

Chapter 10

Electrical Insulation: XLPE Versus Conventional Materials



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1 Introduction

An electrical insulation system (or simply, electrical insulation) represents, by definition, the electrical insulating materials or the assembly of electrical insulating materials that are in direct contact with the conductive parts of an electrical equipment (electric machine, transformer, circuit breaker, contactor, power cable, insulator, etc.) [1]. The electrical function consists in reducing (or, ideally, canceling) the component of the electrical current that flows from one conductor to an adjacent one or from the conductors to the metallic parts of the electrical equipment (magnetic cores, enclosures, etc.) through the environment (air, earth, etc.). The thermal function consists in ensuring the easiest transmission of the heat developed in conductors (Joule losses), magnetic cores (losses through hysteresis and Eddy currents) and in themselves (dielectric losses) to the cooling environment (forced cooling system (with air, hydrogen, etc.) or natural (air)). The mechanical function consists in ensuring a mechanical fixing of the conductors (in the magnetic cores, in the electrical installations) and/or to protect them against mechanical stresses (static or dynamic) of the electromagnetic field, etc.

The diversification of the constructive forms regarding the electrical equipment and the fields of use alongside the increase of the electrical, thermal and mechanical

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stresses on the insulation systems have required the performance of systematic investigations on the structure and properties of the insulating materials related to:

- (a) more accurate rating of insulation systems (use of insulation at maximum permissible stresses, in order to reduce the costs of the electrical equipment);
- (b) taking into account the new operating conditions of the insulation systems (high humidity and/or intense radiation environments, low operating temperatures [cryogenics, superconductivity]);
- (c) obtaining materials with higher dielectric strength and operating temperature (for reducing the insulation systems size);
- (d) obtaining insulating materials that require technological processes with low energy consumption;
- (e) obtaining insulating materials with special properties (required in various applications);
- (f) reduction of the pollution produced by the insulating materials disposal in the environment (within the process of production or exploitation);
- (g) producing biodegradable electrical insulating materials;
- (h) increasing the lifetime of the insulation systems.

The construction and structure of the insulation systems are related to the types of equipment they are part of (electric machine, transformer, power energy cable, etc.), substance (copper, aluminum, etc.) and geometric shapes of the conducting paths (round, square, rectangular, etc.), their character (organic, inorganic, etc.) and the physical state (gas, liquid, solid) of the used electrical insulating materials, etc.

Due to the fact that cross-linked polyethylene (XLPE) is mainly used for the insulation of medium, high, and very high voltage power cables [2], this chapter presents information on XLPE and other materials' properties used in the manufacture of power cables and an analysis regarding their application in present and future.

2 Power Cables

A *power cable* is an electrical cable (one or more wires running side by side or bundled), respectively, an assembly of one or more electrical conductors (usually held together with an overall sheath) used for the transmission of electrical energy (power). Power cables may be installed as permanent wiring in buildings, underground, overhead, or exposed.

Besides some technical and aesthetic considerations, the overhead lines arise some safety hazards to lineworkers themselves, firefighters and public. Therefore, underground lines increasingly replace the overhead line structures. Hence, this chapter will be related only to underground power cables, simply called *power cables*.

Power cables consist of three major components, namely conductors, insulation, and protective jacket, while the construction and the material are settled by three main factors:

- (a) working voltage, defining the nature and the thickness of the insulation;
- (b) current-carrying capacity, defining the cross-sectional size of the conductors;
- (c) environmental conditions (temperature, water, chemical or sunlight exposure, and mechanical impact) defining the properties of the outer cable jacket [3].

The first cable insulations were manufactured in the early 1880 s for voltages up to 10 kV based on gutta-percha, natural vulcanized rubber, rosin oil, castor oil, vax, jute, hemp, cotton, black asphalt, oil-impregnated -paper, etc. [2]. For higher voltages (over 35 kV), cables were performed with pressurized-oil, low-viscosity-oil-impregnated-paper (after 1928) and with solid dielectrics (after 1950). For high voltages (275–500 kV) and powers (10 GVA), compressed SF₆ gas power transmission cables were performed (after 1974). In the case of very large capacity power transmission (over 10 GVA), superconducting cables were proposed (see Fig. 1) [4]. Currently, for the transport and distribution of electricity (beside airlines) are used Oil-Impregnated Paper Power, Oil-Pressurized Power Transmission, Solid-Dielectric Extruded Power Transmission, Solid Extruded Dielectric Power Distribution, Underwater (Submarine), Compressed SF₆ Gas Power Transmission, and Superconducting Power Transmission Cables.

Oil-Impregnated Paper Power Cables are, in general, three-phase cables with a nominal voltage of 15–35 kV (but can reach up to 69 kV) (see Fig. 2) [4]. The limitation of these cables for medium voltages is due to the high level of partial discharges that occur at high voltages within the insulation cavities (formed during the manufacturing process or during the load cycling in service). In the case of *Oil-Pressurized Power Transmission Cables*, the effect of the cavities was eliminated by the introduction of a low-viscosity-oil-impregnated-paper insulating system and, therefore, the operating voltages could be increased up to 750 kV. In this case, the cavities formation is practically avoided by maintaining a pressure slightly above

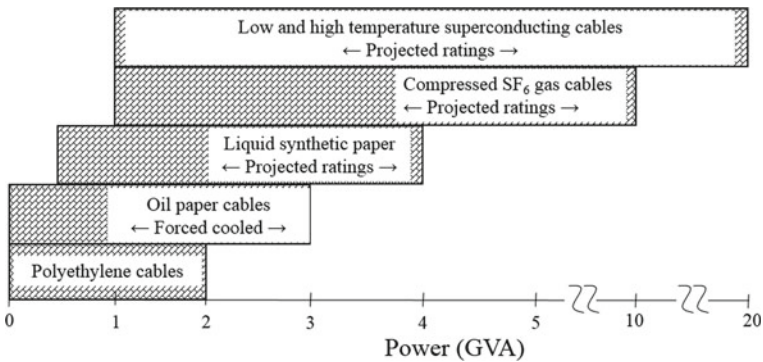


Fig. 1 Ratings of power transmission cables (Redrawn and adapted figure from reference [4])

atmospheric condition of the insulating oil. Starting with 1980, the paper (Kraft) was replaced by polypropylene-laminated-paper (PPLP) as insulation in cables (with lower dielectric constant and losses and higher breakdown strength; see Fig. 3 and Table 1), while branched dodecyl benzene used as an impregnating liquid, reached operating voltages of 750–800 kV [5, 6].

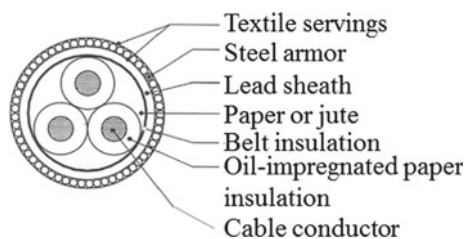
Even though the reliable long-term performance of the oil-paper transmission cables has been proven over years (some cables working even after 60–70 years), however, from environmental (elimination of oil leaks) and maintenance (elimination of hydraulic oil reservoir tank systems, highly skilled personnel for operation, maintenance and repair [8]) considerations, these cables were (after 1950) extensively replaced by *Solid-Dielectric Extruded Power Transmission Cables*. Initially, the insulation was performed from thermoplastic-type low-density linear polyethylene (LDPE) (up to 225 kV; see Fig. 4), and from thermosetting-type solid extruded XLPE (up to 800 kV; see Fig. 5) after 1975 [9].

The problems that arise in these cables during operation are, in particular, the thermo-oxidative degradation of the insulation and the appearance of cavities (with or without water) inside them (which facilitate the development of partial discharges and electric and water trees) (see Fig. 6, [1]). In addition to LDPE and XLPE, butyl rubber, low-density high-molecular-weight polyethylene (HMWPE), tree-retardant XLPE (TR-XLPE) (see Fig. 7a), and ethylene propylene rubber (EPR) are also used (see Fig. 7b). In general, the constructions of other thermoplastic and thermosetting insulated transmission and distribution power cables (medium, high, and very high voltage) are similar to those shown in Fig. 7c [9].

In general, extruded HVDC cables offer significant advantages over traditional paper insulated cable types: a higher conductor temperature, a more compact cable for the same power rating, lighter moisture barriers (resulting in a lighter cable), and an easier way of joining the extruded cables, which requires less skills and avoids the significant long-term environmental hazards associated with oil leaks.

Submarine cables are used for crossing water sectors to interconnect systems (between an island and adjacent shoreline) and may be self-contained oil-filled type (for short distances transmission), high-viscosity oil-impregnated paper (for long distances) or solid extruded dielectric type (XLPE) (see Fig. 8, [12]). *Superconducting cables* are using as insulation cellulose paper, polypropylene or polyethylene paper/tape, and extruded XLPE (Fig. 9, [4]). *Gas-insulated transmission lines* (GITL) are in use for system voltages up to 765 kV. A single-phase

Fig. 2 Cross section of three-conductor belted-type oil-impregnated paper power cable (Redrawn and adapted figure from reference [4])



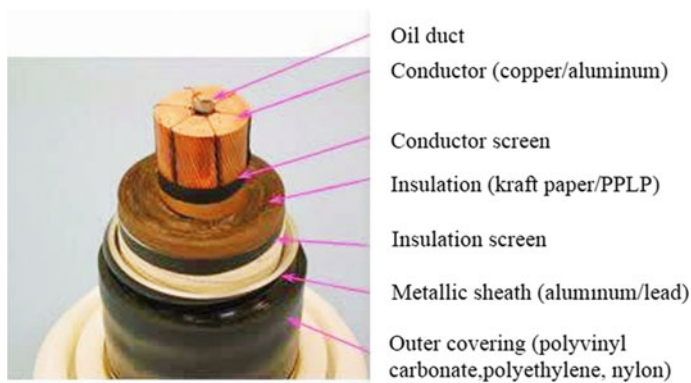


Fig. 3 Extra-high voltage oil-filled cable 110-500 kV (Redrawn figure from reference [7])

Table 1 Electrical characteristics of Polypropylene Paper Composite Tapes (PPP) and Kraft Paper (KP) tapes impregnated with branched dodecyl benzene [5]

Tape	PPP	KP
Thickness (μ)	170	200
Dielectric constant (-)	2.58	3.4
Dissipation factor at 20 kV/mm and 80 °C (-)	5.3×10^{-4}	2.0×10^{-3}
Breakdown strength (MV/m)	150	80
Impulse breakdown strength (MV/m)	256	150

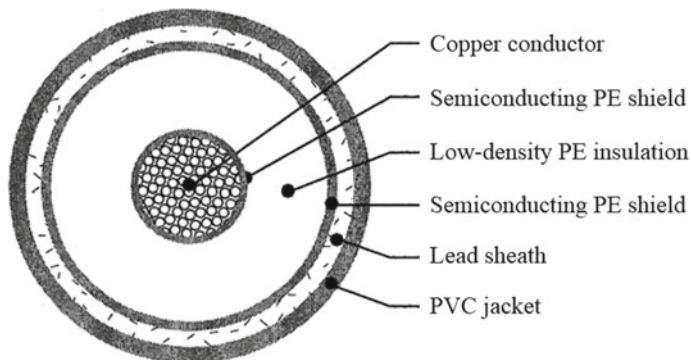


Fig. 4 Cross section of 225 kV LDPE transmission cable (Redrawn and adapted figure from reference [4])

consists of two coaxial cylinders (the inner being the load current conductor and the outer being the grounded pressure vessel that contain gas), which are maintained coaxial by means of the solid-dielectric spacers. These cables present very small

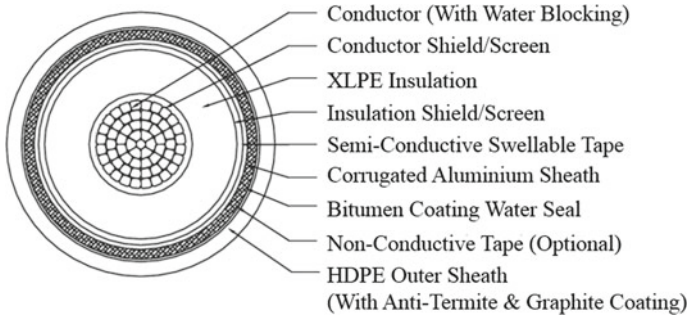
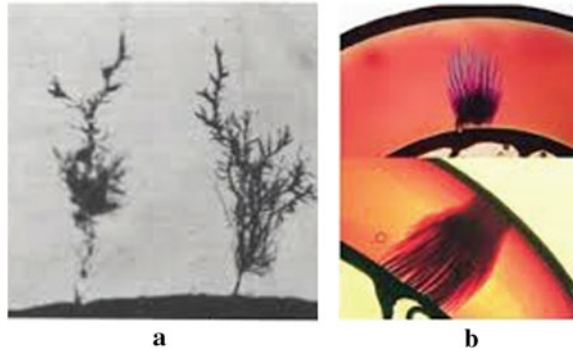


Fig. 5 Cross section of 132 kV XLPE-insulated and HDPE sheathed cable (Redrawn figure from reference [9])

Fig. 6 Electrical (a) and water (b) trees within XLPE insulation [1]



dielectric losses, both in gas (SF_6 for pressures up to 3.5 bars at 20 °C) and in spacers (performed by epoxy resins filled with silica or alumina) [4].

3 Insulating Materials for Power Cables

Electrical insulating materials (or simply insulators) are substances with the electrical conductivity sufficiently low to separate two conductive parts with different electrical potentials. Their electrical resistivity ρ is between 10^6 and 10^{18} Ωm , and the real part of the relative complex permittivity ϵ'_r (or dielectric constant ϵ_r) between 1 and 16. Solid insulators show widths of the forbidden band Fermi w_F between 5 and 8 eV [13].

Considering the very large number, as well as the fast development of the insulators' production (especially in the last 20 years) with increasingly diversified properties and applications, the accomplishment of a complete classification of the

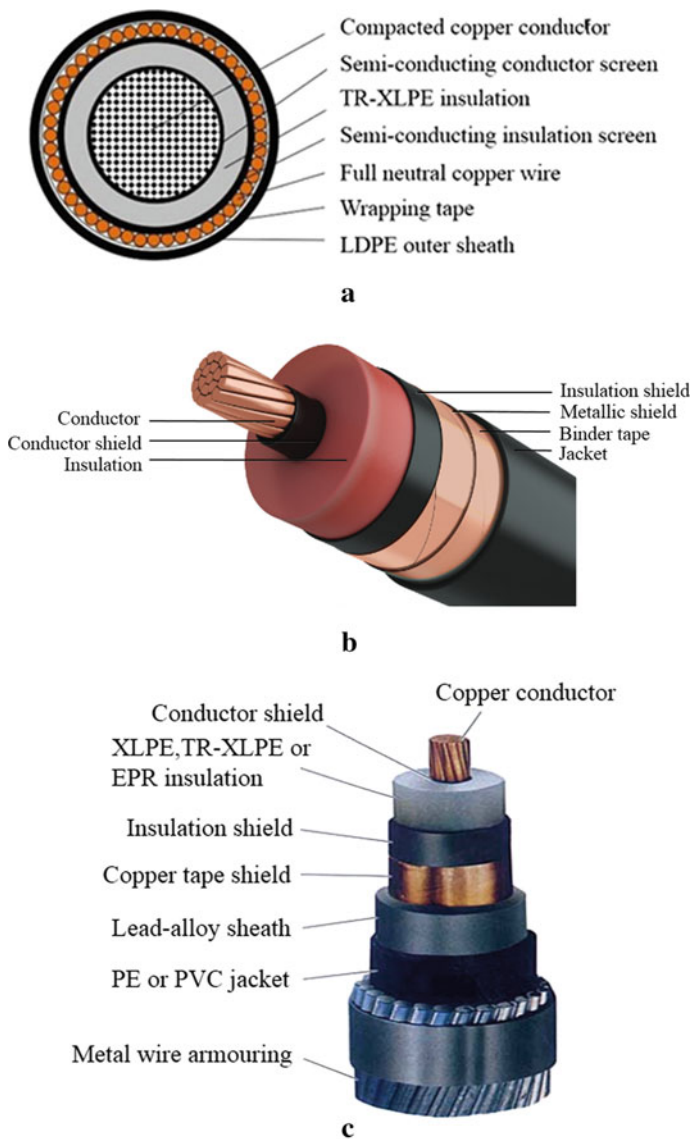


Fig. 7 **a** High voltage cable insulated with TR-XLPE [10]; **b** medium-voltage (35 kV) shielded power cable insulated with EPR [11]; **c** solid extruded dielectric power cable [9]

electrical insulating materials, including all the elements characteristic for their behavior in service is extremely difficult. For this reason, several types of classifications appeared (each with advantages and disadvantages) as follows by:

Fig. 8 Cross-sectional configuration of the bipolar 250-kV DC-XLPE submarine cable within the Hokkaido–Honshu HVDC link (Redrawn and adapted figure from reference [12])

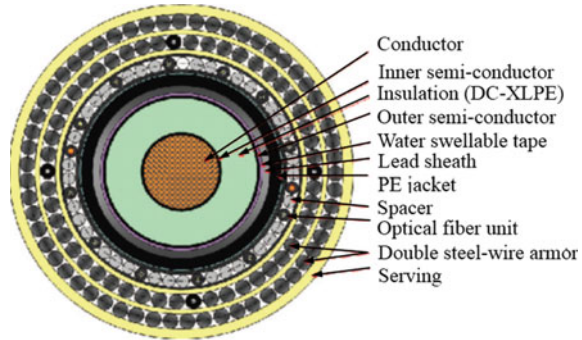
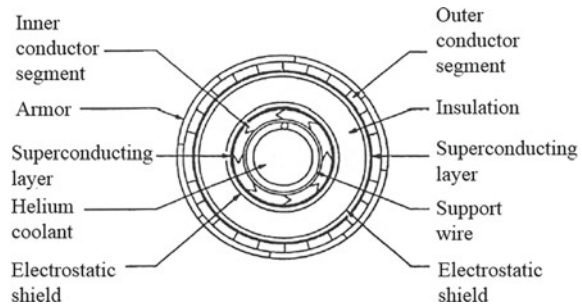


Fig. 9 Cross section of superconducting coaxial cable (Redrawn and adapted figure from reference [4])



- (a) thermal stability (materials were divided into seven classes of insulation, starting with rubber and cellulose products, and ending with inorganic materials),
- (b) chemical composition (organic, transient, inorganic),
- (c) behavior under thermal stresses (thermoplastics and thermosets),
- (d) main component of the final material (mica, synthetic resins, varnishes, etc.),
- (e) usage domain (notch insulation, between layers, impregnation, and coating materials),
- (f) certain practical considerations (defined by the Encyclopedia of electrical insulating materials), etc.

As the electrical insulation is subjected during the operation to multiple simultaneous stresses, it is recommended that the insulators themselves to be characterized by *performance indices*. These values depend, both on the final state of the materials, and on their behavior under the action of temperature, electric field, mechanical stress, radiation, water, etc. [1].

The characteristics of power energy cables are essentially determined by those of the conductive and electrical insulating materials used in their construction. The electrical insulating materials must satisfy the following main conditions:

- (a) increased dielectric strength and resistivity;
- (b) reduced loss factor, dielectric constant, and space charge accumulation;
- (c) high resistance to partial discharges, electric and water trees;
- (d) high thermal conductivity and stability;
- (e) high stretching, tensile strength, and compression resistance;
- (f) high resistance to environmental action (solvents, acids, bases, oxygen, etc.);
- (g) reduced pollution and increased biodegradability.

The general properties of some materials used as insulation of power cables are presented below.

3.1 Oils

Although for a long time, only mineral oils with a certain content of aromatic and naphthenic hydrocarbons have been used as insulation of Oil-Impregnated Paper and Oil-Pressurized Power cables, currently synthetic oils replace them. In the case of pipe-type cable applications polybutene liquids (with a viscosity of 10.6–11.1 cSt, at 99 °C) are used and for the self-contained hollow-core cables, alkyl benzenes are in current use [4].

A predominant role in the use of an oil for power cables insulation is referred to the values of its viscosity at the paper impregnation temperature, due to the fact that during the manufacturing process of the cable, the oil determines the impregnation rate, and at the operating temperature, the viscosity influences the oil speed in the cable insulating system. Moreover, when the cable charge disappears and the oil cools down, its viscosity must be low enough, so that it does not leak out of the paper and produces cavities where partial discharges can develop. The flash point of the oil provides the value of the limit beyond which the oil cannot be heated to avoid the fire hazard of the more volatile emitted vapors. The pour point of the oil is a useful quantity that indicates the lower value of temperature at which partial wax separation within the oil will occur. Furthermore, at lower ambient temperatures, the pour point defines the temperature limit at which no free movement will occur within the cable [4].

The performance of a cable oil in service is determined by the level where it forms sludge and excessive acidity compounds in the presence of oxygen. To reduce the corrosivity of oils, they must be free of sulfur and inorganic chlorides and sulfates, caused by direct contamination or incorrect refining.

Mineral oils (based on crude oil) used for impregnating Kraft paper are composed of aromatic $C_{4n+2}H_{2n+4}$ (12%), naphthenic C_nH_{2n} (38%), and paraffinic C_nH_{2n+2} (50%) hydrocarbons (see Fig. 10). The lengths and structures of the oil molecules are much diversified. One possible molecular arrangement is being the one shown in Fig. 11 [4]. The properties of oils depend on the hydrocarbon contents, as well as on the operating conditions (temperature, oxygen, water, etc.). Aromatic hydrocarbons lead to the increase of dielectric losses of oils, but they are

necessary to decrease the gas production in oils under the action of the electrical stress. Naphthenic hydrocarbons are very stable with a low freezing point, whereas paraffinic ones have a high freezing point, which increase the viscosity of oils [13].

The dielectric constant of cable oils is in the order of 2.2 at room temperature (see Table 2) and decreases with temperature (due to the decreased density [14]). The dissipation factor $\tan\delta$ is less than 10^{-4} and increases with temperature (due to the increased ionic conductivity) [13–15]. It should be emphasized that the magnitude of dielectric losses in oil-impregnated paper are determined, essentially by the impregnated paper instead of impregnating liquid [16–18], as can be observed as well in Figs. 12 and 13 [14, 19].

Polybutene oils have become increasingly popular for use in pipe-type oil-filled cables, both as higher viscosity impregnates and as pipe filling oils, due to their lower costs and electrical and physical properties comparable to those of cable-type mineral oils (see Table 3) [4]. They are obtained by olefins polymerization and contain very long molecules with isobutene as the base unit, characterized by methyl group side chains and molecular weights between 300 and 1350 [20].

The molecular structure of *alkyl benzenes* intended for cable oil applications is a branched one and has the chemical formula $C_6H_5CHR^1R^2$, where $R^1 = C_nH_{2n+1}$, and $R^2 = C_mH_{2m+1}$, where m, n are integers $m \geq 0, n \geq 1$ (typically 10–16). The

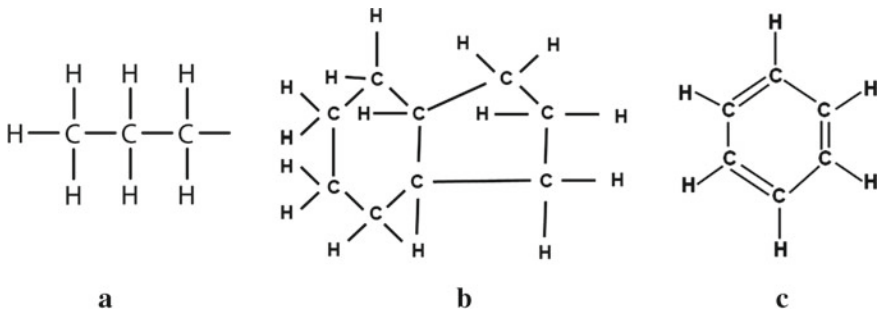


Fig. 10 Molecular constituents of mineral cable insulating oil: **a** paraffinic hydrocarbon; **b** naphthenic hydrocarbon; **c** aromatic hydrocarbon

Fig. 11 Possible molecular structure in mineral cable oil [4]

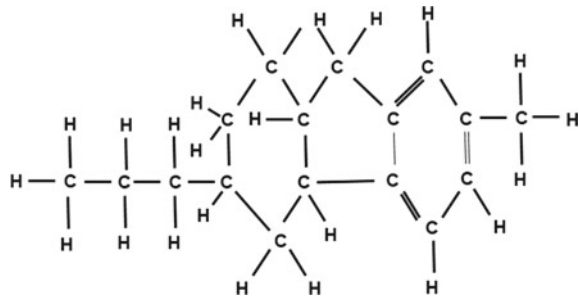
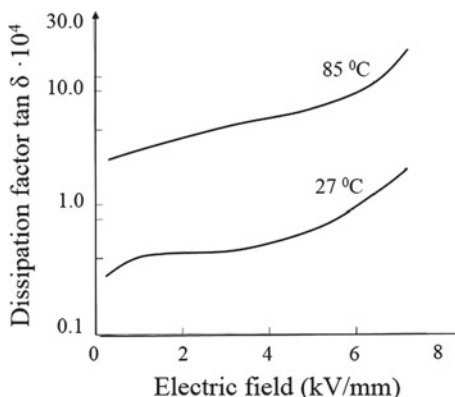


Table 2 Physical and electrical properties of cable oils

Property	Pipe cable oil	Heavy cable oil	Polybutene cable liquid	Self-contained cable oil	Dodecyl benzene
Viscosity (cSt)—at 37.8 °C	170	490	—	7.29	6.0
—at 100 °C	10	21	10.6	1.91	4.5
Flash point (°C)	196.1	243.3	154	130	130
Acidity(mgKOH/g)	0	0	0.01	0.05	0.02
Pour point (°C)	-26.1	-17.8	-34.0	-50.0	-45.0
Density (g/cm ³)	0.928	0.926	0.862	0.883	0.871
Thermal conductivity (W/m °C)	0.125	0.125	—	0.126	0.581
Dielectric strength (kV/mm)	>12	>12	—	>12	>12
Dielectric constant at 60 Hz, 25 °C	2.15	2.23	2.17	2.30	2.20
Dissipation factor at 60 Hz	0.001	0.001	0.0005	0.001	0.0011
Volume resistivity at 100 °C (Ωm)	2×10^{11} (100 °C)	7×10^{11} (100 °C)	1×10^{12} (25 °C)	5×10^{11} (25 °C)	2×10^{11} (25 °C)

Adapted table from reference [4]

Fig. 12 Variation of the dissipation factor with the electric field for mineral oil used in self-contained oil-filled cables (Redrawn and adapted figure from reference [14])



values of n determine the lengths of the molecular chains and, respectively, the average molecular weight (approx. 320 for the self-contained hollow-core cables [4]). The addition of alkyl benzenes to mineral oils greatly reduces the gas production and improves the properties of mineral oil during its exploitation. For pipe-type cables, it is recommended to use polybutene-alkyl benzenes mixtures, with good physical and electrical properties (see Table 4).

Fig. 13 Variation of the dissipation factor with the electric field for mineral oil-Kraft paper insulating system used in self-contained oil-filled cables (Redrawn and adapted figure from reference [19])

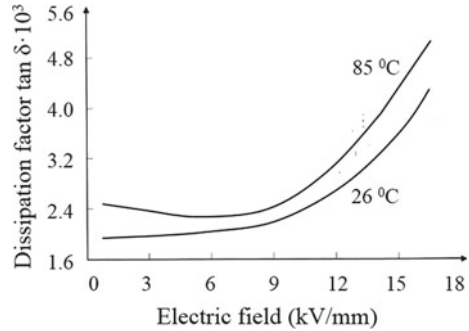


Table 3 Physical and electrical properties of polybutene oils manufactured by costen oil and chemical company [4]

Property	OSH oil	06SH oil	015sh oil	30SH oil
Average molecular weight	340	450	570	1350
Viscosity (SUS*) —at 38 °C	110	575	3440	115,000
—at 99 °C	41	63	158	3070
Flash point (°C)	132	154	160	232
Pour point (°C)	-51	-40	-23	4.4
Acidity (mgKOH/g)	0.01	0.01	0.01	0.01
Water content (ppm)	15	15	15	15
Dissipation factor (60 Hz, 100 °C)	0.0003	0.0003	0.0002	0.0002
Dielectric constant (1 MHz, 25 °C)	2.14	2.16	2.17	2.24
Dielectric strength at 80 °C (kV/mm)	>14	>14	>14	>14
Volume resistivity at 100 °C (Ωm)	8×10^{12}	1×10^{13}	1.2×10^{13}	1.5×10^{13}

SUS*—Saybolt universal seconds

Table 4 Physical and electrical properties of alkyl benzenes (A) and alkyl benzene polybutene mixture (B) [4]

Property	A	B
Average molecular weight	120	380
Viscosity (SUS*) —at 38 °C	100	500
—at 99 °C	38	59
Flash point (°C)	177	177
Pour point (°C)	-50	-20
Acidity (mgKOH/g)	0.02	0.02
Water content (ppm)	25	25
Dissipation factor (60 Hz, 100 °C)	0.0002	0.0002
Dielectric constant (1 MHz, 100 °C)	2.10	—
Dielectric strength at 25 °C (kV/mm)	50	40
Volume resistivity at 100 °C (Ωm)	1×10^{13}	5×10^{12}

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3.2 Papers

Papers used for power cables insulation are composed of cellulose fibers felted together to form mechanically strong sheets (see Fig. 14). These papers are obtained by Kraft process (also known as Kraft pulping or sulfate process), a process by which the conversion of wood into wood pulp (i.e., the main component of paper) is performed.

The Kraft process entails treatment of wood chips with a hot mixture of water, sodium hydroxide (NaOH) and sodium sulfide (Na₂S), which breaks the bonds that link lignin, hemicellulose, and cellulose [21]. The cellulose paper used for common electrical insulation contains ca. 90% cellulose, 6–7% lignin and the rest, up to 100% consists mainly of pentosans [22, 23]. The cellulose molecules (C₁₂H₂₀O₁₀) of which the cellulose fibers are composed consist of a series of glucose repeating units (see Fig. 15) [24]. Cellulose molecules contain carboxyl groups (–COOH), which determine cellulose to behave as a weak acid with an ionization constant of about 2×10^{-14} . These groups are responsible to some extent for ionic conduction and dielectric losses in cellulose paper at lower frequencies. Cellulose paper contains pores with sizes between 10 and 100 Å. Its fibers form a complex interwoven channel system, allowing significant ions displacement (of smaller dimensions), which leads to increased dielectric losses [18]. If the paper temperature reaches 200 °C, the chemical bonds are easily broken and the structure of the paper breaks

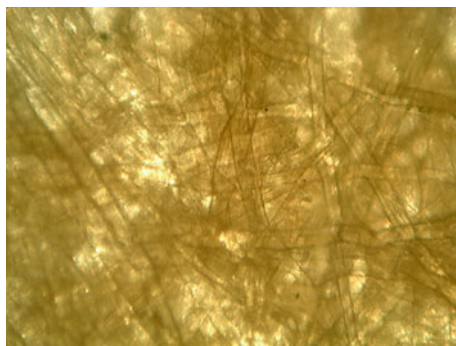


Fig. 14 Structure of the cellulose chains inside Kraft paper [21]

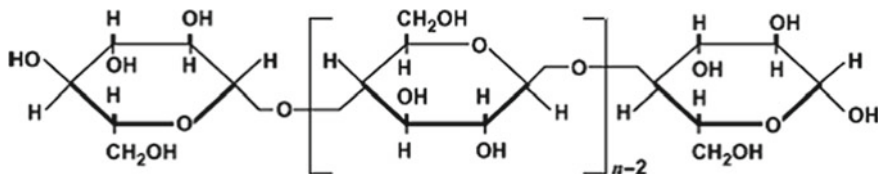


Fig. 15 Molecular structure of cellulose [24]

down gradually to $\text{H}_2\text{O} + \text{CO}_2 + \text{CO}$ [4], the degree of polymerization decreases and the mechanical properties are reduced.

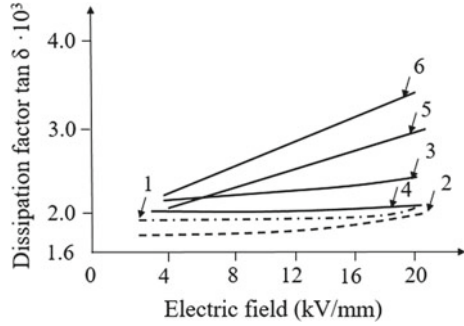
The paper absorbs moisture from the surrounding air (up to 12% under normal conditions) and therefore must be dried in vacuum before impregnation (the water content being reduced to 0.5–1%). The dry paper shows, at the industrial frequency, a relative permittivity of approx. 2.2 (due to the presence of air or vacuum in the pores) and a loss factor of 0.002 [4]. Dried and impregnated with electrical insulating liquids, Kraft papers show high dielectric strength and low losses, necessary properties for AC and DC cables. In addition, Kraft papers have other useful properties, such as lightness, flexibility, compatibility with insulating liquid impregnates and can be manufactured with different values of density, surface friction, mechanical strength, and thickness (0.05–0.2 mm). Since the density of unimpregnated paper is usually 0.75 g/cm^3 and that of cellulose is 1.54 g/cm^3 , it results that Kraft paper is very porous and the oil-impregnated-paper insulation contains one half of oil impregnant by volume. The mechanical strength is 760 bars in the longitudinal direction and 350 bars in the transversal direction [4]. The separation in time of cellulose fibers from paper causes a reduction in the mechanical properties of the paper. On the other hand, another inherent and common defect of Kraft paper is the formation of wrinkles, which causes creases. As the oil tends to fill in the wrinkles in pressurized cables, partial discharges may occur in the oil-impregnated insulation.

Higher density paper tapes contain more water, which results in higher dielectric losses. On the other hand, these bands are less porous and thereby show a higher tensile strength and dielectric constant. To reduce the ions content (and thus the electrical conductivity and dielectric losses), the papers are washed in deionized water. The increased porosity and the existence of pinholes cause a worsening of oil-paper impregnated systems characteristics. Thus, pinholes lead to reduced breakdown voltage values and the increased porosity cause an increase in dielectric losses (due to the increased ion mobility in impregnated paper).

The relative permittivity of oil-impregnated paper is about 3.6 and decreases relatively slow with temperature increasing. The impregnated paper shows high values of dielectric constant due to the high values of the cellulose fibers themselves (6–10). The dissipation factor ($\tan\delta$) of the oil-paper system is approx. 0.002 and increases with temperature (due to the intensification of ionic conduction) [13, 17, 19]. The relatively high values of $\tan\delta$ prevent the use of oil-paper system for cables with nominal voltage higher than 750 kV. The dielectric strength of normal oil-impregnated paper is 40–50 kV/mm for frequencies of 50–60 Hz and 100–200 kV/mm for impulse voltages [4].

The dielectric strength increases with the increase of paper's density, but in the same time, the values of $\tan\delta$ increase, too. The $\tan\delta$ values of the impregnated paper depend not only on the characteristics of the paper, but also on the characteristics of the impregnating oil, temperature, intensity of the electric field, etc. Figure 16 shows the variation curves of the dissipation factor with the electric field intensity and temperature for cables impregnated with a mixture of 06SH and 015SH (Table 3) and an equivalent mixture of mineral pipe cable filling and

Fig. 16 Variation of the dissipation factor with the electric field and temperature for polybutene impregnated paper (1, 25 °C), (2, 85 °C), and (3, 105 °C) and pipe filling and impregnating mineral oils (4, 25 °C), (5, 85 °C), and (6, 105 °C) (Redrawn and adapted from reference [4])



impregnating oils [4]. It can be observed that for 85 and 105 °C, the losses in the mineral oil samples exceed those in the polybutene samples.

3.3 Natural Rubber

Natural rubber is an elastomer which, under tensile stress, will stretch to twice its normal length and return to its initial length after the removal of stress. It has the chemical formula $(C_5H_8)_n$ (see Fig. 17) similar to that of gutta-percha (a trans isomer of natural rubber). Both materials were used in the earlier days for cable construction (up to 25 kV). In order to improve its mechanical, thermal, and environmental (under the action of water) properties, the natural rubber is vulcanized with sulfur (see Table 5). The introduction of sulfur, carbon black, antioxidants, etc., generally, produces a deterioration of dielectric characteristics as follows: the permittivity and the dielectric losses increase (see Fig. 18), whereas the dielectric strength and volume resistivity decrease.

Fig. 17 Molecular structure of natural rubber *cis*-(C_5H_8)_n

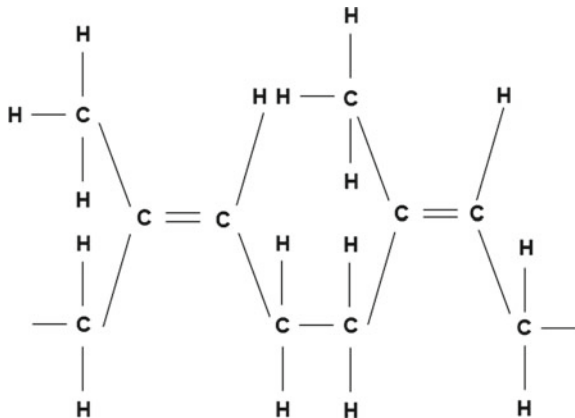


Table 5 Electrical and physical properties of elastomers [25, 26]

Property	Butyl rubber	EPR	EPDM	Neoprene	Natural rubber	Silicone rubber
Volume resistivity (Ωm)	10^{15}	10^{13} – 10^{15}	10^{13} – 10^{15}	10^9	10^{13} – 10^{15}	10^9 – 10^{15}
Dielectric strength (kV/mm)	35	35–41	41	6–35	–	4–26
Dielectric constant at 1 kHz	3.1–3.4	3.17–3.34	3.0–3.5	9.0	2.3–3.0	3.0–3.5
Dissipation factor at 60 Hz	0.0030	0.0066–0.0079	0.004	0.030	0.0023–0.0030	0.001–0.010
Tensile strength, gum (MPa)	17.24–20.68	3.45	1.38	26.68–27.58	17.24–20.68	2.76
Tensile strength, loaded stock (MPa)	17.24–20.68	5.52–20.68	5.52–24.13	20.68–24.13	24.13–31.08	4.14–12.42
Elongation, gum (%)	750–950	200	200	800–900	750–850	200–800
Shore A hardness	15–75	30–90	30–90	20–95	20–100	30–80
Specific gravity, gum	0.91	0.86	0.86	1.23–1.25	0.92–0.96	0.97
Low-temperature brittle point ($^{\circ}\text{C}$)	–60	–51 to –73	–51 to –73	–40 to –57	–62	–68 to –129
Continuous temperature limit ($^{\circ}\text{C}$)	150	150–175	150–175	107	150	260
Processability	G	G	G	G	G	F to E
Resistance to: Oxidation	G to E	E	E	E	E	E
Ozone	E	E	E	E	E	E
Tear	G	F to G	F to G	G	VG	F to G
Abrasion	G	G to E	G to E	E	E	P to G
Radiation	P	–	–	P	F	F to E
Concentrated acids	E	E	E	G	F to G	E
Dilute acids	E	E	E	E	F to G	E
Alkalies	VP	VG	VG	G	F to G	P to G
Aliphatic hydrocarbons	P	P	P	G	P	P
Aromatic hydrocarbons	P	P	P	F	P	P
Chlorinated hydrocarbons	P	P	P	VP	VP	VP
Oil and gasoline	VP	P	P	G	VP	P to G
Animal and vegetable oils	E	G to E	G to E	G	P	E
Water absorption (swelling)	E	E	E	G	E	E
Sunlight aging	VP	E	E	VG	P	E
Heat aging (100 $^{\circ}\text{C}$)	G	E	E	G	G	E
Flame	P	P	P	G	P	F to E

E excellent, *VG* very good, *G* good, *F* fair, *P* poor, *VP* very poor

Natural rubber is used as insulation for flexible electrical pipes, cables for indoor installations, etc., at low voltages and in environments without mineral oil, oxygenated or halogenated solvents, etc.

3.4 *Butyl Rubber*

Butyl rubber (see Fig. 19) is a synthetic product made by co-polymerization of isobutylene ($C[CH_3]_2=CH_2$) (95–99%) and a small amount of isoprene ($CH_2=C[CH_3]-CH=CH_2$) (1–5%) at very low temperatures, in the presence of aluminum chloride. During the polymerization process, sulfur is used as crosslink agent. Butyl rubber has a good resistance to environment, partial discharges, ultraviolet radiation, oils, tearing, aging at elevated temperatures and good electrical properties (see Table 5).

3.5 *Ethylene Propylene Rubber*

Ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE) are typical thermosetting insulation compounds. Ethylene propylene rubber is an elastomer synthesized from ethylene and propylene with a ratio of 1:1. The molecular structure is presented in Fig. 20, where x and y are the repeating units and take values between 2000 and 3000. The average molecular weights of the EPR used in cables extend from 150,000 to 250,000. Some manufacturers polymerize a diene monomer with ethylene and propylene to form a terpolymer named ethylene propylene diene monomer rubber EPDM (the incorporation of diene allows the curing with sulfur) [27].

The EPR polymer chain formed is not flat, as shown in Fig. 20, but rather three-dimensional with hydrogen atoms and methyl groups from propylene arranged along a zigzag chain of carbon atoms extending above and below the plane. The arrangement of ethylene and propylene molecules is random so that the resulting polymer structure is neither alternating nor very blocky. Statistics regarding ethylene/propylene monomer feed ratio, selectivity of the Ziegler–Natta catalyst, and the polymerization conditions determine the blockiness of EPR and whether it is completely amorphous or contains some crystalline content (due to the ethylene groups that tend to form organized repeated segments, if the ethylene content reaches 60%) [27]. Nevertheless, by increasing crystallinity, the processability is reduced, thus the flexibility of the cable becomes poorer and the hardness of the extruded cable is augmented [4].

When greater hardness is required, the EPR compound can be blended with polyethylene (PE) or polypropylene (PP) to achieve improved physical properties. Mechanical properties include resistance to compression, cutting, impact, tearing and abrasion. Although EPR does not offer a good resistance to oils, it is resistant to

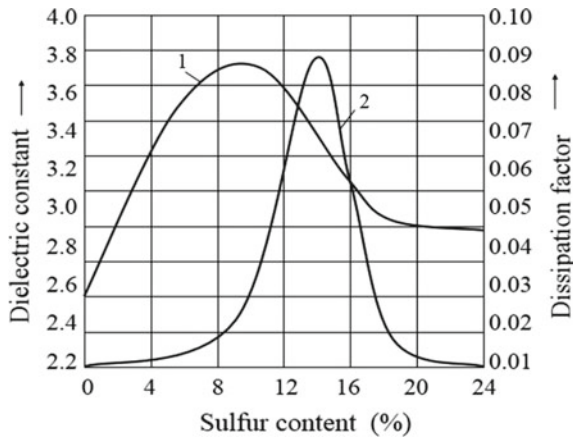


Fig. 18 Variation of relative permittivity (1) and dissipation factor (2) of natural rubber with sulfur content (Reprinted, with permission, from author [13])

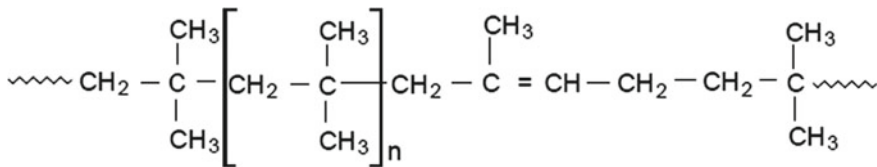
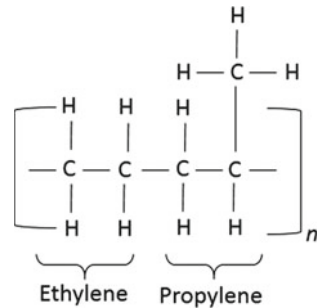


Fig. 19 Molecular structure of the butyl rubber

Fig. 20 Molecular structure of EPR



a wide range of other chemicals including many acids, alkalis, and organic solvents. It is also highly resistant to moisture.

Amorphous EPR insulated power cables are expected to be more stable under high-temperature conditions than crystalline XLPE-insulated cables. The properties of amorphous EPRs are slightly affected by temperature ranging from -30 to 150 °C. The properties of crystalline XLPE deteriorate as temperature exceeds the melting point (around 100 °C) in the crystalline regions. Probably reinforced

amorphous EPR insulated cables are expected to be more stable in wet locations than unfilled XLPE-insulated cables. They do not fail as a result of the formation of water trees as primary mechanism, since the bonds between fillers and polymer are stronger than the forces responsible for water trees formed in XLPE cables in service. The reinforcing effect of fillers in EPR makes questionable any extrapolation from high stress treeing studies of unreinforced PE, XLPE, or EP polymers. A water impermeable metallic sheath, which act against corrosion, mechanical damage, fatigue, cracks, etc., should protect the insulation in order to operate as long as possible in wet locations. Any other insulation will eventually fail to continued exposure at water and electrical stress.

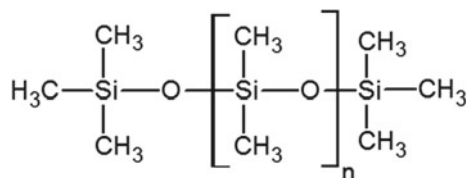
Unlike XLPE, EPR is a compound where the rubber resin (about 50%, [26]) is mixed with other additives (normally eight or more additives) to improve the mechanical and electrical properties. Typical ingredients of an EPR compound may be ethylene propylene rubber (EPR), inorganic mineral fillers, antioxidants/stabilizers, flame retardants (for low-voltage insulation materials), curing catalysts/coagents, and metal oxides including lead oxide. Both EPM and EPDM have outstanding resistance to ozone and oxygen, excellent weathering and heat resistance, low-temperature flexibility, and excellent electrical properties. Weatherability can be achieved without antioxidants or antiozonates. EPR is suitable for continuous service up to 150 °C with excursions up to 175 °C or higher. Chemical resistance to polar materials, such as acids, alkalis, oxygenated solvents, water, and steam, is excellent. Resistance to nonpolar hydrocarbon solvents, such as toluene and gasoline, is poor. The low specific gravity for EPR of 0.86 g/cc can result in reduced costs for final products [27].

Key insulation users are low- and medium-voltage power cable, control and instrument, automotive ignition and motor lead wire, mining cable, etc. [28]. Furthermore, EPR insulation is suitable for many higher voltage applications and while its dielectric properties are not as good as those of XLPE, it does have some important advantages over XLPE including extra flexibility, reduced thermal expansion, and low sensitivity to water treeing [28].

3.6 *Silicon Rubber*

Silicon rubber is an organic-inorganic elastomer obtained by polymerization of organic siloxanes [13]. The number of dimethyl-siloxanes n (see Fig. 21) determines the length and properties of silicone rubber. Cross-linking (vulcanization) of silicone rubber is carried out by the use of different peroxides such as benzoyl peroxide or dichlororobenzoyl peroxide or by gamma or electron radiation. For the improvement of certain properties (mechanical, etc.), different fillers such as silica, calcium carbonates, titanium, iron oxides are introduced in the silicone rubber [29]. They show good dielectric properties (see Table 5), low water absorption, good resistance to partial discharges and can be used as insulations that operate from very low temperatures (−85 °C) to very high temperatures (260 °C).

Fig. 21 Chemical structure of silicone rubber



3.7 Polyethylene

Polyethylene (PE) is obtained by polymerization of ethylene (C_2H_4) (see Fig. 22a), at high pressure (1000–3000 atm and 200–250 °C) resulting in a low-density material (LDPE) or at low pressures (up to 60 atm) resulting in a high-density material (HDPE) (see Table 6). It has symmetrical and linear molecules, and hence, it is nonpolar and thermoplastic. LDPE has a partially crystalline structure and reduced mechanical properties, mainly, due to the presence of $-\text{CH}_3$ radicals, which blocks the ordering of macromolecules (see Fig. 22b). HDPE (low pressure HDPE) has a high degree of crystallinity (up to 93%), which gives it higher hardness, softening temperature, and an improved behavior at lower temperatures (up to -40 °C) than LDPE. In general, the degree of crystallinity influences both physical and electrical properties (such as treeing resistance).

The free radicals generated in LDPE from peroxide at elevated temperatures may induce the ethylene molecules to add linearly, in a normal way, to each other or alternatively, causing a short growth of the side chains of the polymer. The appearance of numerous side chains of various lengths gives to polyethylene a low density. The existence of side chains is also due to the addition of certain amounts of butene (C_4H_8), hexene (C_6H_{12}), or octene (C_8H_{16}) (see Fig. 23). In the case of HDPE, the addition of butene, hexene, or octene leads to an increase in both, the number of side branches and the crystallinity [13]. The presence of such side branches is a reason for variations in a number of important physical properties

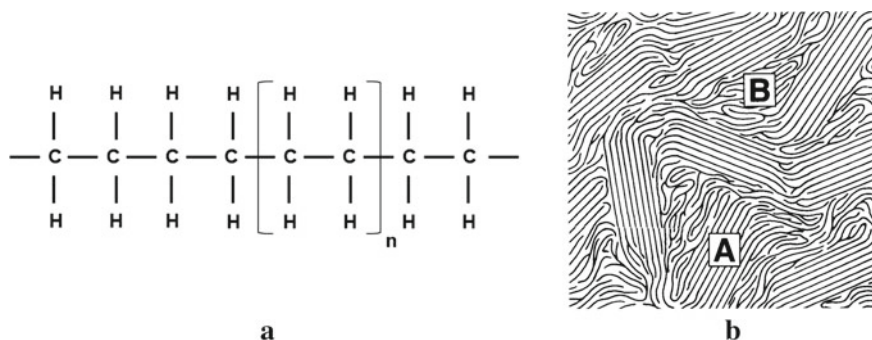


Fig. 22 **a** Molecular structure of polyethylene; **b** crystalline (A) and amorphous (B) zones in polyethylene [30]

Table 6 Electrical and physical properties of polyethylenes [31]

Property	Low-density PE	High-density PE	XLPE
Volume resistivity (Ωm)	$>10^{14}$	$>10^{13}$	$>10^{13}$
Dielectric strength (kV/mm)	18–28	18–20	22
Dielectric constant at 60 Hz	2.3	2.3	2.3
Dissipation factor at 60 Hz	0.0002	0.0002	0.0003
Density (g/cm^3)	0.910–0.925	0.941–0.965	0.92
Elongation (%)	20–650	15–700	550
Tensile strength (MPa)	9.65–13.10	17.93–31.03	16.55
Modulus of elasticity (MPa)	117–242	552–1035	790
Thermal conductivity ($\text{W}/\text{m } ^\circ\text{C}$)	0.335	0.461–0.502	0.24–0.32
Heat distortion temperature ($^\circ\text{C}$)	41–50	49–66	54–107
Operating temperature ($^\circ\text{C}$)	70 (90)*	80 (120)*	90 (130)*
Water absorption (%)	<0.02	<0.01	0.02–0.035

(*)—for short duration

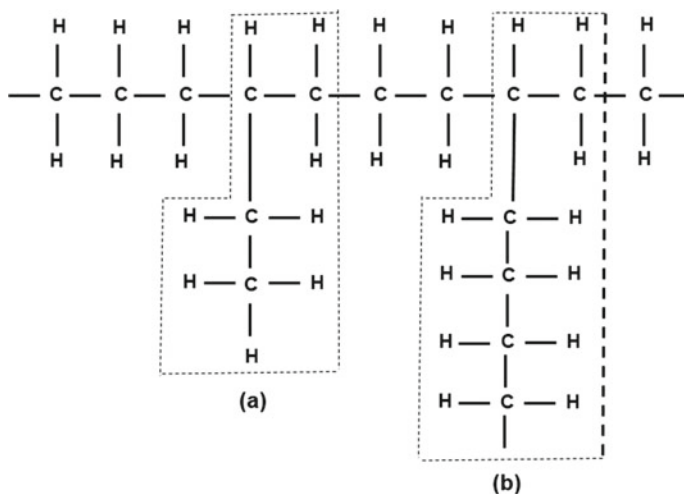


Fig. 23 Polyethylene molecular chain with side branch of butene (a) and hexene (b)

(such as density, hardness, flexibility, and melt viscosity), which delimit polyethylene resins. Chain branches also become points in the molecular network where oxidation may take place [30].

In order to insulate cables, especially LDPE is used. The operating temperature of LDPE may not exceed 80 $^\circ\text{C}$ continuously and 90 $^\circ\text{C}$ for a short time. LDPE shows [13]:

- (a) excellent resistance (no attack/no chemical reaction) to dilute and concentrated acids, alcohols, bases, and esters;
- (b) good resistance (minor attack/very low chemical reactivity) to aldehydes, ketones, and vegetable oils;
- (c) limited resistance (moderate attack/significant chemical reaction, suitable for short-term use only) to aliphatic and aromatic hydrocarbons, mineral oils, and oxidizing agents;
- (d) poor resistance (not recommended for use) with halogenated hydrocarbons.

The disadvantages of polyethylene include high thermal expansion, poor weathering resistance subject to stress cracking, difficult to bond, flammable, poor temperature capability, low strength/stiffness, etc.

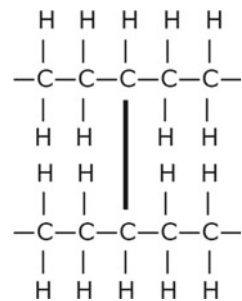
During the operation of cables, under the action of the electric field, polyethylene is degraded due to the partial discharges, the electric and water trees. Against these phenomena, different additives are added [2].

3.8 Cross-Linked Polyethylene

The cross-linking process causes polyethylene a change from a thermoplastic to a thermosetting material with an important improvement in both physical and electrical properties (see Table 6) [2]. Therefore, XLPE (see Fig. 24) is used, both for the insulation of low- and medium-voltage power cables, as well as for those of high and very high voltage. The cross-linking agent is usually dicumyl peroxide, which is decomposed and the acetophenone is formed. The presence of acetophenone in XLPE cables insulation leads to a delay (attenuation) of electrical phenomena [32] and water treeing [33].

The insulation of XLPE power cables that are steam cured present a considerable amount of moisture, which remains in or diffuses out of the insulation. Both cases facilitate the development of water trees. The use of dry curing process has the effect of reducing the concentration of microvoids and, therefore, a reduction in the

Fig. 24 Molecular structure of XLPE



speed of water trees development. However, even in this case, the operation of cables in a moisture environment leads to the initiation and development of water trees [34].

Due to the fact that XLPE is a thermosetting material, it maintains its mechanical properties even at temperatures where linear polyethylenes (LDPE or HDPE) melt, lose shape, and flow. XLPE has good properties at low temperatures and shows increased resistance to ozone and partial discharges (as compared to linear PE) and good impact, abrasion and environmental stress cracking resistance characteristics. As power cables with XLPE insulation can operate at conductor temperatures of 90 °C (e.g., LDPE insulated cable operates at 75 °C), and as the conductor temperature is proportional to the amount of current sent through the cable, it turns out that more power can be sent through an XLPE cable than through a non-cross-linked cable of the same size. Under short-circuit conditions, XLPE insulation withstands for one second to a conductor temperature of up to 250 °C, compared to PVC cable, which supports for one second a conductor temperature of up to 160 °C. XLPE cable possesses higher overloading capacity under emergency conditions. It also can withstand vibration and has up to 100 times more moisture resistance capacity compared to PVC.

Another characteristic of XLPEs is their capability to employ higher filler loadings without significant deterioration of physical properties. Cross-linking forms bonds around a filler and their incorporation into the polymer matrix reduce its effect on the compound [30]. On the other hand, by using a cross-linkable resin base, flame retardant, mineral filler, or carbon black can be disposed in higher concentrations by maintaining physical properties at acceptable levels. This enables the development of highly flame retardant, abrasion resistant, or semiconductive wire compounds [30].

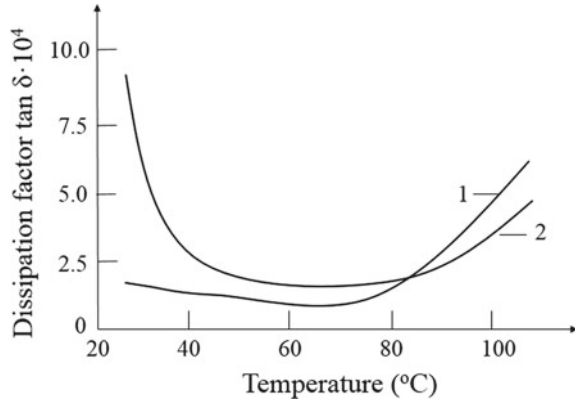
By using certain nano-fillers (e.g., MgO [6]), we can be obtained XLPEs used in DC (DC-XLPE) with high volume resistivity, low space charge accumulation, long DC lifetime, and high DC breakdown strength than the usual XLPE used in AC (AC-XLPE) [35].

3.9 Tree-Retardant XLPE

The use of tree-retardant XLPE (TR-XLPE) for power cables insulation has led to increase initiation times and development rate of water trees. Among the first inhibitors of water, trees were used dodecanol ($\text{CH}_{12}\text{CH}_2\text{OH}$) and ethylene vinyl acetate (EVA), but their effectiveness decreased over time [4]. In 1983, Union Carbide proposed a tree-inhibiting compound with a strong polar character, which resulted in a greater reduction of development rate and water tree concentrations [36]. Definitely, the introduction of a polar additive in XLPE causes an increase in dielectric losses, but smaller than those in EPR compounds.

The variation of dissipation factor ($\tan\delta$) with temperature for the insulation (aged and unaged) of a 20 kV cable is shown in Fig. 25 [37]. It was found that at

Fig. 25 Variation of the temperature dissipation factor within the insulation of a 20 kV cable from XLPE with polar tree-retardant, before (1) and after aging (2) (Redrawn and adapted figure from reference [37])

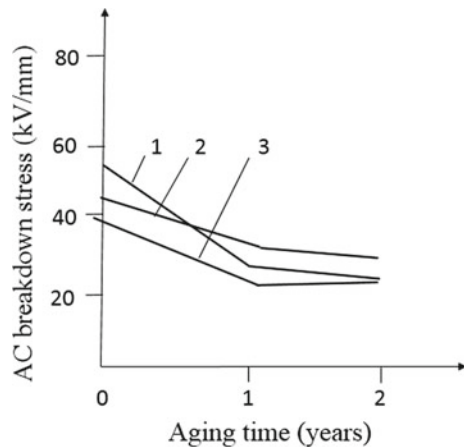


lower temperatures, $\tan \delta$ has lower values for the unaged insulation than for the aged ones, due to the reduction of the molecular dipoles orientation caused by some residual products (peroxides), which are eliminated in the aged insulation. The increase of $\tan \delta$ values, for higher temperatures, in XLPE by the addition of tree-retardant is due to the reduction of effective charge trap depths and to the introduction of mobile ion constituents, whose mobility is intensified at higher temperatures (thermal agitation [13]).

The addition of a polar tree retardant to XLPE diminishes greatly the number and size of bow-tie water trees, when state-of-the-art semiconducting shields are employed. However, the effect on vented-type water trees is essentially insignificant [36, 37]. On the other hand, the use of tree-retardant leads to the reduction of dielectric strength of XLPE cable insulations (see Fig. 26). In general, TR-XLPE is used for the insulation of high and very high voltage power cables.

The worldwide tendency in using HVDC transmission lines makes the demand for better insulation materials increasingly greater and urgent. Many manufactures

Fig. 26 Variation of AC breakdown stress with aging time (30 kV, 50 Hz) for an XLPE 20 kV cable insulation: 1 Conventional XLPE cable; 2 XLPE with tree-retardant and conventional semiconducting shields; 3 XLPE with tree-retardant and higher purity carbon semiconducting shields (Redrawn and adapted figure from reference [37])



have developed XLPE materials that are more adapted to DC power cables insulation, such as the super-clean XLPE (lower concentration of impurities) and XLPE-based nanocomposites [38].

3.9.1 Polyvinyl Chloride

Polyvinyl chloride (PVC) is obtained by polymerization of vinyl chloride (see Fig. 27), in the form of hard PVC without plasticizers or soft PVC with plasticizers (e.g., phthalic, phosphoric, citric acid esters, etc.). Being a polar material, it has lower dielectric characteristics than polyethylene and dependent—as well as mechanical ones—on the plasticizer content (see Figs. 28 and 29). It performs better than natural rubber, both on the action of ozone and mineral oil. However, it has low thermal stability (70 °C) and its properties are inferior to those of polyethylene (see Tables 7 and 8) and vary greatly with frequency and temperature (see Figs. 30 and 31).

Due to low corona resistance, PVC is used to insulate conductors and power cables of low and medium voltages, respectively, between 1 and 20 kV. It is clean to handle and is reasonably resistant to oils and other chemicals. As in DC, it ages very quickly (i.e., due to the electrolysis of salts from the additives), and at high frequencies, it presents high dielectric losses ($\tan\delta = 0.015\text{--}0.3$), and PVC is used only in AC fields of industrial frequencies. PVC has high resistance to abrasion and fire although the wires may burn when exposed to fire and can cease to burn when the source of fire has been eliminated. Nevertheless, when PVC burns, it emits dense smoke and corrosive hydrogen chloride gas. In addition, certain types of PVC can be used for applications where the cables may be exposed to high or low temperatures (including arctic-grade PVC for extreme low conditions), or where protection against UV light is required to avoid degradation [40]. PVC is often used for electrical cable jacketing due to its excellent electrical insulating properties and dielectric constant.

3.10 Polypropylene

Polypropylene (PP) is a thermoplastic resin obtained by polymerization of propylene as a monomer (see Fig. 32, [41]), and depending on its methyl group position

Fig. 27 Chemical structure of polyvinyl chloride

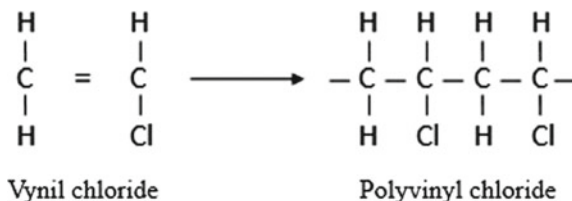


Fig. 28 Variation of relative permittivity (1) and volume resistivity (2) with plasticizer content for PVC (Reprinted, with permission, from author [13])

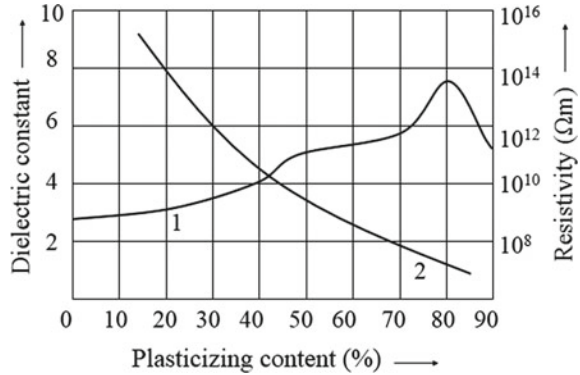


Fig. 29 Variation of tensile strength (1) and relative elongation at break (2) with plasticizer content for PVC (Reprinted, with permission, from author [13])

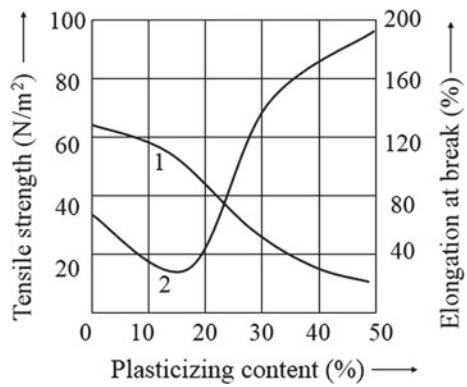


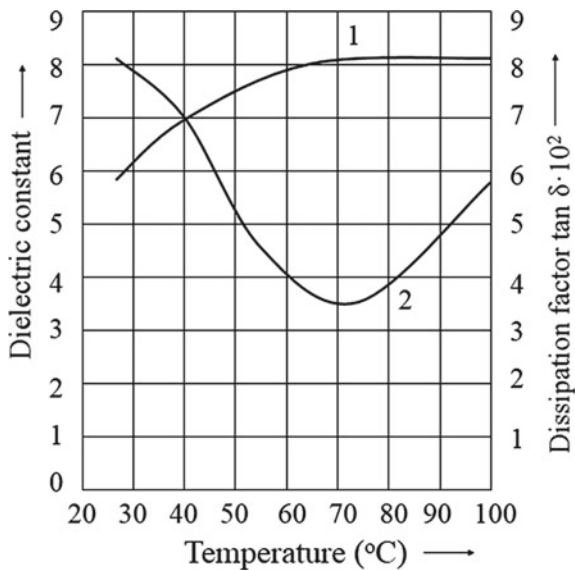
Table 7 Physical properties of polyvinyl chloride (PVC) [13, 39]

Property	Rigid PVC	Flexible PVC
Density (g/cm ³)	1.3–1.45	1.1–1.35
Thermal conductivity (W/(m°C))	0.14–0.28	0.14–0.17
Yield strength (MPa)	310–560	2.14–4.14
Young’s modulus (GPa)	3.4	0.05
Tensile strength (MPa)	50	11
Compression strength (MPa)	66	
Coefficient of thermal expansion (linear) (10 ⁶ mm/mm °C)	50	190
Volume resistivity (Ω m)	10 ¹⁶	10 ¹² –10 ¹⁵
Surface resistivity (Ω)	10 ¹³ –10 ¹⁴	10 ¹¹ –10 ¹²

Table 8 Characteristics of polyethylene (XLPE) and polyvinyl chloride (PVC) insulation

Feature	Insulation	
	XLPE	PVC
Temperature range (°C)	-55 to +100	-10 to +60
Cold Bend	Excellent	Good
Moisture resistance	Excellent	Good
Chemical resistance	Excellent	Good
Abrasion resistance	Excellent	Good
Cut-through resistance	Excellent	Good
Elongation resistance	Excellent	Good
Rodent resistance	Poor	Poor

Fig. 30 Variation of relative permittivity (1) and dissipation factor (2) with temperature for PVC (Reprinted, with permission, from author [13])



on one side of the polymer backbone, it may be isotactic polypropylene (iPP), syndiotactic polypropylene (sPP), and atactic polypropylene (aPP) [41, 42].

Polyethylene (PE) and polypropylene (PP) are bulk commodity polymers, comparably priced and both have an intrinsically nonpolar molecular structure. However, several significant differences exist, such as

- (a) the melting temperature of isotactic polypropylene (iPP) is much higher than that of XLPE;
- (b) the morphology of iPP is based on a number of different crystal structures (notably α , β , and γ);
- (c) iPP tends to form particularly large spherulites and the material is intrinsically clean;

Fig. 31 Variation of volume resistivity with temperature for PVC plasticized with dioctylphthalate (1) or tricresylphosphate (2) (Reprinted, with permission, from author [13])

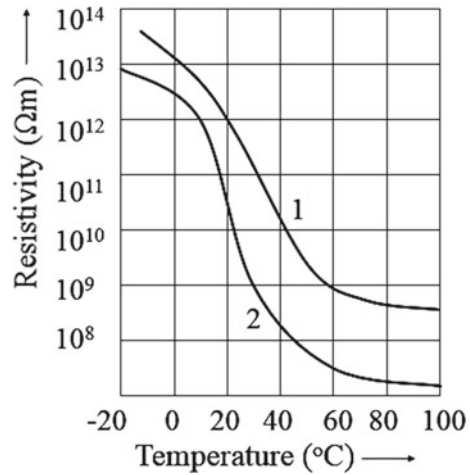
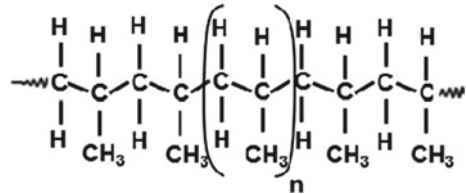


Fig. 32 Molecular structure of isotactic polypropylene



- (d) large spherulites mean that interspherulitic regions are particularly weak;
- (e) synthesis methods of PP do not produce branched molecular structures similar to LDPE.

PP is one of the lightest polymers (with a density of 0.9–0.91 g/cm³; see Table 9) with good chemical resistance to acids, alcohols, bases, aldehydes, esters, aliphatic hydrocarbons, ketones. It maintains its mechanical and electrical properties at elevated temperatures, in humid conditions and submerged in water is non-toxic. It is, however, a highly flammable material, and it is sensitive to microbial attacks, such as bacteria and mold. The melting point of PP can reach more than 150 °C, about 40–50% higher than that of PE, and the long-term working temperature can reach 90 °C.

PP is a nonpolar material with high dielectric breakdown (even over 300 kV/mm [44]), high volume resistivity (up to 10¹⁶ Ωm), and less space charge accumulation. PP hardly absorbs water, so its insulation properties are less affected by the ambient humidity. In addition, PP materials have high mechanical strength without cross-linking treatment and can be recycled and used in line as environmentally friendly cable insulations. However, PP has some disadvantages, such as high

Table 9 Properties of polypropylene [41, 43]

Property	Value
Density (g/cm ³)	0.9–0.91 g/cm ³
Glass transition temperature (°C)	–10
Transparency (%)	85–90
Dielectric constant	2.3
Dielectric strength (kV/mm)	20–28
Dissipation factor	$(3–5) \times 10^{-4}$
Volume resistivity (Ωm)	$(1.6–1.8) \times 10^{14}$
Thermal conductivity (W/mK)	0.15–0.21
Coefficient of linear thermal expansion (1/°C)	$(6–17) \times 10^{-5}$
Melting point (°C)	160–165
Elongation at break (%)	150–600%
Flexural modulus (GPa)	1.2–1.6
Young modulus (GPa)	1.1–1.6
Strength at break (tensile) (MPa)	20–40
Strength at yield (tensile) (MPa)	35–40
Max continuous service temperature (°C)	100–130
Min continuous service temperature (°C)	–20 to –10 °C
Gamma radiation resistance	Poor
UV light resistance	Fair

brittleness at low-temperature, poor aging resistance, and low thermal conductivity, which assess certain limitations on the application of DC cable insulation.

Due to the high values of dielectric strength at high or low temperatures (see Table 10), PP films are used as dielectrics for capacitors [42] or superconducting cables insulation [45]. The insulation of superconducting cables is made of polypropylene sheets (PPLP) or Kraft paper, the resistivity of which did not change with the increase in number of layers [46].

It should be noted that PP has shown great potential as a recyclable HVDC cable insulation material. However, PP has the disadvantages of poor low-temperature impact performance and low thermal conductivity, as well as the problem of space charge accumulation and polymer aging in Dc field. Therefore, PP needs to be modified in order to meet the electrical, thermal, and mechanical properties of the cable insulation material under the complex working conditions of DC high voltage [42].

Table 10 Dielectric strength values of XLPE and sPP [42]

Temperature (°C)		25	90	110
Breakdown strength (kV/mm)	XLPE	135	115	–
	sPP	180	132	112

There is much interest in the development of XLPE replacement materials that are both recyclable (i.e., thermoplastic) and capable of high-temperature operation. Thermally, PP is the ideal choice, although its stiffness and low electrical breakdown strength make a challenging materials design problem [47].

3.11 Polytetrafluoroethylene (PTFE)

Polytetrafluoroethylene (PTFE) is a synthetic fluoropolymer obtained by the polymerization of tetrafluoroethylene (F_2C-CF_2), with a similar structure to PE (see Fig. 33) [48]. PTFE is nonpolar, has good dielectric properties, and does not burn. Due to the high values of bonding energy between carbon (C) and fluorine (F) atoms, PTFE has high thermal stability (250 °C). Microgaps (cavities) where partial discharges can develop appear in PTFE in the case of significant temperature variations due to the large coefficient of linear expansion. Therefore, PTFE is not used in intense electric fields. PTFE is used for the manufacture of insulation systems that operate at higher temperatures (over 180 °C), in humid environments or in highly corrosive atmospheres, as insulation of conductors and high-frequency cables, etc.

The performance of PTFE thermal conductivity over a wide range of temperature is excellent compare to other polymers. The thermal stability is due to the linear high crystalline arrangement of C-F atoms, which give a high value of the melting point (342 °C). PTFE has good mechanical properties, especially if it contains nano-fillers (aluminum oxides, copper, silicon dioxide) [49]. Naturally, PTFE is non-reactive and insoluble due to the strongly bonded C-F atoms. Common reagents such as hydrofluoric, hydrochloric, and chlorosulfonic acids do not affect PTFE. Even above the transition temperature (327 °C), PTFE is insoluble in organic solvents such as hydrocarbons, chlorinated hydrocarbons, or ester and phenol. This is due to the very fewer interaction forces between fluorocarbon and other molecules [49].

PTFE is a thermoplastic polymer (white solid at room temperature) with a density of about 2.2 kg/cm³ (see Table 11). It maintains high strength, toughness, and self-lubrication at low temperatures (5 K) and good flexibility at temperatures above 194 K [48].

PTFE insulation has several advantages, such as excellent thermal stability (from -65 to +260 °C); inert to practically all chemicals (even at elevated temperatures);

Fig. 33 Chemical structure of polytetrafluoroethylene (PTFE)

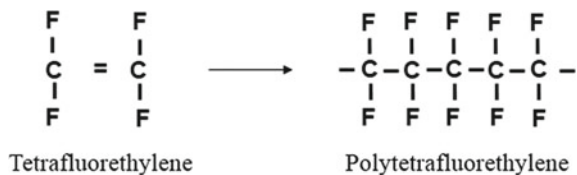


Table 11 Properties of polytetrafluoroethylene (PTFE) [48]

Property	Value
Density (kg/cm ³)	2.2
Glass temperature (°C)	114.85
Melting point (°C)	326.85
Thermal expansion (K ⁻¹)	(112–125) × 10 ⁻⁶
Thermal diffusivity (mm ² /s)	0.124
Young's modulus (GPa)	0.5
Yield strength (MPa)	23
Bulk resistivity (Ωm)	10 ¹⁶
Dielectric constant (60 Hz)	2.1
Dissipation factor (60 Hz)	<2 × 10 ⁻⁴
Dielectric strength (MV/m)	60

lowest dielectric constant and dissipation factor (see Table 11); excellent flex life, good mechanical strength, excellent resistance to ultra-radiation and stress cracking, good resistance to fungus and mold growth, smaller in size, more flexible, lighter in weight and higher reliability, fire and flame proof, non-contamination, non-toxic, and bio-compatible [50].

4 Synthetic Solid–Liquid Insulations

As cellulose paper–oil insulation system has high dielectric losses, it cannot be used as insulation for cables of voltages over 750 kV. As a result, research has been carried out to obtain low-loss synthetic tapes, chemically compatible with impregnating liquids and with lifetimes at least as long as those of cellulose papers.

The first synthetic solid–liquid insulations were those made of polycarbonate tapes (with $\tan\delta = 0.0025$) in conjunction with mineral oils and silicone liquids (see Table 12) [51]. For a voltage stress of 18 kV/mm, a polycarbonate–mineral oil insulation has a loss factor of 0.003 at room temperature and 0.0022 at 85 °C. If the mineral oil is replaced with a silicone one, $\tan\delta$ values of 0.0015 are obtained at 25 °C and 0.001 at 85 °C, respectively [52]. Using hydrogenated polybutene with 5% tri-isopropylbenzene as impregnated for polycarbonate tapes, a $\tan\delta$ value of 0.00078 was obtained at room temperature [53]. On the other hand, the use of fluorocarbon polymers in conjunction with polybutene fluids has reduced the loss factor of solid–liquid insulation to 0.0003 [54].

Tests were also performed on insulations based on synthetic paper comprising polyester fibers and porous polycarbonate phase impregnated with dodecyl benzene. It has been found that dielectric properties of the insulation are satisfactory ($\tan\delta = 0.0005$ at 80 °C), but the level of partial discharges is too high [55].

Numerous researches have been carried out to characterize the insulations based on laminated polypropylene paper (PPP) and their properties (both unimpregnated

Table 12 Properties of solid–liquid insulating systems [4]

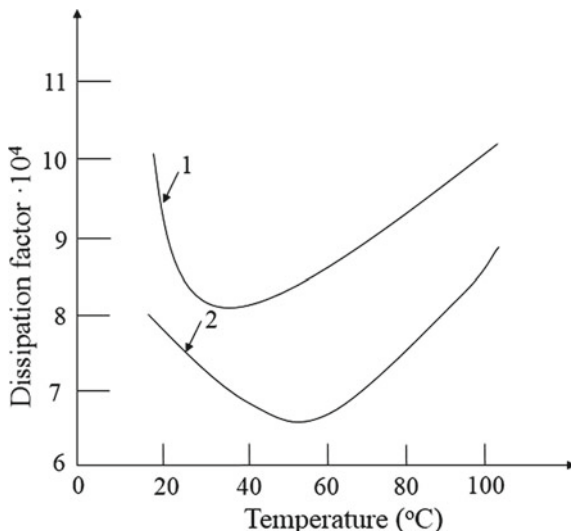
Solid tape	Impregnating liquid	Voltage stress (kV/mm)	Tanδ at operating temperature
Kraft paper	Mineral oil	18	0.0057, 85 °C
Kraft paper	Silicone liquid	18	0.0031, 85 °C
High-loss polycarbonate	Mineral oil	18	0.0022, 85 °C
High-loss polycarbonate	Silicone liquid	18	0.0010, 85 °C
Fluorocarbon	Polybutene liquid	18	0.0030, 100 °C
Polyolefin synthetic paper	Polybutene liquid	12	0.0003, 80 °C
Polyester-polycarbonate	Dodecyl benzene	10	0.0005, 80 °C
Spun-bonded polyethylene fiber	Liquid nitrogen	20	<0.00001, 70 K
Kraft paper-polypropilene-Kraft paper (PPP)	Dodecyl benzene	20	0.00096, 100 °C

and impregnated with dodecyl benzene) have been remarkable (see Table 13). It was concluded that an insulated cable with PPP could operate at 70% higher stresses than those insulated with Kraft paper [4].

Table 13 Physical and electrical properties of PPP tape of thickness *g* (unimpregnated (UIM) and impregnated with dodecyl benzene) (IM) [56]

Property	<i>g</i> = 125 μm	<i>g</i> = 155 μm
Polypropylene to total PPP	0.42	0.42
Dissipation factor for:		
– UIM	0.00098	0.00093
– IM at 100 °C	0.00099	0.00096
Dielectric constant for:		
– UIM	2.8	2.8
– IM	2.82	2.82
AC Breakdown stress (kV/mm)	129.8	128.2
Impuls breakdown (kV/mm)	225.2	217.8
Density (g/cm ³)	0.89	0.89
Tensile strength (N/mm ²)		
– Longitudinal	110	145
– Transverse	58	79
Elongation (%)		
– Longitudinal	3.3	3.4
– Transverse	9.9	10.4

Fig. 34 Variation of dissipation factor with for PPP impregnated (24 h at 100 °C) with dodecyl benzene, before (1) and after impregnation (2)



The impregnation of PP bands with dodecyl benzene is done at 100 °C for 24 h. Following this process, it results in a considerable reduction of loss factor (see Fig. 34) [56]. The variation of the loss factor with temperature highlights the importance of ionic conductivity in dielectric losses: PP bands form barriers against ions movement between adjacent layers, and the charges accumulated at the interfaces between layers generate small, but detectable interfacial polarization losses [4].

A model of insulated cable with PE fiber tapes impregnated with liquid nitrogen and helium was tested under cryogenic conditions [57]. For an electric field of approx. 20 kV/mm, a $\tan\delta$ value of less than 10^{-5} was obtained. Although the losses are much reduced, the use of this insulation system is disadvantageous due to the very high initial costs (for cooling equipment) [58, 59].

5 Gas–Solid Spacer Insulating Systems

Gas-insulated cables have been constructed using compressed sulfur hexafluoride gas (SF₆) and conductors fixed by epoxy or PE spacers. SF₆ has the breakdown strength values of 2.3 times greater than dry nitrogen. It is non-toxic and non-inflammable and can be used for cables up to 500 kV. Under the action of PDs and SF₆ electric arc, it decomposes chemically, resulting in toxic gases that degrade the adjacent insulation and can affect the environment, if leaks occur. In gas-filled cables, it is very important to match the coefficient of thermal expansion of the epoxy spacers to that of the conductor (Cu, Al), in order to avoid stress cracking or separation of the epoxy resin from the metal, respectively the occurrence of PDs [60].

Table 14 Properties of epoxy resins [61]

Property	Unfilled	Silica filled
Volume resistivity (Ωm)	10^{10} – 10^{15}	10^{11} – 10^{14}
Dielectric strength (kV/mm)	16–22	16–22
Dielectric constant at 60 Hz	3.5–5	3.2–4.5
Dissipation factor at 60 Hz	0.002–0.050	0.008–0.03
Specific gravity	1.11–1.14	1.6–2.0
Modulus of elasticity (GN/m^2)	2.1–2.4	2.1–2.4
Elongation (%)	3–6	1–3
Flexural strength (MN/m^2)	89–144	55–97
Compressive strength (MN/m^2)	103–144	103–276
Heat distortion temperature at 1.8 MN/m^2 ($^{\circ}\text{C}$)	46–288	71–288
Thermal conductivity ($\text{W}/^{\circ}\text{C m}$)	0.1672–0.209	0.418–0.836
Thermal expansion (10^{-6} $\text{m/m } ^{\circ}\text{C}$)	45–65	20–40
Water absorption (%)	0.08–0.15	0.04–0.10

In this regard, inorganic fillers such as silica are used, which leads to an important increase of the thermal conductivity and to the reduction of volume resistivity, relative permittivity, coefficient of thermal expansion, and water absorption (see Table 14).

6 XLPE Versus Conventional Materials

The use of XLPE or other electrical materials for insulation and coating of power cables depends on their thermo-electrical stresses, environment stresses, level of safety in operation required by the user, and, of course, costs of the cables (to the manufacturer) and their maintenance costs (to the user). From all accounts, apart from the separation function of the conductors with opposite electrical potentials (for which they must satisfy certain mechanical, thermal, chemical and electrical requirements), the insulation must support the two conductors and to maintain their separation. Moreover, the insulation must often withstand rough handling and abuse during installation, as well as thermal overloading during its service life. In different works, the characteristics of polyethylene (PE), filled PE, cross-linked polyethylene (XLPE), polypropylene (PP) ethylene propylene rubber (EPR), ethylene propylene diene monomer (EPDM), silicone rubber (SR), polytetrafluoroethylene (PTFE), etc., were analyzed. There are many good, solid dielectrics available today, and each has a unique combination of properties [62].

As it will be seen below, some of the electrical insulating materials have one or more properties superior to all the others, properties that recommend them for certain applications.

6.1 Electrical Properties

The choice of a certain material for electrical equipment insulation is based primarily on the electrical properties of the materials, namely the electrical conductivity and permittivity, dielectric losses, dielectric strength, and accumulation of the space charge. In numerous papers, the values and variations with different factors (temperature, intensity, and frequency of the electric field, etc.) of these parameters are analyzed for XLPE, PE, PP, EPR, EPDM, SC, and PTFE. A comparative analysis of the general properties of XLPE and EPR is presented in [62].

6.1.1 Electrical Conductivity

The electrical conductivity σ is the main parameter that characterizes an electrical insulating material (and, therefore, the behavior of the insulation in operation) and is determined with different empirical relations [63–68], such as

$$\sigma(E, T) = A \exp\left(-\frac{E_a}{kT}\right) \frac{\sinh((aT + b) \ln E)}{E^\alpha} \quad (1)$$

where E_a is the activation energy, A , a , b , and α —material constants, k —Boltzmann constant, T —the temperature, and E —the applied electric field (reported, dimensionless). In the case of XLPE, it is considered $\alpha = 1$ [63], and in the case of EPR, $\alpha = 0.21$ – 0.23 [68].

The electrical resistivity values of the insulation materials used in electrical engineering determined by DC or AC measurements must be as low and less dependent on the intensity of the electric field and operating temperature of the insulation, as the values of resistive currents and dielectric losses to be as small as possible. In numerous papers, the values of LDPE, XLPE, EPR, silicone rubber resistivity are determined under standard conditions and are presented and analyzed as variations with different stress factors (temperature, electric field, etc.).

Figures 35, 36, 37 and 38 show the variations of DC electrical conductivity (σ) with the intensity of the electric field and temperature for XLPE and EPR. It was found that the values of σ are lower for XLPE insulation than for EPR, but increase with temperature and electric field intensity for both materials [69]. On the other hand, the variations of σ with temperature and electric field are lower for XLPE than for EPR. This could be due, among other things, to lower values of the impurity concentrations [70] and activation energy ($E_a = 0.88$ eV [63]) of XLPE compare to EPR ($E_a = 0.55$ eV [68]). The AC conductivity values vary with the frequency and are lower in XLPE samples than in EPR samples (see Fig. 39).

It should be noted that the least significant loss in a power cable is due to the insulation resistance (respectively, electrical conduction in insulation). The annual cost of this loss is only a few cents per 300 m, a small fraction of the costs incurred due to other internal cable losses [71]. Insulated Cable Engineers Association

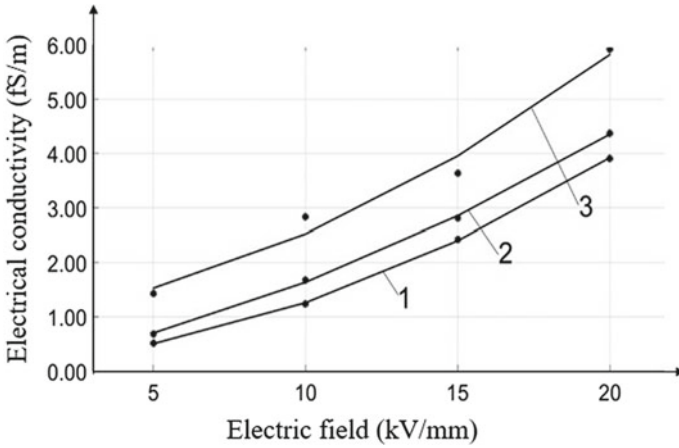


Fig. 35 Variation of DC electrical conductivity of XLPE with the electric field, at $T = 30\text{ }^{\circ}\text{C}$ (1), $50\text{ }^{\circ}\text{C}$ (2) and $70\text{ }^{\circ}\text{C}$ (3) (Reprinted, with permission, from author [63])

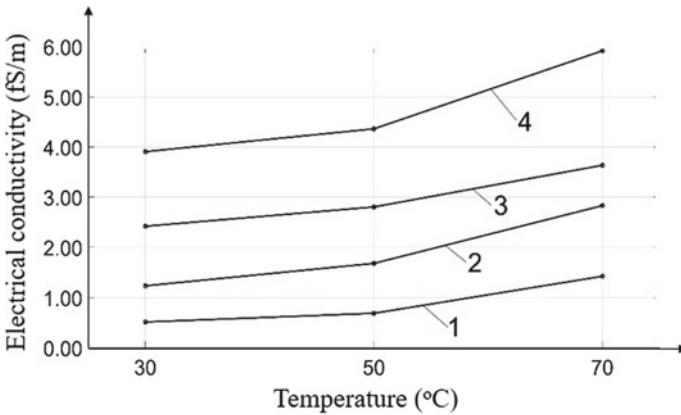


Fig. 36 Variation of DC electrical conductivity of XLPE with temperature, at $E = 5\text{ kV/mm}$ (1), 10 kV/mm (2), 15 kV/mm (3) and 20 kV/mm (4) (Reprinted, with permission, from author [63])

(ICEA) recommends values of the insulation resistance not less than 500–10,000 MΩ for a conductor length of 300 m, in the case of low-voltage insulations, and not less than 20,000 MΩ for medium-voltage insulations. For cables with XLPE pure unfilled insulations, the resistance values can exceed 100 GΩ for 300 m [71].

The introduction of nano-fillers in XLPE leads to important changes in the values of the electrical conductivity (respectively, of the resistivity). Thus in the paper [35], it is shown that by adding nano-fillers in PE, an insulating material was obtained for the DC cables with the electrical resistivity of approx. 100 times higher than that for AC cables (AC-XLPE).

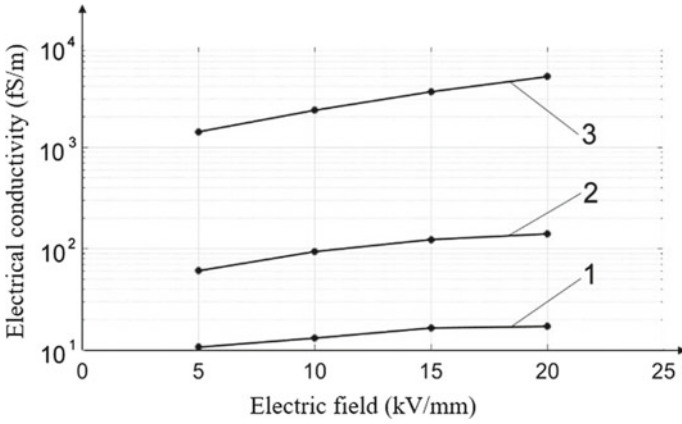


Fig. 37 Variation of DC electrical conductivity of EPR with electric field, for $T = 30\text{ }^{\circ}\text{C}$ (1), $50\text{ }^{\circ}\text{C}$ (2) and $70\text{ }^{\circ}\text{C}$ (3) (Reprinted, with permission, from author [68])

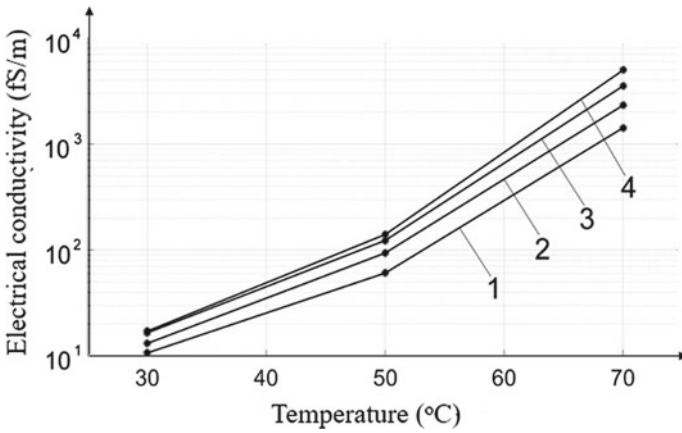


Fig. 38 Variation of DC electrical conductivity of EPR with temperature, for $E = 5\text{ kV/mm}$ (1), 10 kV/mm (2), 15 kV/mm (3) and 20 kV/mm (4) (Reprinted, with permission, from author [68])

6.1.2 Electrical Permittivity

Electrical permittivity is the second main characterization parameter of the insulating materials used in electrical engineering, after the electrical conductivity. The permittivity is a complex parameter ϵ_c and is determined in harmonic electric fields of frequency f (respectively, pulsation $\omega = 2\pi f$), as follows:

$$\epsilon_c = \epsilon' - j\epsilon'' \tag{2}$$

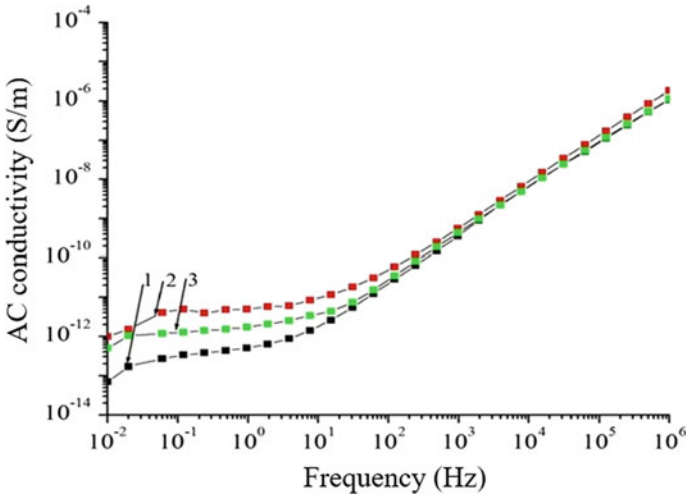


Fig. 39 Variation of the AC electrical conductivity with frequency f , for samples from XLPE (1), EPR (2) and XLPE/EPR (3) ($T = 30\text{ }^{\circ}\text{C}$) (Reprinted, with permission, from author [68])

where the real part of the complex permittivity ϵ' characterizes the temporary electrical polarization of the material, and the coefficient of the imaginary part ϵ'' —the dielectric losses (by electric polarization) [13].

The parameter $\epsilon_r' = \epsilon'/\epsilon_0$ is called relative permittivity or dielectric constant and is noted, simply, ϵ_r . The values of the dielectric constant must be as small as possible, so that the values of the capacitance and of the electric capacitance currents in insulations to be as low as possible. The values of the dielectric constant depend on the material nature and on the characteristics of the stresses (electric field, temperature, radiation, etc.) to which it is subjected in operation.

Thus, in the report [72] it is shown that the decrease of the electric field frequency to small values (of mHz order) determines an increase of the ϵ_r values (see Figs. 40, 41 and 42). Thus, ϵ_r values of the XLPE, for any temperature and frequency, are lower than for EPR and EPDM. On the other hand, the increase in temperature leads to an increase in the ϵ_r values, but these increases are more important in the case of EPR (see Fig. 41) than in the cases of XLPE (see Fig. 40) and EPDM (see Fig. 42).

The experimental tests on XLPE and EPR flat samples with a thickness of 1.14 mm [73] showed that ϵ_r values are influenced by the electric field. Thus, when the electric field increases from 17.3 to 19.15 MV/m, ϵ_r values increase from 2.338 to 2.358 for XLPE samples and decrease from 2.72 to 2.52 for EPR samples. The increase of temperature leads to the reduction of the dielectric constant values of the cable insulations, both for XLPE and EPR (see Fig. 43).

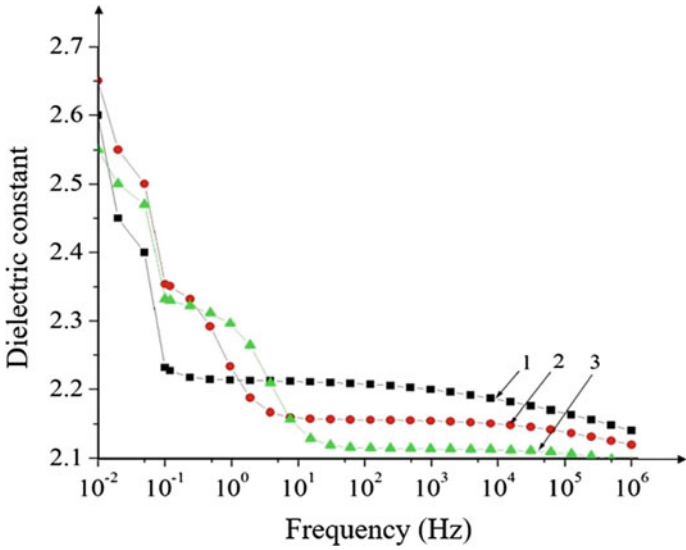


Fig. 40 Variation of the dielectric constant with the frequency for XLPE samples, at 30 °C (1), 60 °C (2), and 80 °C (3) (Reprinted, with permission, from author [72])

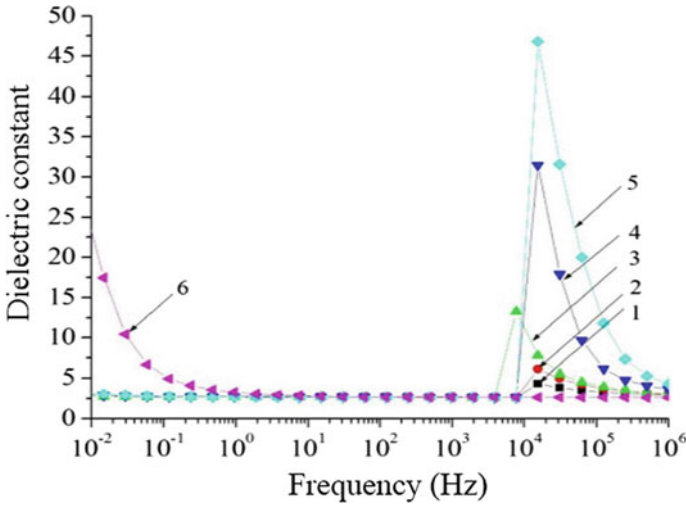


Fig. 41 Variation of the dielectric constant with the frequency for EPR samples, at 30 °C (1), 40 °C, (2), 50 °C (3), 60 °C (4), 70 °C (5), and 80 °C (6) (Reprinted, with permission, from author [72])

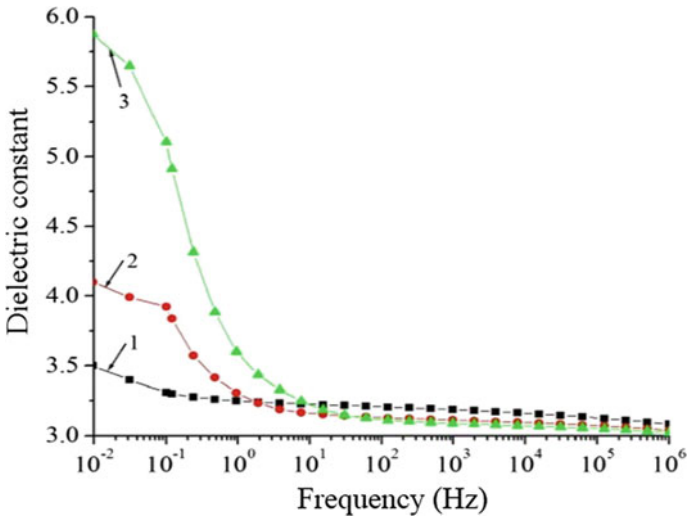


Fig. 42 Variation of the dielectric constant with the frequency for EPDM samples, at 30 °C (1), 60 °C (2), and 80 °C (3) (Reprinted, with permission, from author [72])

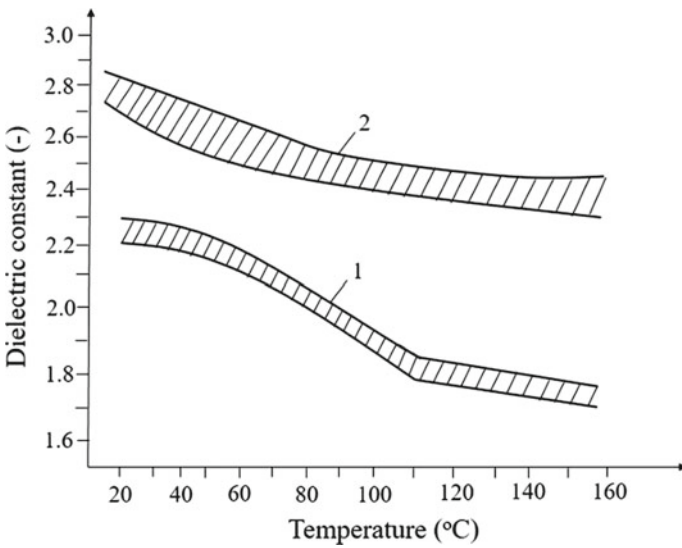


Fig. 43 Variation of the dielectric constant with the temperature for XLPE (1) and EPR (2) samples (Reprinted, with permission, from [62])

6.1.3 Loss Factor

The loss factor (dissipation factor) $\tan\delta$ is defined as the ratio between the coefficient of the imaginary part of the complex permittivity ε'' and its real part ε' , respectively:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} + \frac{\sigma}{\omega\varepsilon'} \quad (3)$$

where $\omega = 2\pi f$ and $\tan\delta$ characterizes the total losses produced in the electrical insulating material by polarization and electrical conduction [13].

In general, for the electrical equipment insulation systems, insulating materials with the lowest $\tan\delta$ values are used. These values depend not only on the chemical nature and on physical structure of the material, but also on the intensity and frequency of the stresses to which they are subjected in operation.

As shown in Figs. 44, 45 and 46, XLPE presents the lowest $\tan\delta$ values for any value of electric field frequency and temperature. On the other hand, for all the other studied materials, the values of $\tan\delta$ are higher in the case of very low frequencies (mHz) and have peaks for different values of the frequency (depending on the nature of the material). For these values, the losses within insulations are maximum. The increase of the temperature from 30 to 80 °C leads to an increase in $\tan\delta$ values for all materials, but these variations are much higher for EPR and EPDM than for XLPE. It should be emphasized that if temperature rises, its $\tan\delta$ values decrease in the case of very low and high frequencies and increase in the case of industrial frequencies (5–500 Hz) (see Figs. 44–46).

The loss factor increases with the intensification of the electric field, the increase being lower in the case of XLPE (where the electrical conductivity is lower) and more important in the case of EPR and Kraft paper impregnated with mineral oil (see Fig. 47).

The experimental tests on XLPE and EPR flat samples with a thickness of 1.14 mm [73] showed that $\tan\delta$ values are influenced by the electric field intensity. Thus, when the electric field intensity increases from 17.3 to 19.15 MV/m, $\tan\delta$ values increase from 0.00018 to 0.000258 for XLPE samples and decrease from 0.09 to 0.07 for EPR samples.

The variations of loss factor with temperature for EPR and XLPE insulations are shown in Fig. 48. It was found that, in the case of EPR, its $\tan\delta$ values increase continuously with temperature. Whereas, in the case of XLPE, $\tan\delta$ decreases up to 75 °C, after which it starts to increase (but remain lower than for EPR). A major disadvantage of EPR over XLPE establishes the important variations of dissipation factor from one cable length to another. For instance, for the lengths of 150 kV EPR cable, its $\tan\delta$ values can vary (at 20 °C) between 0.0027 and 0.004 [26]. In general, $\tan\delta$ values of XLPE cables are at least 20 times lower than that of EPR

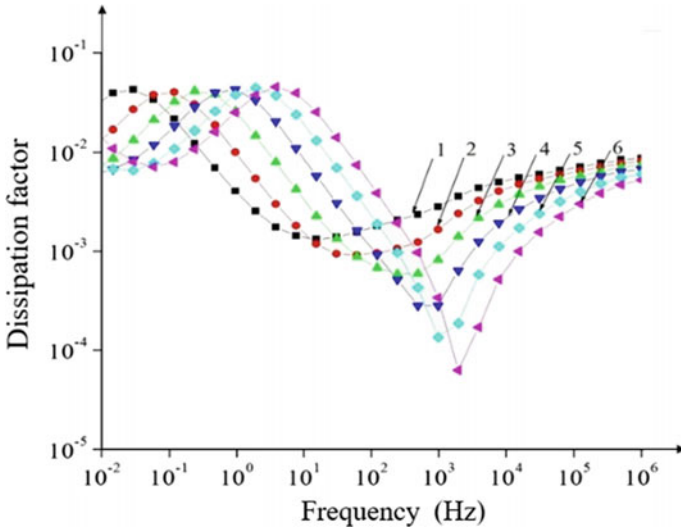


Fig. 44 Variation of the dissipation factor with the frequency for XLPE samples, at 30 °C (1), 40 °C, (2), 50 °C (3), 60 °C (4), 70 °C (5), and 80 °C (6) (Reprinted, with permission, from author [72])

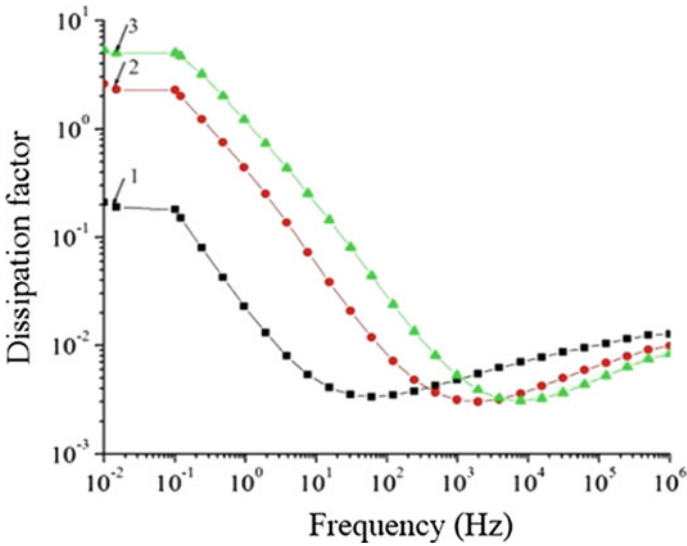


Fig. 45 Variation of the dissipation factor with the frequency for EPR samples, at 30 °C (1), 60 °C (2), and 80 °C (3) (Reprinted, with permission, from author [72])

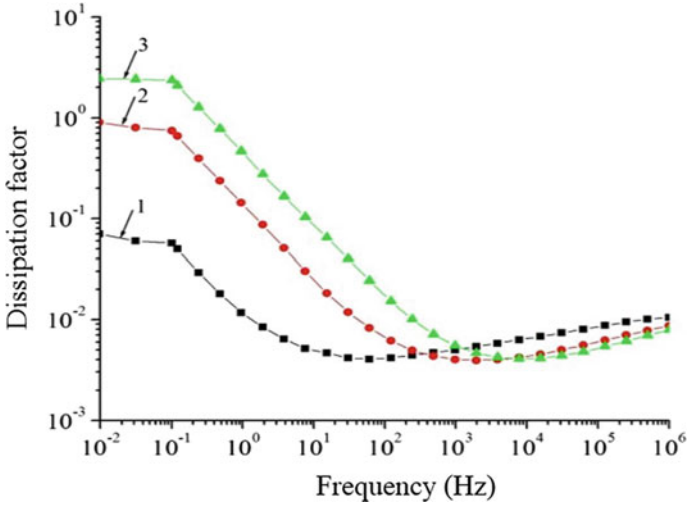
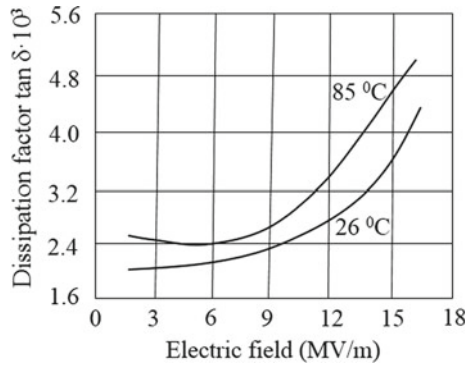


Fig. 46 Variation of the dissipation factor with the frequency for EPDM samples, at 30 °C (1), 60 °C (2), and 80 °C (3) (Reprinted, with permission, from author [72])

Fig. 47 Variation of the dissipation factor with the electric field intensity for Kraft paper cable impregnated with low-viscosity mineral oil [20]



cables. Thus, with XLPE cables, the energy savings per year can be in the order of 15 MWh/cct-km for a 69 kV system, 52 MWh/cct-km for a 138 kV system and 127 MWh/cct-km for a 230 kV system (cct = three-phase circuit kilometer length).

In conclusion, it can be said that very pure insulations such as PE and XLPE exhibit very low $\tan \delta$ values. TR-XLPE has a slightly higher $\tan \delta$ than XLPE, while materials as EPR and PVC have still higher $\tan \delta$ values. However, both EPR and TR-XLPE have acceptably low values for medium-voltage applications.

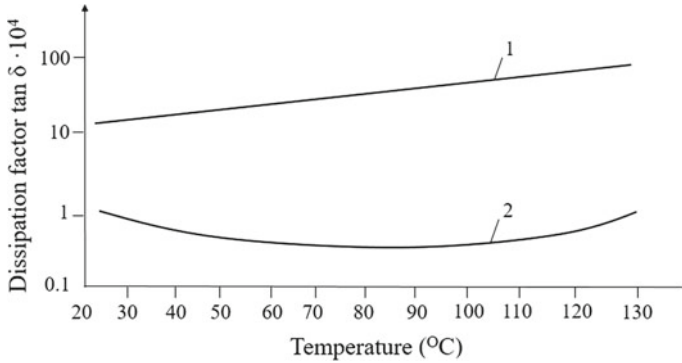


Fig. 48 Variations of the dissipation factor with temperature for insulation from EPR (1) and XLPE (2) [26]

6.1.4 Breakdown Strength

Dielectric strength E_{bd} is determined in harmonic electric fields, on standard samples and with plane, cylindrical or spherical electrodes and represents the ratio between the breakdown voltage of the sample V_{bd} and the distance between the electrodes d [74, 75]:

$$E_{bd} = \frac{V_{bd}}{d} \quad (4)$$

The electrical insulating materials used in electrical engineering must have E_{bd} values as high and less variable as possible with the operating stresses (e.g., temperature, mechanical stresses, environment, etc.). Evermore, the dielectric breakdown strength of oil-paper (ca. 40 kV/mm) and solid-dielectric extruded polymer insulation (ca. 70 kV/mm) is well above their normal accepted operating stress values (5–20 kV/mm).

The variations of dielectric strength with temperature of filled XLPE and EPR are shown in Fig. 49 [4]. It was found that for values below 100 °C, E_{bd} values are higher for XLPE than those for EPR and for temperatures above 100 °C, E_{bd} takes higher values for EPR. Similar results are presented in [62], where it is shown that the breakdown strength of XLPE exceeds that of EPR by 50% for temperature values up to 90 °C (see Fig. 50).

On the other hand, if cables are immersed in water for more than 2 months, those with XLPE insulation will continue to have a higher value of the breakdown voltage than those with EPR insulation (see Fig. 51) [62, 76].

In the paper [47], the dielectric breakdown behavior of electric mini-cables insulated with PP and XLPE was studied. The authors used two sets of PP- and XLPE-based mini-cables, with a length of 6 m and an insulation thickness of about 4 mm. The samples were subjected to a stepped DC test, and the failure voltage was

Fig. 49 Variation of breakdown strength with temperature for filled XLPE (33%) (1) and EPR (38%) (2) [4]

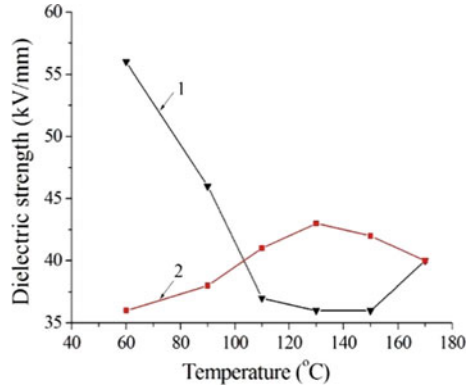


Fig. 50 Dependence of breakdown strength on temperature for XLPE (1) and EPR (2) (Reprinted, with permission, from [62])

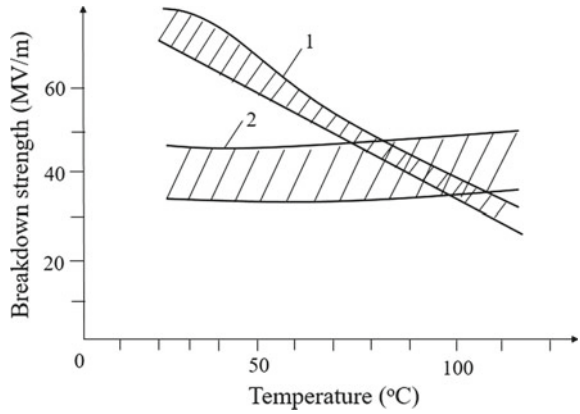
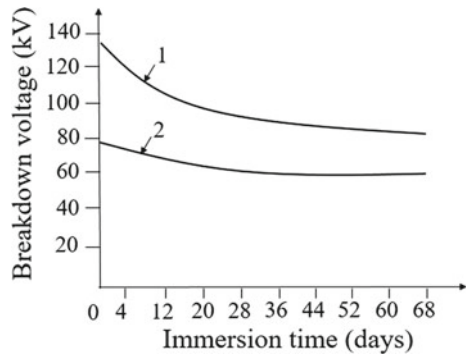


Fig. 51 Variation of AC breakdown voltage with aging duration (water at 70 °C) for 11 kV XLPE (1) and EPR (2) cables [76]



noted. In the case of XLPE-insulated cables, it was found that all samples breakdown around 200 kV, whereas in the case of samples insulated with PP, the values of the breakdown strength exceeded 400 kV. In the paper [35], it was shown that

the addition of nanoparticles in XLPE leads to an increase of dielectric strength of about 2.2 times, as a result of deep-traps produced by nano-fillers.

6.1.5 Impulse Strength

The same variations were found for breakdown strength impulses in the studies [4, 62]. Thus, as can be seen in Fig. 52, for temperatures below 90 °C, XLPE is superior to EPR.

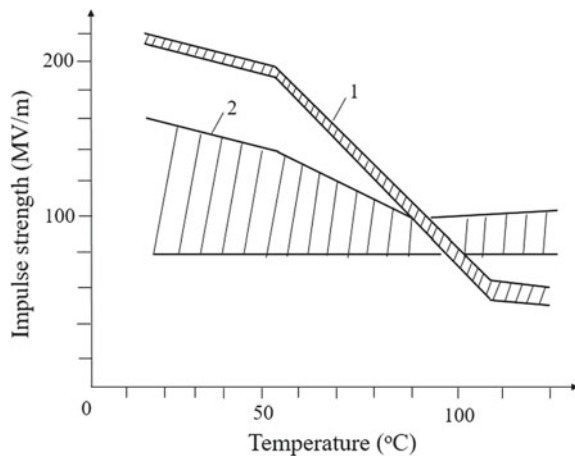
6.1.6 Space Charge Accumulation

Space charge consists of electrons, holes, and ions and is generally understood (as shown in [2]) as:

- (a) a separation of free charge in the volume or interface of their insulation components due to carriers generated in the technological processes,
- (b) a space charge injection on the electrodes,
- (c) the field-assisted thermal ionization of impurities from the insulation,
- (d) the insulation degradation under the action of (electrical, thermal, mechanical, etc.) stresses during operation and the electric and/or water trees development [77].

The presence of space charge in insulations leads to the local intensification of the electric field and, consequently, to the intensification of the degradation processes and to the reduction of the insulations' lifetime. Therefore, especially in the case of DC cables of very high voltages (up to 800 kV), new materials and technological processes that will lead to the reduction of the space charge in insulations are requested [78]. For instance, in the case of XLPE, various additives are

Fig. 52 Dependence on temperature of impulse strength for XLPE (1) and EPR (2) (Reprinted, with permission, from [62])



introduced (e.g., 2,4-Diphenyl-4-methyl-pentene-1, dissolving oxygen, etc.), which prevents the formation of space charge or enables its dissipation.

In numerous studies, the information regarding the values and the distribution of the space charge in insulations based on PE, XLPE, EPR, etc., is presented. The electric stress conditions that can generate space charge in polymeric insulation (going from DC to power electronic repetitive impulses), the effect of space charge promoting acceleration of aging processes and bringing to early failure of electrical apparatus, the influence of space charge on degradation mechanisms, such as electron avalanche and partial discharges are discussed in [79]. It is shown that the space charge accumulated in a polymer under an applied voltage is a cause of aging due to the relevant local field enhancement and associated electromechanical energy storage, whose main effect of lowering the free energy barrier is exceeded and degradation can occur. In the paper [80], the factors that determine the formation and accumulation of space charge are analyzed in detail. Electronic charge injection (with the formation of homo- and heterocharges), field-assisted thermal ionization of impurities (with the formation of ions and molions), spatially inhomogeneous electric polarization (which produces an apparent volume space charge) and the charge generated by steady DC current coupled with a spatially varying ratio of permittivity and conductivity are discussed.

The variations of space charge volume density ρ_v in plane samples based on LDPE and HDPE are shown in [81] (see Fig. 53). It has been found that ρ_v has higher values in LDPE than in HDPE samples. In the paper [82], space charge accumulation profiles were compared for LDPE, LDPE plus antioxidant (LDPE—AO) and XLPE, with consideration of thermal treatment effects in LDPE and XLPE. Significant variations (decreases) of accumulated space charge and apparent mobility have been remarked going from LDPE to LDPE-AO and XLPE which may be associated with the formation of deeper trap levels (or an increase of their density) [83]. As can be seen in Fig. 54, the space charge density accumulated in XLPE samples has lower values than those from LDPE and LDPE-AO, especially for electric field values higher than 5 MV/m.

Fig. 53 Charge build up with unaged HDPE (Reprinted, with permission, from [81])

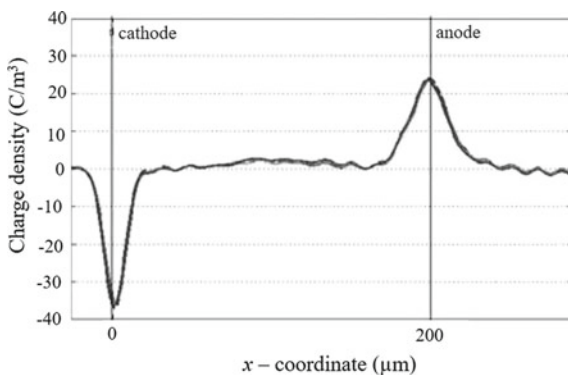
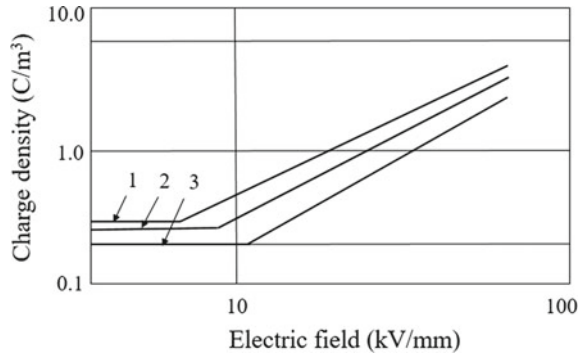


Fig. 54 Variation of the charge density with the electric field for LDPE (1), LDPE-AO (2), and XLPE (3) (Redrawn and adapted figure from reference [82])



In the case of cables insulation with water trees, the average volume density of the space charge increases [84–88]. This increase depends on the number and size of the trees and is higher in LDPE than in XLPE and, especially, in TR-XLPE. Using the step method, in the study [89], the charge accumulation and the remaining field in cross-linked polyethylene (XLPE), very low-density polyethylene (VLDPE), isotactic polypropylene (PPiso), and a polyethylene/polypropylene copolymer (PPCop) samples were determined. It was found that the amount of charge accumulated under AC conditions might reach a maximum value at a given temperature, while the highest space charge was found in polyolefins with the lowest crystallinity ratio (see Table 15).

Space charge measurements in power cables insulation showed that no space charges have been found in either Kraft paper nor PPLP insulation (which denotes a very safe insulation for operating HVDC superconducting cables) [90].

To achieve space charge reduction, the insulation produced should not be heated above 230 °C for periods less than 10 min. This suppresses the production of polar by-products, such as acetophenone and cumyl alcohol [91]. Other methods of reducing the space charge in XLPE are based on the introduction of polar groups bonded to XLPE (e.g., dissolving oxygen gas in the LDPE during the extrusion process), addition of organic (glycerol fatty acid ester) and inorganic additives (TiO₂, BaTiO₃, I, MgO, etc.), carbon black, grafting of PE with maleic anhydride, etc. [92]. While the inclusions of surface modified MgO, TiO₂, ZnO, and Al₂O₃ nanoparticles can suppress space charge accumulation in nanocomposites, the inhibition effect depends on the type of nanoparticles. Nanocomposites based on PP

Table 15 Values of the remaining field for some polyolefin after ac conditioning during 14 days under an rms field of 40 kV/mm [89]

Material	VLPPE	PPCop	XLPE	Ppiso
Crystallinity (%)	10	40	42	55
Remaining field (MV/m)	9.73	3.42	1.78	0.96

with MgO, TiO₂, and Al₂O₃ show the most desirable space charge suppression for a lower content of nanoparticles (under 3 phr) [93]. This result is consistent with the results obtained on MgO/LDPE, MgO/XLPE, TiO₂/LDPE, and Al₂O₃/LDPE nanocomposites [84, 94, 95].

6.1.7 Repetitive Lightning and Switching Impulses

The application of repetitive lightning impulse overvoltages is one of these factors that lead to the aging of polymer insulations [81]. The effect of switching impulses was clearly identified due to the long time of switching impulses and space charge accumulation into the bulk of samples [96]. Repetitive lightning impulse overvoltages may also lead to the acceleration of aging processes of insulating materials [97, 98].

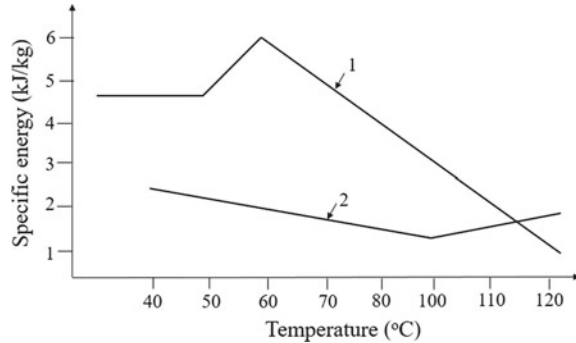
In the work [81], the lightning aging processes of two high voltage insulation materials, namely HDPE and LDPE, were analyzed. The authors used samples with a Rogowski profile and thickness of 200 μm (coated with gold), to which lightning pulses with a front/tail time of 1.2/40 μs and a peak electric field of 85 kV/mm were applied. Both positive and negative lightning impulses (3000 or 6000) were investigated. The authors measured breakdown strength and found that repetitive lightning impulses can reduce the breakdown strength of HDPE, but do not affect LDPE. There was almost no difference between the effects of positive and negative impulses. Concerning the space charge, HDPE becomes lossier and space charge builds up more effectively after aging, while LDPE is largely unaltered.

A study regarding the aging of high voltage EPR and XLPE cables under applied switching impulses is presented in [96]. For tests, 15 kV cable samples were used and were subjected to 4500 switching impulses with a magnitude of 100 kV. Apparent space charge corresponding to PDs and AC breakdown voltage V_{bd} were chosen as parameters to evaluate the status of cables. The results showed that the apparent charge magnitudes for XLPE cables are significantly higher than EPR cables. On the other hand, with the increase in number of impulses, the apparent charge magnitudes have a strong downward trend for XLPE cables opposed to a slight downward trend for EPR cables. For lower values of the impulses number N (up to 1000), the breakdown voltage increases, both for XLPE and EPR, while for $N > 5000$, V_{bd} decreases significant in the case of XLPE (from 130 to 90 kV).

6.1.8 Partial Discharges Resistance

Partial discharges (PDs) deteriorate the insulation (through combination of chemical, mechanical, thermal, and radiative processes), but it does not cause immediate failure or breakdown. If PDs continue to occur for long time, they lead to complete failure of the insulation [99]. There are two necessary conditions for initiation of PDs within a cavity, respectively, the electrical field must be larger than certain critical value E_c and free electrons must be available to start the electron avalanche

Fig. 55 Dependence of partial discharge resistance on temperature for XLPE (1) and EPR (2) (Reprinted, with permission, from [62])



[2]. It has been found that PDs result in gaseous by-products (CO_2 , CO , CH_4 , H_2 , and H_2O) [100, 101], and liquid droplets (mixtures of simple organic compounds, such as formic, acetic, and carboxylic acids) [100, 102], in association with solids, such as oxalic acid crystals [100, 103] (see Fig. 55) [2].

An analysis of the products nature that arise as a result of PDs action on the cavity walls of XLPE cable insulation is presented by Gamez-Garcia et al. in [104] and [100]. The authors subjected XLPE foils (of 160 μm in thickness) to PDs action and analyzed the resulting chemical compounds. It was shown that under PDs action, both gaseous products (CO , CO_2 , H_2O) and liquids and solids result. The liquid and solid products have been found to result from the synthesis reactions taking place in the vapor phase across the interelectrode gap-space. Acetophenone, which evaporates from the XLPE surface after the cross-linking, plays an important role in the formation of other observed degradation products. Benzoic acid, benzamide, toluene, and other aromatic compounds result from corona-chemical reactions of this volatile compound during the degradation process [2].

Figure 55 shows the variation of the energy required to erode or decompose (by PDs) one kg of material (XLPE and EPR) under test as a function of temperature. It can be observed that for temperature values lower than 110 $^\circ\text{C}$, the energy required for XLPE degradation has higher values than for EPR, respectively, that XLPE has a PD resistance higher than EPR.

In general, the apparent charge associated with PDs takes higher values in EPR insulations of the cables, than in XLPE, under the same conditions (humidity, temperature, mechanical stresses, etc.) and for the same aging times [105]. On the other hand, the manufacture of XLPE nanocomposites with inorganic fillers or linear low-density polyethylene (LLDPE)/natural rubber (NR) blends with 4 phr nano-sized montmorillonite filler causes a reduction in the level of PDs [106].

6.1.9 Electrical Treeing Resistance

Electrical trees (ETs) are initiated by the high divergent AC field of a stress enhancing geometrical feature, such as a point or wire electrode (see Fig. 56), or by

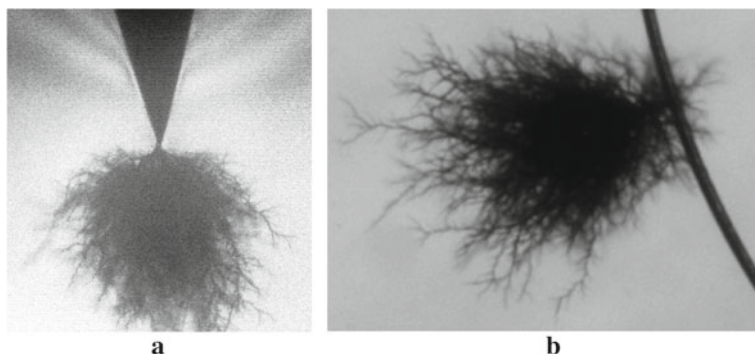


Fig. 56 Electrical trees produced in XLPE with needle (a) and wire (b) electrodes [109]

partial discharges taking place in a gas-filled cavity [107]. In addition, ETs may be produced during a short circuit or polarity reversal of DC fields.

ETs are very fine channel networks (including gases at high pressures) initiated near insulation and/or electrodes defects, which are developing in the insulation during the operation of the electrical equipment. ETs represent one of the main causes of damage and failure in electrical power cable insulation [2]. Propagation of ETs in solid insulation can bridge the electrode gap, leading to the breakdown of the insulation.

The ETs channels are formed by the local destruction of the material under the synergetic action of the electric field, PDs (from the voids and channels) [108], heat and mechanical stresses produced by the electric field and gases from the channels (resulted from the material decomposition). The ETs initiated near the electrodes are called vented trees, and they are developed from the electrode to the 'inside' of the material. In contrast, the ones generated inside the insulation (near voids, metal inclusions, etc.) have a structure of channels developed along the electric field lines on both sides of the defect (electric field concentrator) and they are called bow-tie trees [2].

ETs inception is firmly associated with the injection of charge into the polymer [110] either by a high field electrode or by gas discharges in a cavity [13, 107]. The formation of a discharging tubule (channel) is due to the impact excitation of molecular species by hot electrons (electrons with sufficient kinetic energy to initiate a route to chemical degradation [110]) or by chemical bonds breaking through ultraviolet (UV) radiation emitted during charge recombination [111]. It follows, therefore, that the initiation times and the development speeds of the ETs depend both on the characteristics of the electric field (size, frequency, etc.) and on the chemical structure and nature of the insulation. The higher the bonding energy values corresponding to the constituent elements of the molecules, the less expected the rupture of the bonds and the initiation and development of the ETs are more difficult.

ETs were highlighted in all types of cable insulations, respectively, in LDPE, HDPE, XLPE [2, 110, 112–114], EPR [110, 115], EPDM [108], etc. However, there is no systematic comparative study regarding the development of ETs in polymers. Different polycyclic compounds can be used to reduce the development speeds of ETs in XLPE [116]. The effect of polycyclic compound is related to the temperature. With the temperature increase, the suppression effect to ET growth of polycyclic compounds decreases. If the trees developed in XLPE are of bush tree or branch-pine tree types, those developed in PP have the form of branch tree (see Fig. 57) [42]. On the other hand, in the XLPE insulation, the lifetime of the ETs initiation is higher and the development rate is faster than in PP insulation.

In order to increase the resistance of XLPE to electrical treeing, lately, the use of new stabilizers, respectively, benzyl-, thioxanthone- fullerene-, and melamine-types, has been studied [109]. They were found to cause an increase in resistance toward electrical treeing in the range between twenty up to well above one hundred percent.

6.1.10 Water Treeing Resistance

There is no organic material impermeable to moisture, but the only commonly used high polymer less permeable than PE is PVC (SARAN). At 23 °C, the concentration of water absorbed by XLPE is 350 ppm (0.035%) in boards and 850 ppm in cables insulation [62]. EPR absorbs about 1% moisture by weight after two weeks immersion in water at 80 °C. When removing from water, EPR was observed to dry out much more rapidly than it had been infused with moisture. In general, the water absorption in XLPE and TR-XLPE insulation is much slower than in EPR (see Fig. 58) [105].

Higher water permeability of cables insulation facilitates the formation of water trees. Water treeing is generally observed as a dendritic pattern of water-filled

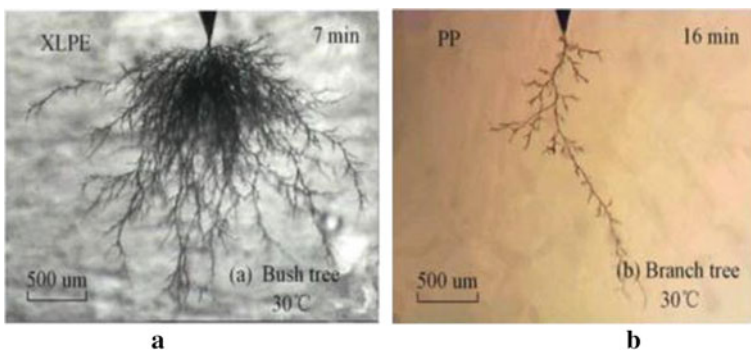
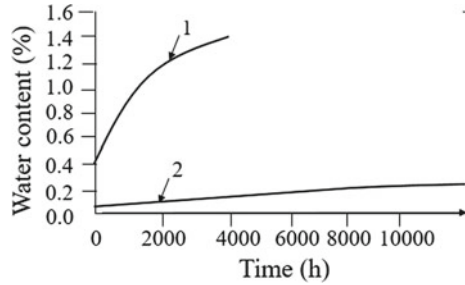


Fig. 57 Electrical trees in XLPE (a) and PP (b) (Redrawn and adapted figure from references [11] and [42])

Fig. 58 Variation in time of water content in EPR (1) and TR-XLPE (2) cable insulation (Redrawn and adapted from reference [105])



microcavities in the polymer connected by oxidized ‘tracks’ (about 10 nm wide) and is described as a self-propagating pattern of electro-oxidation. Self-propagation results from the electro-oxidation of hydrophobic polymer to a more hydrophilic state, which causes condensation of moisture from the surrounding hydrophobic polymer region. Such self-propagation (water treeing) is likely to occur in any polymer that can be oxidized to a substantially more hydrophilic state [117].

As for most organic polymers, PE and XLPE meet all the requirements for water treeing (i.e., they are hydrophobic and can be oxidized to a substantially more hydrophilic state). However, PE is normally very ‘clean,’ with a very low ion concentration. Thus, the water in PE cable, normally dielectric, shows a too low conductivity to create the chemical potential necessary for water treeing. However, the chemical potential will increase with any increase in water conductivity, so that the ionic impurity at the dielectric–semiconductor interface can increase the chemical potential (at about 1 eV) and cause a water tree.

Tests performed on cable insulation samples aged for eight months at three times rated voltage showed relatively large density and a lower length of water trees in unfilled XLPE compared to filled XLPE and EPR (see Table 16). On the other hand, EPR insulation has the lowest density and highest average length of bow-tie trees. In unfilled XLPE, each ‘bow’ is relatively spherical in nature, in contrast to ‘bows’ in EPR, which are longer and narrower (see Fig. 59).

In the case of vented trees (VTs), the values of trees density are much lower in all insulations (see Table 17), but as in the case of bow-tie trees, they are higher in XLPE than EPR. On the other hand, the lengths of the VTs are longer in XLPE than EPR.

Initiation sites of bow-tie trees in XLPE are associated with cavities, particle agglomerates, and flaws such as cracks. These trees are initiated relatively easy, but

Table 16 Bow-tie trees (BT) in XLPE, filled XLPE and EPR cable insulation [117]

Material	BT density (mm^{-3})	BT length (μm)	Water absorption (ppm)
XLPE	>28	90	17
Filled XLPE	4	180	260
Filled EPR	0.3	390	470

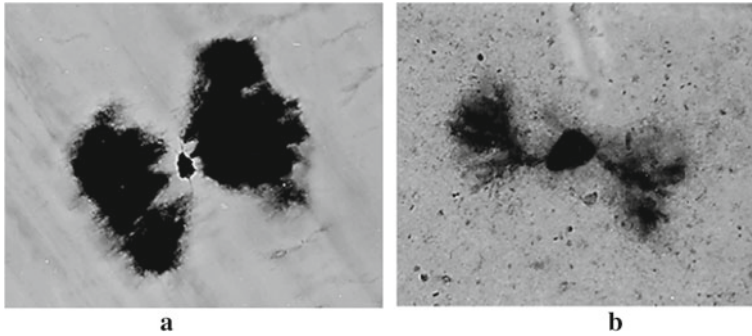


Fig. 59 Bow-tie trees in XLPE (a) and filled EPR (b) (Redrawn and adapted figure from reference [117])

Table 17 Vented trees (VT) in XLPE, filled XLPE and EPR cable insulation [117]

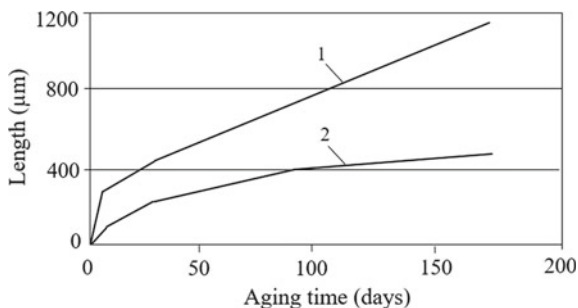
Material	VT density (mm^{-3})	VT length (μm)
XLPE	0.3	60
Filled XLPE	0.2	120
Filled EPR	0.01	45

they are growing slowly [117]. In EPR, initiation sites are somehow associated with catalytic impurities such as iron oxides and vanadium compounds (catalyst residue).

Bow-tie trees are easily initiated and have a high density in steam cured XLPE as a result of the high cavity content and segregation of ionic impurities into such cavities. In newer dry-cured XLPE cables, bow-tie trees density is much lower as a result of the much lower density of cavities in the insulation. In EPR, and due to a lower degree in filled XLPE, bow-tie trees are difficult to initiate, but once initiated appears to grow quite aggressively. The difficulty in initiating bow-tie and VTs in EPR is probably the result of three factors: significant reduced hydrophobicity of EPR relative to unfilled XLPE (see Table 16), higher ionic content of EPR and presence of catalytic ions (vanadium, iron), which reduce the activation energy required for electro-oxidation. In general, the observed treeing patterns are similar to those formed in PE and XLPE insulation [118].

In the case of filled XLPE, the moisture absorption is less than for EPR so that the hydrophobicity is higher in EPR and lower in XLPE. As a result, in terms of the resistance to water treeing, filled XLPE lies between unfilled XLPE and EPR. Filled XLPE and EPR cable insulations have an inherent water tree resistance. The water tree resistance of EPR insulations is caused by the reduced hydrophobicity (which reduces the tendency of water to condense from the bulk dielectric into electro-oxidized regions) and, possibly, relatively high ionic content (which may tend to render any liquid water in the dielectric to conductive that cause water tree growth).

Fig. 60 Variation of tree lengths with the development aging time in XLPE (1) and TR-XLPE (2) (Redrawn and adapted figure from reference [119])



The additives employed to make XLPE insulation water tree resistant, increase its water absorption (i.e., make the polymer less hydrophobic). As it is well known, TR-XLPE insulation does not stop water trees growth, but prevents water trees growth (i.e., the number and size of water trees are reduced) (see Fig. 60), and their forms are changing (see Fig. 61) [119]. The reduction in number of water trees is probably the result of greatly improved cleanliness of modern semicons and reduced hydrophobicity of TR-XLPE. Certain types of TR-XLPE contain a dispersion of hydrophilic molecular clusters in the hydrophobic matrix. The hydrophilic clusters ‘stop’ water tree channels (when a water tree channel ‘hits’ a tree-retardant cluster, it stops propagating—the hydrophilic cluster impedes condensation of water in any electro-oxidized region near it, so that the water tree cannot propagate).

To increase the resistance of cable insulation to water treeing, a blend of PE with ethylene alkyl acrylate copolymer, named ‘copolymer XLPE’ is used. In [120], it is shown that after an aging time of 365 days in water and electric field, the dielectric strength of copolymer XLPE insulations was approx. 40 kV/mm, compared to 35 kV/mm as shown by XLPE-insulated cables, and much lower than TR-XLPE cables insulation (approx. 60 kV/mm).

6.1.11 Tracking Resistance

Tracking deterioration is caused by the carbon formed on the surface of materials, which is precipitated due to the heat from the discharge started locally across a dry band. The surface is carbonized by the heat energy of the discharge and the carbonized conduction path finally forms over the short-circuited path [121]. Therefore, the use of materials with highest tracking resistance is important for the safety and reliability of electrical equipment. For tracking resistance determination, the procedures presented in IEC Publication 587 [122] and IEC Publication 112 [123] can be used. In general, the voltage that will cause failure with the application of 50 drops of electrolyte, respectively, CTI indicator [122], is determined. In [124],

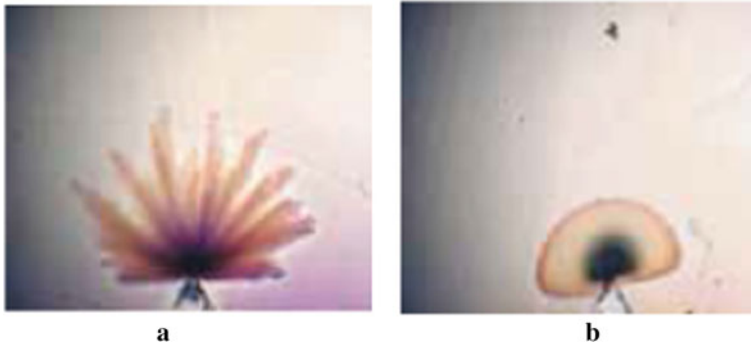


Fig. 61 Water trees in XLPE (a) and TR-XLPE (b) [119]

Table 18 Time to tracking breakdown (h) [124]

Polymer	Filler	Virgin	Acid rain 120 days
Epoxy resin	Al(OH) ₃	>6	>6
PTFE	–	>6	>6
XLPE	Al(OH) ₃	>6	2.20
Silicone rubber	Al(OH) ₃	1.95	0.42
EPR	Al(OH) ₃	0.17	0.32

the results of tests carried out on polymer samples without fillers and with aluminum rehydrate filling, without and with artificial acid rain, at a voltage of 4.5 kV (see Table 18) are presented. It was found that the durations of breakdown appearance due to the tracking phenomenon are much longer in XLPE than silicone rubber and EPR.

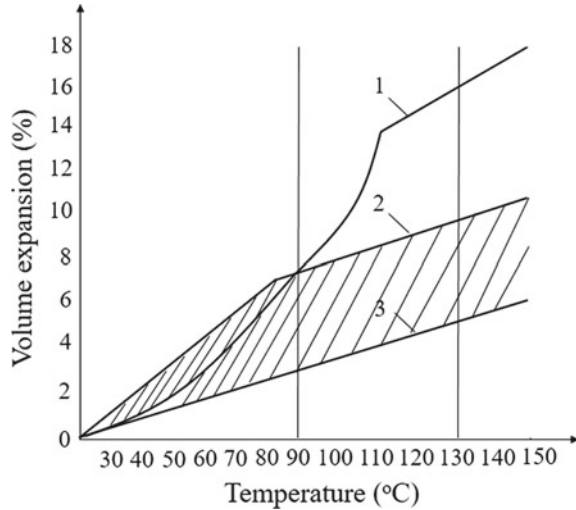
6.2 Thermal Properties

The most important thermal properties of organic high polymers used as electrical insulations on flexible power cables are thermal expansion, thermal conductivity, and thermal stability (see Table 19). Fundamental and analytical investigations of these properties have been published [62, 125] and can be used to provide background and understanding.

Table 19 Properties of cable insulations from polyethylene (PE), cross-linked polyethylene (XLPE) and polyvinyl chloride (PVC) [126]

Insulation	Specific gravity (-)	Tensile yield strength (MPa)	Tensile modulus (GPa)	Coefficient of linear expansion (m/m °C)	Thermal conductivity (W/m °C)	Specific heat (J/kg °C)	Temperature limit (°C)
PE	0.95	22.1	0.827	162	0.462	2303	70
XLPE	0.94	19.3	0.858	162	0.462	2303	90
PVC	1.4	55.2	2.830	54	0.159	1047	65

Fig. 62 Variations of relative (thermal) volume expansion with the temperature for XLPE (1) and EPR semi-crystalline (2) and EPR amorphous (Reprinted, with permission, from [62])



6.2.1 Thermal Expansion

During thermal cycling of a cable, the conductive layers over the conductor and insulation will expand and shrink as the temperature varies. The change in expansion characteristics exhibited by XLPE, particularly in the temperature range near the transition point (see Fig. 62) can lead to increase in dimensions at overload conditions, which cause great pressure on the insulation shield, either extruded or metallic. As a result, splits or cavities may occur between the insulation and the insulation shield.

The thermal expansion is a major issue when a HV cable operates above 90 °C. Over the full operation of a cable from low to high temperatures, thermal expansion differences of up to 20 times may occur. This is caused by differences in thermal expansion coefficient of the metals from conductors, screens and shields (copper, aluminum, lead), which load the main insulation over the full operational temperature range. This does not mean significant changes in the molecular conformation, but the molecules move further apart from another. As an example, typical XLPE used in cable insulations expands with about 15% when going from room temperature to 105 °C, while copper or aluminum expands less than 3% in the same temperature range. The resulting pressure may affect the dielectric properties and can cause damage to the sheath and joints [127].

At any point of physical discontinuity along a cable, such as splices, terminals, grounds, and clamps, the higher expansion of XLPE appears when it is subjected to high thermal cycles that may cause distortion, material migrations, and voids. Shrinking of the insulation can also occur when the end of the cable is cut prior to termination and the longitudinal stresses freezed in the insulation are relaxed. This has proven to be a major problem associated with highly crystalline materials used in cable insulations, since molded terminations may no longer fit properly.

Differences in thermal expansion characteristics between XLPE and EPR can also be a contributing factor in failures that occur at the junction of two types of insulation, which are normally in contact in cable joints [128].

Many electrical failures, which have been experienced in joints and splices, are caused by this incompatibility in expansion characteristics. Consequently, the values of thermal expansion coefficients of the insulation components should be as close as possible to each other, as well as those of the semiconductor layers or conductors that are in contact. All the organic materials expand much more than metals and minerals when their temperature increases in from 0 to 200 °C range. PE and XLPE expand more than mineral-filled EPR or EPDM. This is because homopolymers are partially crystalline and have melting temperatures around 115 °C, also because the fillers have relatively negligible expansion in this range.

The work [62] showed that, starting with the solid phase, as thermal energy is supplied to crystalline regions by heating, molecular motion increases till PE crystallites are disrupted and the ordered molecular segments add to the amorphous fraction. The result of this effect is shown in Fig. 62, curve 1.

The long concave upward portion of XLPE curve results from the fact that crystalline regions, called crystallites, have lattice energies or stabilities proportional to their sizes. Hence, small crystallites have low stability and their lattice energies are exceeded by the thermal energy of the molecules, which decompose them at low temperature. As temperature increases, crystallites of larger and larger size are melted, causing an increase of the rate of expansion until the largest is melted. After this point, called thermodynamic melting point (MP), the material is completely amorphous.

Thermal expansion increases with further temperature then continues at a constant rate characteristic of the molecular structure. From 20 to 90 °C, EPR expands between 3.5 and 6.5%, while XLPE expands with 6 or 7%. That is a small difference, particularly for the new, higher voltage, partially crystalline EPRs that lie at the top of EPR range. The literature contains many data on PE thermal expansion [62], but rather on filled compounds of EPR or EPDM. XLPE and PE expand more than mineral-filled EPR or EPDM. This is because homopolymers are partially crystalline and have the melting temperature around 115 °C, and also because the fillers have relatively negligible expansion in this range.

6.2.2 Thermal Conductivity

Thermal conductivity (λ) of the cable's insulation controls how rapidly the heat generated by conductor and dielectric losses can be transferred to the surroundings. Thus, it is a major factor with the nature of surroundings, in determining the cable ampacity [62]. In order to eliminate the losses as efficiently as possible, insulations must have the highest thermal conductivity. Figures 63 and 64 present comparing data of the thermal conductivities of XLPE, PE, EPDM, and EPR over a wide temperature range.

Fig. 63 Variation of thermal conductivity with temperature for semi-crystalline EPR (1), amorphous EPR (2) and XLPE (Reprinted, with permission, from [62])

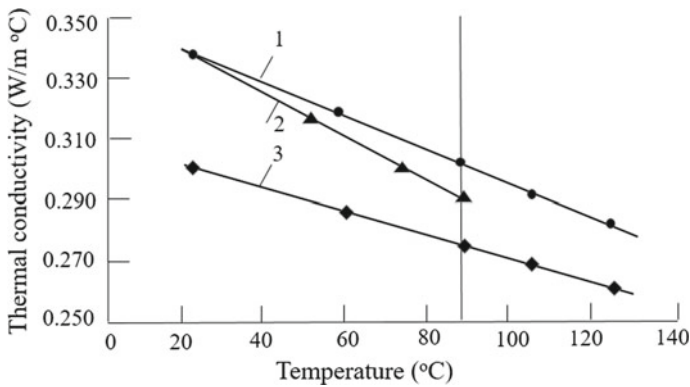
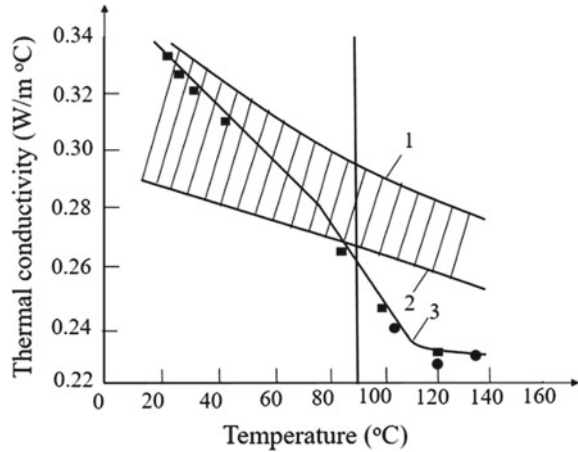


Fig. 64 Variation of thermal conductivity with temperature for XLPE (1), PE (2) and EPDM (Reprinted, with permission, from [62])

If in Fig. 63, the variation of an XLPE-type conductivity for temperatures higher than 90 °C shows a sharp decrease, in Fig. 64 its variation is linear and in agreement with the results presented in several works [62, 129, 130]. On the other hand, for temperatures below 90 °C, there are no significant differences between the values of thermal conductivity of XLPE, PE, and EPDM, only the values for EPDM being slightly lower. It should be noted that the values of λ are higher for EPR than for XLPE. For example, at 90 °C, $\lambda = 0.268\text{--}0.272$ W/m °C for EPR and $\lambda = 0.226$ W/m °C for XLPE [128].

Tests performed on samples based on EPR with different filler concentrations and TR-XLPE [131] showed that commercially available EPR and TR-XLPE cable dielectrics have typically about the same thermal conductivity although the thermal

conductivity of TR-XLPE above the melting point of crystallites drops below that of EPR dielectrics.

6.2.3 Thermal Stability

Thermal stability of XLPE and EPR has been evaluated in the laboratory in an inert nitrogen atmosphere at temperatures up to 427 °C on other copolymers of ethylene [132], to determine their suitability for high-temperature and dry nitrogen curing. It was observed that degradation started at 360 °C for a cross-linked EPR formulation and at 375 °C for XLPE.

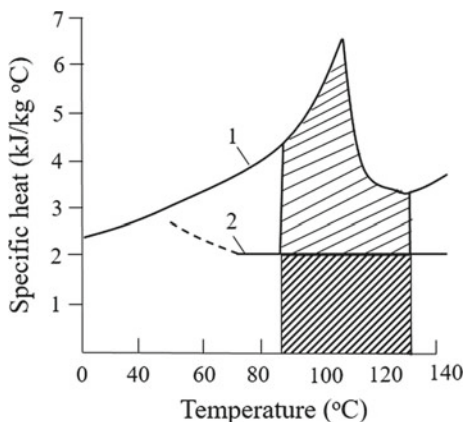
In isothermal studies, the initial degradation rates for XLPE and EPR at 260 °C were 0 and 0.013% wt. loss per minute. At 315 °C, the rates were 0.013 and 0.121, respectively, while at 370 °C, the rates were 0.186 and 0.200. These low rates indicate that thermal stability of EPR, as XLPE, should be satisfactory for the curing process in pure nitrogen. Other thermal analysis studies carried on in air showed that temperatures at which rapid oxidation started were 160 °C for EPR and 230 °C for XLPE [62].

6.2.4 Effect of Melting

However, a cable operates at its maximum permissible continuous temperature of the conductor, at 90 °C, which is suddenly overloaded by a substantial amount. Thus, the conductor temperature will rise and the insulation temperature will follow. Under these conditions, EPR insulation will reach an overload temperature of 130 °C faster than XLPE, because XLPE must be completely melted before its temperature to exceed about 115 °C (as shown in Fig. 65).

Figure 65 shows that the areas below the two curves, between 90 and 130 °C, give the amount of heat required to cause that temperature increase. For EPR, it is

Fig. 65 Variation of specific heat with temperature for XLPE (1) and EPR (2) (Reprinted, with permission, from [62])



about 7.369 MJ/kg, while for XLPE is about cca. 2.5 times higher, respectively 18.42 MJ/kg. As a result, the time required for XLPE heated from 90 to 130 °C is approx. 2.5 times higher than for EPR heating. Obviously, when the overload disappears, the cable cools down, but the cooling is done much faster in EPR insulation than in XLPE insulation.

6.2.5 Working Temperature

The values of working temperature (T_w) of an insulation depend, first on the chemical nature of its components, and also on the physical structure and their stresses. In Table 20, it is observed that the highest values of T_w were showed by silicone rubber insulation, followed by those of XLPE and EPR.

6.2.6 Mechanical Properties

In general, the mechanical properties of XLPE are better than those of thermoplastic PE, respectively, XLPE, which has deformation at a lower temperature (see Fig. 66), a higher resistance to tensile strength (see Fig. 67), lower elongation at break (see Table 21), etc. [133]. In addition, the mechanical properties of XLPE are superior to those of EPR [62].

Table 20 Operating temperature values for insulating and sheathing materials

Material	Max. cond. temp. for continuous operation (°C)	Max.cond.temp. for short circuit (°C)	Min. working temperature (°C)
Natural Rubber	60	200	-55
Ethylene Propylene Rubber (EPR)	90	250	-50
Polychloroprene (PCP)	70	200	-40
Chlorosulphonated Polyethylene (CSP)	90	200	-35
Silicone rubber	150/180	350	-55
XLPE	90	250	-40
Styrene butadiene rubber	60	200	-55
Butyl rubber	85	220	50

Fig. 66 Dependence of the heat deformation on the temperature for PE (1) and XLPE (2) [133]

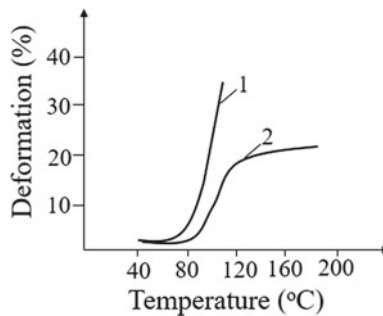


Fig. 67 Dependence of the tensile strength on the temperature for PE (1) and XLPE (2) samples [133]

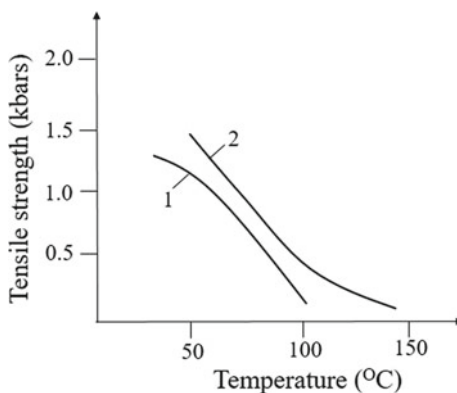
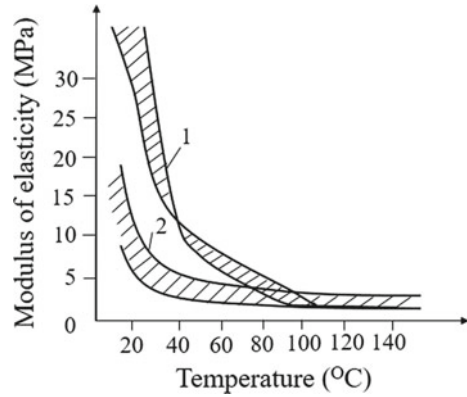


Table 21 Values of elongation at break of several polymers (%) [134]

Polymer	Minimum value	Maximum value
HDPE—High-density polyethylene	500	700
LDPE—Low-Density Polyethylene	200	600
LLDPE—Linear low-density polyethylene	300	900
XLPE—Cross-linked Polyethylene	100	550
PTFE—Polytetrafluoroethylene	200	400
PVC, Plasticized	100	400
PVC Rigid	25	80
PP (Polypropylene) homopolymer	150	600
PP (Polypropylene) copolymer	200	500
PA 6—Polyamide 6	200	300
FEP—Fluorinated ethylene propylene	250	300

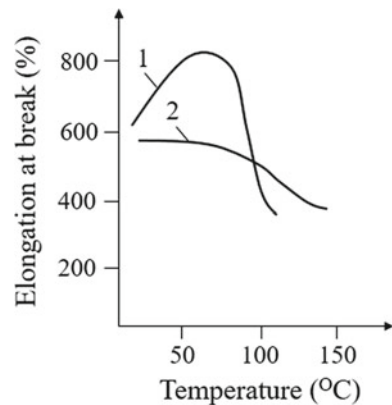
Fig. 68 Variation of modulus of elasticity in tension with temperature for XLPE (1) and EPR (2) (Reprinted, with permission, from [62])



6.2.7 Modulus of Elasticity

Cable insulation is stressed in tension (E_t) at temperatures below 40 °C during installation in trench or when pulling around corners and in ducts. Figure 68 displays the modulus of elasticity in tension as a function of temperature for XLPE and EPR. It was found that for temperatures below 90 °C, there are significant differences regarding the values of the modulus of elasticity in tension for XLPE and EPR. Thus, at 23 °C, E_t takes a value of 121 MPa for XLPE and values between 4.8 and 13.8 MPa for EPR [62]. For temperatures above 100 °C, these differences are insignificant (see Fig. 68). Similar variations were obtained in the case of modulus of elasticity in compression [62].

Fig. 69 Dependence of the elongation at break on temperature for PE (1) and XLPE (2) [133]



6.2.8 Tensile Elongation at Break

Elongation at break or tensile elongation at break is related to the ability of a plastic specimen to resist at changes of shape without cracking and represents the ratio between increased length and initial length after breakage of the tested specimen at a controlled temperature. For temperatures below 90 °C, the values of elongation at break for XLPE are lower than for PE (see Fig. 69) and higher than for EPR (see Table 21).

The toughness of a material is defined as the amount of energy that it can absorb before failure occurs, and it is related to its tensile strength and elongation. It is a function of the rate of strain. An estimation of the amount of energy absorbed during tension (extension or stretching) of a polymer sample is made by integrating the area under a stress–strain curve.

6.2.9 Tensile Strength and Toughness

Numerical or graphical integration of the areas under the XLPE and EPR curves presented in Fig. 70 (for a strain rate of 8 mm/sec starting with 25.4 mm long specimens) gives the toughness values of 143 J/cm³ for XLPE and 48 J/cm³ for EPR [62]. Results that EPR is soft and resilient at low stresses, but XLPE will absorb much more energy before it breaks.

To find out the behavior of insulators at low temperatures (for cryogenic cables), the tensile strength of EPR was measured in comparison with LDPE and XLPE, after that the samples were shrunk freely in liquid nitrogen [135]. As shown in Table 22, the tensile strength of EPR is equivalent to that of XLPE and is a little larger than that of LDPE. Then EPR had smaller shrinkage than XLPE and LDPE between room temperature and 77 K.

Fig. 70 Stress versus strain curves used for determination of toughness for XLPE (1) and EPR (2) (Reprinted, with permission, from [62])

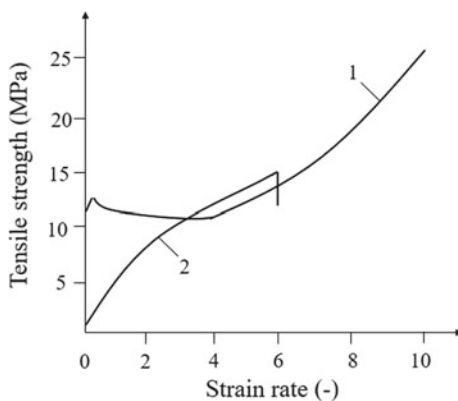


Table 22 Values of mechanical properties of samples shrunk freely at 77 K [135]

Property/ Material	Shrinkage (%)	Elongation (%)	Elastic modulus (GPa)	Tensile strength (MPa)
EPR	1.1	6.7	2.38	137
LDPE	1.6	5.6	2.28	119
XLPE	1.6	7.1	2.23	139

6.2.10 Compressibility

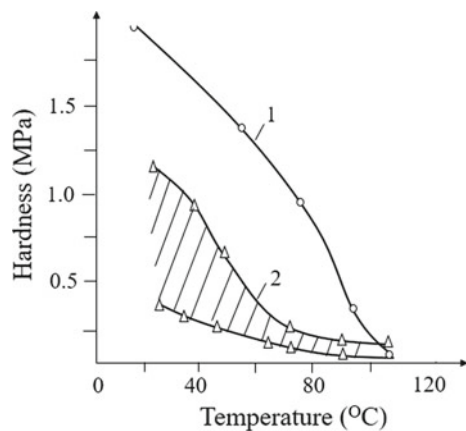
Compressibility (also known as the coefficient of compressibility or isothermal compressibility) is a measure of the relative volume change of a fluid or solid as a response to a pressure (or mean stress) change. It was stated earlier that all organic materials expand more than metals or minerals when heated. As shown in Fig. 62, XLPE expands from 12.5 to 15%, while EPR expands from 5 to 9% between the temperatures of 20 and 130 °C. Among 20 and 90 °C, the difference between materials is about 2% or less.

Therefore, if cables are not designed to accommodate this expansion that can destroy them because the force of thermal expansion is almost irresistible [62]. Therefore, the values of compressibility coefficient should be as low as possible.

6.2.11 Hardness

Hardness is a measure of the resistance to localized plastic deformation induced by either mechanical indentation or abrasion. This property relates directly to possible damage of a cable before or during installation. Figure 71 shows the relation between temperature and the force required to indent the surface of a thick section

Fig. 71 Variation of the hardness with the temperature for XLPE (1) and EPR (2) (Reprinted, with permission, from [62])



with a standard indenter [62]. At all important temperatures, the hardness of XLPE is about twice that of the hardest EPR and over ten times that of the softest EPR.

The study [131] showed that mechanical properties of EPR cable dielectrics are much more stable with temperature than TR-XLPE. EPR polymer is essentially amorphous so that EPR cable dielectrics do not suffer from the very large thermal expansion of TR-XLPE, as its crystallites melt between about 80 and 120 °C.

EPR cable dielectrics also have much more uniform stiffness as a function of temperature. Its stiffness varies only by a factor of 100 from -40 to 140 °C, while the stiffness of XLPE varies by a factor of 10,000 over the same temperature range. A combination of large thermal expansion and low stiffness (or yield stress) at elevated temperatures can cause problems with cable accessories, as discussed above. For these reasons, the upper temperature limit for operation of XLPE is often limited to 90 °C or 105 °C, and EPR cable dielectrics can operate safely until 140 °C.

6.3 Chemical Resistance

When solid organic materials are exposed to or immersed in organic liquids of lower molecular weight, they are usually swelling as they imbibe some of the lower molecular weight material. Thus, for cables immersed in oil at 23 °C, there is an

Table 23 Chemical resistance of some electro-insulating materials [43, 137–139]

Material	Chemical resistant to:
Polyisoprene	Acetone, acids, alkalies, alcohols
Butadiene	Glycerol, glycol, acids, alkalies, weathering
Styrene butadiene	Glycerol, glycol, acids, alcohols, salts, oxidation
Acrylonitrile butadiene	Glycerol, glycol, acids, ketones, alcohols, petroleum products, salts, heat or high temperature, vegetable oils, weathering
Polychloroprene	Glycerol, glycol, alcohols, petroleum products, salts, heat or high temperature, ultraviolet light, vegetable oils, weathering, ozone
Isobutylene-isoprene	Phenol, glycerol, glycol, alkalies, salts, ultraviolet light, vegetable oils, weathering, oxidation, ozone
Polyethylene	Acetic acid, glycol, ethanol, glycerin, mercury, methanol, acetone, formaldehyde 10–40%, oils, isobutanol, isopropanol, gasoline, phenol, vaseline
Polypropylene	Chlorhydric acid, caustic soda, sodium cyanide, aniline, alcohols, carbon dioxide, carbon monoxide, hydrogen sulfide
Polyvinyl chloride	Alcohols, chlorinated water, oils, diesel fuel, glycol, fatty acids, formaldehyde, gasoline, hydrocyanic acid, kerosene, mercuric chloride, phosphoric acid, sulfurous acid, water
Silicone rubber	Acetamide, aniline, clophene, salts, mineral oils, phenols, sulfuric acid, glycol
Epoxy resins	Acetylene, alcohols, amines, benzol, gasoline, hydrocyanic acid, kerosene, mercury, oils, propane

increase of the insulations diameter by 2.5% and of the masses by 7.6% in the case of XLPE and by 30% and, respectively, 151%, in the case of EPR [136]. As noted, the changes in weight and volume for EPR when immersed in oil are surprisingly great. The increase in temperature from 23 to 60 °C leads to a higher increase in diameters and masses of the insulations, as follows: The diameters increase by 12% and the masses by 13% for XLPE and 46.9%, respectively, by 232.9% for EPR. Similar tests with joint box compound (Bitumen) showed smaller changes: only 5.1% increase in weight for EPR and 3.6% for XLPE at 60 °C [136].

Tests performed on different electro-insulating materials under the action of chemical agents with which electrical equipment insulation can come in contact, showed that, in general, XLPE insulations have superior chemical resistance to those of tires. This means that the deterioration and aging process is much slower in XLPE than in other insulations. Some of the organic acids, bases, and solvents to which the materials used for electrical insulation have a good resistance are presented in Table 23.

6.4 Microorganisms, Termite, and Rodent Resistance

Cables insulation used especially in the field of irrigation are sometimes destroyed by microorganism, termites and, above all, by rodents (especially gophers).

Microorganisms (e.g., bacteria, mold, fungi) contribute to the degradation of insulating materials both by the action of the acids that they produce, and by the channels, they dig inside the bodies, subsequently penetrated by water. The action of microorganisms is more important in humid environments and at temperatures of 15–40 °C. Obviously, not all materials are attacked by bacteria or fungi and not with the same intensity. Thus, PVC has a very good resistance to the action of fungi, if plasticizers as aliphatic esters of phthalic acid, dimethyl- and dioctyl

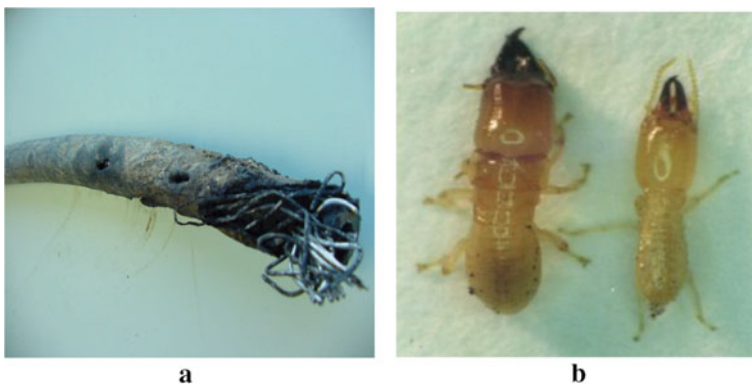


Fig. 72 Cable jacket (a) attacked by termites (b) (Reprinted, with permission, from author [13])

phthalates, etc., are used. However, its resistance decreases when using fatty acid derivatives. Natural and synthetic rubbers are attacked only if they come in direct contact with water, while mica, ceramics, phenolic, or melamine plastics with inorganic filling, etc., are not attacked by fungi. To avoid mold deposition, insulating materials have fungicidal substances (e.g., pentachlorophenolate and sodium trichlorophenolate, salicylic anhydride, phenyl mercury combinations, etc.) in their composition.

The termites, particularly, attack wood, synthetic fibers, polymer insulation, etc. [39] (see Fig. 72). In order to protect them from termites, the insulating materials are impregnated with pentachlorophenol, creosote, metal naphthalenes, zinc chloride, etc., which reduce the electrical and/or mechanical properties of cable insulations and jackets.

The teeth of a gopher grow about 18 cm per year and the chewing of hard objects is essential to keep the teeth trimmed and at a comfortable length. Unfortunately, neither PVC nor PE insulated conductors offer much resistance to the sharp teeth of rodents. In order to protect the insulations, all the recommendations require the protection of the wire with either a stainless-steel tape, a bronze tape, fine braided wire, or concrete. The armored cable could be either a PE or PVC insulated copper conductor with a steel covering and a PVC outer jacket. The product with PE insulation a slightly lower cost [39].

The selection of materials with respect to their resistance to chemical environments largely depends on the degree of exposure to these substances. In the case of occasional spills of hydrocarbon solvents, materials based on XLPE and EPR/EPDM would survive without significant loss of physical properties. However, if prolonged exposure is likely, the selection of materials based on chloroprene or chlorosulfonated polyethylene may be necessary [71].

6.5 Radiation Resistance

Under the action of solar radiation or other types of radiation (α , β and γ , fast or slow neutrons, electrons, etc.) in the structure of insulating materials (especially in the case of polymers) irreversible transformations occur, causing important variations (degradation) in their properties. The destructive action of the radiation becomes important only if their energy is comparable to the bonding energy w_l of the chemical elements that build the molecules of which the material subjected to the action of radiation is composed (see Table 24). This is achieved, not only in the

Table 24 Chemical bonding energy values

Bond	C–C	C=C	C–H	C–O	O–H	O–O	C=O	C–Cl
Bonding energy (kJ/mol)	350	610	410	360	470	150	750	340

case of high-energy radiation (used in nuclear technology), but even in the case of solar radiation. Indeed, if $w = hv = hc/\lambda$ represents the energy of the wavelength radiation λ , then for λ in the range 0.29–0.4 μm , radiations with energies values of $W = N_A w = 418\text{--}300$ kJ/mol (where $N_A = 6,022 \times 10^{23} \text{ mol}^{-1}$ is Avogadro's number) are obtained. Therefore, the energy of ultraviolet radiation, the value of which is in the range determined above, is sufficiently large to cause breaking of the chemical bonds as O–O, C–C, C–O, C–K, etc.

By fracturing the macromolecules, free radicals are formed and react with each other—giving rise to new products—or form bridges between the molecular chains that contribute to the cross-linking of the bodies and, therefore, to the modification of their mechanical and thermal properties. In addition, free ions and electrons, which modify their dielectric properties (reducing the resistivity and dielectric strength, increasing the electrical permittivity, forming space charges), etc., are produced. The modification of the materials properties subjected to the action of radiation depends, on both the nature and structure of the materials, as well as on the dose rate and the total dose of radiation absorbed (i.e., meaning the energy absorbed by 1 kg of material). For example, in the case of elongation at break by traction, a reduction of its value by 50% compared to the initial value is obtained by irradiation with a dose of 350 J/kg for XLPE and PE and only 1.5 J/kg for PTFE [13]. The tests performed at CERN on products prepared by PIRELLI GROUP [140] showed that, for the same value of the total irradiation dose, respectively, 100 Mrad, the values of the elongation at break by traction are reduced compared to the initial values of 3.2 times in the case of XLPE, of 3.4 either in the case of EPR and EPDM, 4.2 times in the case of PE, 9.7 times in the case of neoprene, and only 2.2 times in the case of PVC. In the same irradiation conditions, the tensile strength by traction decreases by 1.9 times in the case of XLPE, 1.5 times in the case of PE, 1.1 times in the case of EPR and remains unchanged in the case of PVC. It can be said that PVC insulation has the highest resistance to radiation.

The paper [141] presents a study on the behavior of the PCV cables insulation used in the nuclear power plants. Cables insulated with eleven different PVC compounds representing fire retardant, non-fire retardant with the rating temperatures 60, 75, and 90 °C were evaluated. The specimens were subjected to accelerated thermal, radiation, and sequential radiation and thermal exposure, simulating 15, 20, 30, and 40 years in-service environments in Ontario Power Generation Nuclear Plants. The radiation level was limited from 12 to 30 Mrad. A part of the samples was sequentially irradiated and thermally aged and subjected to an additional 5 Mrad accident radiation exposure, followed by a simulated loss of coolant accident (LOCA). Similarly, thermal only aged specimens with 2 Mrad of background radiation representing powerhouse environment were subjected to a main steam line break (MSLB) test. Although the present acceptance criterion used for installed cables is 50% absolute elongation at break [142, 143] after the stresses were applied, the elongation and insulation resistance were measured. It is generally assumed that this elongation value will provide sufficient margin to ensure that the insulation maintains its electrical properties during a design basis event.

The electrical behavior of PVC insulated cables during the steam test indicates that there was no correlation between the performance and the elongation value, specifically when cables were subjected to an irradiation environment >17 Mrad. On the other hand, in the case of fire retardant cross-linked polyethylene (FR-XLPE) and fire-retardant ethylene propylene rubber (FR-EPR) insulated cables, it was shown previously that those cables were working through the additional accident radiation and steam conditions with elongation values in the range of 5% [144–146]. The authors conclude that the elongation values were not a good indicator of electrical performance for radiation and thermal aged specimens.

7 Lifetime

Estimating the lifetime (L) of cables polymer insulation is of particular importance for their users. There are numerous models and methods for estimating L values, corresponding to electrical, thermal, mechanical, and environmental stresses, performed in laboratories based on accelerated, single- or multifactor tests [13, 22, 147]. In [147], the procedures for accelerated testing under thermo-electrical stresses are discussed and applied to EPR and XLPE used for HV cable insulation. It was concluded that EPR has a slightly larger temperature index, while XLPE displays a threshold that has not been detected for EPR. On the other hand, it shows that any comparison cannot be extended to the general category of materials to which insulation belongs, so that it cannot be said that XLPE is better than EPR.

The study [148] presents the lifetime curves of some insulated cables with XLPE and PVC subjected to permanent thermal stresses, using the weight loss as the diagnostic factor. As can be seen in Fig. 73, XLPE is more endurable than PVC. For example, at 100 °C XLPE lifetime is more than 10,000 h, while PVC lifetime is around 1,000 h.

Fig. 73 Thermal lifetime curves of XLPE (1) and PVC (2) based on weight loss (Redrawn and adapted figure from reference [148])

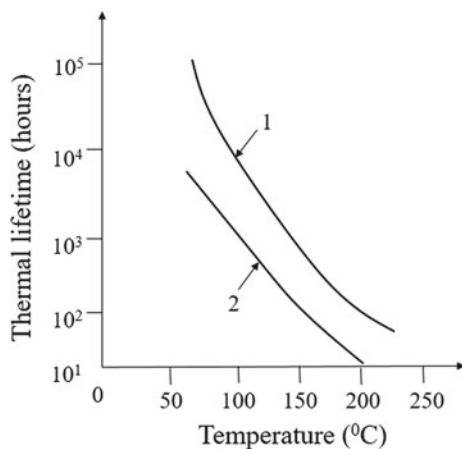


Fig. 74 Failure rate of 20 kV XLPE (■) and EPR (□) cables [26]

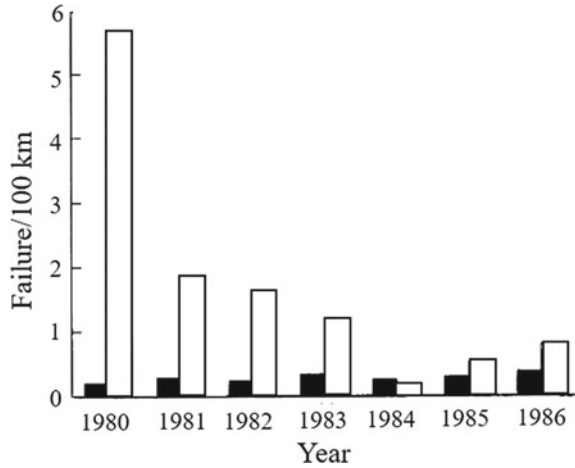


Figure 74 shows a failure rate data for 20 kV cables from 1980 to 1986 [26]. It was found that XLPE insulation for medium-voltage cables are superior to EPR, in terms of cable performance reliability. Moreover, as the insulating compounds used in medium-voltage cables are generally the same or very similar to the ones used in high voltage cables, it turns out that the same conclusion can be drawn for transmission cables.

Table 25 Comparison of common insulating materials

Material	Advantages	Disadvantages
PVC	Cheap; Durable; Widely available; Reduced risk of flammability, and fire propagation	Highest dielectric losses; Melts at high temperatures; Contains halogens; Not suitable for MV/HV cables
PE	Lowest dielectric losses; High initial dielectric strength; Reduced weight; Easier to repair faults	Highly sensitive to water treeing; Material breaks down at high temperatures
XLPE	Low dielectric losses; Improved material properties at high temperatures; Does not melt but thermal expansion occurs; Reduced weight; Easier to repair faults	Medium sensitivity to water treeing (although some XLPE polymers are water tree-resistant)
EPR	Increased flexibility; Reduced thermal expansion; Reduced weight; Low sensitivity to water treeing; Easier to repair faults	Medium-High dielectric losses; Requires inorganic filler/additive
Paper/Oil	Low-Medium dielectric losses; Not harmed by DC testing; High dielectric strength; Known history of reliability; Long lifetime	High weight; High cost; Requires pumps for insulating fluid; Difficult to repair; Degrades with moisture

XLPE is suitable for voltage ranges from low to extra high, surpassing other insulation materials such as PVC, ethylene propylene rubber (EPR), and silicone rubbers. Cross-linking PE also enhances the chemical and oil resistance at elevated temperatures and makes it suitable for use as a low smoke zero halogen material.

The mechanical properties of XLPE are superior to many other insulations, offering higher tensile strength, elongation, and impact resistances. The addition of carbon black can be used for further enhancement of hot deformation and cut-through resistance. The XLPE insulation will not melt or drip, even at temperatures of soldering irons, and it has increased flow resistance and improved aging characteristics.

Improved water tree resistance is another benefit of XLPE insulation for LV and MV cables over PE insulations. Water treeing is a defect, which is the result of imperfections in the insulation where fracture lines occur and grow in the direction of the electric field, increasing with electrical stress. A comparison of the advantages and disadvantages of some materials used as electrical insulation of the power cables is presented in Table 25.

The most readily available insulations for low-voltage (600 V) and medium-voltage (5–35 kV) cables installed in petroleum and chemical plants are polyvinyl chloride (PVC), polyethylene (PE), cross-linked polyethylene (XLPE), tree-retardant cross-linked polyethylene (TR-XLPE), and ethylene propylene rubber (EP, EPR, or EPDM). Chlorosulfonated polyethylene (CSPE), chlorinated polyethylene (CPE), and polyamide (nylon) are sometimes used for the second layer in dual-layer insulations. The temperature rating of these materials is usually 75 °C for thermoplastic materials and 90 °C for thermoset ones. For installations in areas with high ambient temperatures, cables with special high-temperature insulations are used. These cables carry temperature ratings ranging from 125 to 450 °C and beyond. High-temperature insulations include specially formulated EPR, cross-linked polyolefin, silicone rubber, various fluoropolymers, ceramic tapes, aramid fiber, and glass-reinforced mica tape. High-temperature cables are frequently constructed with a combination of one or more of the above materials. Common fluoropolymer insulations include fluorinated ethylene propylene (FEP), polytetrafluoroethylene (PTFE), and ethylene chlorotrifluoroethylene (ECTFE).

8 Conclusions

Cross-linked polyethylene (XLPE) has replaced, decades ago, oil-paper insulated systems as primary solution for medium and high voltage AC cables, due to its numerous advantages (very good dielectric properties, higher operating temperatures, etc.). They can be produced with high throughput and well-controlled extrusion technology. XLPE has become the global preferred insulation for power cables, both for distribution and transmission system applications. This insulation system provides cost efficiency in operation and acquisitions, installation and operation as well as lower environmental and maintenance requirements, reduced

risk of fire during earthquakes, when compared to older impregnated paper system. Currently, conventional XLPE is at the limit of its capabilities due to the intrinsic limits of purity that can be obtained with the most commonly adopted cross-linking chemistries, and thermal performance of the materials concerning their relatively low melting points. Nonetheless, XLPE technologies are widely adopted and are expected to remain a key cable insulation system into the future.

The very good general properties of XLPE and EPR recommend these materials for use as insulations of AC and DC medium, high and very high voltage power cables. Each of these insulation materials is used preferentially in different parts of the world: in France LDPE, in Italy EPR, and in most of Europe, Japan, and the USA, XLPE. The reason for this difference is that no one who extruded dielectric insulation material has emerged as conclusively superior to the others in all aspects for every application, including manufacturing, cost, and reliability. In general, these insulation systems have important advantages such as no operation and maintenance requirements, high reliability, higher normal operating, and short-circuit temperature ratings, reduced time required for repair, small dielectric losses, etc.

Materials used for semiconducting extruded conductor and insulation shields are semiconducting PE, XLPE, and EPR compounds. PE compounds are used with PE and XLPE insulation, XLPE compounds with XLPE insulation, and EPR compounds with EPR insulation. Cable jackets are typically extruded PE and on rare occasions polyvinyl chloride (PVC). XLPE and EPR, a copolymer of ethylene and propylene, offer good electrical characteristics, ease to process, at acceptable cost, and therefore have been popular extruded dielectric materials. When properly formulated and compounded, EPR is in some ways superior to XLPE, but it is generally more expensive.

The worldwide tendency to use HVDC transmission lines makes the demand for better insulation materials to increase greater and urgent. Many manufactures have developed XLPE materials that are more adapted to DC power cables insulation, such as super-clean cross-linkable polyethylene and XLPE-based nanocomposites. XLPE has higher dielectric losses than PE, but has better aging characteristics and resistance to water treeing. On the other hand, filled XLPE (with titanium dioxide) has a lower water resistance than XLPE. It can be said that, generally, XLPE is preferred where a material with excellent dielectric properties is required, while EPR/EPDM is preferred where there is a need for a more flexible cable.

The electrical properties of XLPE (e.g., volume resistivity, dielectric constant, and loss factor) are better or equal to those of thermoplastic polyethylene (PE). Under high temperatures, XLPE presents a breakdown voltage higher than PE and is practically equal at low temperatures. Physical properties are in many (but not all) cases more temperature sensitive than electrical properties, and XLPE is often (but not always) more temperature sensitive than EPR. As the electrical conductivity of XLPE is highly dependent on the presence of polar molecules (assisting in charge transportation), one way to reduce the conductivity is to decrease the concentration of potential charge carriers or polar substances, respectively, to create a material as clean as possible.

Syndiotactic polypropylene (sPP) has excellent insulating properties, but it is actually prohibitively expensive. On the other hand, PP has the disadvantages of poor low-temperature impact performance and low thermal conductivity, as well as the problem of space charge accumulation and aging of the polymer in the DC field. Therefore, PP needs to be modified in order to meet the electrical, thermal, and mechanical properties of the cable insulation material under the complex working conditions of DC high voltage. It should be emphasized that PP has shown great potential as recyclable HVDC cable insulation material.

The half of the failures of utility cable systems is due to the splice or termination failures. A greater potential for splicing and termination problems exists for XLPE/TR-XLPE cables than for those insulated with EPR/EPDM. During the manufacture of cables, the insulation is extruded on the conductor under high mechanical stresses and at elevated temperatures. As the conductor and insulation have different axial coefficients of thermal expansion, residual stresses can be ‘frozen in’ when the cable is quenched or cooled after extrusion. Stresses care are low in the case of EPR/EPDM than in XLPE/TR-XLPE. This can result in an appreciable amount of ‘shrink-back’ away from a splice or termination component interface, creating voids. Therefore, corona discharges may be produced and can eventually result in failure.

In general, unfilled insulation formulations of high-molecular-weight PE (HMWPE) and XLPE provide the highest level of dielectric strength. This does not mean, however, that any insulation will provide a stable dielectric strength over the lifetime of a cable, especially in wet operating environments. Filled or chemically altered formulations such as ethylene propylene rubber (EPR) and trees retardant cross-linked polyethylene (TR-XLPE) maintain their dielectric strength better in wet locations involving medium-voltage cable designs. Where higher voltage strength must be achieved because of the electrical system demands (overvoltages, switching surges, excessive ground-fault clearing time, etc.), increased insulation thicknesses (up to 133% or 173%) should be considered.

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