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Life assessment of marine ethylene propylene rubber power cables based on hardness retention rate

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Abstract: The lifetime of ethylene propylene rubber (EPR) insulated cables will decrease because of complex aging processes. From the safety perspective, insulation condition assessment of the cable is essential to maintain an efficient and reliable operation. As a nondestructive and online evaluation method, a hardness retention rate was used to estimate the lifetime of cable. First, accelerated thermal aging tests in the laboratory were performed to measure the elongation at break retention rate (EAB%) and a hardness retention rate at different temperatures. Second, the aging values were processed by the Arrhenius equation and time temperature superposition to assess aging lifetime of insulation at different temperatures and end levels. As the insulation condition assessment of the cable by hardness retention test has no approved standard, the EAB% data were correlated with hardness retention to provide an evaluation basis. The results show that when EAB% picks out the time corresponding to a certain amount of 50% degradation, 10% of hardness retention was chosen as the termination index.

Key words: ethylene propylene rubber (EPR), nondestructive, hardness retention rate, elongation at break retention rate (EAB %), termination index

1. Introduction

There are many cables that perform safety-related roles in marine and should implement condition monitoring during the operation period to assess the remaining qualified life and extend the qualified life. Under the normal operation condition, cables may be exposed to high heat, humidity, thermal and mechanical shock, which can cause them to lose their desired characteristics earlier than expected and accelerate their aging. While faults can occur in any portion of a cable, there is a need to develop advanced methods for nondestructive evaluation of cable insulation that is universally applicable [1].

In-situ, main test technique for cable maintenance is visual and tactile inspection, which identifies cracks, visible contamination and discoloration of the cables [2]. In an industrial test, the key indicators of the cable's condition are its mechanical, chemical and electrical properties of age-related degradation [3].

Commonly used analytical techniques for mechanical property changes include elongation at break (EAB), indenter modulus (IM), dynamic mechanical analysis (DMA) and ultrasonic measurements (UM) [4]. Chemical property changes include differential scanning calorimeter (DSC), thermo-gravimetric analysis (TGA) and Fourier transform infrared spectrometer (FTIR). Electrical property changes include time-frequency domain reflectometry (TDR and FDR), insulation resistance (IR), partial discharge (PD) and tan delta.

Table 1 summarizes the pros and cons of the various inspection methods that are considered viable for detecting flaws and aging in cables. As can be seen in Table 1, DMA, UM, DSC, TGA, FTIR, TDR/FDR and Tan-delta need expensive testing equipment and trained personnel [5]. IR needs to disconnect the cables to install instrumentation. PD is good for determining voids or defects in insulation of medium voltage cables, but not suitable for the cable described in this paper. The EAB has been widely accepted as an industry standard to predict remaining lifetime, but it needs a large amount of samples, and an experiment time is longer in other methods. Moreover, all methods except IM, TDR/FDR and Tan-delta profiling are destructive, while EAB and IM were the most common tests performed.

Table 1. Comparison of cable inspection methods

Method	**Sensitivity**	**Wide applicability**	**Amount of sample**	**Destructive**	**Detection range**	**Cost**	**On line**
mechanical							
EAB	high	yes	large	yes	part	low	no
IM	high	no	none	no	part	low	yes
DMA	high	no	small	yes	part	low	no
UM	high	no	small	no	part	high	no
chemical							
DSC	high	yes	small	yes	part	high	no
TGA	high	yes	small	yes	part	high	no
FTIR	high	no	small	yes	part	high	no
electrical							
T/FDR	high	yes	none	no	whole	high	no
IR	low	yes	none	no	whole	low	yes
Tan	high	yes	none	no	whole	high	yes
PD	low	no	none	no	part	high	yes

We focused on the IM, which can measure the hardness retention rate of the cable described in this article [6]. This method is selected because it is nondestructive and needs short testing time and small sized equipment. Because the insulation condition assessment of the cable by hardness retention rate test has no approved standard [7], the goal of the research presented in this paper is to correlate hardness retention measurement with EAB% data through the lab test to provide an assessment of a cable's current condition as well as its remaining useful life (RUL).

2. Experimental methods

Fig. 1 shows the structure of the 0.6/1 kV EPR cable and the cross sectional area of the conductor is 120 mm^2. The cable consists of: the copper conductor, EPR insulation and outer sheath. The experiment specimens were prepared by removing the sheath and the central conductor to leave only the insulation layer.

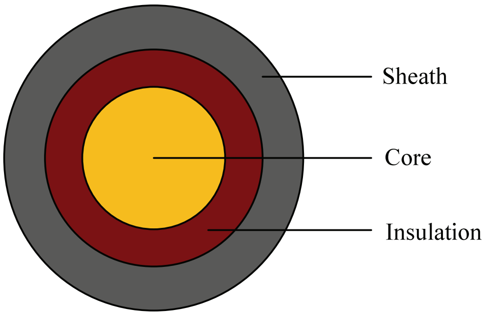

Fig. 1. The cross section of EPR cable

In this paper, the insulation layer was selected as the raw materials and according to the IEC 60811-1-1:2001, IDT, the shape and dimension of dumb-bell specimens were shown in Fig. 2. A manual punching machine was used to make dumb-bell specimens and a sample thickness of 2 mm and difference less than 0.1 mm was chosen as the standard specimens.

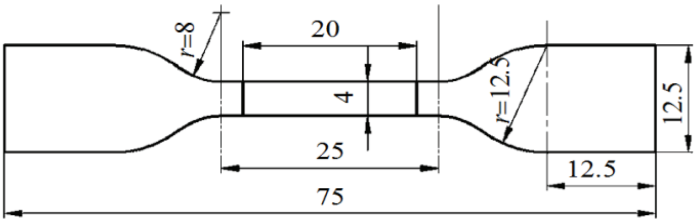

Fig. 2. Dimension of dumb-bell specimen (mm)

2.1. Accelerated thermal aging

Electric ovens with air circulating fans were used to accelerate aging of specimens. According to specification of American power stations and IEC 60216, the accelerated thermal aging temperatures of 120°C, 135°C, 150°C and 165°C were selected. There were five standard dumb-bell specimens aged in different sampling periods of each ageing temperature. Thermal aging temperatures and sampling periods were shown in Table 2.

Table 2. Thermal aging temperatures and sampling periods

Temperature	**Periods/h**							
120°C	120	192	264	456	648	1108	1440	2088
135°C	96	192	240	360	456	648	1108	1272
150°C	48	96	144	192	240	288	312	324
165°C	24	36	48	60	72	84	96	108

2.2. Elongation at break measurement

The specimens were air cooled for 16 h after finishing the accelerated aging. The JDL-1000 tensile machine was used to measure the elongation of the cable under different aging conditions and the speed of elongation was 50 mm/min and at 23 ± 2°C, 50% RH. There were five standard dumbbell samples at each experimental temperature. One of the most common methods for EAB% was to use the Arrhenius Equation (1), where t_1 is the estimated age, t_2 is the time the specimen was aged, T_1 is the service temperature, T_2 is the aging temperature, E_a is the activation energy, and R is the Boltzmann constant.

$$t_1 = t_2 e^{[(E_a/R)(1/T_1 - 1/T_2)]} . \tag{1}$$

2.3. Hardness retention rate

Hardness testing is a nondestructive aging evaluation method, which measures the hardness retention of a cable by pressing a cable surface with a steel probe in the vertical direction.

According to the standard of GB/T531.1-2008, ISO 7619-1:2004 and the thickness of the specimens, the Shore AM durometer was used to determine the hardness of the insulation. There were five points tested were made for each aged cable specimen. The lowest and highest values were excluded and the remaining values were used in the statistical evaluation. According to the calculation method of property variation percent during aging in GB/T 3512-2014, the hardness retention was proposed in this paper and the equation was described as e.g. (2):

$$p = \frac{100 - X}{100} \times 100\% , \tag{2}$$

where: p is the hardness retention rate; X is the hardness value after aging.

2.4. Time-temperature superposition

Time-temperature superposition has been used for long-term structural durability design with short-term accelerating tests at elevated temperatures [8]. Many previous work [9] had shown that the time-temperature shifting was applicable to the life estimation of insulation materials. Correspondence between the time and the temperature can be achieved by time-temperature shifting with suitable shift factors α_{Ti}, it could be described as e.g. (3):

$$\alpha_{Ti} = \frac{t_{\mathrm{ref}i}}{t_i}, \tag{3}$$

where: $t_{\mathrm{ref}i}$ is the time of reference temperature T_{ref}, t_i is the original time before shifted at T.

The shift factors can be correlated with the temperature by the Arrhenius Eq. as e.g. (4):

$$ln\alpha_{Ti} = \frac{E_a}{R}\left(\frac{1}{T_{\mathrm{ref}}} - \frac{1}{T}\right). \tag{4}$$

For calculation the reliability of the time-temperature shift factors at each temperature, an optimal calculation method was proposed as e.g. (5):

$$R^2 = \frac{S_{xy}^2}{S_{xx}S_{yy}}, \tag{5}$$

where:

$$S_{xx} = \sum_{i=1}^{n}\sum_{j=1}^{n_i}(\alpha_{Ti}t_{ij})^2 - \frac{1}{\sum_{i=1}^{m} n_i}\left(\sum_{i=1}^{n}\sum_{j=1}^{n_i}\alpha_{Ti}t_{ij}\right)^2, \tag{6}$$

$$S_{yy} = \sum_{i=1}^{n}\sum_{j=1}^{n_i}(P_{ij})^2 - \frac{1}{\sum_{i=1}^{m} n_i}\left(\sum_{i=1}^{n}\sum_{j=1}^{n_i}P_{ij}\right)^2, \tag{7}$$

$$S_{xy} = \sum_{i=1}^{n}\sum_{j=1}^{n_i}\alpha_{Ti}t_{ij}P_{ij} - \frac{1}{\sum_{i=1}^{m} n_i}\left(\sum_{i=1}^{n}\sum_{j=1}^{n_i}\alpha_{Ti}t_{ij}\right)\left(\sum_{i=1}^{n}\sum_{j=1}^{n_i}P_{ij}\right), \tag{8}$$

where: $\alpha_{Ti} = 1$, $\alpha_{Ti} > 1$ ($i = 2, \ldots, m = 4$), i presents the sequence numbers of each temperature, $j = 1, \ldots n_i = 8$ are the sequence numbers of i, p_{ij} is the insulation property variation percent, t_{ij} is the aging time.

3. Results and discussion

The cable insulation was thermally aged at 120°C, 135°C, 150°C and 165°C, Table 3 showed the average value of EAB% and the hardness retention rate (P) for different thermal aging time. The EAB% and P were decreased with the increase of aging time.

According to time-temperature superposition theory, the EAB% and P values of thermal aging temperature of 120°C were selected as the reference temperature, then shifting data at each higher temperature of 135°C, 150°C and 165°C horizontally by the constant multiplicative factor that gives the best overall superposition used the optimal calculation method with the reference curve ($\alpha_T = 1$ for the reference temperature).

Table 3. The experimental data of EAB% and hardness retention rate testing

Temperature/°C	**Time/h**	**EAB%**	**P(%)**	**Temperature/°C**	**Time/h**	**EAB%**	**P(%)**
120°C	120	97.7	31.4	135°C	96	94.8	30
	192	94.3	30.8		192	90	28.8
	264	92.5	30.2		240	88.1	27.7
	456	85.8	27.4		360	84.4	26.5
	648	78.8	25		456	78.8	25.8
	1108	67.1	19		648	70	23
	1440	56.1	16		1108	48	14
	2088	15.2	7		1272	22.2	9
150°C	48	90.1	29	165°C	24	88.3	28.6
	96	83.4	28.2		36	82.6	27.8
	144	79.6	26.4		48	76.8	27
	192	70.6	24		60	70.3	25
	240	60.3	20		72	64.8	21
	288	45	14		84	60.8	17
	312	22.9	11		96	54	14
	324	18.7	8		108	27.3	10

As shown in Fig. 3 and Fig. 4, the shift factors of EAB% and P were (18, 6.4, 1.6, 1) and (17, 5.8, 1.6, 1), respectively. It is clear that the EAB% and P change curves at different temperatures have the same shape and show an excellent superposition.

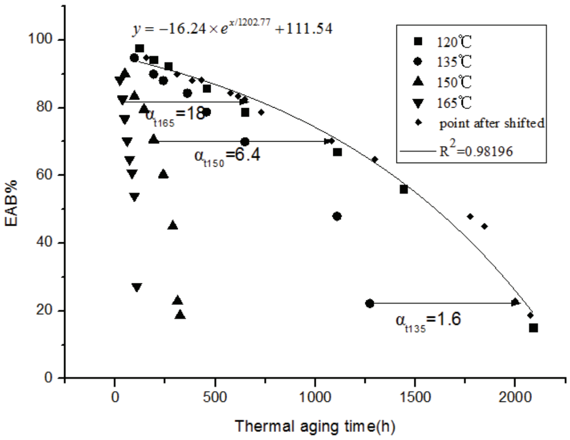

Fig. 3. The fitting curve of EAB%

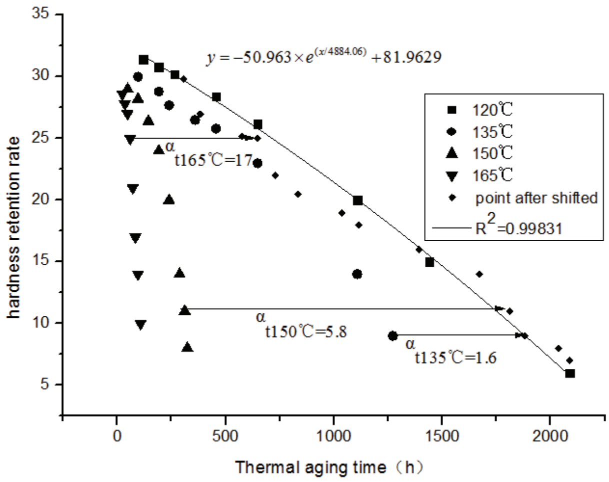

Fig. 4. The fitting curve of hardness retention rate

The fitting curve equations were described as e.g. (9):

$$\begin{cases} \text{EAB\%} = -16.24\times e^{t/1202.77}+111.54 \\ P=-50.963\times e^{t/4884.06}+81.9629 \end{cases}, \tag{9}$$

where: t is the aging time at 120°C, P is the hardness retention rate; EAB% presents elongation at break retention rate.

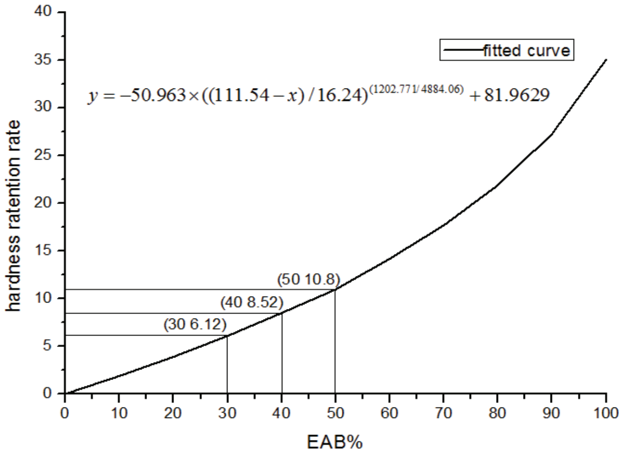

Fig. 5. The relation of EAB% and hardness retention rate

Once the shift factors are determined, they can be tested with Arrhenius Equation 4, the slope of the $ln(\alpha_T)$ versus inverse absolute temperature yields a linear curve with the slope representing the activation energy, as shown in Fig. 6.

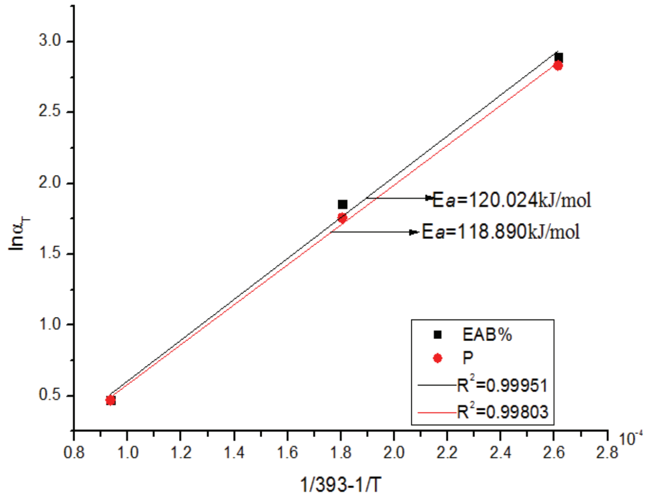

Fig. 6. The Arrhenius plot of the shifting factors at a reference temperature of 120°C

The activation energy represents the minimum energy needed for the aging reactions to occur. By obtaining the activation energy from the accelerated aging tests and assuming the aging reaction remains the same at lower temperatures, the lifetime can be predicted for the low-temperature, long-term aging conditions. The activation energy values obtained from the EAB% and the P were 120.024 kJ/mol and 118.890 kJ/mol, respectively.

4. Life prediction and correlation

The traditional Arrhenius analysis of EAB% usually picks out the time corresponding to a certain amount of 30%-50% degradation, but an indent test has no approved standard. In order to provide a standard to determine the lifetime through the indent test, this paper correlate hardness retention rate with EAB% data to provide the assessment of a cable's current condition as well as its usefulness in life.

According to Equation 4 and the activation energy, the lifetime of cable insulation under different temperatures as well as end levels as shown in Table 4. It can be seen that the errors between EAB% and the hardness retention rate at different temperatures and end levels were very small. When EAB% picked out the time corresponding to a certain amount of 50%, 40% and 30% degradation, the termination index of hardness retention was between 10.8%, 8.52% and 6.12%. The histograms shown here demonstrate that when the working temperatures were 70°C, 75°C, 80°C and 85°C, the maximum differences were 2.3a, 1.1a, 0.5a and 0.2a, so it was proved that the nondestructive evaluation method based on a hardness retention rate can correctly predict the durability of cable under different condition. It can also be seen that only the temperature effect was considered in the calculation in this paper and a certain margin of error was lift, so only 10% of the hardness retention rate was chosen as the termination index.

Table 4. The aging lifetime (a) of cable under different temperatures and end levels

T	70°C	75°C	80°C	85°C
EAB% = 50%	38.7	21.1	11.7	6.6
P = 11%	37.1	20.4	11.4	6.5
EAB% = 40%	43.1	23.5	13.1	7.4
P = 8.52%	41.0	22.5	12.6	7.2
EAB% = 30%	46.9	25.6	14.2	8.0
P = 6.12%	44.6	24.5	13.7	7.8

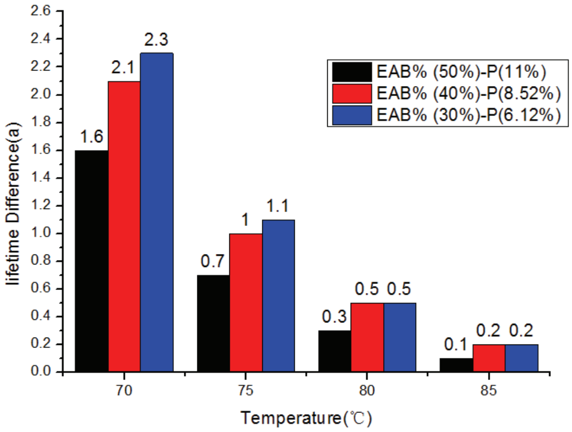

Fig. 7. The difference between EAB% and hardness retention rate

5. Conclusions

The insulation of EPR cable was subjected to age at 120°C, 135°C, 150°C, and 165°C. The following conclusions can be drawn:

1) The elongation at break retention rate and hardness retention rate of specimens were measured, the data at different aged time were successfully superimposed by horizontal shifting along the logarithmic time axis according to the Arrhenius equation.
2) Based on EAB% picks out the time corresponding to a certain amount of 50% degradation, the termination index of hardness retention was 10.8%. Taking the other factors into consideration, 10% of hardness retention rate was chosen as the termination index.
3) The detection method of hardness retention rate proposed in this paper is a nondestructive procedure. One just needs to know the hardness retention rate value of cable obtained in the process of testing, and then the method is easy to implement.

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