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Examining and Comparing the Signal of Ceramic and Silicon Insulators in Medium Pressure Voltage

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Abstract

The review article discusses the use of ceramic and silicone rubber (SiR) insulators in high voltage (HV) applications over the past thirty years. It highlights the need for detailed characterization and aging analysis to enhance the long-term performance of SiR insulators under various environmental, mechanical, and electrical stresses. The article focuses on silicon applications, the chemistry and polymerization of SiR, and the enhancement of their properties through fillers and ceramic materials. It also covers engineering requirements for polymer insulants and provides an overview of HV electrical insulators and their aging processes. The influence of micro/nano-sized fillers on the physical, thermal, mechanical, and electrical properties of SiR insulators is analyzed, including aspects like tensile strength, thermal degradation, and dielectric strength. The article concludes that further research is necessary to optimize SiR blends with fillers for specific applications.

Keyword: pressure voltage, ceramic, silicon, polymer insulants.

Introduction

The identification of defective insulators in air-level electricity distribution networks is crucial, particularly for high and medium pressure systems. Due to the extensive length of these networks, especially in rural and telecommunication areas, there are fewer protective devices, making troubleshooting challenging. To address this, various equipment is employed to detect issues before they lead to failures. A new method is being developed to quickly identify defective insulators using the Altarsonic device, allowing for efficient classification and assessment in a laboratory setting. Electrical insulators are very important components in distribution/transmission lines and substations. Porcelain/ceramic and glass insulators have satisfactory mechanical, surface and UV resistance properties. However, surface wettability, brittleness, and high weight are the major disadvantages of glass and ceramic insulators used in high voltage (HV) dielectrics [1, 2]. Since 1970, ceramic and silicone insulators and ethylene-propylene-diene monomer (EPDM) insulators are the two main polymer insulators widely used in HV applications [3]. Due to their light weight, good insulating properties, easy installation/transportation, and better mechanical, thermal, and electrical properties, polymer insulators are gradually replacing traditional glass and ceramic insulators in HV transmission and distribution systems [4]. Insulators, bushing coatings) SiR dielectrics are widely used for their stable thermal properties, excellent resistance to corona, aging and ozone. Additionally, hydrophobicity and recovery after temporary loss are the most important features of SiR materials. However, when high-voltage insulation is used, these insulators (due to their organic nature) are exposed to electrical (corona, partial discharge, dry strip arc) and non-electrical (chemical, moisture, temperature, UV, cyclic loads) stresses and consequently physical traces. /Caused by erosion and insulation failure [2,5,6]. Therefore, over time, the degradation of materials due to UV, acid rain, heat, mechanical and electrical stresses affects the performance (electrical, mechanical and thermal properties) of the insulator [7,8]. The long-term deterioration of insulating properties under various stresses is called aging [9]. Even now, tracking/erosion, water/moisture intrusion and aging are still major dilemmas for HV polymer insulation to be solved. This was investigated in [10]. To improve the performance and reliability of polymer insulators, various phenomena such as aging, tracking, and erosion have been investigated worldwide by incorporating micro/nano-sized inorganic particles into the polymer matrix [11,12]. There are two methods for measuring electrical quantity: ultra-high frequency (UHF) and capacitive pulse coupler. The UHF method measures electrical resonance up to 1.5 GHz, allowing for the identification and localization of partial discharge (PD) sources. It offers advantages such as low noise due to transformer protection, resistance to interference within its operational frequency range of 300 MHz to 1500 MHz, and immunity to external noise because the UHF sensor is connected to the transformer in a non-electric manner, ensuring reliability and safety. The capacitive coupler method, on the other hand, measures PD-induced induction flow in a coil.

RICHARD‘S 1960, prognostication about the future of nanotechnology is especially suitable for present investigations of HV polymer insulants [13]. In-order to formulate polymer insulators for HV insulations, many scholars have studied, the amalgamation effect of micro/nano-sized particles (fillers) into solid insulating materials. Particles such as micro/nano-sized silica (SiO_2) and alumina-trihydrate ($Al_2O_3{\cdot}3H_2O$ (ATH)) have gained attention owing to their enhanced thermal, mechanical, fire retardant, volume/surface resistivity, tracking/erosion, water/moisture penetration, and weathering properties of base polymer [14-18].

Amin et al. [19-28], studied the influence of multiple stresses (electrical and non-electrical) on aging behavior of polymeric insulators for HV applications through lab as well as field aging (simulating Pakistan environment). Salman et al. [20,21,2426,29], focused on natural aging of ceramic and silicone insulator and thermoplastic elastomer (TPE) insulators in clean and polluted (industrial) environment. Likewise, Ali et al.[30, 31], examined the influence of microSiO_2 (of size: 5 □m) and nano-SiO_2 (of size: 12 nm) particles on mechanical, thermal and electrical performance of EPDM, SiR and epoxy insulators. Moreover, Khattak et al. [22,32-34], studied the longterm multi-stress accelerated aging of HV nano insulators.

The first commercial nano-composite of 6-polyamide/montmorillonite was prepared by Toyota with improved mechanical features [35]. Much effort has been made to investigate the effect of filler type, size and concentration on the properties of base material for desired applications [36]. Generally, incorporation of these fillers (alumina, silica, ATH) into polymer matrix varies from 1 to 80% by weight [37].In addition, there is increasing trend in preparation and characterization of hybrid (mixture of micro & nano particles) insulators [38-40]. As the polymer insulator service condition in different areas/ countries varies, therefore no monotonous and mature test technique is available [41]. However, various material properties (mechanical, thermal, electrical), weathering, tracking/erosion and water immersion-resistance of polymer insulants can be evaluated by various characterization and analysis methods. This includes scanning electron microscopy(SEM), visual observation, hydrophobicity, leakage current, Fourier Transform Infra-red spectroscopy (FTIR) and Inclined Plan Test (IPT) [42-44]. Moreover, it is pertinent to mention that the impact of individual filler has been widely investigated with only few studies about polymer hybrid (micro/ nano-SiO_2, micro-ATH/nano-SiO_2 and micro-ATH/ micro-SiO_2 co-filled particles) insulators [45]. Limited research has been conducted to examine the combined effect of ATH and SiO_2 particles (hybrid) on SiR properties. Silicon insulator composite-dielectrics are comparatively new, their long term performance (mechanical, thermal and electrical) and expected lifespan under contaminated and multi-stress environment is not well-known, which needs to be addressed and investigated. Active research is going on to prepare and characterize new SiR-blends to improve their electrical, mechanical, thermal, erosion/tracking-resistance and water immersion-resistance properties over long-term weathering. Therefore, the practical knowledge and in-depth investigations of HV SiR insulators is necessary for electrical professionals in the power field. This paper highlights the most recent research work and characterization results relating to particles (micro/nano-sized) filled polymer insulants used for HV insulations. Moreover, possible future work concerning improved mechanical, thermal, electrical, tracking/erosion and aging performance of polymer insulators suggest promising concepts for HV insulation applications (large motors, generators, transformers and other electrical devices).

COMMON FEATURES ANDAPPLICATIONS OF CERAMIC AND SILICONE MATERIAL

By resemblance with ketones, the name “ceramic and silicone” was given in 1901, by Kipping to describe new insulators of the brut formula $(R_2SiO)_n$. These insulators were quickly recognized as being polymeric and in fact analogous to Polydialkylsiloxanes. Commercially, ceramic and silicone insulants have been fabricated since 1940s, which are generally non-reactive, stable, resist severe environmental conditions and maintain useful properties over a wide range of temperatures, i.e., from -55 °C to +300 °C [46-48]. These properties make ceramic and silicone rubber a good choice for HV insulation, building construction, aerospace, cosmetics and transportation industries. The properties of ceramic and silicone rubber like thermal stability, anti-oxidation and weathering comes from SiO bond strength in their polymer structure. Likewise, due to low surface energy, ceramic and silicone insulants exhibit features of both organic and inorganic materials, which results in numerous benefits compared to other organic elastomers [49]. The binary nature of ceramic and silicone has remarkable consequences for particle (filler) interaction in polymer matrix. In order to impart mechanical, thermal and other properties, Ceramic and silicones are commonly loaded with various types of particles [50,51]. According to final properties (electrical, thermal and mechanical) required, other fillers of small size can also be used to modify the interaction between base rubber and filler particles [52,53]. Recently, the reliability and performance of thousands of commodities/products depend in some way on Ceramic and silicones, like SiR-grease, release agents, antifoam agent, ceramic and silicone rubbers, sealants, paper coatings, and hydrophobic agents [54,55]. For example, in aerospace or industrial applications, ceramic and silicones are also found to increase the components' life time. Furthermore, the conservation of historical monuments and windows/bathroom seals can be improved by ceramic and silicone coatings [56]. Telecommunications and electronics industries also need ceramic and silicone for solar cells, wafers, and optical fiber manufacturing. The general applications of ceramic and silicone materials are summarized in Fig. 1 [24,57]. On the basis of curing temperature, ceramic and silicone rubbers are classified into two types: Low viscosity ceramic and silicone rubber, named as room temperature vulcanizing ceramic and silicone rubber (RTV-SiR), and high viscosity ceramic and silicone rubber, i.e. high temperature vulcanized (HTV) SiR. RTV-SiR is extensively used for coatings on ceramic surfaces to enhance their hydrophobicity, whereas HTV-SiR is used for the production of sheaths/weather-sheds of composite insulators [58,59]. HTV is cured through hydrosilylation at high temperature and pressure, while RTV cures at room temperature via a condensation reaction. RTV contains 5 wt.% cyclic low molecular weight poly-di-methyl-siloxane (PDMS), whereas HTV contains 3 wt.% of both cyclic and linear low molecular weight PDMS. These differences in composition and curing methods lead to varying reinforcements and properties in insulants [60,61]. Moreover, to enhance the long-term performance of ceramic insulators, RTV-ceramic and silicone coatings are applied to HV ceramic insulators [58]. Ceramic and silicone rubbers possess high insulation resistance (1TΩ to 100TΩ) and maintain stable insulating properties across various temperatures and frequencies. Their performance remains largely unaffected when submerged in water, making them excellent insulating materials. Additionally, they demonstrate good corona resistance under high voltages. As a result, these materials are commonly used as insulators in high voltage applications due to their superior resistance in extreme conditions[62].

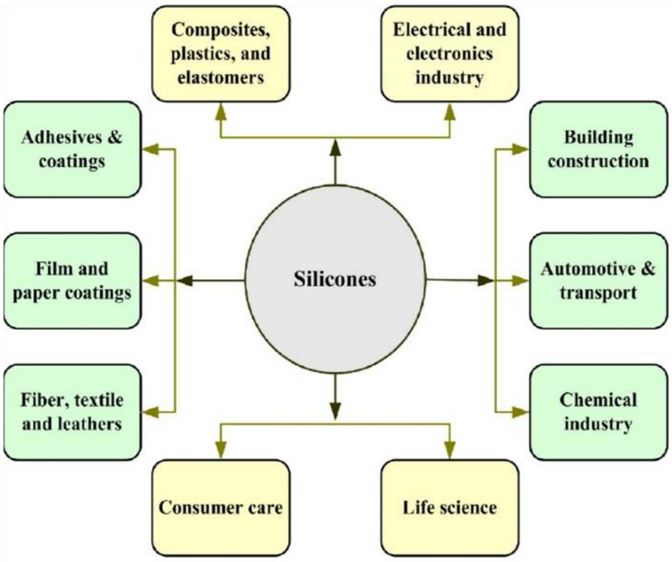


Fig. 1. Ceramic and silicones applications.

SILICONE CHEMISTRY

Silicone rubbers have a unique chemical composition that sets them apart from other polymers, as they do not have predecessors. Their effective use requires a deep understanding of their basic chemistry rather than relying on experience. Silicone and ceramic rubbers are primarily composed of siloxane structures, which consist of alternating rings, networks, and chains of silicon and oxygen atoms. This distinct structure differentiates them from natural, organic, synthetic, and petroleum-based materials, which are primarily based on carbon atom chains [63].The backbone of SiR is siloxane bonds (-Si-OSi-O-), which are highly stable (with 433 kJ.mol^{-1} bond energy) than C-C bonds (355 kJ.mol^{-1}) of other petrochemicals. Additionally, other reason of ceramic and silicone stability is lower electronegativity than C, which leads to strong intermolecular interactions due to highly polarized Si-O bonds [64,65]. Furthermore, the rings, networks and chains configuration of siloxane in SiR is analogous to ceramic and silicone (Si) and oxygen (O) structure found in silicate minerals and silica (SiO_2) particles. This siloxane (-Si-O-) chain assigns inorganic features to SiR insulants. However, it should not be supposed that due to analogy with silica, Si should exhibit porcelain or quartz like chemical stability [66, 67].

History of SiR chemistry

The evolution of ceramic and silicone chemistry includes several principal steps. In 1824, it was discovered by Berzelius from the reduction of potassium fluorosilicate with potassium:

$$4K + K_2SF_6 \rightarrow Si + 6KF \tag{1}$$

Further reaction of silicon with chlorine gave a volatile compound, later identified as tetrachlorosilane ($SiCl_4$):

$$Si + 2Cl_2 \rightarrow SiCl_4 \tag{2}$$

Moreover, in 1863, the next step was made by Friedel and Craft, with the synthesis of the first ceramic and silicone organic compound, tetraethylsilane:

$$2Zn(C_2H_5)_2 + SiCl_4 \rightarrow Si(C_2H_5)_4 + 2ZnCl_2 \tag{3}$$

In 1871, Ladenburg noted that diethyl-die-thoxy-silane produced a stable oil in diluted acid. In 1940, Muller and Rochow discovered a method to react ceramic and silicone with methyl chloride gas, leading to the production of liquid methyl-chloro-silanes and sparking a global boom in ceramic and silicone manufacturing. In 1947, WACKER became the first European company to explore the rubber field, and its subsequent developments were crucial for the efficient production of organo-chloro-silanes and related products. Chemically, ceramics and silicones, known as polydiorgano-siloxanes, have a structure similar to quartz, featuring an inorganic backbone of alternating silicon and oxygen [63,70,71]:

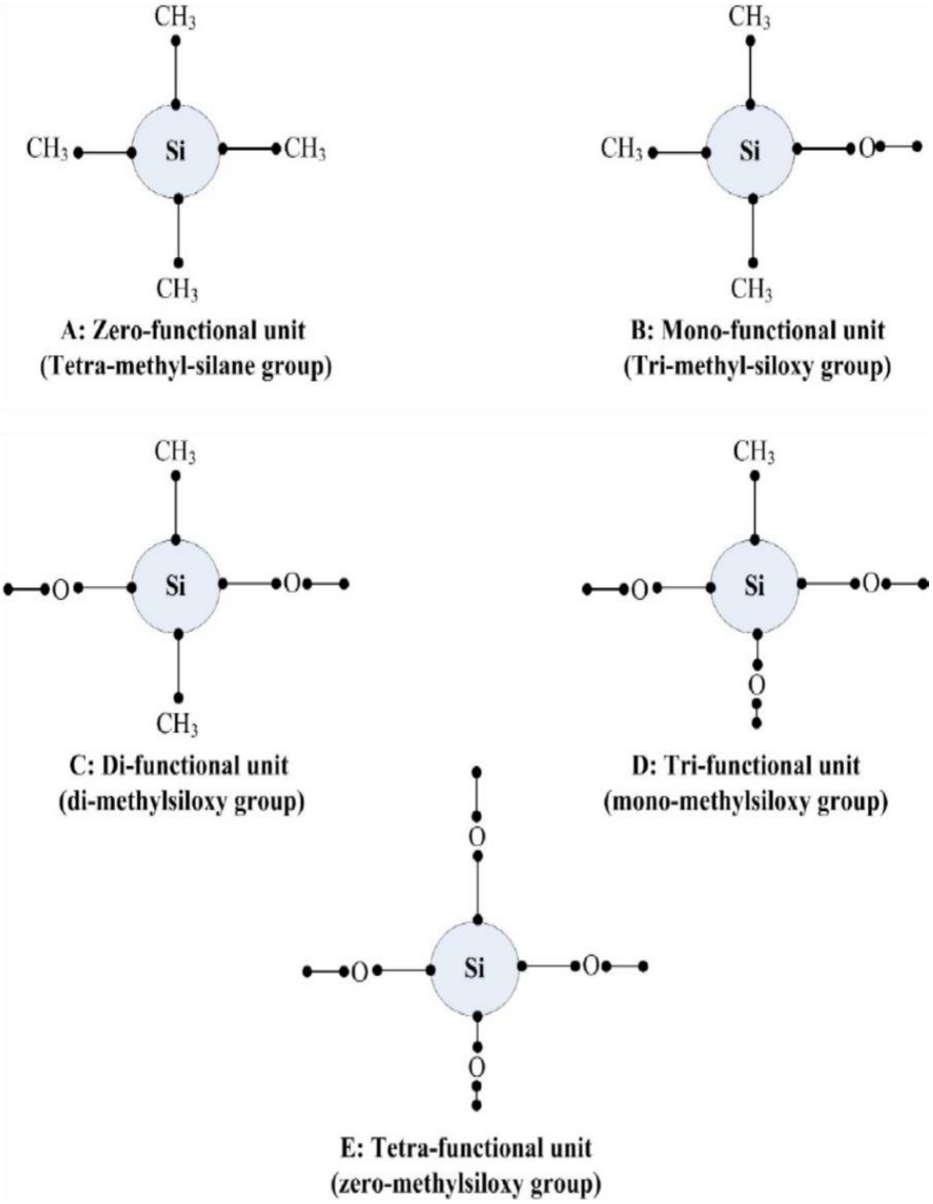
Zero-functional unit (Tetra-methyl-silane group): It has no reactive element, therefore exhibits zero functionality to build a polymer.

Mono-functional unit (Tri-methyl-siloxy group): It acts as terminal group or chain blocking group, but not propagating like di-functional group.

Di-functional unit (di-methyl-siloxy group): This group forms the backbone (important chain builder) in methyl-polysiloxanes, which extends cyclic or linear polymers but does not terminate macromolecular chains and ring compounds.

Tri-functional unit (mono-methyl-siloxane group): This group not only enlarges a ring or extends a chain, but also produces branched molecules and forms the basis of resins (crosslinking).

Tetra functional unit (zero methyl-siloxane group): In structure, this unit resembles with silica structure, which is capable of creating two-branches or extending polymer chains. Moreover, it maintains its structure whether occurs in quartz crystal or cross-linked SiR.



A: Zero-functional unit (Tetra-methyl-silane group)

B: Mono-functional unit (Tri-methyl-siloxy group)

C: Di-functional unit (di-methylsiloxy group)

D: Tri-functional unit (mono-methylsiloxy group)

E: Tetra-functional unit (zero-methylsiloxy group)

Fig. 2. Ceramic and silicone structural variety.

From the above discussion it is obvious that only four functional units of Si are capable of constructing organo-siloxane polymers. Moreover, among the above functional units, the moderate molecular weight cyclic and linear chain-blocked polymers are found in liquids, whereas high-molecular-weight (HMW) linear compounds are elastomers. In addition, the Si cross-linked polymers based on tetrafunctional or tri-functional units are found resinous [63,72].

Factors effecting SiR chemistryand properties

The chemical instability of ceramic and silicone polymers is primarily due to two factors: the less cross-linked siloxane chains and the presence of organic groups. Exposed areas of silicone rubber (SiR) are particularly vulnerable to various stresses, such as chemical, electrical, and environmental, which can weaken the Si-O bonds and lead to the breakdown of the polymer backbone. For example, hydrofluoric acid can vaporize organo-fluoro-silane fragments, causing depolymerization, while alkalis can form salts that damage the polymer chains. Additionally, incorporating organic or inorganic groups into these materials can alter their properties, including curing, dielectric strength, solubility, flexibility, and resistance to erosion and oxidation. [73,74].

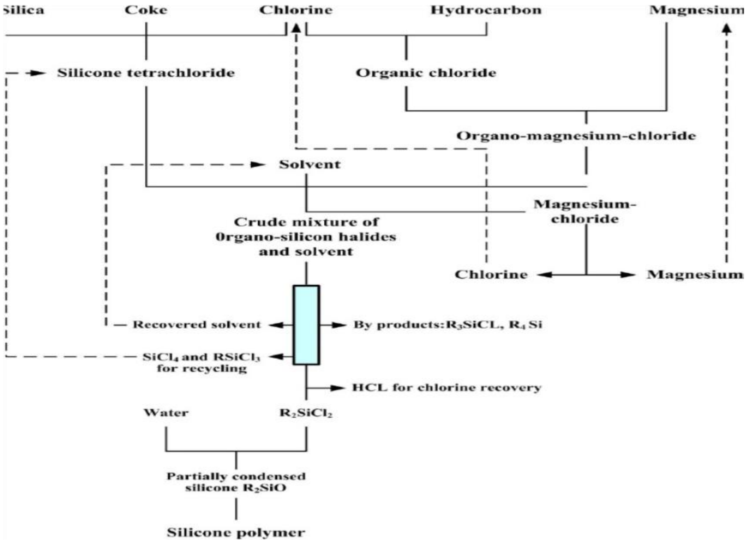


Fig. 3. Ceramic and silicone polymer production: Grignard procedure.

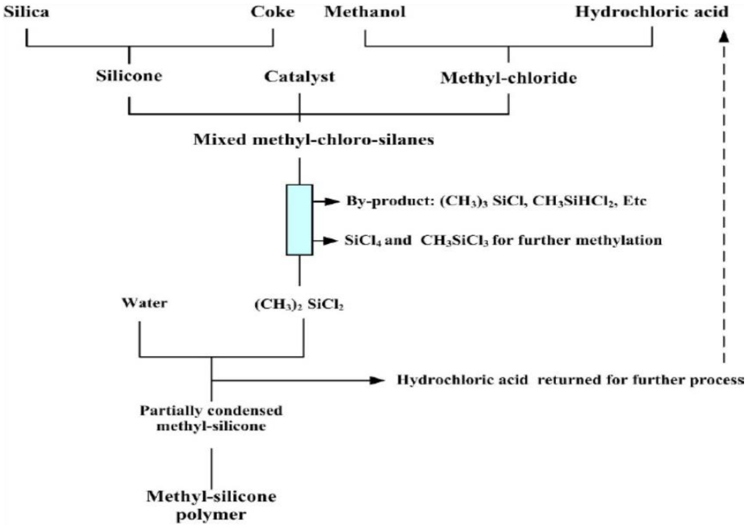


Fig. 4. Direct method: Methyl-ceramic and silicone polymer production.

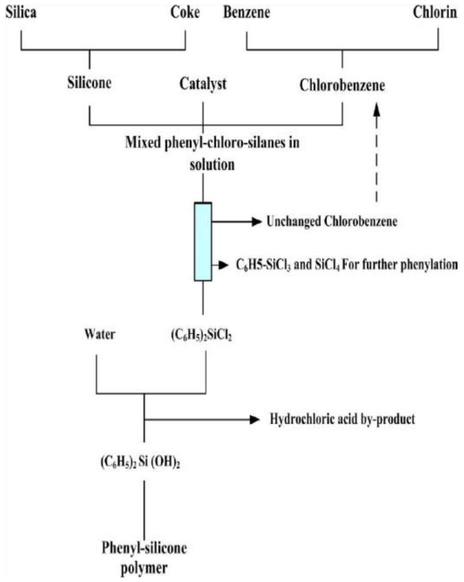


Fig. 5. Direct method: Phenyl-ceramic and silicone polymer production.

Ceramic and silicone polymerization

There are various techniques for production of Si polymers. Methyl, ethyl or any other alkali group's polymer with ceramic and silicone can be achieved using the guidelines of the following important methods as summarized in Figs. 3, 4, and 5 [63,75,76]. a. Grignard method
b. Direct method
Moreover, all types of ceramic and silicone polymerization comprises four basic steps as follows [77],
・SiO_2 reduction to Si
・Chloro-silanes synthesis
・Chloro-silanes hydrolysis・Polymerization and poly-condensation.

CERAMIC AND SILICONE RUBBER PROPERTIESENHANCEMENT BY ADDITION OF FILLERS

Under wet operating conditions (i.e. heavy fog, moisture, and acid rain etc.) pure SiR insulators suffer from hydrophobicity-loss, weak tracking and erosion-resistance, surface deterioration, and poor mechanical, thermal and dielectric properties. The loss and recovery of hydrophobicity in ceramic and silicone rubber has been the subject of several research works [78]. Moreover, to improve the performance (mechanical, thermal and electrical properties) of polymer insulants, micro/nano-sized particles (such as silica, quartz, ATH etc.) have been added into polymer matrix [79]. According to the literature, extensive research has been conducted to investigate the influence of size, shape, concentration, dispersion and type of filler on the characterization of ceramic and silicone rubber insulants [11,80-82]. Ghunem et al. [83] studied the impact of ATH and SiO_2 on dry-band-arcing suppression of ceramic and silicone rubber using leakage-current wavelet-based multiresolution analysis. They found that by addition of ATH or silica, the thermal-conductivity of SiR increases, thereby delaying the eroded temperature. Jun-Wei et al. [84] reported the impact of hybrid fillers (micro-Si_3N_4-nano-Al_2O_3) on mechanical, thermal and dielectric properties of SiR insulators.

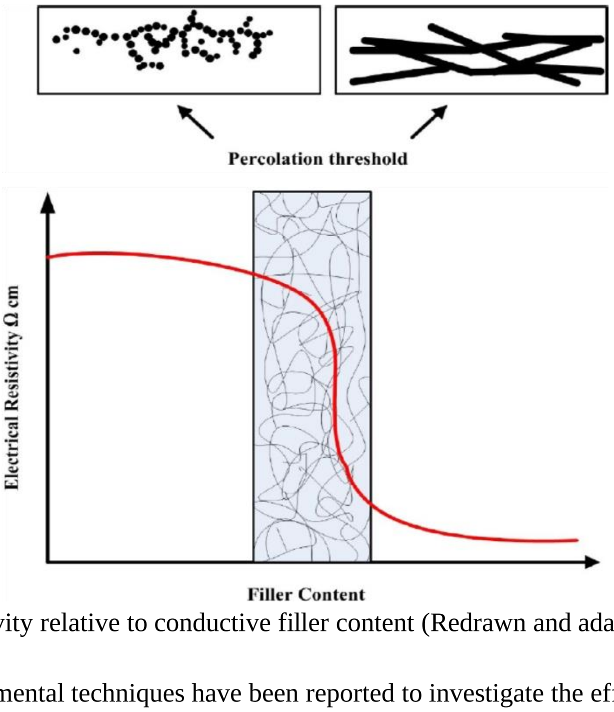


Fig. 6. Polymer resistivity relative to conductive filler content (Redrawn and adapted figure from [84]).

In literature, various experimental techniques have been reported to investigate the effects of SiO_2 characteristics (i.e. silica grade, type, surface treatment, loading & dispersion) on properties of natural and synthetic rubber insulators [34,85,86]. Other researchers correlated silica loading with erosion suppression of polymer insulators [87,88]. Moreover, majority of polymer insulators are non-conductive, but in some applications conductivity in needed for electrostatic charge-dissipation.In addition, to fabricate the conductive polymers, conductive-type of micro/nano particles can be incorporated into polymer matrix. For known quantity of conductive particles called percolation-threshold, a stable and continuous-network of fillers is formed across the polymer matrix. Consequently, the material undergoes abrupt changes from insulator ($>10^{10}$ Wcm) to conductor ($<10^{5}$ Wcm) state as demonstrated in Fig. 6 [61,89,90]. Additionally, the increased molecular interaction between polymer matrix and fillers enhances thermal degradation and stability. Secondly, the amalgamation of inorganicfillers reduces the quantity of polymer materials thereby reducing the overall cost [91].In addition, for some applications, coupling-agent can be used to enhance the interaction between fillers and base polymer thereby enhancing the material properties [92]. The commonly used inorganic particles that can be incorporated into rubber matrix are listed in Table 1 [93-97].

Table 1. In-organic fillers and their role in insulator characterization.

Particle type	Property modification
Al2O3	Anti-tracking, anti-erosion and thermal-conductivity
SiO_2	Anti-tracking, anti-erosion and thermal-conductivity
TiO_2	Photo-catalytic, relative-permittivity and thermal-stability,
Varistor (ZnO)	Mechanical property, electrical-conductivity, permittivity
$CaCO_3$	Flame retarding, hydrophobicity
$BaTiO_3$	Relative permittivity, thermal stability
Al2O3**.**3H2o	Thermal conductivity
Sb_2O_3 + SnO	Electrical conductivity

Besides, the properties variation of micro/nano insulators by various parameters (filler type, size and loading), the fillers improper-dispersion in the improvement of insulators properties is often cited as a key diminishing-factors [98-101]. Hence, to enhance the filler-dispersion in polymer matrix, different mixing-procedures such as physical and chemical dispersion techniques can be adopted.

Physical-dispersion techniques

For fillers dispersion in polymer matrix, the physical-dispersion techniques include ultrasonic-agitation and conventional mechanical-mixing. In ultrasonic-agitation, the vibrations releases trapped gases by avoiding the development of voids in the composite matrix, whereas mechanical-mixing is obtained by applying the shear-force to stimulate the particle-surface, physico-chemical properties and changing the external crystal-structure. The only advantage of such techniques are the use of limited extra-additives. Moreover, characteristically simple mechanical-mixing is not suitable for homogeneous filler dispersion: because during mixing, the breaking of some large particles (larger than 100m) into small one may occur in a short-time. Consequently, further particle-dispersion cannot be achieved. Another flaw of such methods are the base-polymer degradation due to shear-heating.

Chemical-dispersion techniques

Such techniques of filler dispersion depend on the existence of auxiliary-additives to vary the fillers surface properties, which includes both chemical and physical modifications. Physically some macromolecule-chemical-additives are used in liquid form to cover or absorb the micro/nano particles and hinder the fillers agglomeration. Moreover, for physical-surface modification, the surfactants and dispersants are common chemical additives. Due to the dissociation process, the dispersants are electrified and absorb into the particle-surface thereby changing the fillers surface-characteristics. Consequently, it improves the surface-potential in such a way that the repulsive forces becomes stronger between particles [91,102].

Among the particles when the repulsive-forces becomes greater than the attractive-forces, the disintegration of filler agglomeration may take place. Additionally, with in the same molecule the surfactants can be characterized by hydrophobic and hydrophilic chain-segments [103]. The authors of [104], used Triton-TM-X-100 (Triton)-

surfactant for nano-silica surface modification, thereby enhancing the particle-dispersion in the RTV-SiR polymer matrix, which was confirmed by the SEM-images and reduced eroded-mass.

Tee et al. [105] used the conductive-nano-silver (which was treated by silane coupling agent) with epoxy to develop epoxy-nano-insulators. They found that treated nano-silver (Ag) exhibited outstanding flexural and electrical properties compared to un-treated samples. Hence, it can be inferred that polymer insulators with surface-modified micro/ nano-particles has led to improved properties relative to un-treated particles. Furthermore, to attain the desired results, the selection and optimum concentration of chemical-additives must be carefully controlled.

CERAMIC MATERIALS

In this modern age of science and technology, the composite material science and engineering play a vital role [106]. Ceramic materials can be defined as: the mixture of two or more materials, working together in such a way so as to produce a compound with enhanced properties (mechanical, thermal and electrical). Examples are, steel-reinforcedconcrete, glass reinforced polymer, straw in baking-bricks, fiber embedded in other material matrix and carbon/silica-reinforced polymers [107].

Insulators consist of host matrix (base-material) and one or more filler particles. The insulators having one filler particle referred to as binaryinsulators, whereas, insulators having two filler particles are referred to as ternary-insulators and so on. The prefix micro/nano just denotes particle size. Furthermore, in ceramic materials the filler size and shape are the key parameters which modify the host matrix characteristics (i.e., mechanical, thermal and electrical properties) [108].

However, the cause of these enhancements are not yet fully explored. Therefore, the influence of micro/nano-fillers on characterization of polymeric materials have been investigated [109]. Moreover, insulators are commonly classified into two types. The first type refers to host-matrix constituent, whereas, type-2 is based on reinforcement form (filler type) as summarized in Figs. 7a and 7b [110,111]. In addition, the historical context and relative importance of metals, ceramics, insulators and polymers have been presented by Ashby as shown in Fig. 8 [107,112].

In electrical engineering, the use of insulators is not new, and their most common application includes HV polymer insulants. A polymer composite-insulator refers to a micro/nano-insulators, with SiR/EPDM/Epoxy as host matrix and micro/nanosized particles as filler.

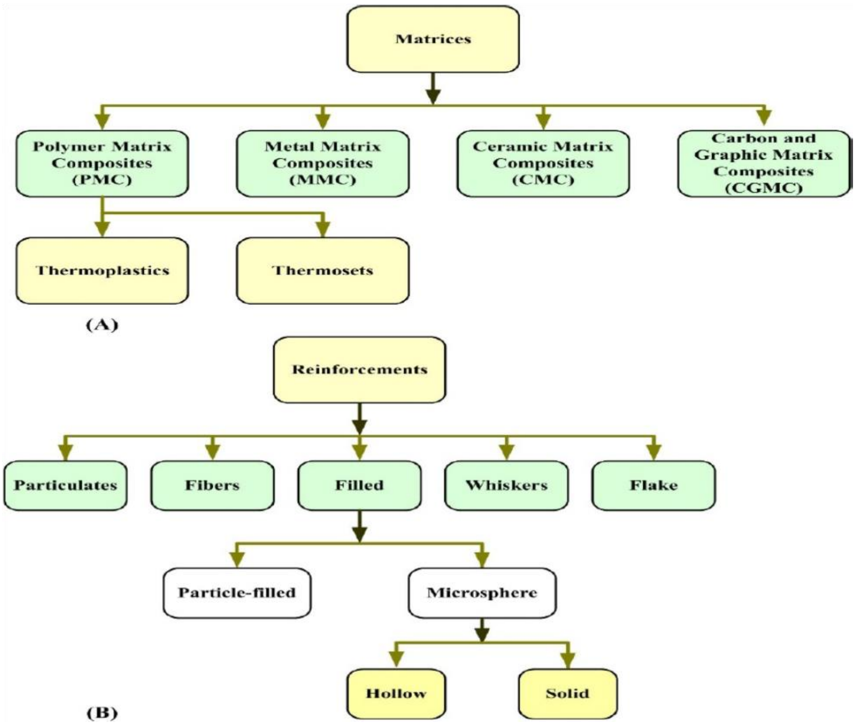


Fig. 7. A: Type 1 on the basis of matrix, B: Type.2 on the basis of reinforcements.

However, the main purpose of using particles in polymer insulators are to enhance their thermal, mechanical and electrical properties. In both laboratory and field testing, considerable improvements in their properties have been described, but actual reason is still a challenge to be identified [113, 114]. Therefore, in this research, both binary and ternary polymer insulators, filled with ATH and SiO_2 are prepared and comparatively investigated for various characteristics.

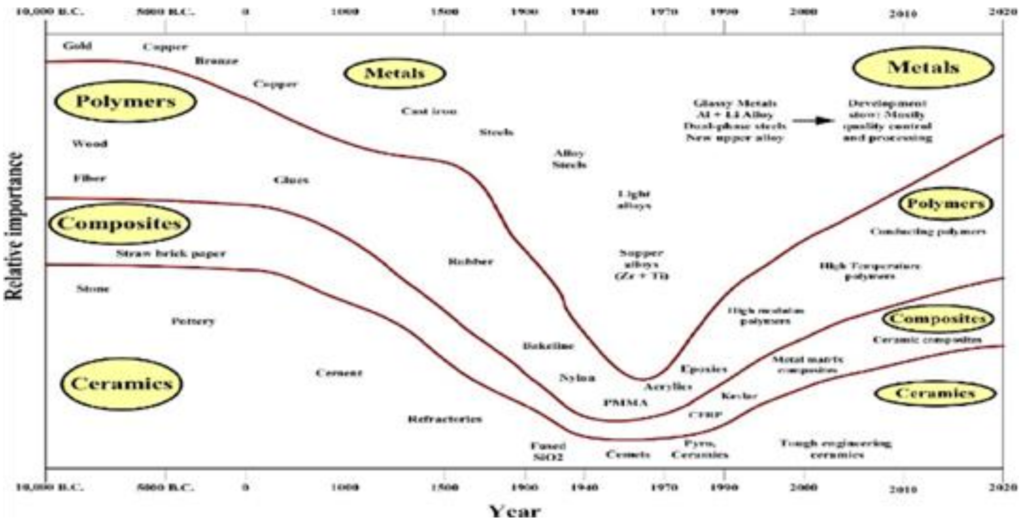


Fig. 8. Historical background of different materials (Redrawn and adapted figure from [107]).

Materials classification

Engineering materials

In material science/engineering, the various factors which form the base of numerous physical systems are: *(i) m*aterial

In material science/engineering, the various factors which form the base of numerous physical systems are: *(i) m*aterial chemical composition, *(ii)* material occurrence mode, *(iii)* compounding and the refining process, *(iv)* material crystalline and atomic structure and *(v)* material technical and industrial use [115].

However, within the scope of engineering and material science, the common engineering materials may be categorized into one of the following groups [116]: • Alloys and metals
- Organic/inorganic polymers
- Semiconductors
- Advanced-materials
- Bio-materials
- Ceramics
- Insulators

Polymeric materials

Polymeric-materials are the diversified sets of engineering-materials which are the core constituents of paints, plastics, resins, rubbers and adhesives. Mostly polymers are organic in nature (i.e. containing carbon), comprise of large molecules: each consist of various atoms. Examples are the polyamides (PA), poly-vinyl-chloride (PVC) and polyethylene resins, etc. Moreover, few commonly used polymers for engineering applications are summarized in Table 2 [117].

Furthermore, based on their application performance polymeric materials can be classified into four groups [118].

Table 2. Polymeric materials.

Polymer	Abbreviation	Polymer	Abbreviation
Polyethylene	PE	Polytetrafluoroethylene	PTFE
Polypropylene	PP	Poly (vinyl fluoride)	PVF
Polystyrene	PS	Poly (vinyl chloride)	PVC
Polybutylene	PB	Poly (vinyl acetate)	PVAC
Poly(methylmethacrylate)	PMMA	Polyacrylonitrile	PAN
Polyisoprene rubber	IR	Epoxy	EP
Ceramic and silicone polymer	Si	Polyurethane	PUR

1.**Commodity Insulants**: These include materials like polyethylene and polystyrene, characterized by low cost and inferior performance, but are widely used due to their large consumption.
2. **Intermediate Insulants**: This category features materials such as acrylic and polypropylene, which offer better thermal, mechanical, and electrical properties compared to commodity insulants.
3. **Engineering Thermoplastics**: Comprising materials like polyamide and polycarbonate, these insulants exhibit random mechanical properties and are more robust than the previous categories.
4. **High-Performance Engineering Materials**: These materials, including high-temperature nylon and ceramic polymers, maintain superior properties under harsh conditions, such as high temperatures and exposure to moisture or chemicals. They are also flame-retardant.
The competitive landscape among polymer producers has led to the development of over 26,000 resin grades, providing a wide range of options for end-users.

Filter design

In general, the conductor carrier of the partial discharge signal can have the effects of noise or radio waves, so they must be removed or reduced in a way of using filters, each of which has its features, each with its features. Reduces a percentage of these noise. Figure (9) shows the general scheme of a filter.

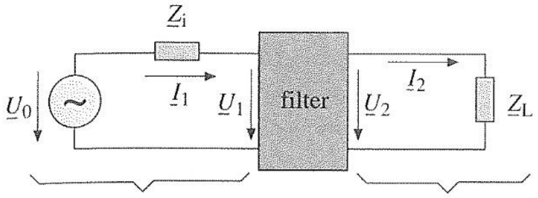


Figure 9. General Schemes of a Filter

The Affective Factor index is used to evaluate the effect of the filters, which indicates the proportion of the filter's output to the input.

$$a_F = 20\log\left|\frac{U_{20}}{U_2}\right| \quad (4)$$

Using a capacitor or a predecessor alone, it can create up to 30 dB of damping, with the amount of damping for LC filters to 60 and for LC chain filters to 100 dB. Figure (10) shows an LC filter with parasitic elements.

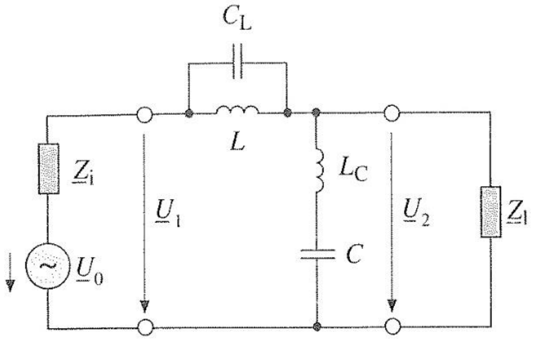


Figure 10. A LC from an LC filter

In Figure (10) the capacitor is inductor L and plays the role of the parasite for the capacitor C. Resonance frequencies for the filter are:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{5}$$

$$f_1 = \frac{1}{2\pi\sqrt{LC_L}}$$

$$f_2 = \frac{1}{2\pi\sqrt{L_C C}}$$

$$f_3 = \frac{1}{2\pi\sqrt{L_C C_L}}$$

The index was calculated between resonance frequency intervals (19-19).

$$f_0 < f < f_1 : \ a_f = 10\log\{./25[(1-\omega^2 LC)^2 + (\omega\frac{L}{Z} + \omega CZ)^2]\} \tag{7}$$

$$f_1 < f < f_2 : \ a_f = 10\log[(1+\frac{C}{C_L})^2 + ./25(\omega CZ - \frac{1}{\omega C_L Z})^2]$$

$$f_2 < f < f_3 : \ a_f = 10\log[(1-\frac{1}{2\omega^2 L_C C_L})^2 + ./25(\frac{1}{\omega C_L Z} + \frac{Z}{\omega L_C})^2]$$

The filter effect can be obtained by selecting the appropriate values for the filter parameters and calculating the presentation coefficients.

Thermal characteristics

The variation in material properties with respect to change in temperature are known as thermal-properties. During normal operation, one can foresee the performance of polymer-insulants by knowing their thermal-characteristics (latent-heat, thermal-conductivity, specific heat, thermal-stress and thermal expansion). For engineering applications these characteristics perform an important-role in material selection [115,134].

As temperature rises in solid insulation materials, insulation losses increase, leading to decreased resistance and potentially resulting in insulation failure. In contrast, transformer oil behaves differently; experiments show that within normal temperature ranges, increased temperature raises the oil's failure voltage. This phenomenon may be attributed to two factors: a decrease in moisture content in the oil with rising temperature, or increased gas solubility in the oil. Additionally, temperature influences partial discharge activity in transformers, with higher temperatures correlating with increased voltage at which partial discharges begin. As the temperature rises, polymeric insulants tend to enlarge. Moreover, compared to ceramics and metals, the thermal-expansivity (á) of unfilledpolymers are generally higher. They exhibit lower thermal-conductivity compared to metals/ceramics due to lower energy transfer through polymer-networks. Therefore, in foam/fiber-form polymerinsulants are broadly applied for HV thermalinsulations. The thermal-characteristics of some typical-polymers are summarized in Table 3 [135,136]. Furthermore, among thermal-characteristics, few can be described as follows [120,134,137]:

Table 3. Thermal expansivity/conductivity of polymeric-insulants.

Polymer	Thermal-conductivity (W/mK)	Thermal-expansivity(10^6 K^{-1})
PS	0.181	70.1
PC	0.210	60.0
PMMA	0.180	70.0
PVC	0.170	80.0
PP	0.220	150.0
HDPE	0.510	200.0
LDPE	0.410	250.0
PA-6	0.290	80.0

· **Thermal Conductivity (K):** It represents the material ability to transfer certain amount of heat through a unit-area in a unit-time at constant temperature. Quantitatively, copper/aluminium have higher conductivity compared to Bakelite (poor-conductor). So higher the thermal-conductivity, more will be the heat transfer rate through a unit piece of material. Mathematically, thermal-conductivity can be described by the following formula:

OVERVIEW OF HIGH VOLTAGEELECTRICAL INSULATORS

For operating efficiency and operational-safety of high voltage transmission-lines and substations, electrical insulators are widely used by meeting the system reliability. The main tasks of insulators are to insulate the power line conductor from grounding supports/structures and provide protection to the power system equipment. More than 100-years ago, insulators made of glass/porcelain materials were used for HV distribution and transmission lines [71,200]. Although efficiency and reliability of porcelain/ceramic insulators are well known, but heavy weight and maintenance issues limit its applications.

For HV use, a new polymeric insulants (ethylene-propylene rubber (EPR), cycloaliphatic-epoxy (CE)) were developed in the early-1970s, by polymeric-material industry. Nowadays, polymeric-insulators made of SiR, EPDM and EPR are in extensive use around the world at all voltage levels [201,202]. Depending on their functionality, different types of line insulators are employed on transmission and distribution lines, which are classified according to their materials and applications as depicted in Fig. 12 [203].

In addition, for HV applications, these insulators are exposed to electrical and non-electrical (sunlight, wind, contamination and precipitation) stresses. To ensure the efficiency and safe operation of transmission and distribution lines, HV-insulators must be resistive to erosion/tracking, flammability, arcing, weathering, chemical-attacks, UVradiations, moisture and physical degradations [204]. Additionally, due to enhanced hydrophobicity, higher volume/surface resistivity, low dielectric loss and good tear-strength, the insulators suppresses partial discharges as well as leakage current under densely-contaminated conditions [205]. Different types of HV insulators are discussed in the following section.

Porcelain-insulators

Basically porcelain is the compound of potassiumaluminum-silicate ($4K_2^{O.\ Al}{}_2O_3{}^{.\ 3SiO}{}_2$), which was developed by agglomeration of quartz, clays and potassium-alumino-silicate. For HV applications, porcelain-insulators are still in use as it was introduced in 1850's. Ceramic/porcelain insulators are also used in micro-electronics devices and power equipment. To meet the requirements of HV and modern power-transmission, the manufacturing and design of HV insulators should be enhanced to satisfy the required electrical-leakage-distance. Furthermore, above 100 kV, it leads to abnormal results due to massive and longer size [206].

In porcelain insulants, the ratio of amorphous and crystalline phases considerably effects the physical and dielectric characteristics. Characteristically, the insulators made of porcelain are dense, noncombustible and hard.

Additionally, its compressive strength is 8-10 times higher than tensile-strength showing enhanced performance. Due to low impact-strength, porcelain insulators tends to fracture, when struck by hard object. It can be further classified into the following three types [202, 207]:

Pin-type porcelain-insulator: For rigid mounting usually pin-type insulators are used below 69 kV. Possible puncturing caused by heavy-arcing and mechanical shocks limits its application for higher (more than 69 kV) voltages. Pin-type porcelain insulator.

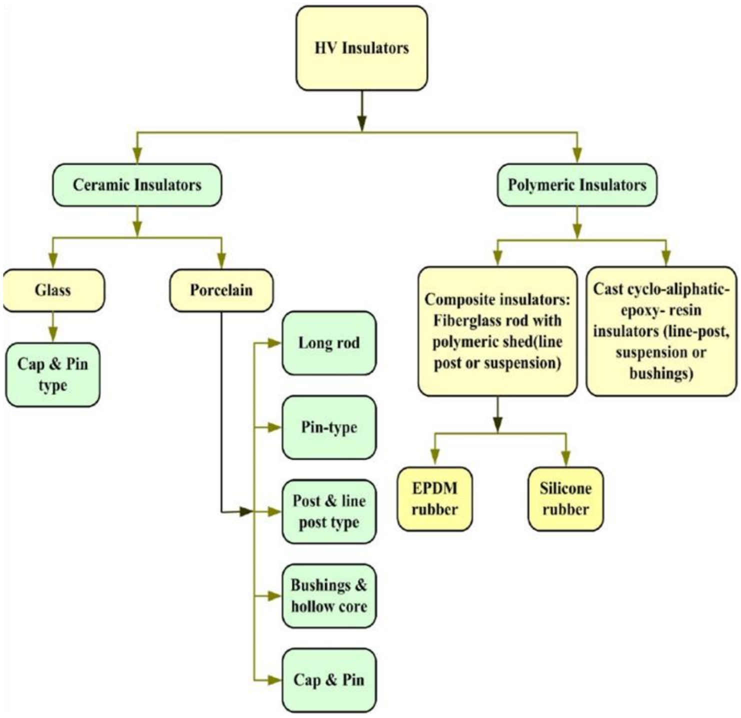


Fig. 12. Classification of HV insulators.

Post-type porcelain-insulator: This type of insulators are used for rigid and direct mounting in the form of columnar shape (Fig. 13b). On the pole sides such insulators can be installed in cross-arms as well as side-post with particular foundations in vertical-configurations.

Suspension-type porcelain-insulator: It consist of non-rigid individual-disc insulators which are coupled to each other and consist of coupling and shell-hardware, and cap-and-pin units as shown in Fig. 13c.

Polymer composite insulators

The insulator formed by combination of two or more materials (base material + other material) is known as composite insulator. It consist of central core to provide mechanical-strength, weather-sheds for long-time electrical insulation stability and metal end-fittings. The polymer composite insulator profile and weathershed/sheath material constituents are shown in Fig. 14.

Recently, polymer-composite-insulators have captured a wider market share, due to their light weight, easy transportation/ maintenance, better volume/surface resistivity, excellent hydrophobicity and lower cost [211,212]. Among polymeric materials, ceramic and silicone rubber is extensively employed in HV insulations. In HV applications, SiR insulators are simultaneously subjected to environmental, electrical and mechanical stresses, which causes material degradation and surface tracking/erosion [213,214]. The progressive degradation of a solid insulating surface due to surface contamination and local discharges, result in the formation of conducting path, which is known as tracking. Therefore, a quantified and considerable understanding of resistance to tracking/erosion during service condition of SiR is needed [44,215].

Worldwide, a considerable effort has been devoted to enhance the performance and reliability of polymer insulants by improving the erosion/tracking resistance. However, tracking is still the main common degradation problem to be overcome in SiR HV insulations.

Furthermore, polymeric composite insulators are fabricated either as post or long-rod type as shown in Fig. 15. Nowadays, polymer-composite insulants are widely used for bushings of instrument-transformer, surge-aresters housing as well as line terminations. Additionally, for polymer-insulators, the mostly used materials are RTV/HTV-SiR, EPR, and EPDM for high voltage insulations [92,202]. The fiberreinforced core and sheath/shed interfaces of composite-insulators are sensitive to liquids/moisture permeation. Therefore, it is required that polymer housing should withstand the environmental and electrical stresses without losing electrical, mechanical and thermal characteristics [216-218].

For HV transmission-lines, substations and electrical apparatus, the use of polymer-composite insulators have been successfully achieved. It is now conceivable to plan the whole substation based on composite-technology. Furthermore, based on damage-risk-minimization and operational safety, majority of bushings are fabricated using compositetechnology. Composite insulators can be further classified on the basis of applications as follows [71]:

- Composite-long-rod insulators
- Composite post-insulators
- Insulated-cross arms for compact lines
- Interphase spacers
- Composite hollow-core insulators

Furthermore, oxidative stability, weathering resistance, chemical inertness and temperature insensitive physical properties are important characteristics of polymer insulators, which are correlated with its molecular structure. The coating of SiR on ceramic insulants is an effective technique to enhance the insulator performance (mechanical, thermal and electrical), which has been investigated by many authors and are effectively employed as maintenance tool (by power utilities) [103,219,220].

Despite of many advantages, they (polymercomposite insulators) are susceptible to chalking, surface erosion/tracking, sheds hardening, discharges, brittle and bonding fracture, electrical failure and increased-contamination. These limitations of composite insulators have forced the researchers and manufacturers to develop the composite insulators with satisfactory performance at all voltages and contaminated environmental conditions [203,221].

The passage of time on polymer composite ceramic and silicon insulators

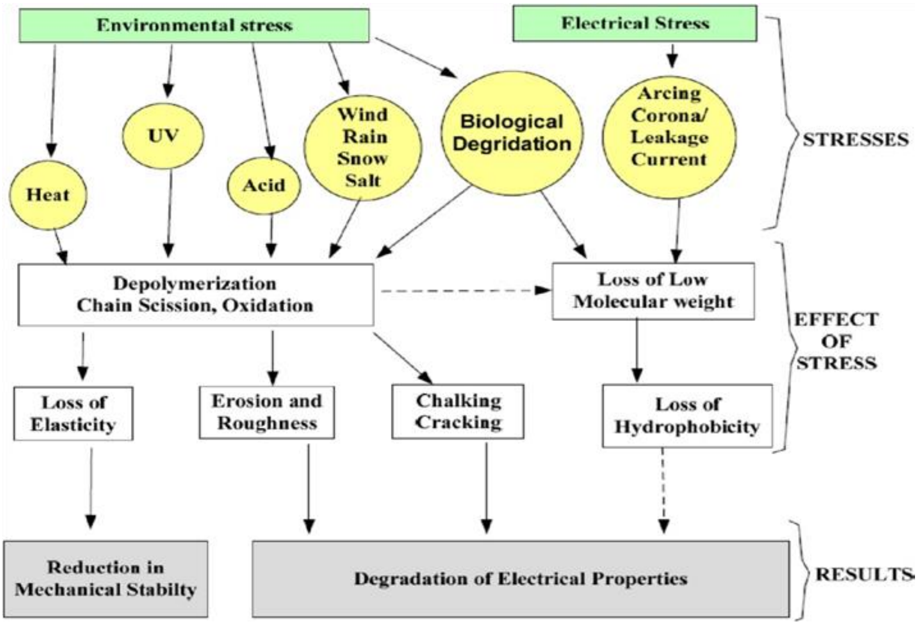


Fig. 13. Factors involved in aging of a polymeric insulator.

For HV insulations, the polymer-composite insulators have been used around the world for more than 50 years. Polymer composite insulators, with glass fiber core, metal end fitting and ceramic and silicone rubber outer sheds/sheath are promising, reliable and emerging candidates for high voltage transmission and distribution systems [19]. Moreover, ceramic and silicone rubber insulants with excellent electrical, mechanical, chemical, anti-pollution and superior aging performance are increasingly replacing the porcelain and glass insulators [222]. However, due to mechanical, electrical and environmental stresses (UV radiation, dry-band arcing), polymer insulants in service condition become hydrophilic and allow leakage current (LC) to flow through the surface. Consequently, surface tracking, erosion, hydrophobicity loss, partial discharge and complete failure takes place [223]. Moreover, the main hindrance of polymer composite insulators are the long-term performance and un-known aging behavior in different environmental conditions [224].

These irreversible and long-term changes in physical-properties of polymer-insulator due to the influence of one or more stresses are known as aging [9]. The deterioration caused by one factor is known as single factor aging, whereas deterioration caused by many factors is called multi-factor aging. Furthermore, over the course of weathering, the degradation due to aging may become so effective that complete breakdown of insulation occurs [225].

Primarily, aging influences the insulation service life, beyond which the insulant would not be able to work properly. For instance, if the electric field (stress) is increased beyond the insulant dielectricstrength, the insulator would fail (breakdown). It means that with increase in stress magnitude and time, the insulation failure-rate increases [226]. Hence, the characteristics (mechanical, thermal and electrical properties) of an insulators which are affected by aging, relies the stress nature as well as type of polymeric material. Stresses which produce aging are called aging factors. The important stresses and their effects on insulator characteristics are summarized in Fig. 16 [225,227].

In addition, with the passage of time, aging of polymer insulants become so serious that dielectric-breakdown finally occurs. In this case, insulation life can be determined by knowing the final breakdown time. Practically, measuring the failure time is tedious and time consuming, because mostly it takes decades to breakdown. However, to predict the insulation life and time to breakdown, the actual field environment can be simulated in multistressaccelerated aging chamber according to ASTM/IEC standards [34,228 229].

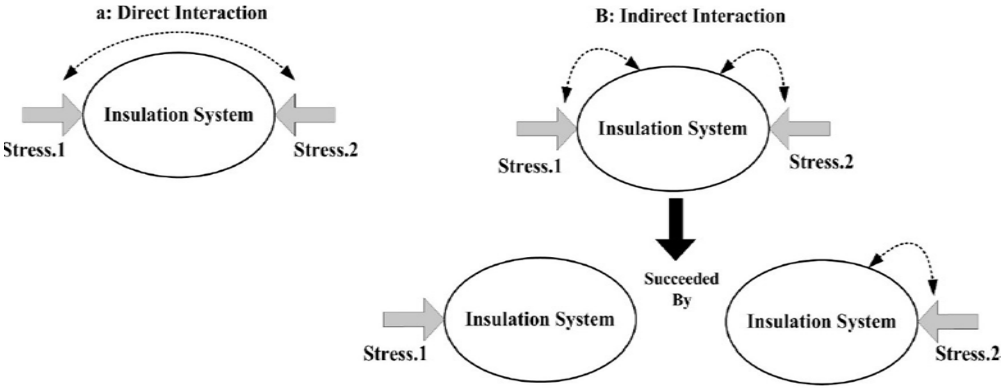


Fig. 14. (a) Direct Interaction, (b) Indirect Interaction.

In addition, each year, photo-degradation and weathering of polymer insulants causes millions of dollars of valuable equipment damage, which includes strength loss, color changes, chalking, arcing, tracking and erosion [230]. Due to inorganic nature they (SiR insulators) are more susceptible to chemical changes and weathering, thereby reducing their long-term performance and reliability [231].

Over the past decade, many scholars, have investigated the impact of environmental, electrical, mechanical and thermal stresses on performance of composite insulators. The authors of [232,233] reported the benefits of ATH and silica in SiR formulations. Likewise, the authors of [234], investigated that insulators failure is initiated by dry-band arcing and large leakage current. Other researchers investigated the correlation among discharge activity, leakage current, aging deterioration and surface wettability of insulator [28,42,235]. Furthermore, the authors of

[236], studied the lab and field aging of 28 kV polymeric insulators in US environment under the influence of various stresses.

Moreover, many researchers have investigated the effects of thermal, UV-radiation, tracking and corona discharge on aging and characterization of insulator sheds [6,28,83,145,146,237-239]. To simulate the actual service condition of composite insulants, various types of accelerated-weathering (aging) experiments were conducted under the influence of multiple or single aging factors. However, the insulator service condition in different areas/countries varies, therefore no monotonous and mature test technique is available [41].

Gorur et al. [43] indicated that in HV serviceconditions the aging of polymer-insulators begins with the hydrophobicity-loss due to DBA and weathering. Chen et al. [148], examined higher degradation of organic-groups on the side-chains than the backbone (Si-O-Si) of liquid-ceramic and silicone-rubber. In another study, Nazir et al. [162] studied the effect of AC-corona discharge on SiR aging at higher altitudes. They indicated that by dispersion of nanosilica (5 wt %) in base-matrix (SiR), corona-resistance can be improved.

Moreover, the authors of [240], reported that the fuzzy-comprehensive-evaluation-model can reflect the insulators aging-state accurately. Du et al. [241] investigated the influence of Silicon carbide (SiC) particles on space-charge behaviors of HTV-SiR insulators. They suggested that under high electric field, the dc-conductivity of SiR/SiC-insulators can be improved.

In other work Cheng et al. [242] studied the correlation among the operating years and aging-index. They determined that the lifespan of SiR insulants can be predicted by knowing their thermal oxidation process. Moreover, polymer insulants operating life in service-conditions can be predicted by using corresponding aging models [225,226,243]. The most suitable approach to improve the time-tofailure of polymer-insulators is knowing the physics and chemistry of aging-process [244].

Phase of partial drainage in different conditions

figure (15) shows the phase of the partial discharge for the states mentioned. As you can see, partial drainage occurs in different insulators with a different phase angle.

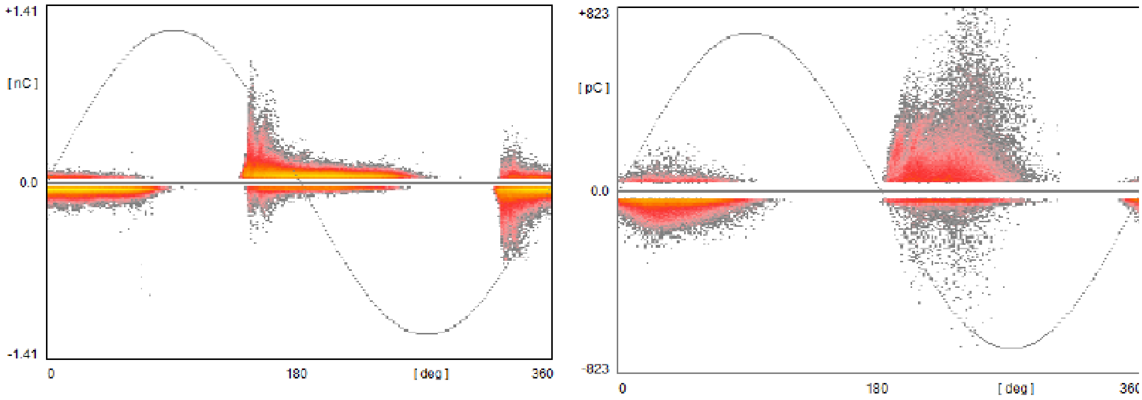


Figure15. A) surface discharge in ceramic b) The surface discharge in silicone

In the above figure, the partial discharge fingerprint in the phase and time is shown for polymer and ceramic insulators, which are widely used in insulating materials in the electricity industry. Liquid insulators such as oil in transformers and separating keys are used. And solid insulators such as polymeric, ceramic and even carp are used in insulators, bushings and transformer insulators.

Modeling defects in solid ceramic and polymer insulators

The schematic diagram for partial discharge detection inside the solid insulation is shown in Fig. 16 [1]. This includes high voltage transformer (VS), filter unit (Z), high voltage measuring capacitor (CM), coupling capacitor (CK), Solid insulation model called test object (CT), detector circuit for minor measurement . Discharge (ZM) and measurement tool (Mi). The detector's circuit for measuring the PD is a parallel combination of resistance, indigenous and capacitors. A different possible form of the blank model for the experimental object of the insulation material is considered. These values are displayed as CA, CB and CC values related to the shape of the space. In the equivalent circuit, the experimental object is shown in the form of a small capacity and the CC capacity of the empty space inside the solid insulation, the CB related to the remaining insulation capacity with the empty space (CC) and CA related Solid insulation.

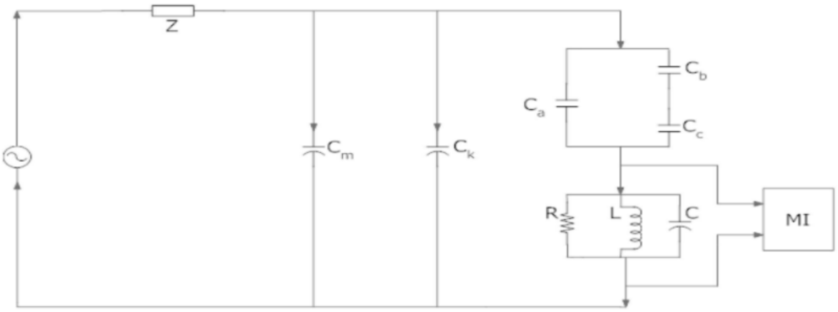


Figure 16: Electric equivalent circuit model existence in solid ceramic and polymer insulation

This model is the equivalent of the electric equivalent of the empty space (experimental object) in the solid insulation with the circuit of power equipment. AC voltage, frequent discharge occurs CC charging, reaches the cavity failure voltage, recharged and damaged. The voltage in the CC cavity is equal to:

$$V_c = \frac{V_a V_b}{V_a + V_b} \tag{7}$$

In which VA, VB and VC are related to the capacity of CA, CB and CC, respectively. The appearance of q is measurable throughout the experimental body during the PD activity within the solid insulation, which is calculated by the following relationship.

$$q = C_b . V_c \tag{8}$$

Synergy concepts

Under the influence of electrical and thermal (elevated-temperature) stresses, the failure of polymeric materials may occur sooner compared to the individual stresses. In this case the insulation failure may not be due to the combined stresses (thermal and electrical-aging), but another phenomenon known as synergy effect takes place under the influence of several stresses. The interaction among different aging-stresses (factors) are known as synergy-effects [225]. It can be classified as directinteraction and indirect-interaction [245].

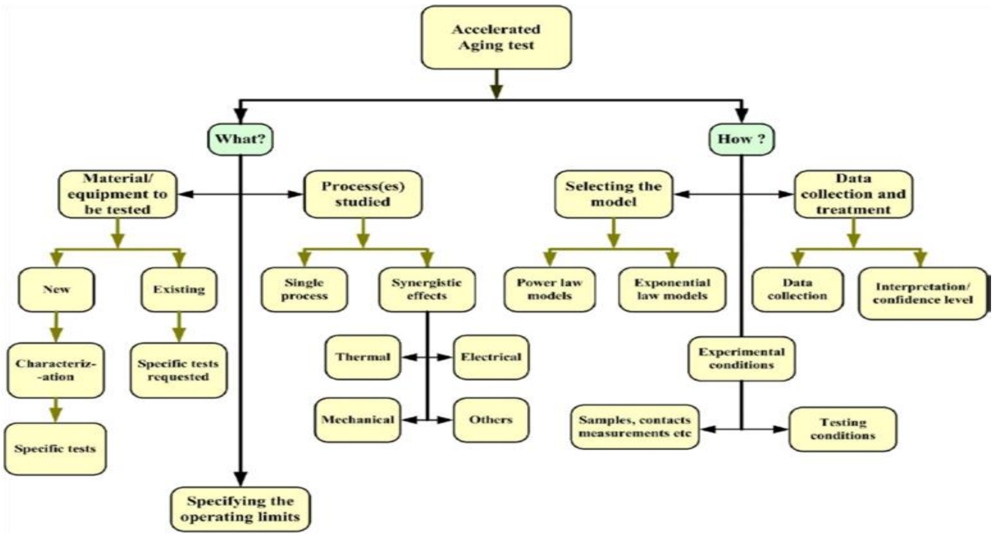


Fig. 17. Different steps of accelerated-aging-tests.

Direct interaction: The interaction among concurrent (simultaneous) applied-stresses (i.e., thermal & electrical factors), which varies from sequentially applied stresses is known as direct interaction. Fig. 17, shows that insulation-system is exposed to two stresses instantly instead of sequential stresses. Example of direct-interaction is the oxidation: which require both oxygen and temperature to produce synergy-effect.
Indirect interaction: The interaction among concurrent (simultaneous) applied stresses (factors) which remain un-changed with sequentially appliedstresses as summarized in Fig. 17. This type of interaction is caused by aging-factors (stresses). Subsequently, the insulation-system may be exposed to electrical-stresses (or simultaneously-applied) which leads to additional weathering due to partial-discharges (synergy-effects).

Testing of insulation aging

Over the past years much effort has been done to predict the lifetime of electrical-insulators. Yet, there are few empirical-tests and concepts which describe the in-service aging phenomenon of HV insulation systems. Under normal operating conditions, the life-prediction of polymer insulators are out of the question (longer duration testing not possible). Moreover, to quantify and simulate the insulator operating-conditions, it is usual to perform accelerated-weathering-tests by exposing polymer samples to single or multiple-stresses (mechanical, electrical and thermal) according to the standard procedures [246,247].
In addition, planning the multi-stress-accelerated aging-test is not a simple task because it includes a number of parameters, which comprises all inservice degradation. Hence, it is pertinent to define distinct aims and understand the in-service stresses/ factors before conducting accelerated-aging tests. Additionally, before planning process, two important points should be considered as follows: · Desired test objectives (i.e., what you wish to learn from the test) and
· Test procedure (i.e., how you expect to achieve the test).
In the planning and development of multi-stressaccelerated aging tests, various-steps are summarized in Fig. 18 [248]. Moreover, in the determination of aging-tests, the selection of an appropriateaging model which explains the aging process under consideration is of utmost importance. Furthermore, the model selection measurement techniques and data-analysis methods are also critical.

CONCLUSIONS

For high voltage insulations research and development of polymer insulants are challenging. In the last decades many researchers have reported the benefits of such emerging polymer insulants. Moreover, many queries remains to be answered. In order to elucidate the fundamental relationship between properties (mechanical, thermal and electrical) and structure of polymer insulators, their detailed characterization analysis is needed. In consequent, this relationship will help in understanding the chemistry and physics of micro/nano blends of polymer insulants. Hence, upon knowing all the mechanisms and properties of SiR matrix, the desired insulators with tailored properties can be developed for HV insulations.

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