Journal of Materials and Environmental Science
ISSN : 2028-2508
e-ISSN : 2737-890X
CODEN : JMESCN

J. Mater. Environ. Sci., 2025, Volume 16, Issue 9, Page 1721-1730

http://www.jmaterenvironsci.com

Experimental Analysis of Mechanical Properties of Polymeric Insulation in HV Underground Cables

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Received *07 Aug 2025,*
Revised *10 Sept 2025,*
Accepted *11 Sept 2025*

Keywords:
- ✓ *Underground cables;*
- ✓ *Mechanical assessment;*
- ✓ *Polymeric layers;*
- ✓ *Tensile tests;*
- ✓ *Datasheet.*

Citation*: Naboulsi N., Majid F., Zekriti N. (2025) Experimental Analysis of Mechanical Properties of Polymeric Insulation in HV Underground Cables, J. Mater. Environ. Sci., 16(9), 1721-1730.*

Abstract: Cables play a critical role in modern energy transmission and distribution systems, with most installations buried underground. However, underground cables are susceptible to various forms of degradation that can compromise both their performance and operational safety. Failures may affect all structural components, including the conductive core and the surrounding polymer-based dielectric layers. These deteriorations often result from mechanical stress during installation, environmental exposure, and long-term electrical loading. This study presents a detailed mechanical assessment of the individual polymeric layers of a high-voltage underground cable in service. A series of tensile tests was conducted on specimens from each layer to evaluate their mechanical integrity and to compare the observed properties with those specified in the datasheet of the cable type C33 223 630 AL X5 12/20(24) kV. The findings aim to identify signs of aging and material fatigue, particularly in the outer sheath, to anticipate failure mechanisms and support predictive maintenance strategies.

1. Introduction

For years, various systems have used the transmission network to transport electrical energy from generation centers to consumers (Chen *et al.,* 2015, Lamah *et al.,* 2024). These networks are primarily composed of overhead and underground networks, especially in and around urban areas. Today, most utility companies have opted to phase out the construction of new overhead lines operating below 150 kV. Consequently, it is expected that, in the near future, the entire distribution system will increasingly rely on underground cable networks (Arias Velásquez & Mejía Lara, 2020). However, several types of faults can affect the reliability of underground cables (Wang *et al.,* 2007, Chen *et al.,* 2020). Among the most significant are overheating (Belardi *et al.,* 2021, Rasoulpoor *et al.,* 2017), which can lead to premature degradation of insulation materials (Abed *et al.,* 2022, Clements & Mancarella, 2017), and material fatigue caused by mechanical or thermal cycles (Balaji *et al.,* 2023). Most cable failures and resulting power interruptions are actually due to mechanical constraints, which can damage either the polymeric insulation layers (Ammirato *et al.,* 2007, Han *et al.,* 2018) or the conductor wires (Zhang *et al*., 2019, Ghorbani *et al.,* 2013, Barbooti *et al.,* 2018, Eve *et al.,* 2022). This type of damage results in the progressive deterioration of the mechanical properties of cable materials (Liu *et al.,* 2024, Babouri *et al.,* 2022).

To better understand the context, **Table 1** shows the normative classification of voltage levels in electrical power systems. This classification helps define the design requirements for cable types based on their position in the grid hierarchy and the range of voltages they are intended to carry.

Table 1. Normative classification of voltage levels in electrical networks according to standards NFC 15-100, NFC 13-200 and UTE C 18-510.

AC Voltage	Abbreviation	Designation
50 kV ≤ U	HV-B	High Voltage B
1 kV ≤ U ≤ 50 kV	MV or HV-A	Medium Voltage or High Voltage A
500 V ≤ U ≤ 1 kV	LV-B	Low Voltage B
50 V ≤ U ≤ 500 V	LV-A	Low Voltage A
U < 50 V	ELV	Extra Low Voltage

In addition, **Figure 1** provides an overview of the voltage distribution architecture within a typical transmission and distribution grid. It illustrates the flow of electricity from the generation plant to the final users, showing how voltage levels are stepped down at various stages depending on transmission distance and load demand.

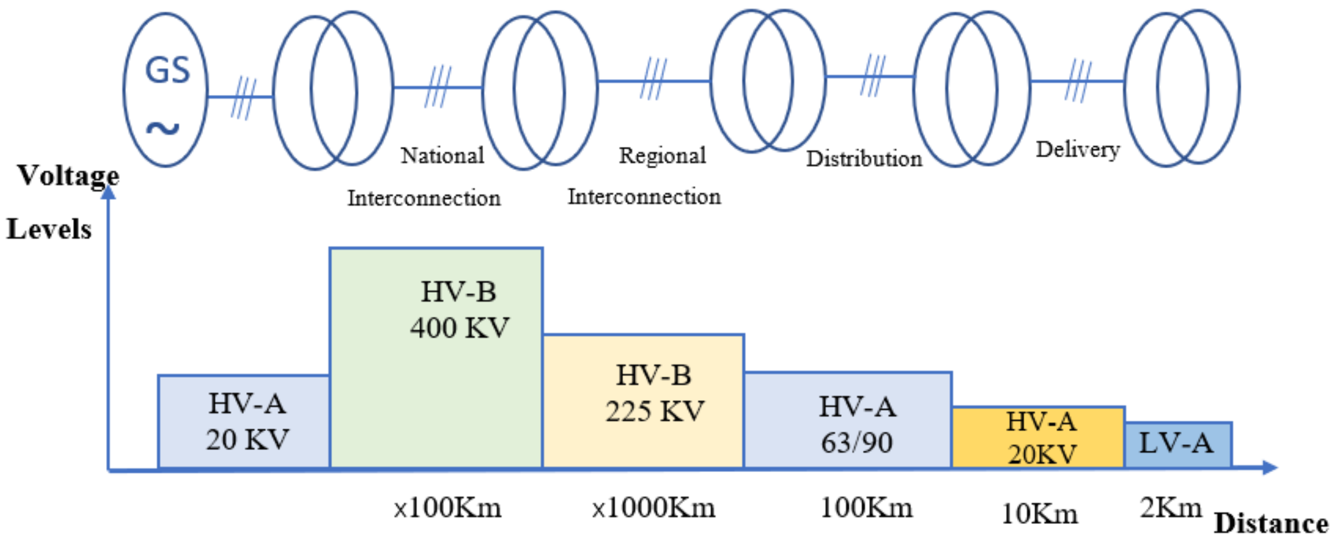


Figure 1. General schematic of voltage levels and distances in electrical transmission networks

Given the critical role of underground cables in energy transmission, ensuring service continuity requires assessing the life cycle and mechanical integrity of each component in a cable, which becomes very crucial to prevent unexpected service interruptions (Ezrin & Lavigne, 2007) and optimize maintenance strategies. Therefore, the aim of this study is to conduct a comprehensive mechanical analysis of all functional layers of a high-voltage underground cable. First, the characteristics of the HVA cable under investigation are described, including a detailed presentation of its multi-layered structure. Then, a series of tensile tests were performed on five specimens from each layer of the cable, from the aluminum conductor to the outer PVC sheath, using a standardized crosshead speed of 10 mm/min. The experimental setup, test protocol, and standardized specimen geometry are also described. All tests were conducted to extract and compare the mechanical properties of each polymeric insulation layer from the in-service cable with the manufacturer's datasheet specifications, with the aim of identifying signs of material fatigue and supporting predictive maintenance.

2. Material and Methods

2.1 Studied cable

In this paper, we have studied an underground medium-voltage electrical cable of the type "C33 223 630 AL X5 12/20(24) KV". The cross section presented in **Figure 2** shows the different layers of the cable. The structure of the cable is composed of an Aluminum conductor with a radius of 15 mm, an inner semiconductor of 16 mm, an XLPE insulation of 22 mm, an outer semiconductor of 24 mm, and a PVC outer sheath of 27.5 mm. The radii are measured from the center of the Aluminum conductor.

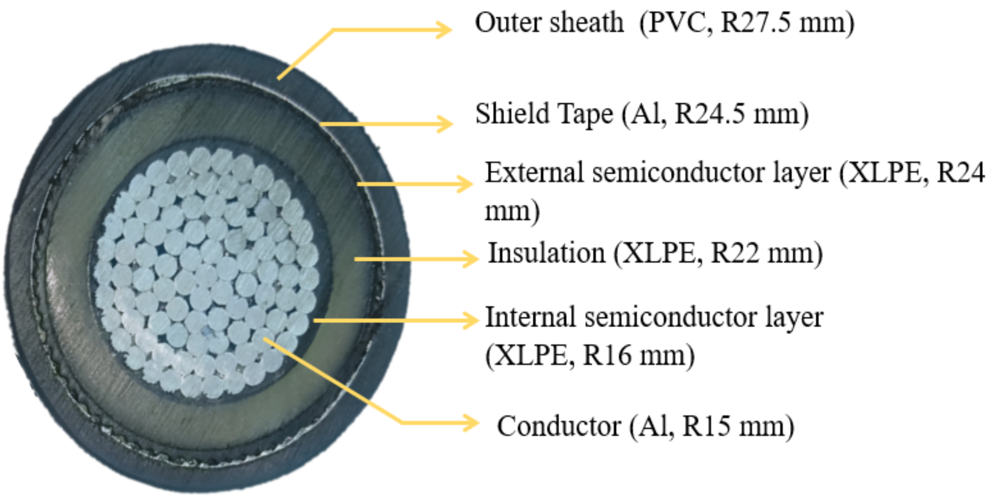


Figure 2. Cross-section of 12/20(24) KV Underground electrical Cable.

2.2 Tensile Test machine

The tensile test is one of the most widely used methods for determining the mechanical properties of a material. During this test, a gradually increasing force or a constant rate of deformation is applied to standardized specimens, causing the material to deform until it ultimately fractures. The tensile testing machine used to characterize the cable in this study is shown in **Figure 3.**

From the resulting stress-strain curves, several key mechanical properties can be extracted, including the elastic modulus, yield strength, ultimate tensile strength, and the material's ductile or brittle behavior. These measurements allow for the evaluation of the elastic and plastic responses, as well as the failure resistance of the various layers that make up the cable, under uniaxial loading conditions.

2.3 Sample Preparation

According to the ISO 527-2 standard for tensile test specimens, and using the dimensions illustrated in **Figure 4**, five samples were prepared from each layer of the underground HVA electrical cable.

Figure 3. Tensile test machine.

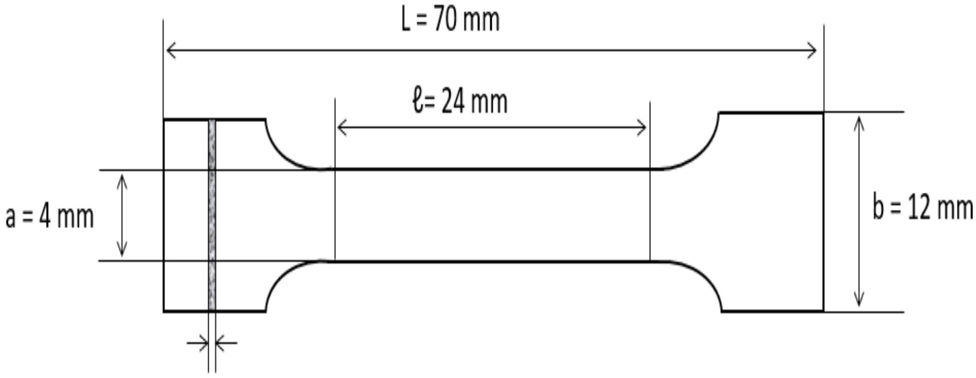


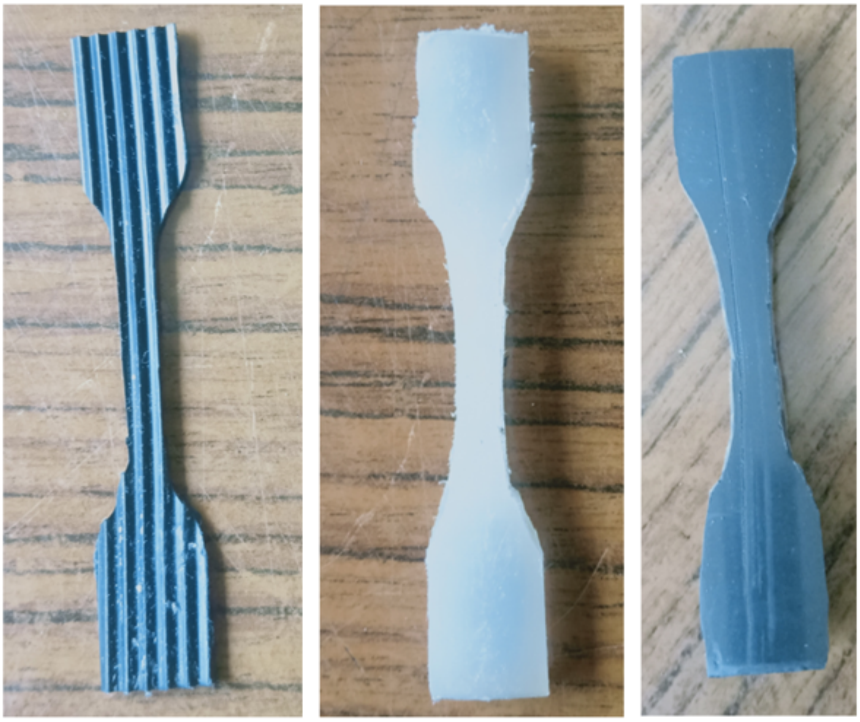
Figure 4. Dimensions of the specimens according to the ISO 527-2 standard.

In order to perform the tensile tests on the components of the underground power cable, we first cut five cylindrical sections of the cable, each 100 mm in length. From each section, the various polymeric layers were carefully separated. In order to ensure the accuracy of the results, the study required the analysis of 5 samples of each layer from the cable. Five samples of the PVC outer sheath (thickness: 4 mm), five samples of the XLPE insulation layer (thickness: 5.5 mm), and five samples of the outer XLPE semi-conductive layer (thickness: 1.5 mm).

These specimens were cut in a helical shape to conform to ISO 527 requirements, as illustrated in **Figure 5**.

2.4 Tensile test

The prepared specimens from each layer of the cable were subjected to a series of uniaxial tensile tests, conducted at a constant crosshead speed of 10 mm/min, in order to obtain the average tensile curve for each component. Representative images of some specimens during the tensile tests are illustrated in **Figure 6**.



a) b) c)

Figure 5. a) Dumbbell specimen of XLPE semiconductor layer ; b) Dumbbell specimen of XLPE insulation layer ; c) Dumbbell specimen of PVC outer sheath.

a) b) c)

Figure 6. Uniaxial tensile testing of different cable layers: a) Specimen from the XLPE semi-conductive layer. b) Specimen from the XLPE insulation layer. c) Specimen from the PVC outer sheath.

3. Results & Discussions

3.1 Mechanical behavior of each polymeric layer of the cable

The tensile test was performed by applying a maximum load capacity of 30 KN while measuring the displacement of each sample as the strength increased. **Figure 7** illustrates the tensile stress-strain curves for the three main polymeric layers constituting the HTA underground power cable: the PVC outer sheath, the XLPE semiconductor layer, and the XLPE insulation layer.

The PVC outer sheath of underground power cables plays an important role in protecting the cable from external mechanical and environmental constraints. In this work, the tensile curve of the PVC shows a typical ductile behavior and passes through three main stages: The first is the initial linear elastic phase, where the material deforms reversibly with a Young's modulus around 98.99 MPa. Subsequently, a yielding phase appears when the applied stress marks a progressive irreversible elongation with a regular decrease in cross-section throughout the test with a yield stress of 8.48 MPa, is showing that it can support significant loads to resist underground installation and operating conditions. And finally, the softening stage reaches a maximum tensile stress of 27.249 MPa before failure, which occurs at 24.21 MPa. These properties make it well-suited as an outer protective layer and confirm the sheath's ability to endure significant strain and maintain its integrity under underground mechanical constraints such as compression, movement, and soil pressure.

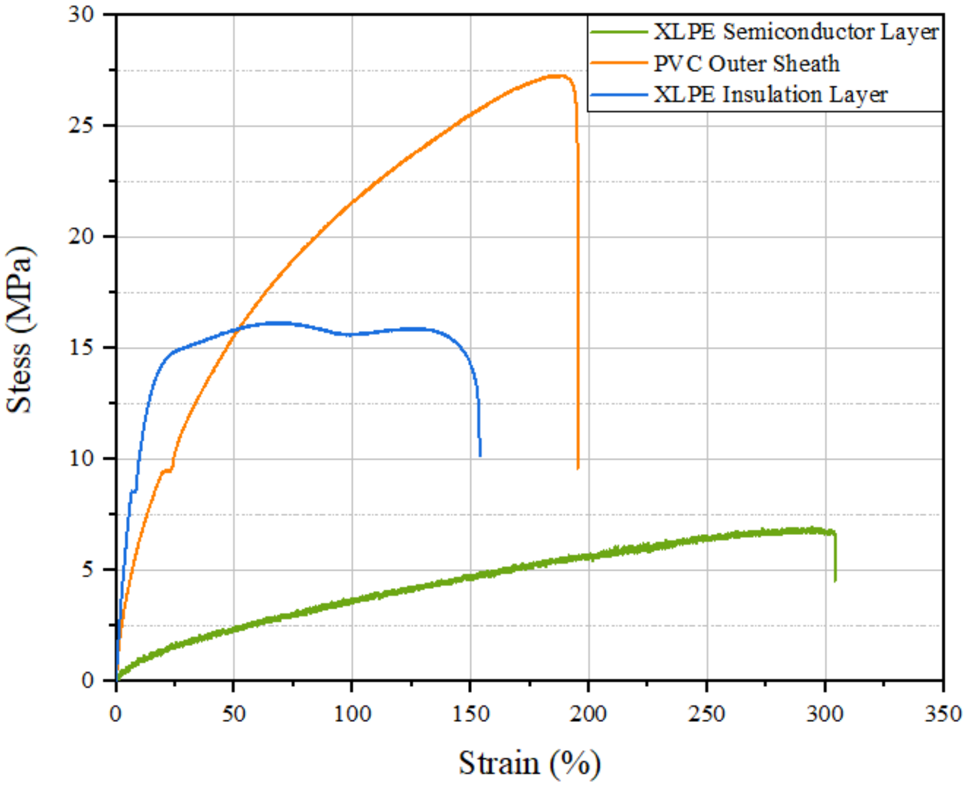


Figure 7. Tensile test curves of the different layers forming the HTA electrical cable.

The XLPE semiconductor layer is designed to provide a smooth voltage gradient within the cable and prevent partial discharges. Mechanically, this layer displays low stiffness, with a Young's modulus of 7.69 MPa, indicating high flexibility as confirmed in **Table 3**. However, it exhibits a low yield stress around 1.34 MPa, a maximum stress of 6.84 MPa, and a breaking strength of 6.48 MPa. These values illustrate its operational function: it is not designed to offer mechanical resistance but rather to support the electrical function while accepting a certain degree of deformation. Its low rigidity gives it the ability to react to thermal variations without cracking, helping to preserve electrical integrity. Finally, the XLPE insulation layer presents high rigidity and good mechanical strength. With a Young's modulus of approximately 228.76 MPa. This stiffness is crucial for preserving the structural and dielectric stability of the cable. It presents a yield stress of about 12.70 MPa, a maximum stress of 16.099 MPa, and a breaking strength of 10.10 MPa, confirming its ability to resist both mechanical and thermal stresses while reliably insulating the conductor under varying conditions. The mechanical properties extracted from the tensile test results are provided in **Table 2**:

Table 2. Mechanical characteristics of HV power cable layers.

Mechanical characteristics	PVC outer sheath	XLPE semiconductor layer	XLPE Insulation layer
Young's Modulus (MPa)	≈98.99	≈7.69	≈228.76
Yield stress (MPa)	≈8.48	≈1.34	≈12.70
Maximal stress (MPa)	27.249	6.84	16.099
Breaking strength (MPa)	24.21	6.48	10.10

3.2 Comparison of mechanical properties between studied cable layers and manufacturer specification

The aim of this comparative study between the mechanical properties of high-voltage (HVA) cable components and the supplier's datasheet specifications is to evaluate how closely the actual mechanical behavior of a cable material in service aligns with both the manufacturer's data and the mechanical performance requirements defined in the NFC 33-226 standard.

Beyond verifying conformity, this type of analysis serves several crucial purposes. It allows for the detection of any discrepancies that may arise due to manufacturing variability, storage conditions, or handling. More importantly, it provides an in-depth understanding of the mechanical role of each functional layer of the cable and whether each layer meets the mechanical robustness expected for safe and durable high-voltage applications.

In addition, this study establishes a reference baseline for future assessments on aged cables, making it possible to quantify the extent of material degradation over time. Ultimately, such comparisons contribute to improving the selection of materials, refining manufacturing processes, and reinforcing the safety and reliability of electrical infrastructure.

The differences in mechanical characteristics between the HTA underground studied and the industrial cable, as shown by the data sheet values in **Table 3**, have been compared with the NFC 33-226 standard, reflecting a discrepancy between theoretical specifications and practical performance. The data sheet values represent tensile strength and elongation under ideal or standardized test conditions, indicating a greater ability to withstand mechanical stress for the three different polymeric layers of the cable. On the other hand, studied values observed under real-life conditions may be lower due to factors such as variations in material quality, installation practices, or environmental influences impacting cable performance. This discrepancy underlines the importance of considering both data sheet specifications and practical tests to fully understand the cable's mechanical robustness.

The PVC outer sheath matches the two references in terms of strength, with a maximum stress of 27.25 MPa, close to the value given in the data sheet of 29.8 MPa. On the other hand, elongation at break is 195.05%, well below the data sheet value of 970% and below the minimum requirement of standard NFC 33-226 (≥300%). This elongation deficit could reflect a loss of ductility, possibly linked to material aging, service stresses, or structural hardening. The XLPE semiconducting layer has a tensile strength significantly lower at 6.84 MPa than the data sheet value of 18.7 MPa but still complies with the standard threshold ≥7 MPa. However, the elongation of 304.07% is much higher than the required 150%, confirming good flexibility.

For the XLPE insulation layer, the measured tensile strength of 16.099 MPa complies with NFC 33-226, which requires a minimum of 12.5 MPa, although it remains below the manufacturer's data sheet value of 25.3 MPa. The elongation at break, recorded at 153.80%, does not meet the minimum required value of ≥200% as specified by the same standard.

This nonconformity in ductility may be attributed to several factors, including thermal aging, insufficient crosslinking, or the presence of residual internal stresses. Although the material retains an acceptable level of tensile strength, the reduced elongation at break may compromise its long-term reliability, particularly under mechanical stress or elevated temperatures commonly encountered during service (Ouazzani *et al.,* 2024).

Table 3. The tensile strength and deformation of the various cable layers compared with Datasheet.

Mechanical characteristics	**PVC outer sheath**			**XLPE semiconductor layer**			**XLPE Insulation layer**		
	Studied cable	Datasheet	Standard	Studied cable	Datasheet	Standard	Studied cable	Datasheet	Standard
Tensile strength (MPa)	27.249	29.8	≥12.5	6.84	18.7	≥7	16.099	25.3	≥12.5
Elongation (%)	195.05	970	≥300	304.07	350	≥150	153.80	680	≥200

3. Conclusions

This paper focused on the mechanical properties of an underground medium-voltage cable (HVA), with a focus on the behavior of its main polymer components: the PVC outer sheath, the XLPE semiconductor layer, and the XLPE insulation layer. Using tensile tests carried out on samples taken from a cable in service, we assessed properties such as tensile strength and elongation at break and compared them with the values given in manufacturers' data sheets and with the requirements of standard NFC 33-226.

The results highlighted the fact that all three layers generally meet the minimum mechanical requirements defined by the standard in tensile strength. However, when comparing the tested cable to the manufacturer's datasheet specifications, notable discrepancies were observed in elongation, particularly in the outer sheath and insulation layer. The insulation layer failed to meet the required elongation threshold, indicating a lack of ductility. Similarly, the PVC outer sheath, despite its acceptable tensile strength, did not satisfy the elongation criterion set by the NFC 33-226 standard.

These deviations are most likely attributed to intrinsic factors, such as incomplete cross-linking, residual internal stresses, or thermal aging, rather than external environmental degradation, especially considering the internal positioning of these layers within the cable structure. Despite these differences, the cable as a whole appears mechanically sound and suitable for continuous use. This comparative approach not only reinforces the importance of validating commercial data sheets with real-life testing but also highlights how minor variations in manufacture or aging can affect long-term rope performance. Such assessments are crucial to ensure and provide the necessary protection against mechanical damage to the cable. However, every component of underground cables ages and degrades over time, and this degradation can lead to the failure of the entire power line. For this reason, knowledge of an underground cable requires perfect understanding of each of its essential components. That's why, in this article, we focus first on the mechanical characterization of power cable elements in service state for predictive maintenance strategies, reliability assurance, and quality control in power supply systems.

Acknowledgement

The authors would like to express their sincere gratitude to Chouaïb Doukkali University faculty of sciences for providing the equipment necessary for the successful completion of this work.

Funding

The authors declare that no funding organizations were involved in supporting this research.

Conflicts of interest

The authors have no conflict of interest.

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