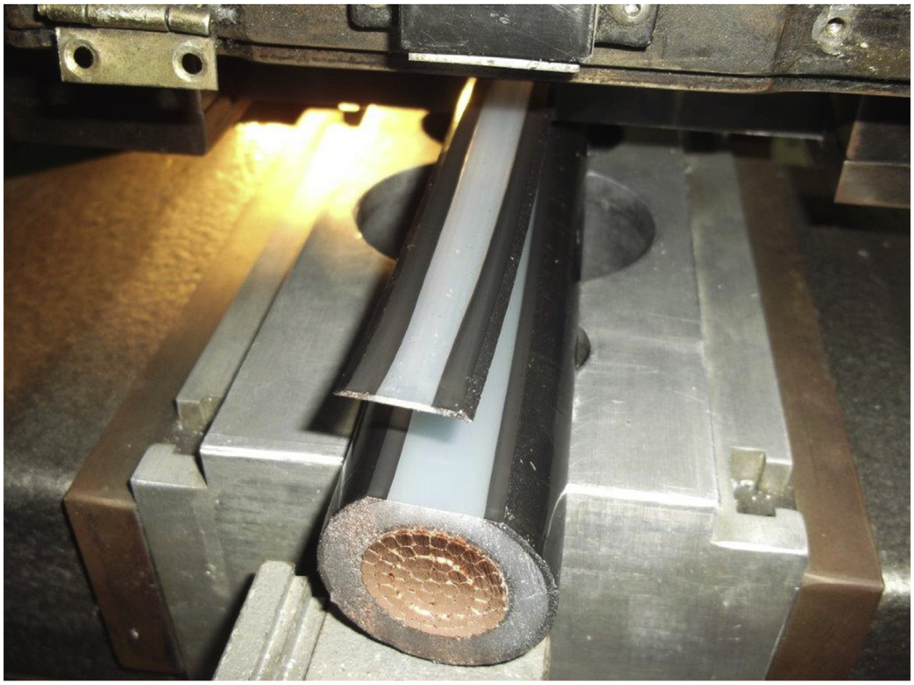

Figure 3. Insulation cutting into strips before preparing the dumb-bell test piece.

to the determination of the appropriate number of specimens at each temperature level, since a sufficient number of specimens were needed to be provided for testing at each temperature level to ensure reaching the endpoint of the selected property. Preparing an additional number of specimens from the same material was also considered during the ageing process to reduce the risk of unforeseen complications arising by a possible non-linear thermal endurance relationship or losing some specimens due to over-heating inside the oven. The number of test specimens for each temperature level is shown in Table 1.

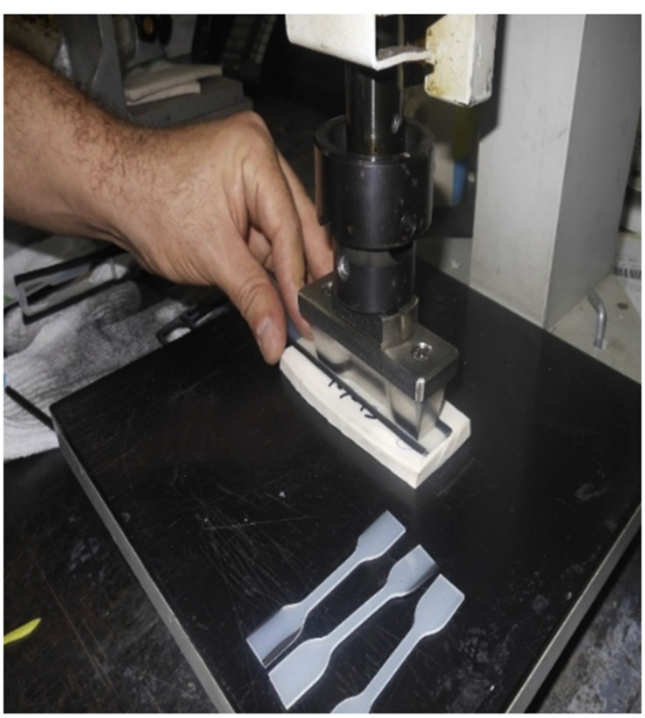

Figure 4. Cutting the dumb-bell test pieces via Zwick cutting presses.

2.2.3. Preparing the dumb-bell test pieces

In this study, the ageing method was applied according to BS EN 60811-401 [9] for dumb-bell test pieces of XLPE insulating material without a conductor. Cutting, preparing, and testing the test pieces are according to BS EN 60811-501 [10]. The mechanical tests which include determination of the tensile strength and elongation at break of the insulating material (exclusive of any semi-conducting layers) were applied before any ageing treatment to ensure the validity of mechanical properties of the insulating material prior to the implementation of the accelerated thermal ageing. The test pieces, whether before or after ageing treatment, were cut from the same batch and from positions adjacent to each other, and the tensile tests of both aged and unaged samples were carried out in prompt succession. For each tensile and elongation at break test, a minimum of five 100 mm-long test pieces were provided. The dumb-bell test pieces were prepared from samples of XLPE insulation removed from the conductor, cut open in the direction of the axis of the core, as shown in Figure 3. Any semi-conducting layer (i.e. conductor screen or insulation screen) was removed mechanically. Then, the insulation sample was cut into strips with adequate length. The insulation strips were cut in a way appropriate to get two parallel smooth surfaces, Figure 4, with a thickness not less than 0.8 mm and not more than 20 mm. Finally, dumb-bell test pieces were punched from each prepared insulation strip with standard dimensions, as shown in Figure 5. Each dumb-bell test piece was then marked with two 20 mm-apart reference marks at the sample center, immediately prior to applying the tensile and elongation at break tests, as shown in Figure 6.

2.3. Detailed ageing procedures

After completing the preparation of test specimens as described above, there were some factors that had to be taken into consideration prior to the ageing process. These factors included the temperatures and times of ageing inside the ovens, the chosen property to reach the endpoint, the determination of endpoint itself and the circumstances and conditions inside the air oven. Moreover, after the ageing process completed, the experimental data were evaluated and the thermal endurance graph (Arrhenius plot) was plotted.

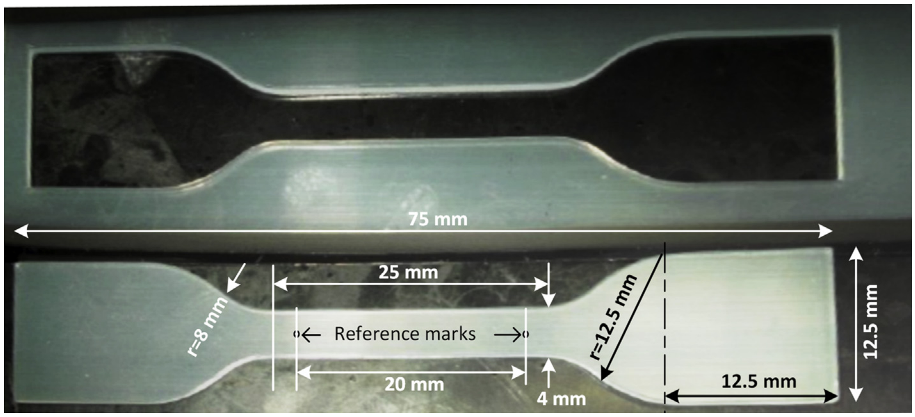

Figure 5. Dimensions of dumb-bell test piece [10].

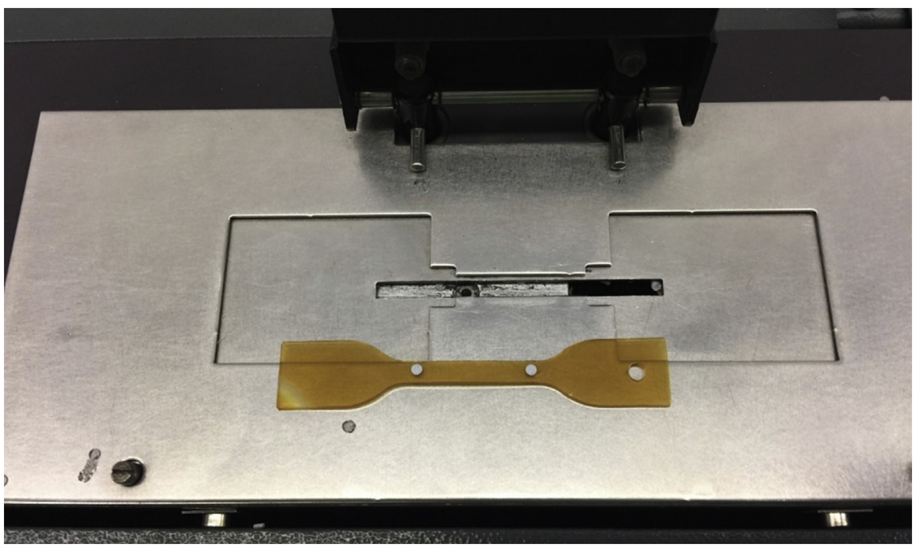

Figure 6. Sample puncture by gage marking device.

2.3.1. Selection of test property

The test property used in this study was the "Elongation at Break". The selection was based on two reference standards; clause 5.1.1.2 of BS 7870-2 [6] and Table 1 of BS EN 60216-2 [11].

2.3.2. Selection of the endpoint

The significance of identifying the endpoint is to determine the deterioration degree of the insulating material and to find out its ability to withstand the stress encountered in the real service. In this study, the selected endpoint of test property was "50% elongation at break" according to clause 5.1.1.2 of BS 7870-2 [6] and Table 1 of BS EN 60216-2 [11]. It is required in practice that the degradation degree indicated as the endpoint of the ageing test represents a permissible safe value for the material property.

2.3.3. Ageing temperature and time

To show a linear relationship between logarithm of time to end-point and reciprocal accelerated ageing absolute temperature, a sufficient range of ageing temperatures was chosen. As per clause 5.1.1.2 of BS 7870-2 [6], a minimum of four temperatures were selected with a maximum temperature not exceeding 160 °C and at least 10 °C interval between the temperatures. It is recommended in clause 5.5 of BS EN 60216-1 [12] to choose at least three temperatures and preferably four but with the following requirements:

- The mean/median time to end-point should be greater than 5000 h at lowest temperature level.
- The mean/median time to end-point should be greater than 100 h at the highest temperature level.
- The extrapolation required for the temperature to find out the insulating material lifetime should not exceed 25 Kelvin.
- The intervals between selected ageing temperatures should be normally 20 Kelvin, but in some cases based on ageing mechanism, it may need to be reduced, but not less than 10 Kelvin.

Eventually, and according to the requirements of the reference standards, the chosen ageing temperatures in this study were 160 °C, 150 °C, 135 °C, and 125 °C.

The ageing treatment was carried out in air ovens operating in the normal laboratory atmosphere (ambient temperature) with either natural air flow or air flow by pressure. In this study, the air flow was controlled by a flowmeter, an instrument that can measure the flow rate inside the oven. The requirements as per BS EN 60811-401 [9] states that the air has to be circulated inside the oven in such a way that it flows over the test specimen surface and subsequently leaves out through an opening in the top. The air must change from 8 to 20 complete air changes per hour at a particular ageing temperature. Figure 7 shows the oven insertion of dumb-bell test pieces into ageing ovens.

Figure 7. Insertion and suspension of dumb-bell test pieces into ageing ovens.

2.3.4. Ageing process

All parameters were specified as indicated above and each group of specimens were inserted into the ovens. Each ageing oven was dedicated for only one type of material at the same time. The test specimens were suspended in a vertical manner basically at the oven's center with a clearance of not less than 20 mm between samples. The area occupied by the test specimens did not exceed 2% of the oven's volume, Figure 8.

Removal of the specimens from the oven was carried out in such a way that a proper sequence of ageing time is achieved at the specified temperature levels. In fact, this depends on the insulating material behavior under elevated temperatures as well as the operator's experience in dealing with the ageing process for such material. At each time of removal, five test specimens were removed and tested together as a test group. Before testing, the specimens were left at ambient temperature for at least 16 h, after their removal from the oven. Figure 9 shows the difference in appearance between aged and un-aged samples.

Thereafter, the tensile strength and the elongation at break tests were applied to reveal the extent of success of samples to reach the endpoint. The ageing treatment was stopped when one of the removed test groups fulfilled the 50% elongation at break, and the time of ageing at that specific temperature level was recorded accordingly. Figure 10 shows Dumb-bell test piece after the elongation process.

Regarding testing, it was carried out using Tensile Testing machine type Z030 made by ZwickRoell, as shown in Figure 11. The test temperature was adjusted to (23 ± 5) °C. The testing requirements according to the standards, regarding the distance between the grips and rate of separation, were taken into consideration. The distance was adjusted to 50 mm in length, while for the rate of separation was set to (250 ± 50) mm/min, as demonstrated in Figure 12.

3. Results and discussion

The ageing treatment was purposed to obtain the required ageing time to end-point at each chosen temperature level (i.e. 160 °C, 150 °C, 135 °C, and 125 °C). These data points were represented on Arrhenius graph with a straight line (regression line), and a regression line equation on the form of a "$y = mx + b$" was derived from the graph. After that, the extrapolation of this line was used as a guidance to obtain any unknown

Figure 8. Dumb-bell test pieces under thermal ageing process inside drying oven.

Figure 9. Difference in appearance between aged and un-aged samples.

Figure 10. Dumb-bell test piece after elongation process.

value on y-axis (*ln (time to end point in days)*) from the known values on x-axis (*1/T*). In Tables 2 and 3, the time to endpoint values obtained by ageing treatment at each temperature level are shown for the materials A and B respectively. It was observed that the time to endpoint dropped by 54 and 59 folds in Material A and B respectively by increasing the temperature from 125 to 160 °C, as shown in Tables 2 and 3.

The graphical representation of the Arrhenius plot for both materials is shown in Figure 13 and Figure 14, where the y-axis is representing the logarithm of time to end-point while x-axis is the reciprocal of the ageing temperatures. From the Arrhenius graphs in Figures 13 and 14, it can be observed that the plotted data points are scattered and not forming a straight line. Therefore, it is not possible to derive the regression line equation if the graph was not a straight line. Consequently, the "Least Squares" is the best statistical method used in such cases to determine a line of best fit for a set of data points by minimizing the sum of squares of the offsets "the residuals" created by a mathematical function. A "square" is specified by squaring the distance between the regression line and any represented data point. In regression analysis, independent variables are appointed on the x-axis while the dependent variables are appointed on the y-axis. Designations of dependent and independent variables can form the equation of the regression line, which is determined by the "least squares" method [13].

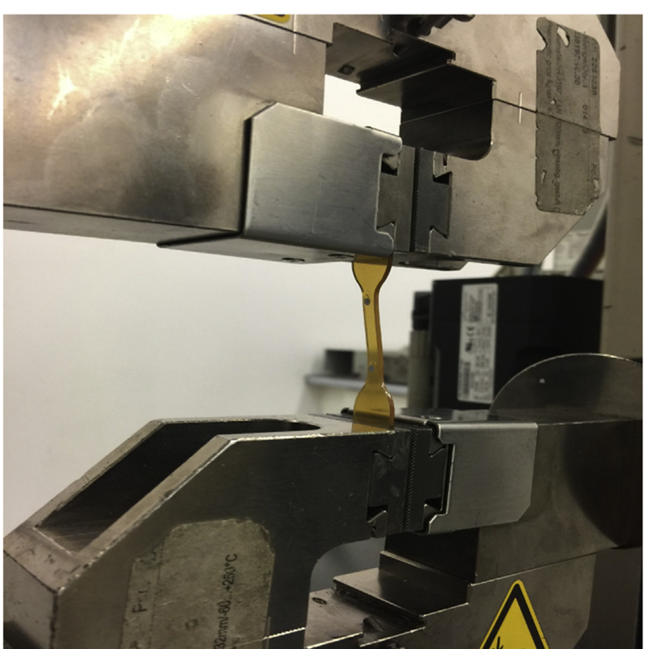

Figure 11. Zwick testing machine (Model: Z030) for tensile and elongation tests.

The regression line equations were determined and presented in Eqs. (4) and (5) for the materials A and B respectively:

$$y = 18641x - 41.422 \tag{4}$$

$$y = 19024x - 42.382 \tag{5}$$

The extrapolation for each regression line was performed, to calculate mathematically the unknown times to end-point at lower temperatures (i.e. 105 °C, 100 °C, and 95 °C). Thereby, any unknown dependent variable on y-axis can be calculated from the known independent variable on x-axis, by compensating in the regression line equation. Tables 4 and 5 show that the expected lifetime has dropped from 27.5 to 13.9 years for Material A, and from 29.7 to 14.9 years for Material B, which is approximately equivalent to a 100% reduction in lifetime, when the temperature was increased from 95 °C to 100 °C. When the temperature increased further by another 5 °C, to 105 °C, the lifetime dropped again from 13.9 to 7.2 years for Material A, and from 14.9 to 7.6 years for Material B. Usually, the lifetime for XLPE is expected to be between 40 and 60 years at 90 °C rated operating temperature [14]. In this study, the estimated cable lifetime is 7–30 years at a rated operating temperature of 95–105 °C. Table 6 summaries the findings of cable lifetime in years for XLPE materials A and B.

It is observed that the rate of increase in lifetime of XLPE cables is inversely proportional to the temperature. As the temperature decreases 5 °C, the rate of increase in lifetime increases almost twice. Mathematically, this rate has a negative exponential factor resulting from the exponential relationship of applied Arrhenius equation. But from technical perspective, it can be interpreted by the occurring of irreversible changes in the molecular structure of the insulating material that led to chemical reactions of cross-linking between chains, hydrolysis, oxidation, etc. and ultimately caused a degradation of materials' electrical and mechanical properties. In a recent study, it was found that crystallinity of the insulation layers was increased in a thermally aged XLPE cable with water-barrier design, and the crystallinity distribution across the radial disappeared [3]. It is well-known that the ageing process is significantly accelerated by certain factors such as temperature, radiation, and presence of water vapor and oxygen. A study of XLPE lifetime estimation under thermal ageing proved that increasing the ageing temperature of XLPE will accelerate the chemical reactions and enhance the material thermal deterioration which can lead to a notable decrease in its mechanical properties and hence a decrease in its lifetime [15]. The

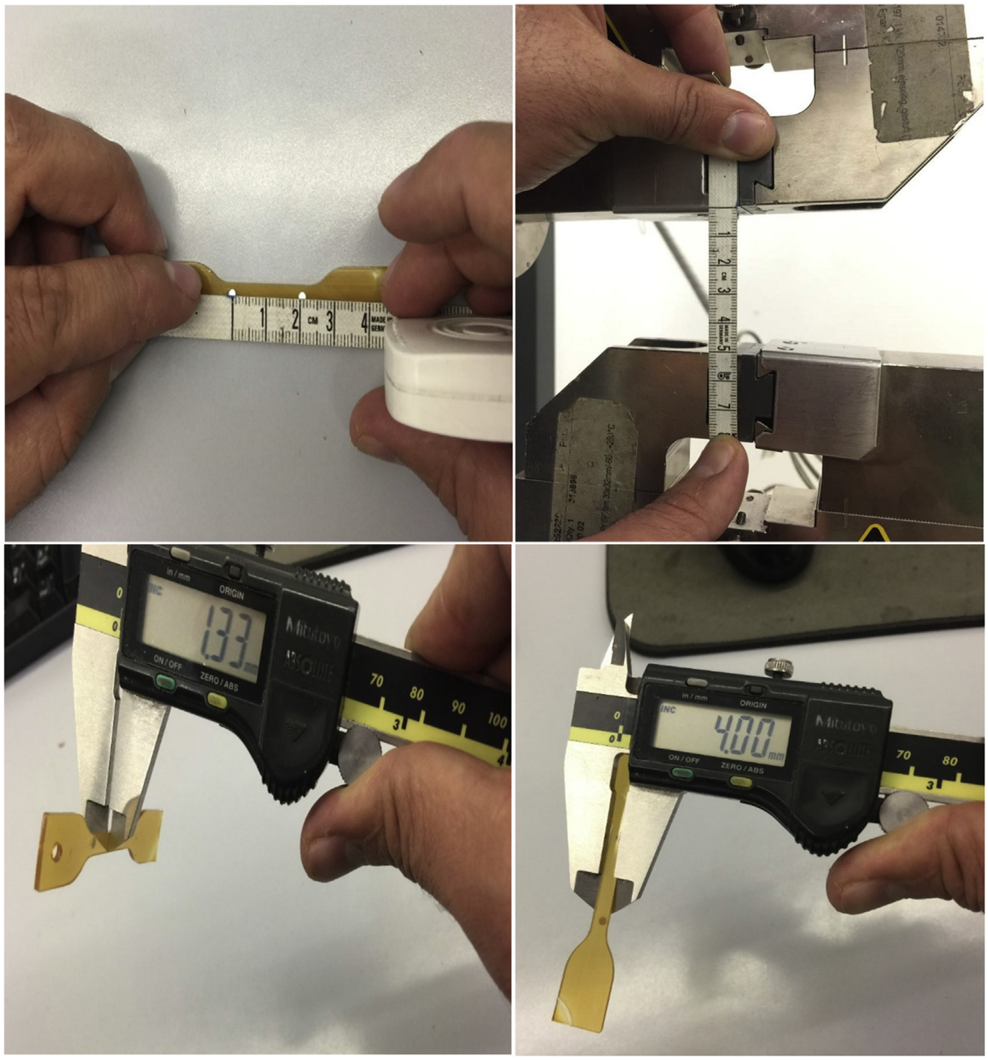

Figure 12. Dimensions measurement of a dumb-bell test piece and between two specimen grips.

Table 2. Data used for graphical representation of Arrhenius plot for material A.

XLPE Insulating Material A

Ageing Temp. in °C	Ageing Temp. in °K (T)	(X-axis) Reciprocal of the ageing temp. 1/T (K^{-1})	Time to end-point in hrs	Time to end-point in days (t)	(Y-axis) Logarithm of time to end-point in days ln (t)
160	433.15	0.00231	107	4.46	1.495
150	423.15	0.00236	430	17.92	2.886
135	408.15	0.00245	1356	56.50	4.034
125	398.15	0.00251	5760	240.00	5.481

Table 3. Data used for graphical representation of Arrhenius plot for material B.

XLPE Insulating Material B

Ageing Temp. in °C	Ageing Temp. in °K (T)	(X-axis) Reciprocal of the ageing temp. 1/T (K^{-1})	Time to end-point in hrs	Time to end-point in days (t)	(Y-axis) Logarithm of time to end-point in days ln (t)
160	433.15	0.00231	97	4.04	1.397
150	423.15	0.00236	420	17.50	2.862
135	408.15	0.00245	1308	54.50	3.998
125	398.15	0.00251	5760	240.00	5.481

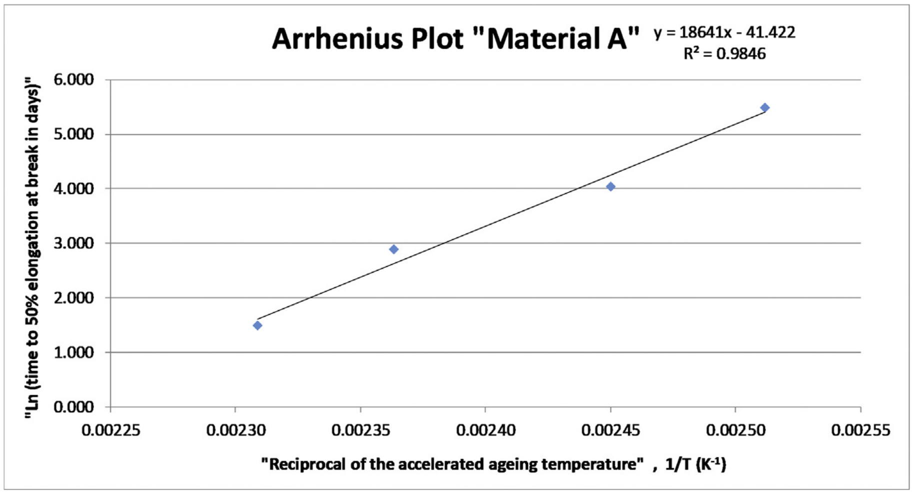

Figure 13. Arrhenius plot of material A.

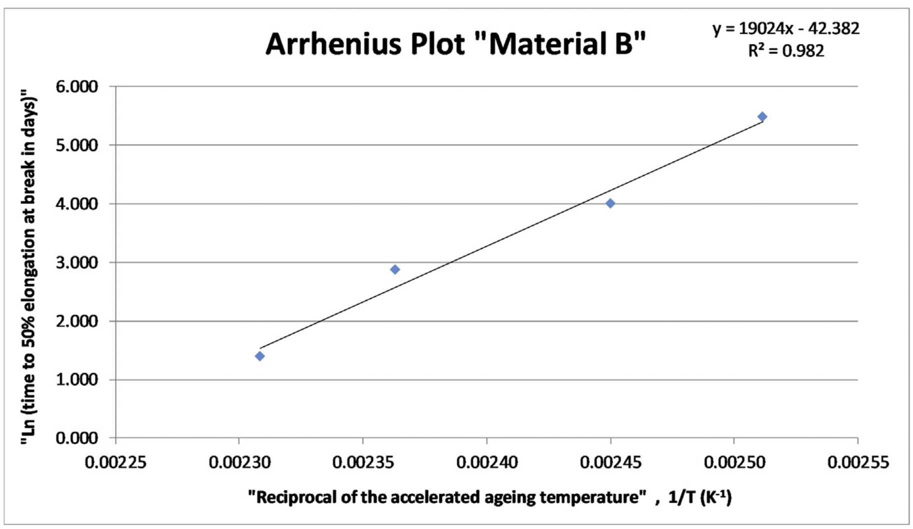

Figure 14. Arrhenius plot of material B.

Table 4. Extrapolation on regression line of material A to get the material lifetime at lower temperatures.

XLPE Insulating Material A

Ageing Temp. in °C	Ageing Temp. in °K (T)	(X-axis) Reciprocal of the ageing temp. 1/T (K^{-1})	(Y-axis) Logarithm of time to end-point in days ln (t)	Time to end-point in days (t)	Time to end-point in years (Cable Lifetime)
105	378.15	0.00264	7.874	2628.46	7.2
100	373.15	0.00268	8.535	5088.11	13.9
95	368.15	0.00272	9.213	10027.71	27.5

Table 5. Extrapolation on regression line of material B to get the material lifetime at lower temperatures.

XLPE Insulating Material B

Ageing Temp. in °C	Ageing Temp. in °K (T)	(X-axis) Reciprocal of the ageing temp. 1/T (K^{-1})	(Y-axis) Logarithm of time to end-point in days ln (t)	Time to end-point in days (t)	Time to end-point in years (Cable Lifetime)
105	378.15	0.00264	7.925	2765.58	7.6
100	373.15	0.00268	8.599	5426.53	14.9
95	368.15	0.00272	9.291	10844.44	29.7

Table 6. Comparison between expected lifetimes of two MV cables with different insulating materials under elevated temperatures.

Operating Temperature (°C)	Operating Temperature (°K)	Material A	Material B
		Cable Lifetime (Years)	Cable Lifetime (Years)
105	378.15	7.2	7.6
100	373.15	13.9	14.9
95	368.15	27.5	29.7

performance of a flame-retardant cross-linked polyethylene (FR-XLPE), when exposed to thermal ageing at 100, 135 and 155 °C for 800–2000 h, was found to be affected progressively, where oxidative degradation happened and an increase in conduction current and the real and imaginary permittivity were noticed [4]. These literatures support the findings of this study and can provide an explanation to the rapid drop in the XLPE cable lifetime when the operating temperature is slightly increased.

The interpretation of regression results is needed to evaluate the scatter of the data points around the fitted regression line. Measurement of the distance between a fitted line on a graph and whole data points that are scattered around that line can indicate the degree of this linear correlation. Such correlation is usually known as the "goodness of fit". The "goodness of fit" can be measured by two substantial keys: the coefficient of determination (R-squared), denoted by R^2 or r^2, and the standard error of the regression (S), also called the standard error of the estimate.

R-squared is a statistical measure term that shows the proportion of the variance in the dependent variables that is determined from the independent variables. R-squared measures the strength of the relationship by defining how close the data are to the fitted regression line on a convenient stated scale from 0 to 100%. R-squared is given by the following formula (6).

$$R^2 = \frac{Variance\ Explained\ by\ the\ model}{Total\ Varience} \tag{6}$$

As the distances between the observed values and the fitted values decrease, R-squared value increases. When R-squared is 0%, this means that the variation in the response data is not around its mean which shows a poor fit model while 100% R-squared means that the variation in response data is around its mean which shows a perfect fit model. The accuracy in the prediction of the dependent variables, by using the independent variables, increases as the R-squared value approaches 100%.

Although R-squared is an important tool in the assessment of the regression model, it has some limitations. R-squared only gives a prediction of the linear correlation for variances of the dependent variable based on the independent variables values. It doesn't clarify whether the applied model is good or bad, nor it determines if the data and coefficient estimates are biased. It is not possible to know that the regression model has an adequate fit to the data points by defining the value of R-squared. The reliability of the model is uncorrelated to the R-squared value. In some cases, a good model has a low R-squared value while another poorly fitted model has a high R-squared value. Accordingly, the determination of the standard error of the estimate is necessary as an assistant factor to evaluate the regression model. The absolute measure of the distances (errors) between the observed values and the fitted values on the regression line is defined as the standard error of regression (S). S is calculated in the units of the dependent variables and it can show how far the data points are from the regression line on average. Model assessment via calculating the standard error of the estimate is valid for linear and non-linear regression models whereas the assessment via R-squared is valid only for the linear regression model. As the value of S is lower, this means that the regression model fits the data well. S is given by the following formula (7).

Table 7. Calculations of R-squared and standard error of the regression for two different MV cable insulating materials.

	Material A	Material B
R-squared	98.46%	98.20%
S	0.258	0.284

Table 8. Measurement uncertainty.

Parameter	Uncertainty (%)
Ageing Temperature	0.94
Elongation at break	0.7686
Total uncertainty (Lifetime uncertainty)	1.7086

$$S = \sqrt[2]{\frac{\sum (\hat{Y} - Y)^2}{n-2}} \tag{7}$$

where,

$\hat{Y}$: is the fitted values (also called estimated values).
Y: is the observed values (also called actual values).
n: is the number of observations.

For the assessment of the two models of this study, the R-squared and the standard error of regression are calculated using Eqs. (6) and (7) respectively as shown in Table 7. Table 7 shows that the two models have high R-squared values, 98.46% for Material A and 98.2% for Material B, with low values of the standard error of regression (S), which are 0.258 and 0.284 for Materials A and B respectively. This means that the data points are very close to the fitted regression line and the distances (errors) between the observed values and the fitted values on the regression line are small, which indicates that both models are reliable and fit data well.

4. Uncertainty calculations

To assess the reliability of ageing process results, it is necessary to calculate the uncertainty of those results. This can help to find out the accuracy of the measurements as well as the confidence level that can inform any future decisions based on its application. In this study, the uncertainty calculation of the material lifetime is essential, to reduce future decision risks. The uncertainty, based on Arrhenius equation, relies on the determination of two major parameters: the ageing temperature and the endpoint, which is represented in the measurement of elongation at break. The total uncertainty expressed in lifetime is the combination of the uncertainty value of ageing temperature plus the uncertainty value obtained from the elongation at break. The uncertainty calculations are detailed in Appendix A. The ageing temperature and the elongation at break uncertainties are 0.94 % and 0.7686 %, respectively. The lifetime uncertainty is the total uncertainty of the ageing temperature and the elongation at break, which is 1.7086%. The uncertainty in the measurement calculations is summarized in Table 8. The total uncertainty reported in the measurement is referred to as the maximum standard uncertainty in the measurement times a coverage factor K = 2, which corresponds to a 95 % confidence interval for a normal distribution.

5. Conclusion

Application of the Arrhenius model together with the accelerated thermal ageing was effective in estimating the cable lifetime of XLPE insulating material working under elevated temperatures. This approach made it possible to compare between two different XLPE insulating materials for medium and high voltage power cables. Experimental results showed an estimated cable lifetime between 7 and 30 years for rated operating temperature between 95 and 105 °C. Based on the above analysis and on the regression model, the accelerated ageing process for estimating cable material lifetime proved to be accurate. This can open pathways for further studies.

From the results above, the XLPE material B has a longer lifetime than the material A, under the same ageing temperature level. This can be attributed to its high degree of purity, the extremely low level of contamination and the appropriate balance of non-staining antioxidant and peroxide, which cornubite to thermal stability and optimum cure levels.

Declarations

Author contribution statement

Abdulsalam S. Alghamdi: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Rayan K. Desuqi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

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