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ASSESSING THE RELATIONSHIP BETWEEN COLOR CHANGE AND TENSILE STRENGTH IN THERMOPLASTIC POLYOLEFIN OUTER SHEATHS OF LOW-VOLTAGE POWER CABLES

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Article Info	Abstract
Article History: Received: February 5, 2024 Accepted: June 24, 2024 **Keywords:** Power Cables; Ultraviolet; UV Test; Cable Tests; Gray Scale Color Test; Insulation.	Power cables used outdoors age prematurely due to ultraviolet radiation. The mechanical strength of the cables may decrease and the color of the outer sheath of cable insulation changes when exposed to outdoor UV radiation. It is of great concern to know how the elongation strength of a cable varies with the exposure time to prevent cable break. The determination of the color of the cable insulator is also an important part of UV tests. In this study, Thermoplastic Polyolefin (TPO) insulation to be used in the outer sheath of low-voltage power cables is aged in a test chamber. 240-, 480-, and 720-hour test durations are chosen in the experiments. It has been found that the color change of TPO does not reflect the elongation at break and tensile strength value changes much and the elongation at break value of TPO is not a monotonous function of UV exposure time.

Alçak Gerilim Güç Kablolarının Dış Kılıfında Kullanılan Termoplastik Poliolefinin Renk Değişimi ile Gerilme Direnci Arasındaki İlişkinin Değerlendirilmesi

Makale Bilgileri	Öz
Makale Tarihçesi: Geliş: 5 Şubat 2024 Kabul: 24 Haziran 2024 **Anahtar Kelimeler:** Güç Kabloları; Ultraviyole; UV Testi; Kablo Testleri; Gri Tonlama Renk Testi; Yalıtım.	Açık havada kullanılan güç kabloları morötesi radyasyon nedeniyle erken yaşlanır. Dış mekânda mor ötesi ışınlarına maruz kaldığında kabloların mekanik mukavemeti azalabilir ve kablonun dış kablo kılıfının rengi değişir. Kablo kopmasını önlemek için bir kablonun uzama mukavemetinin maruz kalma süresine göre nasıl değiştiğini bilmek büyük önem taşımaktadır. Kablonun yalıtkanının renginin belirlenmesi UV testlerinin önemli bir parçasıdır. Bu çalışmada alçak gerilim güç kablolarının kılıfında kullanılacak Termoplastik Poliolefin (TPO) yalıtkanının bir test odasında yaşlandırılması yapılmıştır. Deneylerde 240, 480 ve 720 saatlik test süreleri seçilmiştir. TPO'nun renk değişiminin kopma uzamasını ve gerilme direncinin değişimini fazla yansıtmadığı ve Kopma uzamasının morötesi maruziyet zamanının monoton bir fonksiyonu olmadığı ve tespit edilmiştir.

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1. Introduction

The cable insulations age when exposed to heavy thermal, electrical, environmental, chemical, and mechanical stresses (Thue, 2017, Dang et al., 1996, Shwehdi et al., 2003). Reviews of electrical insulation aging models can be found in the literature (Dang et al., 1996, Choudhary et al., 2022). Insulators of outdoor power cables are exposed to sunlight, ultraviolet, (UV) light, and humidity and that's why the power cables used outdoors age quickly (Arora et al., 2004, Karhan M., 2021, İlhan et al., 2004). UV test chambers are commonly made to examine their mechanical and electrical behaviors (Zhu et al., 2023). Xenon light test chambers are expensive but they can emulate sunlight and UV exposure very well, and that's why they are commonly used in aging experiments (Hedir et al. 2016). In this test, a UV chamber, which was illuminated artificially with a Xenon light lamp (Liu et al., 2021, Pandey, 2008), is used to age the insulators for a predetermined amount of duration described with standards such as IEEE 1580:2021 and UL 2556 (IEEE 1580-2021, 2021, UL 2556, 2021). The aged insulator pieces are cut as dump bells, they are aged in the chamber, and, then, their electrical and mechanical strength is tested (Hedir et al., 2020, Alghamdi et al., 2020, Shwehdi et al., 2003). Elongation at break is one of the commonly made mechanical tests (Alghamdi et al., 2020, Tan et al, 2023). Exposure to sunlight or such an artificial lamp also causes the insulator to change its color (Amin et al., 2011). A gray scale is used to determine the unaged and aged insulators' colors. Thermoplastic polyolefin (TPO) insulation is used in low-voltage power cables (Amin et al., 2011, Ismail et al., 2018). The mechanism of polyolefin photodegradation has been reported (Guillet, 1980). Geussens (2021) has provided a review on it. Degradation studies of polyolefins incorporating transparent nanoparticulate zinc oxide UV stabilizers were conducted by (Ammala et al., 2002). The reactions causing degradation during weathering and photo-oxidation of polyolefins are reviewed comprehensively (Grause et al., 2020). To the best of our knowledge, there are not any studies examining the time-dependent relationship between color change and the mechanical strength of TPO material. This study aims to determine whether the color change implies the mechanical strength of the aged TPO material or not. For this purpose, thermoplastic polyolefin dump-bell pieces are aged in a Q-SUN Xenon light test chamber for three different test durations determined according to UL 2556 (IEEE 1580-2021, 2021), the tensile strength and Elongation at Break values of the unaged and the aged TPO samples are measured as described in UL 2556 (UL 2556, 2021), and their colors are defined using a gray scale tool (Bide, 2010).

2. Material and Method

2.1 UV Ageing Test of the Thermoplastic Polyolefin

The explanation of the experimental procedure of the Ultra Violet test is presented in IEEE 1580:2021 (IEEE 1580-2021, 2021). The flowchart of the test process is presented in Figure 1. The endpoint of the test properties for Thermoplastic polyolefin material is selected as 80 % Elongation at break and Tensile strength in this study whose monitoring is made according to the standard IEEE 1580:2021 (IEEE 1580-2021, 2021).

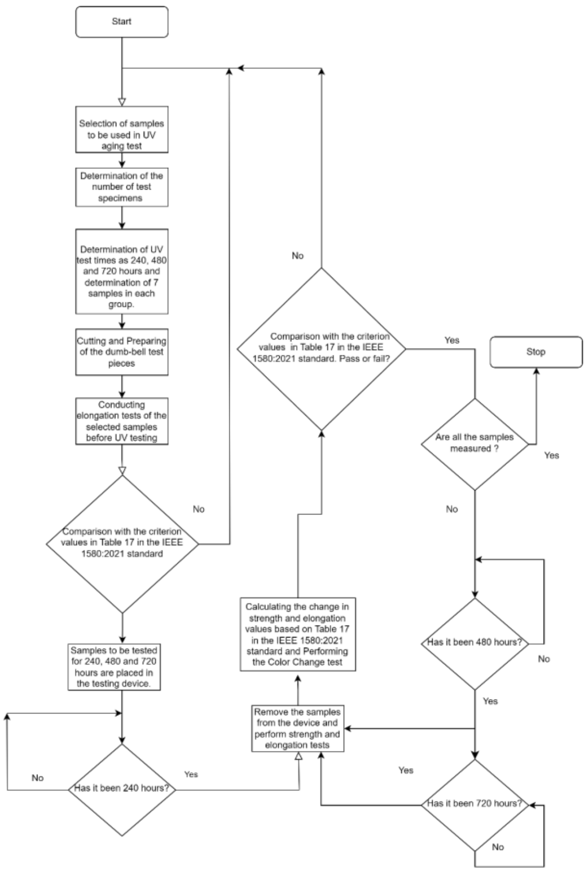


Figure 1. The flowchart of the UV aging experiment

The exposure durations are selected according to standard IEEE 1580-2021 (IEEE 1580:2021, 2021).

12]. Dumb-bell test pieces are prepared with dimensions according to Standard IEC 60811-501 as seen in Figure 2 (IEC 60811-501, 2011).

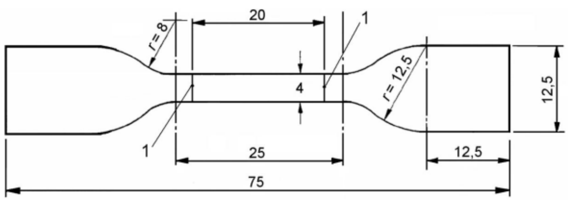


Figure 2. Dimensions of the Dumb-bell test pieces prepared according to Standard IEC 60811-501 (IEC 60811-501, 2011).

2.2. Experimental Results

Thermoplastic polyolefin used in the experiments is made with raw material produced by Avient. The thermoplastic polyolefin dumb-bell pieces are cut with a tensile testing machine and are shown in the photograph given in Figure 3. A total of 28 dumbbell samples were used in the experiments. The Q-SUN Xenon light test chamber used in the tests can be seen in Figure 4 (Q-SUN Xenon light test chamber). The dumb-bell pieces are placed in the Q-SUN Xenon light test chamber as shown in Figure 5.

Figure 3. The thermoplastic polyolefin dumb-bell pieces prepared.

Figure 4. The Q-SUN Xenon light test chamber used for the UV aging test.

Figure 5. The thermoplastic polyolefin dumb-bell test pieces placement in the Q-SUN Xenon light test chamber.

The prepared samples or dumb-bell pieces should be tested for the specified time in the Xenon-arc test chambers, providing that the pH of the water is between 4.5-8.0 and surfaces exposed to the light source should not be polished, stripped, or planed. Impression marks should be applied after conditioning. For comparison purposes, the unaged samples are also prepared in the same manner. Each cycle of the Xenon-Arc apparatus consists of 102 minutes of lighting and 18 minutes of lighting besides water spraying. The samples should be properly mounted in the Xenon-arc apparatus according to the manufacturer's instructions. Following the exposure, the samples are maintained in the testing apparatus and stagnant air under ambient room temperature conditions for not less than 16 hours and not more than 96 hours at atmospheric pressure. The dumbbell samples were tested in a UV tester according to UL2556 standard with reference to ASTM G155 Cycle 1 method (ASTM G155, 2021). After the UV exposure, a photograph of the aged pieces is shown in Figure 6. In general, it has been observed in UV experiments that the strength of the material increases and elongation decreases at the same temperature and after an aging time defined in the standard. This is the case for HFFR (Halogen Free, Flame Retardant) materials.

(a)

(b)

Figure 6. The Dumb-bell Test Pieces a) Before UV Aging Test and b) After a 720 h UV Aging Test

The elongation at break and Tensile strength tests were performed according to international standard IEC 60811-501. A Zwick/Roell Z010 10kN ProLine machine is used for this purpose. and a photo taken during an elongation at break test is shown in Figure 7. A photograph taken during the evaluation of the test results of the broken thermoplastic polyolefin pieces is shown in Figure 8. The average value of the measurement results obtained from each experiment is used to evaluate the experimental results. The average values of the elongation at break and the tensile strength obtained with the UV exposure test and the UV exposure times are presented in Table 1.

Figure 7. The elongation at break test with a Zwick/Roell Z010 10kN ProLine 739384.

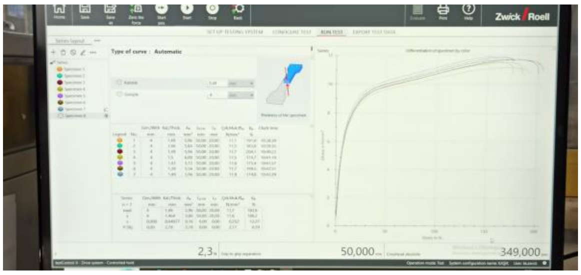


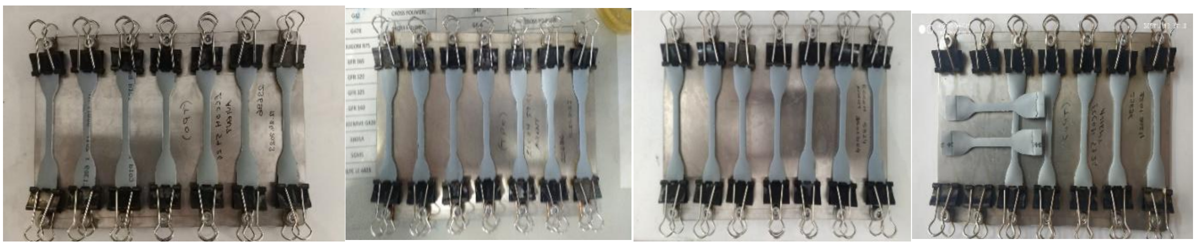
Figure 8. The screen of the Zwick/Roell machine interface program showing the test results of the thermoplastic polyolefin dumb-bell pieces after the tensile strength test.

The tool known as gray scale is based on 5 major and 4 intermediate step gradations and is used to visually evaluate and compare the color loss of a sample. The rating consists of matches of gray swatches, from 5 best to 1 poorest. Each pairing shows the difference in shade between a tested sample and a control sample corresponding to a numbered rating. The gray scale tool shown in Figure 9 is used to evaluate the colors of the test pieces. The color of the samples after being tested in the UV chamber for 240, 480, and 720 hours can be seen in Figure 10. The color of the material has varied from dark gray to light gray. The assessed color codes can be found in Table 1.

Figure 9. The gray scale tool used in this study.

Table 1. Test Results

Test Duration or Exposure Time (h)	0	240	480	720
Tensile Strength (N/mm2)	11.47	11.69	12.52	15.35
Elongation at Break (%)	204.25	183.85	162.38	165.76
Grayscale color code	5	4/5	4	3/4



(a) (b) (c) (d)

Figure 10. Appearance changes of the dumb-bell test pieces with a UV exposure time of a) 0 h (unaged), b) 240 h, c) 480 h, and d) 720 h.

3. Results and Discussion

The elongation at break and Tensile strength values of the samples are shown in Figure 11. The elongation at break has decreased by %18,84 and the tensile strength has only increased by %33,83 after the UV exposure. This indicates that UV exposure increases the tensile strength and the color change does not always indicate the mechanical strength loss. Considering the experimental exposure times, the tensile strength increases monotonously. However, the elongation at break with respect to exposure time decreases first and starts increasing again. It is found that the elongation at break as a function of exposure time can be expressed as the following cubic polynomial:

$$\mathcal{E} = a_3 t^3 + a_2 t^3 + a_1 t + a_0 \quad (1)$$

where $\mathcal{E}$ is the elongation at break and t is the exposure time.

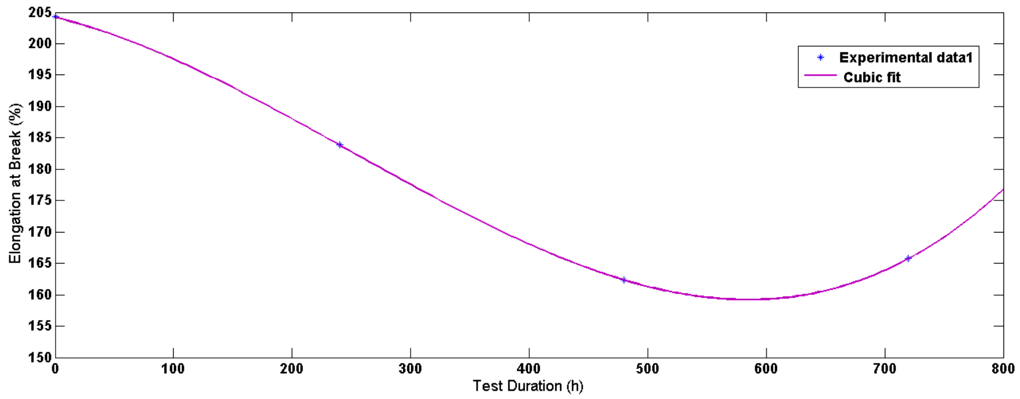
The parameters of the polynomial of the curve fitted elongation at break are found as $a_1 = -0.046771$, $a_2 - 0.00023429$, $a_3 = 3.125\text{e} - 07$, and $a_0 = 204.25$. Norm of residuals of the elongation at break function is pretty low and equal to 1.3024e-13.

The tensile strength as a function of exposure time can be expressed as the following cubic polynomial:

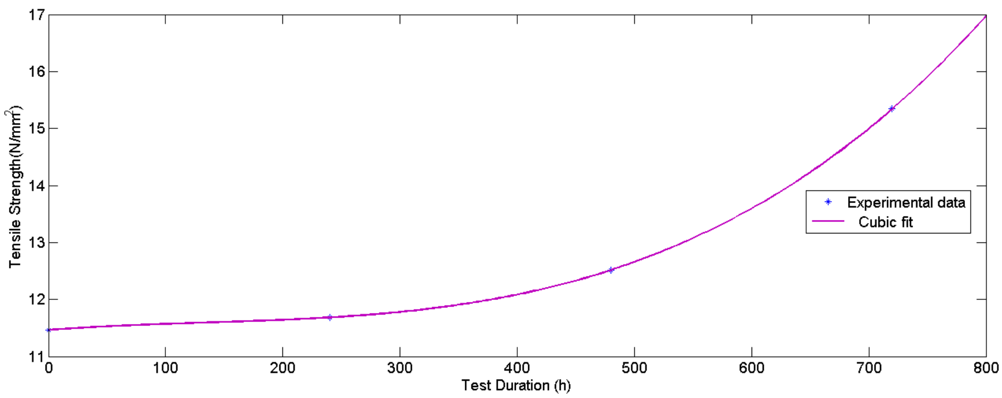
$$\sigma = p_3 t^3 + p_2 t^3 + p_1 t + p_0 \quad (2)$$

where σ is the tensile strength.

The parameters of the polynomial of the curve fitted tensile strength are calculated as $p_1 = 0.0015764$, $p_2 = -6.7708\text{e} - 06$, $p_3 = 1.6758\text{e} - 08$, and $p_0 = 11.47$. Norm of residuals of the tensile strength function is pretty low and equal to 8.1403e-15.



(a)



(b)

Figure 11. Effect of Accelerated ageing on a) Elongation at break and b) Tensile strength of the Thermoplastic Polyolefin İnsulator pieces prepared.

4. Conclusion

UV radiation can induce color changes on the surface or within polymers, and its impact on mechanical strength has been explored in the literature (Harris, R. M., 1999). Some studies indicate that prolonged UV exposure can adversely affect mechanical properties, leading to reductions in tensile strength and increased material brittleness (Lu et al., 2018). However, other research highlights the complexity of directly linking color changes caused by UV radiation to mechanical strength. Color changes often occur on the polymer surface or in superficial layers, whereas mechanical strength largely depends on the material's internal structure and chemical composition. Therefore, surface color changes may not necessarily correlate with significant impacts on mechanical strength (Wypych, 2020).

In this study, a UV aging test of thermoplastic polyolefin polymer to be used in a low-voltage power cable is made according to UL 2556. It has been shown that UV exposure whitens thermoplastic polyolefin polymer, the surface of the thermoplastic polyolefin polymer material under investigation changes color in the first step of aging and then remains almost unchanged in the later stages of aging, and the color of the material has changed from dark gray to light gray. Considering the values of the elongation at break and the tensile strength, the elongation at break's value has dropped by %18.84 and the tensile strength's value has increased by %33.83, suggesting an enhancement in the material's mechanical strength at the end of the UV aging test. While not all polymers exhibit increased tensile strength upon UV exposure, thermoplastic polyolefin polymer does. The effect depends on the specific polymer composition, additives, and the presence of crosslinking agents or functional groups that can participate in UV-induced crosslinking reactions (Wypych, 2020). UV exposure increasing the tensile strength of thermoplastic polyolefin polymer can be attributed to UV-induced crosslinking, where UV light initiates chemical reactions leading to the formation of crosslinks between polymer chains, thereby strengthening the material over time.

The results of the tests show that color change due to aging does not indicate a tensile strength loss for thermoplastic polyolefin polymer. It is also interesting that Elongation at break for thermoplastic polyolefin polymer is not a monotonous function of exposure time. These experimental results may mean that it is possible to use the thermoplastic polyolefin polymer in low-voltage outdoor power cables which are exposed to considerably more UV light than indoor cables. Also, the color change of polyolefin polymer does not mean the tensile strength loss since it is monotonously increasing, and a decrease in Elongation at break since it first falls and starts increasing again concerning the experimental exposure times in this study. These results underscore the importance of understanding the specific composition and additives within polymers used in outdoor power cables, as well as their susceptibility to UV-induced reactions. The findings from this study provide valuable insights for the development and selection of materials that are resilient to UV degradation, particularly in applications requiring prolonged outdoor exposure.

Author Contributions

Formal analysis –Reşat Mutlu (RM), Metin Yurtsever (MY); Investigation – RM, MY; Experiments – Avşin Öztaş (AÖ); Processing – MY, RM, AÖ; Literature review – RM, MY, AÖ; Writing –RM, AÖ, Review and editing – RM, MY, AÖ.

Declaration of Competing Interest

The authors declared no conflicts of interest concerning the research, authorship, and/or publication of this article.

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