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Original Paper

Characteristics and Application Scenarios of Polymer Insulating Materials

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Abstract
Polymer insulating materials, owing to their excellent electrical insulation properties, good mechanical strength, chemical corrosion resistance, and ease of processing and molding, have been widely applied in key fields such as power systems, communication equipment, electronic devices, transportation, and aerospace. With the continuous advancement of industrial electrification, automation, and intelligence, higher requirements are placed on the adaptability and reliability of insulating materials in operating environments. This paper systematically analyzes the fundamental properties of polymer insulating materials, covering multiple dimensions including dielectric constant, breakdown voltage, thermal stability, aging resistance, mechanical strength, and environmental adaptability. It also classifies and compares common thermoplastic, thermosetting, and special engineering plastics. Combining typical application scenarios, the paper deeply explores the practical application value of these materials in industries such as power, communications, automotive, rail transit, and aerospace. Additionally, it analyzes the challenges faced by current materials under complex conditions such as high temperature, high voltage, and high frequency, and prospects the development direction of intelligent and environmentally friendly polymer insulating materials. This work aims to provide theoretical reference and technical guidance for material engineering, electrical engineering, and related industries.
Keywords
Polymer materials, Insulation performance, Electrical engineering, Heat resistance, Application scenarios

1. Introduction

In the context of increasingly complex and high-performance modern electronics, power, and energy systems, insulating materials, as critical components ensuring the safe operation of equipment, directly affect the stability and service life of the entire system. Although traditional inorganic insulating materials possess certain high-temperature resistance, they have limitations in terms of processability, flexibility, and lightweight characteristics. In contrast, polymer insulating materials, with their strong designability, excellent dielectric properties, ease of molding, and moderate cost, have gradually become core materials in high-voltage power transmission, electrical machinery, electronic packaging, communication equipment, and new energy systems. Particularly in high-tech industries such as new energy vehicles, 5G communications, rail transit, and aerospace, stricter technical standards are imposed on materials' insulation, heat resistance, flame retardancy, and environmental adaptability. Therefore, in-depth research on the basic characteristics, structure-function relationships, typical applications, and development trends of polymer insulating materials holds significant theoretical and practical engineering value. This paper will elaborate on four aspects: performance analysis, material classification, application scenarios, and future prospects, aiming to provide systematic support for the R&D and engineering application of polymer insulating materials.

2. Basic Characteristics of Polymer Insulating Materials

2.1 Electrical Insulation Performance

One of the core features of polymer insulating materials is their excellent electrical insulation performance, which forms the foundation for their widespread use in power systems, electronic devices, and communication engineering. Typically, polymers have long-chain molecular structures with weak polarity and very few free electrons between molecules, resulting in very low electrical conductivity and effectively blocking current flow to provide good insulation. For example, polytetrafluoroethylene (PTFE) is a typical polymer insulating material with a dielectric constant of approximately 2.1, showing minimal variation over a wide frequency range, very low dielectric loss, and good electrical field stability. Additionally, PTFE has a high breakdown voltage, generally around 60–100 kV/mm, suitable for use in high-voltage power cables and capacitor dielectrics.

Besides PTFE, thermoplastic polymers such as polyethylene (PE), polypropylene (PP), and polyester (PET) also exhibit good insulation properties and are widely used in engineering due to their superior processability and lower cost. Particularly in high-frequency communication and microwave circuits, strict requirements on dielectric loss make dielectric performance the primary criterion for selecting polymer insulating materials.

Breakdown voltage and tracking voltage are two key parameters measuring insulation capability. Breakdown voltage reflects the maximum electric field intensity the material can withstand at a certain thickness, while tracking voltage relates closely to the surface structure, moisture absorption, and pollution resistance of the material. Through molecular structure design, filler addition, or crosslinking modification, these two parameters can be effectively improved to meet various voltage levels and operating environment needs.

It is worth noting that with modern electronic devices trending towards miniaturization and high integration, insulation materials are required to withstand higher voltages within smaller volumes while maintaining stability for high-frequency, high-speed signal transmission. This presents higher challenges for electrical insulation performance, making fine electrical property regulation and structural optimization critical directions in current insulation material research.

2.2 Thermal Stability and Aging Resistance

Thermal stability is the key factor determining whether polymer insulating materials can maintain stable performance during prolonged exposure to high temperatures. Materials with poor thermal stability may deform, melt, degrade, or even combust during use, losing insulation functionality. High-performance polymer insulating materials such as polyimide (PI), due to their molecular chains containing stable aromatic rings and imide bonds, have excellent heat resistance and can operate continuously at temperatures above 300°C without decomposition or carbonization. Therefore, they are widely used in aerospace, military, and high-temperature motor insulation systems.

Beyond thermal stability, aging resistance is another critical property for long-term applications. Aging includes thermal-oxidative aging, photoaging, electrical aging, and hygrothermal aging. Exposure to ultraviolet light, ozone, oxygen, or humid heat can cause polymer molecular chains to break or crosslink, leading to performance degradation. To improve aging resistance, researchers optimize formulations via copolymerization, crosslinking modification, addition of antioxidants, and photostabilizers. For instance, crosslinked polyethylene (XLPE), through thermal crosslinking, significantly enhances its thermal aging life and mechanical stability, becoming a primary insulating material for high-voltage cables.

In practice, the degree of thermal aging directly impacts the lifetime and operational safety of equipment. For example, thermal aging of insulation materials is a primary cause of insulation failure in high-voltage power transformers. By establishing aging models and conducting accelerated aging tests, the performance degradation law under different temperatures and durations can be predicted, providing scientific bases for service life and maintenance cycles.

With the growing demand for heat-resistant and high-stability insulation materials in new energy and high-speed rail transit, developing new high-temperature resistant polymers such as liquid crystal polymers (LCP) and polyaryletherketones (PAEK) is becoming an important research direction in materials science.

2.3 Mechanical Properties

Besides excellent electrical properties, polymer insulating materials must meet certain mechanical property requirements to ensure sufficient strength, toughness, and structural stability during use. Especially in fields like cables, insulating supports, electronic packaging, and transformers, materials need to withstand external forces, thermal expansion/contraction, or mechanical shocks, making good mechanical properties an important guarantee for stable operation.

Common polymers such as polycarbonate (PC) and polyetheretherketone (PEEK) have high tensile strength and impact resistance. For example, PC's impact strength can reach 800–100 MPa, suitable for use in motor insulation components and microcircuit structural substrates in precision engineering.

Flexibility is another important mechanical index. Polymers generally have high chain segment mobility, providing good ductility and bendability. For instance, polyimide films are widely used in flexible printed circuits (FPC) because they can endure thousands of repeated folds without impairing electrical performance or structural integrity.

Mechanical properties are also affected by temperature, humidity, stress concentration, and other external factors. Therefore, glass fiber, carbon fiber, and other reinforcing materials are often added during material design to enhance strength and dimensional stability. Finite element simulations are also employed to predict mechanical responses under various operating conditions, ensuring reliability during long-term use.

In materials engineering, mechanical properties relate not only to safety but also to processing methods, molding technologies, and subsequent assembly, making them indispensable in comprehensive material performance evaluation. One future development direction for high-performance composite insulating materials is to improve overall mechanical strength and structural stability via multiphase structural design while maintaining excellent electrical properties.

2.4 Chemical Corrosion Resistance

Polymer insulating materials generally possess good chemical corrosion resistance, enabling stable long-term operation in harsh environments such as acids, alkalis, salt spray, oils, and solvents. Compared with metals, polymers usually do not undergo electrochemical reactions due to corrosion, thus avoiding electrical failures caused by insulation layer damage or leakage. Hence, they are widely used in petrochemical, power, marine engineering, and heavily polluted industrial environments.

For example, fluoropolymers like PTFE and polyvinylidene fluoride (PVDF) contain strongly polar C-F bonds in their molecular structures, exhibiting extremely high chemical stability and near immunity to acids, alkalis, and organic solvents. They are used in chemical pipelines, cable sheaths, and sealing gaskets for highly corrosive conditions. Although polypropylene (PP) has slightly lower strength than engineering plastics, it also resists many acidic and alkaline solutions well, with low cost, securing a share in medium- and low-voltage insulation applications.

In power equipment, corrosion resistance directly affects the long-term reliability of insulation systems. Outdoor high-voltage insulators and cable terminations are exposed to rain, UV light, acid rain, and dust. Inadequate corrosion resistance accelerates aging and may cause flashover failures. Therefore, modern polymer material designs often incorporate inorganic nano-fillers such as SiO_2 and Al_2O_3 to improve surface hydrophobicity and protective performance.

Some polymers also show excellent oil and moisture resistance, suitable for special environments such as oil-immersed transformers and capacitor packaging. For example, epoxy resin combined with quartz powder can form oil-resistant encapsulation composites used in high-voltage electronic modules.

With the diversification of application scenarios and complexity of environmental conditions, enhancing chemical corrosion resistance while improving electrical and mechanical properties remains an important direction for material optimization. Through integrated structure-function design and composite material technologies, polymer insulating materials will play stable and durable protective roles in more extreme environments.

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3. Main Classifications of Polymer Insulation Materials

3.1 Thermoplastic Materials

(1) Polyethylene (PE)

Polyethylene is a commonly used thermoplastic polymer insulation material. Due to its low dielectric constant and excellent electrical insulation properties, it is widely applied in cable insulation layers and high-frequency signal cables. PE materials are classified into low-density polyethylene (LDPE) and high-density polyethylene (HDPE). LDPE offers good flexibility and processing performance, while HDPE exhibits superior mechanical strength and resistance to environmental stress cracking. Polyethylene has a low water absorption rate and strong resistance to moisture and chemicals, making it suitable for use in humid or chemically corrosive environments. Additionally, its low dielectric loss makes it suitable for high-frequency communication cables. However, PE has poor heat resistance, with a typical long-term operating temperature not exceeding 80°C, limiting its application in high-temperature electrical equipment.

(2) Polyvinyl Chloride (PVC)

Polyvinyl chloride is a widely used thermoplastic material known for its low cost and excellent flame retardant properties, making it extensively used as a sheath material in wires and cables. PVC has good electrical insulation performance; at room temperature, its breakdown voltage and dielectric strength meet the requirements of general electrical equipment. Flame-retardant modified and plasticized PVC can operate stably under relatively complex environments, such as industrial control cables and building cables. Its flame retardant characteristic is especially notable, as it self-extinguishes immediately after the flame source is removed, outperforming many other thermoplastics. However, PVC's heat resistance is limited, typically used below 70°C, and it ages and becomes brittle when exposed to UV radiation for prolonged periods, thus it is unsuitable for long-term outdoor high-temperature environments.

(3) Polypropylene (PP)

Polypropylene is a thermoplastic material with good insulation and heat resistance, commonly used in capacitor films, cable insulation layers, and microwave devices. Compared to polyethylene, PP has a higher heat distortion temperature and can operate continuously at about 120°C, suitable for applications requiring higher temperature stability. It has a low dielectric constant and low dielectric loss, making it an ideal material for manufacturing high-frequency capacitor films. PP exhibits good mechanical strength and chemical corrosion resistance, and its low density results in lightweight products that are easy to transport and install. However, it is more brittle at low temperatures with lower impact resistance compared to PE, and its molding process is more demanding, which somewhat limits its broader application.

3.2 Thermosetting Materials

(1) Epoxy Resin (EP)

Epoxy resin is a widely used thermosetting polymer insulation material, featuring excellent mechanical strength, adhesion, and electrical insulation properties. It is widely employed in motor coil impregnation, capacitor potting, and transformer internal insulation structures. The cured resin exhibits good volumetric stability, maintaining insulation strength under high voltage and high temperature conditions. Furthermore, epoxy resin has excellent chemical corrosion resistance, suitable for operation in humid, acidic, alkaline, or oily environments. EP can be combined with various curing agents to form composite materials with diversified properties to meet different electrical insulation requirements. Its drawbacks include curing shrinkage stress and poor long-term UV resistance, requiring protection when used outdoors.

(2) Phenolic Resin

Phenolic resin is one of the oldest thermosetting insulating materials, widely used in high-voltage electrical switches, terminal blocks, and sockets due to its excellent heat resistance, arc resistance, and dimensional stability. It has a high breakdown voltage and a thermal decomposition temperature above 250°C, maintaining structural strength and electrical performance in high-temperature environments. Phenolic resin carbonizes slowly under arc and corona discharge, making it suitable for applications with frequent arc occurrences. This material is typically combined with paper, cloth, or glass fiber reinforcement to produce laminated boards that enhance its mechanical and processing properties. Despite its excellent electrical insulation, phenolic resin is hygroscopic and brittle during processing, requiring careful storage and encapsulation.

(3) Unsaturated Polyester (UP)

Unsaturated polyester resin is a cost-effective thermosetting resin widely used in electrical insulation panels, switch boxes, and insulating rails. It has good processability and can be molded by compression, casting, or spraying, suitable for mass production. After curing, UP offers good mechanical strength, heat resistance, and electrical insulation, with electrical properties less affected by humidity, suitable for insulation structures in medium- and low-voltage electrical equipment. When combined with glass fiber, it produces fiberglass materials with outstanding strength, heat resistance, and corrosion resistance. However, its thermal decomposition temperature is relatively low (about 150–180°C), making it unsuitable for long-term high-temperature operations. Additionally, the styrene released during curing poses environmental concerns.

3.3 Specialty Engineering Plastics

(1) Polyimide (PI)

Polyimide is a class of high-performance engineering plastics known as the "gold standard of plastics" due to its excellent heat resistance, electrical insulation, and radiation resistance. It decomposes at temperatures up to 500°C and can operate stably above 300°C for long durations, ranking among the best thermally stable polymer materials. It is widely applied in aerospace, electronics, electrical, and nuclear industries. PI films are commonly used for flexible printed circuit boards (FPC), high-temperature wire insulation coatings, and high-frequency transformer winding insulation layers. PI features a low dielectric constant, low loss, excellent dimensional stability, and UV resistance, making it a preferred material for high-reliability electrical systems. Its drawbacks include complex synthesis, high cost, high processing temperatures, and somewhat reduced flexibility in extremely cold environments.

(2) Polyether Ether Ketone (PEEK)

Polyether ether ketone is a semi-crystalline thermoplastic polymer characterized by high mechanical strength, thermal stability, and electrical insulation, excelling in high-end electrical applications. PEEK can continuously operate at 250°C and tolerate short-term exposure to 300°C. Its excellent electrical properties remain stable in high-frequency and high-voltage environments, making it widely used in nuclear power plants, aerospace engine cables, and high-temperature motor insulation components. It also exhibits strong radiation resistance, capable of withstanding high doses of gamma radiation without degradation, making it ideal for nuclear industry use. Moreover, PEEK has outstanding chemical corrosion resistance for long-term operation in harsh environments. The disadvantages are its expensive raw materials, high processing temperatures, and stringent equipment requirements, so it is mainly applied in high-end specialty fields.

4. Application Scenario Analysis

4.1 Power Systems

In modern power systems, polymer insulation materials are widely used in key components such as insulation layers of high-voltage cables, winding insulation and structural insulation of transformers, capacitor encapsulation, as well as shells and internal support structures of instrument transformers. Compared with traditional materials like porcelain and oil-impregnated paper, polymer materials offer significant advantages such as lighter weight, easier processing, and superior dielectric properties. For example, cross-linked polyethylene (XLPE) used in high-voltage and extra-high-voltage transmission cables significantly improves thermal stability and service life of cables; epoxy resin is extensively applied in dry-type transformer potting, enhancing moisture resistance, dust resistance, and insulation performance; polyester and polyimide films are commonly used as insulation gaskets or spacers, providing excellent electrical strength and mechanical toughness. The widespread use of these polymer insulation materials effectively enhances the reliability, operational efficiency, and safety levels of power systems.

4.2 Electronics and Communication Equipment

In the fields of electronics and communications, polymer insulation materials play an indispensable role, widely applied in key parts such as printed circuit board (PCB) substrates, flexible printed circuits (FPC), chip packaging materials (e.g., BGA, CSP packages), and high-frequency signal transmission media. Polyimide (PI) and polyester films are extensively used in flexible circuit boards due to their excellent heat resistance and insulation properties, meeting the demands for miniaturization and high-density electronic devices. Fluoropolymer materials such as polytetrafluoroethylene (PTFE) are ideal insulation substrates in high-frequency communication because of their extremely low dielectric constant and dielectric loss, suitable for microwave circuits and antennas. Epoxy resin and BT resin are commonly found in packaging processes, improving chip heat dissipation and environmental stability. Polymer insulation materials provide key support in enhancing device operational reliability, integration density, and signal transmission speed, forming an important foundation for modern electronics and communication technologies.

4.3 Automotive and Rail Transit

With the development of new energy vehicles and intelligent transportation, polymer insulation materials play an increasingly important role in automotive and rail transit systems. In new energy vehicles, components such as power batteries, high-voltage connectors, motor windings, and inverter modules require highly reliable electrical insulation and thermal management properties. Polymers like polypropylene, polyimide, PBT, and PPS are widely used in cable sheaths, motor insulation wedges, and electronic control system packaging due to their excellent heat resistance, arc resistance, and flame retardancy. Rail transit equipment imposes higher requirements for insulation materials in terms of vibration resistance, temperature cycling tolerance, and long-term stability; thus, PI films and PEEK components are commonly employed in signal control and power supply systems of high-speed trains. These materials not only enhance the electrical safety and operational stability of the entire system but also contribute to lightweight design and extended service life goals.

4.4 Aerospace and Military

Aerospace and military fields demand extremely stringent performance from insulation materials, requiring them to operate stably over long periods under extreme conditions such as high and low temperatures, intense radiation, and severe humidity and heat. They must also possess comprehensive properties such as high strength, light weight, and corrosion resistance. High-performance polymers such as polyimide (PI), polyether ether ketone (PEEK), and polytetrafluoroethylene (Teflon) are widely used in these high-end fields due to their outstanding thermal stability, electrical properties, and radiation resistance. PI films are often used for spacecraft cable insulation and flexible circuits, capable of withstanding temperature variations from −269℃ to 400℃; PEEK is favored for its high mechanical strength, wear resistance, and heat resistance, applied in electrical connector housings, radar modules, and power packaging; Teflon materials are utilized in microwave communication and navigation systems. The application of polymer insulation materials significantly improves the reliability, lightweight characteristics, and overall performance of aerospace and military equipment.

4.5 Green Energy and Environmental Engineering

In the fields of green energy and environmental engineering, polymer insulation materials have become key components in new energy systems such as wind power, photovoltaic power generation, and smart grids. For example, wind turbine generators use epoxy resin, PI, and silicone rubber materials for insulation in generator coils, high-voltage connectors, and converter modules, providing high-voltage resistance, corrosion resistance, and aging resistance to adapt to long-term operation in harsh environments such as offshore or plateau areas. In photovoltaic power systems, EVA (ethylene-vinyl acetate) films are used for module encapsulation, offering excellent transparency, UV stability, and electrical insulation. Meanwhile, polymer materials with halogen-free, low-smoke, flame-retardant properties are extensively used in cable connections and energy storage device insulation in green grids to reduce fire risks and meet environmental protection standards. The broad application of polymer insulation materials contributes to the safe, efficient, and sustainable development of renewable energy technologies.

5. Development Trends and Challenges

5.1 High Performance and Functional Integration

As modern industrial systems evolve towards high frequency, high voltage, high speed, and extreme operating environments, traditional polymer insulating materials can no longer fully meet the demands. Therefore, enhancing material performance and integrating multiple functions have become key research focuses. In areas such as high-voltage, high-power electrical equipment, aerospace electronics, and nuclear facilities, materials are required not only to have excellent insulation properties but also high thermal conductivity, mechanical strength, flame retardancy, and radiation resistance. Current research widely uses nano-fillers (such as SiO_2, BN, AlN, graphene) for composite modification. By constructing micro- and nanoscale thermal conduction networks, these fillers can significantly improve the thermal conductivity and electrical stability of the materials. For example, the addition of BN nanosheets can increase the thermal conductivity of materials by 2 to 5 times while maintaining insulation and thermal stability. Moreover, multifunctional integrated materials, such as composite polymers that combine electrical insulation, self-extinguishing, and antistatic properties, are becoming a new trend for high-end applications.

5.2 Environmental Protection and Biodegradability

Under the global backdrop of carbon neutrality and green manufacturing, the sustainable development of polymer insulating materials has attracted widespread attention. Traditional thermosetting resins and synthetic polymers are difficult to degrade and, if improperly disposed of, may cause long-lasting pollution to soil and water. Therefore, developing bio-based polymer insulating materials derived from renewable resources has become a research hotspot. For example, materials based on polylactic acid (PLA), polyhydroxyalkanoates (PHA), combined with cellulose nanocrystals, chitosan, or inorganic fillers, can produce composites that offer both biodegradability and electrical insulation. This approach not only alleviates resource pressure but also complies with environmental regulations. Meanwhile, developing green synthesis processes (such as solvent-free polymerization and low-temperature crosslinking) is also a key focus for the future. However, current biodegradable insulating materials still lag behind traditional materials in heat resistance and dielectric strength, requiring optimization through molecular design and multi-scale composite techniques.

5.3 Intelligent Materials

Next-generation electrical systems demand higher operational safety and maintenance efficiency, driving polymer insulating materials toward intelligent functionality. Intelligent insulating materials typically possess self-sensing, self-healing, or self-responsive features, with integrated sensing and feedback structures inside or on their surfaces to monitor electrical status, thermal stress, and structural integrity in real-time. For example, embedding microcapsules or cavity structures that encapsulate specific healing agents can automatically release these agents to repair cracks and restore insulation performance. Additionally, constructing conductive nano-networks or doping with carbon nanotubes and graphene can enable online monitoring of strain, electric field, or temperature changes. The development of intelligent materials is expected to significantly extend equipment lifespan, reduce failure rates, and enable predictive maintenance. However, these materials face challenges in structural complexity, process stability, and long-term reliability, necessitating extensive experimentation and engineering validation.

5.4 Problems and Challenges

Despite many advances in performance optimization and function extension of polymer insulating materials, practical applications still encounter a series of technical and economic challenges. First, polymer materials tend to undergo molecular chain breakage, carbonization, or electrical breakdown under high temperature, high voltage, and strong electric field conditions, leading to insulation degradation and even system failures. Second, special polymers with excellent comprehensive properties (such as PEEK, PI) are usually expensive and difficult to process, limiting their widespread industrial adoption and substitution. Moreover, thermosetting materials like epoxy and phenolic resins form stable crosslinked structures after curing, which cannot be remelted or reshaped, making their waste difficult to recycle and causing environmental pressure. Overall, achieving polymer insulating materials with high performance, low cost, and sustainability requires strengthened basic research and industry collaboration in molecular structure design, processing technology control, and lifecycle management.

6. Conclusion

Polymer insulating materials, owing to their excellent electrical properties, thermal stability, mechanical strength, and chemical corrosion resistance, have played an irreplaceable role in various high-end fields such as power systems, electronics, automotive, aerospace, and green energy. This paper starts from the fundamental characteristics of these materials, systematically reviewing the classifications and performance differences of mainstream materials, including thermoplastics, thermosets, and special engineering plastics. Combined with typical application scenarios, a comprehensive analysis of the practical value and technical adaptability of polymer insulating materials is presented. In recent years, with the accelerated trends of electrification, intelligence, and greening, higher comprehensive performance requirements have been placed on polymer insulating materials. Chapter 4 focuses on development directions such as high performance, functional integration, environmental degradation, and intelligent responsiveness, pointing out that new technological pathways like nano-fillers, self-healing mechanisms, and bio-based degradable materials will play significant roles in future materials engineering. However, some constraints remain, including the cost bottleneck of high-performance materials, the non-recyclability of thermosetting materials, and reliability challenges under extreme environments, all of which urgently require solutions through material design and process optimization.

Looking ahead, the development of polymer insulating materials depends not only on advances in fundamental materials science but also on multidisciplinary integration with electronic engineering, intelligent manufacturing, and green processes, promoting their deep expansion in high-end power equipment, new energy systems, and intelligent terminals. Meanwhile, building a full lifecycle evaluation and recycling system for materials to achieve a balance between environmental friendliness and functional integration will become a research focus. Only through the synergistic promotion of technological innovation, industrial application, and environmental policies can polymer insulating materials truly achieve high performance, intelligence, and sustainable development goals.

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