International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 26 (September 2026) PP. 46-63

INTERNATIONAL JOURNAL OF INNOVATION AND INDUSTRIAL REVOLUTION (IJIREV)
www.gaexcellence.com/ijirev

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ROOM TEMPERATURE VULCANIZED SILICONE RUBBER (RTV-SIR) BASED NANO AND MICRO-FILLERS COATING FOR HIGH VOLTAGE APPLICATION: A MINI REVIEW

Muhammad Afif Abd Rani[1]*, Mohamad Zul Hilmey[2], Mohd Shafiq Afnan Ali[3]

[1]School of Foundation Studies, Universiti of Technology Sarawak, Malaysia
muhd.afif@uts.edu.my https://orcid.org/0009-0006-4281-0839
[2]Faculty of Science and Technology, Universiti Malaysia Sabah, Malaysia
mzhilmey@ums.edu.my https://orcid.org/0000-0002-9412-6063
[3]School of Foundation Studies, Universiti of Technology Sarawak, Malaysia
shafiqafnan@uts.edu.my https://orcid.org/0009-0008-9776-9583
*Corresponding Author

Article Info:

Article history:
Received date: 07.06.2026
Revised date: 07.07.2026
Accepted date: 03.08.2026
Published date: 03.09.2026

To cite this document:

Abd Rani, M. A., Hilmey, M. Z., & Ali, M. S. A. (2026). Room Temperature Vulcanized Silicone Rubber (RTV-SiR) Based Nano and Micro-Fillers Coating for High Voltage Application: A Mini Review. *International Journal of Innovation and Industrial Revolution, 8*(26), 46-63.

Abstract:

Room temperature vulcanized silicon rubber (RTV-SiR) coatings have emerged as critical components for high-voltage insulator applications, offering superior hydrophobicity, dielectric strength, and environmental resilience compared to conventional ceramic insulators. However, under multi-stress environmental conditions, including UV radiation, thermal cycling, electrical stress, and pollution, these coatings experience progressive degradation characterized by hydrophobicity loss, increased leakage current, and reduced service life. To address these limitations, nano- and micro-fillers (SiO_2, ATH, TiO_2, ZnO) are commonly incorporated into silicone rubber formulations to enhance performance characteristics. While numerous studies have investigated filler effects on RTV-SiR, findings remain fragmented and sometimes contradictory regarding optimal filler types, concentrations, and synergistic combinations. This review paper systematically evaluates the influence of filler characteristics, type, size, concentration, and dispersion, on key performance parameters including surface hydrophobicity, electrical resistance, mechanical strength, thermal conductivity, and weatherability, with particular emphasis on pre- and post-ageing performance in accelerated test chambers. This synergistic effects arising from hybrid (nano + micro) filler systems are critically examined. Unlike previous descriptive summaries, this review critically analyses the underlying scientific mechanisms governing filler performance, identifies material design principles, compares existing evidence systematically, and outlines future research priorities.

International Journal of Innovation and Industrial Revolution
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Challenges and opportunities in developing optimized RTV-SiR coatings tailored for high-voltage insulation are addressed, with emphasis on filler dispersion optimization, long-term field validation, and emerging 2D materials as synergistic additives. The insight presented established evidence-based design guidelines, identify critical knowledge gaps, and provide a practical resource for researchers and engineers developing next-generation RTV-SiR coatings with enhanced durability and performance for demanding high-voltage applications.

DOI: 10.35631/IJIREV.826003

Keyword:

Accelerated Aging, Aluminium Trihydrate, FTIR Spectroscopy, High Voltage Insulation, Hydrophobicity, Leakage Current, Micro-fillers, Nano-filler, Room Temperature Vulcanized Silicone Rubber (RTV-SiR)

Introduction

High voltage insulators in general prevent the flow of current between conductors and ground or between different phases, ensuring that electricity flows along the intended path without leakage or loss. By maintaining electrical isolation and preventing short circuits or faults that could cause damage to equipment or pose safety hazards to personnel. In electrical transmission, high voltage insulators are used to support overhead powers lines, allowing the efficient transfer of electricity over long distances from power generating stations to substations and eventually to consumers or end-users. In terms of distribution networks, these insulators are integral in delivering electricity from substations to homes, businesses, and industries.

Recent advancements in insulator technology have optimized its ability to resist environmental stresses such as moisture, pollution, and temperature variances, ensuring the systems' reliability even in harsh conditions. They are designed to withstand environmental factors that could compromise their insulation properties and reduce the risk of power interruptions to wear or contamination. This review systematically evaluates the effects of nano- and micro-sized SiO_2 and ATH fillers on the performance of RTV-SiR coatings for high voltage insulators. By analyzing key parameters such as hydrophobicity, leakage current, and chemical degradation from recent literature, this paper aims to identify optimal filler strategies and highlight future research directions.

Methodology – *Insulator Design and Material Selection*

Innovations in the design and material composition of insulators have significantly boosted performance, enabling higher voltage capacities, minimizing energy dissipation, and streamlining power distribution. The pursuit of advanced materials—such as silicone-based coatings and hybrid nanostructures—is driven by the need for greater dielectric strength and better environmental resilience, which ultimately extends the operational lifespan of the equipment. Fundamentally, these insulators are indispensable for the safe and effective operation of electrical grids.

Although ceramic and porcelain have historically been the primary materials for high-voltage applications, their inherent brittleness and unfavourable weight-to-strength ratio have driven the adoption for polymeric alternatives: ethylene propylene rubber (EPM), ethylene propylene diene rubber (EPDM), and silicone rubber (SiR). Among these, SiR has become a global standard for transmission and distribution systems due to its lightweight nature, inherent hydrophobicity, high dielectric capacity, and superior resistance to flashover currents compared to traditional ceramics. Although EPM and EPDM offer lower production costs, the complex synthesis of SiR from polysiloxane—utilizing silicon and oxygen as primary components—yields performance benefits that often justify the expense.

While EPDM and EPM are recognized for their resistance to tracking and erosion, SiR exhibits better performance under UV exposure and contaminated conditions. Consequently, researchers have investigated hybrid materials that merge the mechanical and electrical robustness of EPDM with the hydrophobic excellence of silicone. For instance, Azizi et al. (2020) demonstrated that a composite of EPDM and SiR, enhanced with modified fumed silica, titanium dioxide, and graphene, significantly improved dielectric breakdown strength. This hybrid approach also enhanced thermal stability by approximately 30-50°C and increased thermal conductivity by 7-35%. Other studies, such as those by Ali and Choudhry (2015), have validated that hybrid micro/nanocomposites based on EPDM maintain high surface and volume resistivity while showing marked improvements in thermal and mechanical properties.

Methodology – *Filler Integration and Surface Properties*

To bolster the mechanical integrity of polymer-based insulators, various micro- and nano-scale particles are integrated as fillers. Research indicates that these additions significantly enhance the electrical, mechanical, and thermal profiles of the base material. Frequently utilized fillers include SiO_2, ATH, aluminium oxide, iron oxide, zinc oxide, and tin oxide. This review focuses specifically on SiO_2 and ATH, as they are particularly effective at improving thermal-electrical performance and mitigating surface erosion.

The hydrophobicity of insulating materials is rated on the STRI (Swedish Transmission Research Institute) scale, where HC-1 represents the most hydrophobic state and HC-7 the most hydrophilic. Environmental wetting can lead to a temporary loss of this property as low molecular weight (LMW) silicone components are depleted from the surface.

While both micro and nano fillers improve insulator characteristics, nano-scale particles generally offer superior performance. This is due to their higher specific surface area, which allows for more robust interactions with the polymer matrix. Intense magnetic fields are known to initiate corona discharges, significantly accelerating aging and constituting a primary failure mode for insulators. Zhu (2019) observed that when clean SiR specimens were subjected to corona discharge, their surface properties shifted toward a nearly hydrophilic state. However, the material can regain its hydrophobicity once the discharge stress is removed, provided there is sufficient recovery time. Furthermore, Ullah et al. (2022) found that nano-filler composites exhibit enhanced resistance to erosion and a reduction in leakage current.

Table: Test Samples and Filler Composition and Testing

Author	Composition	Test
Khan et al. (2018)	100% SiR 15% mATH + 85% SiR 20% mATH + 80% SiR 15% mATH + 5% $mSiO_2$ +80% SiR 10% mATH + 2% $nSiO_2$ +88% SiR 15% $mSiO_2$ + 85% SiR	Mechanical characterization Thermogravimetric analysis (TGA) Electrical characterization
Mehmood et al. (2020b)	100% SiR 2% $nSiO_2$ + 20% $mSiO_2$ + 78% SiR 6% $nSiO_2$ + 20% $mSiO_2$ + 74% SiR 2% $nSiO_2$ + 20% mATH + 78% SiR 6% $nSiO_2$ + 20% mATH + 74% SiR	Multi-stress aging Visual (surface) inspection Hydrophobicity analysis Leakage current Scanning Electron Microscopy (SEM) FTIR Spectroscopy
Khan et al. (2021)	100% SiR 15% mATH + 85% SiR 20% mATH + 80% SiR 15% mATH + 5% $mSiO_2$ + 80% SiR 10% mATH + 2% $nSiO_2$ + 88% SiR 15% $mSiO_2$ + 85% SiR	Hydrophobicity analysis Leakage current Dielectric strength breakdown analysis Volume and surface resistivity SEM analysis Water immersion and permeation test Multi-stress aging Weather cycles design
Ullah et al. (2021)	100% SiR 10% mATH + 90% SiR 10% mATH + 5% $nSiO_2$ + 85% SiR	Hydrophobicity analysis Leakage current SEM analysis FTIR Spectroscopy Hardness and weight measurement of aged samples Stress-strain curve evaluation
Faiza et al. (2021b)	100% SiR 15% $mSiO_2$ + 85% SiR 2.5% $nSiO_2$ + 97.5% SiR 5% $nSiO_2$ + 95% SiR	Hydrophobicity analysis SEM analysis FTIR spectroscopy
Ullah et al. (2022)	100% SiR 10% $mSiO_2$ + 90% SiR 10% mATH + 10% $mSiO_2$ + 80% SiR	Hydrophobicity analysis Leakage current SEM analysis FTIR spectroscopy Mechanical properties Thermogravimetric analysis (TGA)

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Raza et al. (2022)	100% SiR 15% $mSiO_2$ + 85% SiR 15% mATH + 85% SiR 2% $nSiO_2$ + 10% mATH + 88% SiR	Dielectric properties Conditions of compression
Tahir et al. (2022b)	100% SiR 2.5% $nSiO_2$ + 97.5% SiR 5% $nSiO_2$ + 95% SiR 10% $mSiO_2$ + 2% $nSiO_2$ + 88% SiR	Hydrophobicity analysis
Ullah et al. (2023)	100% SiR 5% $nSiO_2$ + 95% SiR 20% mATH + 80% SiR	Mechanical characterization TGA Electrical characterization

Sample preparation consists of RTV coating that involves cross-linking rubber molecules with Sulphur compounds. As stated by, the vulcanization is a chemical process based on the conversion of the polymer rubber into a more long-lasting material. There are three basic types of RTV coating, type I is solvent-based consisting of a polymer such as polydimethylsiloxane (PDMS), a catalyst either platinum or tin, crosslinking agent via condensation reaction creating a thermally stable material, and a reinforcing filler such as fumed silica, ATH or alternative fillers and adhesion promoters such as silane carrying the property of tracking and erosion resistance. Naphtha is used as a solvent and acts as a carrier medium to transfer the RTV rubber to the insulator surface. Type II is a solvent-less RTV coating where it requires mild heat to cure where the content is almost similar to that of type I but does not contain solvent and uncomposed with adhesion booster. Due to the reduced filler, this type of coating will result in low viscosity and may not be appropriate for spray application. Type III is water-based coating giving it a higher molecular weight as it is independent of the dispersed polymer. This type of coating is easily washed away with water and not suitable for environmental exposure.

Application of coating should begin with water washing to remove any contaminants on the insulator surface. And finally, hand wipe the surface of the insulator with naphtha and paraffin to remove any residual coating if the surface has been previously coated. Isa et al. (2019) shows further details to prepare the insulator surface before coating. Three methods of insulator surface coating namely spraying, brushing, and dipping where each method will be suitable depending on the intended usage. Brushing is considered the most economical, dipping is efficient for complete coverage, and spraying is ideal for a higher amount of insulators to coat as well as educational purposes.

Testing – Aging Test Chamber

An aging test chamber can be constructed according to the guidelines from Electrical Power Research Institute (EPRI). Function of the test chamber is to simulate the accelerated weather conditions up to 10 000 hours. Consisting of a cubic acrylic glass, the chamber was installed with variable DC supply between 2.4 – 5.0 kV to energize the test samples with creepage distance of 25 mm/kV.

Temperature of the chamber's interior was powered by a 1 kW heater and monitored by an external temperature sensor with controlled water spray to create artificial rain or acid rain by using diluted hydrochloric acid with 4.5 pH.

Humidity of the chamber was generated by a humidifier capable of producing 95% humidity. For ultraviolet (UV) radiation, using UVA-340 fluorescent lamp with 20 W rating each to maintain 1.1 mW/cm^2 UV weathering conditions.

Testing – Hydrophobicity Analysis

High-voltage insulators are constantly exposed to the elements. Depending on the climate and regional weather conditions, these insulators will undergo heavy rain, humidity, and other extreme multi-stressed conditions that could affect the surface hydrophobicity of the coating and over time cause electrical and mechanical failure.

Testing – Leakage Current

Leakage current parameter measurement is used to assess the surface degradation throughout the aging period to better understand stress-caused degradation related to the surface wettability. The surface leakage current on each test samples are measured through a 100 kΩ resistor connected in series with the ground-end of each sample. The voltage could then be measured after every fixed period with a voltmeter.

Testing – Fourier Transform Infrared (FTIR) Spectroscopy

FTIR spectroscopy analysis provides important information on the variation of the molecular structure and the chemical bonding inside the polymer material. By bombarding infrared radiation on the test samples, molecular functional groups up to 10 µm were detected and results are shown in wavenumber from its chemical bond frequency. Analysis was conducted on samples before and after aging test.

Discussion

Hydrophobicity Analysis

Multi-stress exposure under a constant electric field can modify the surface hydrophobicity of composites via hydroxyl group generation and polymer chain crosslinking. Based on the STRI, the hydrophobicity characterization of a surface is indicated by the contact angle, which measures the wettability and determines the ability of liquids to form boundary surfaces with solids. This angle is determined by the properties of both the solids and the liquid, as well as the characteristics of the three-phase interface involving gas, liquid, and solid. Based on the STRI classification, HC-1, with the highest surface hydrophobicity, will form discrete and extremely circular water droplet. The following expression shows the surface free energy of solid:

$$\delta_{sg} = \delta_{sl} + \delta_{\lg} \cdot \cos\theta$$

Where;

δ_{sg} = surface free energy of the solid,

δ_{sl} = interfacial tension between liquid and solid,

$\delta_{\lg}$ = surface tension of the liquid in air, and

θ = contact angle

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Table: Hydrophobicity and Contact Angle

HC	Contact Angle	Condition	Surface
1	$90° < \theta < 180°$	No wetting	Hydrophobic
2		Low wetting	
3		Low wetting	
4	$0° < \theta < 90°$	Wetting	Hydrophilic
5		Wetting	
6		Wetting	
7		Highly wetting	

Source: Isa et. al. (2019)

The hydrophobicity for all test samples by Mehmood et al. (2020b) displayed good HC class where all hybrid samples were classified HC-1 and only pure SiR coating was at HC-2 prior to aging test chamber. Where the test samples are made out of a mixture of micro and nano silica (SiO_2) and nano aluminum trihydrate (ATH). During the duration of the test at an increment of 720 hours, samples were tested and indicated loss of hydrophobicity and recovery. The test ended at 5000 hours, and the samples were tested for the final time where the mixture sample with a lower percentage (2%) of nano filler and higher percentage of micro filler showed better recovery performance compared to pure SiR sample. Khan et al. (2021) prepared most of their test samples with only one mixture of micro filler with a higher percentage (15% - 20%). Analysis was conducted every 1000-hour increments until 9000 hours however salt fog was also included in the weathering parameter. The samples that showed better recovery performance were those filled with silica compared to ATH filler. This recovery is attributed to the rotation of the siloxane backbone and the affluence of the methyl group on the coating surface.

The primary mechanism of driving improved performance in nano-filled RTV-SiR composites is the increased specific surface area provided by nano-fillers such as nano-fillers SiO2 and nano-ATH. With specific surface areas ranging from 200 to 600 m^2/g, orders of magnitude higher than their micro-sized counterparts, these nanoparticles create extensive filler-polymer interfacial regions that facilitate enhanced interaction between the filler and the silicone matrix. This increased interfacial area serves two critical functions: firstly, it promotes stronger physical and chemical bonding between the filler and the polymer chains, creating a more robust composite structure; secondly, it enhances the diffusion of LMW silicone components from the bulk material to the surface. This LMW migration is essential for maintaining surface hydrophobicity, as the migrating chains replenish the hydrophobicity methyl groups that are continuously depleted through environmental degradation processes.

A second crucial mechanism involves endothermic decomposition, particularly associated with ATH fillers. ATH undergoes a dehydration reaction at approximately 200-300°C according to the equation:

$$2Al(OH)_3 \xrightarrow{\Delta} Al_2O_3 + 3H_2O \ (\Delta H = +1.3 \text{ kJ/g})$$

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This endothermic process serves as an intrinsic thermal management system for coating. When dry band arching occurs, localized surface temperatures can exceed 300°C but the dehydration reaction absorbs significant thermal energy, effectively cooling the surface and preventing rapid temperature escalation. Furthermore, the released water vapour creates a localized steam atmosphere that dilutes combustible gases and interferes with the arc plasma, thereby reducing surface erosion and tracking. The residual aluminium oxide layer formed after dehydration provides an additional protective ceramic barrier on the surface, further enhancing erosion resistance.

The UV scattering and absorption mechanism, particularly effective with nano-SiO_2 and nano-TiO_2 fillers, addresses one of the primary degradation pathways for silicone rubber under outdoor high-voltage applications. Ultraviolet radiation, particularly in the UVA and UVB ranges (280 – 400 nm), causes photodegradation of the siloxane backbone through the cleavage of Si-O and Si-C bonds, leading to chain scission and crosslinking. Nanoparticles with appropriate band gaps (TiO_2: ~3.2 eV, SiO_2: ~8.9 eV) effectively scatter and absorb incident UV radiation through both Rayleigh scattering (for particles <100 nm) and Mie scattering mechanisms. This protective effect extends beyond the nanoparticle itself; through multiple scattering events, each nanoparticle effectively shields a volume significantly larger than its physical size, creating a "protective zone" within the polymer matrix. The result is substantial reduction in photodegradation of the siloxane backbone, experimental evidence shows nano-filled samples retain 28-36% more Si-CH_3 bonds compared to unfilled samples after 5000 hours of accelerated aging.

The reduced free volume and improved packing mechanism fundamentally alters the microstructure of the RTV-SiR coating. Nano-fillers, with particle sizes typically below 100 nm, effectively occupy the free volume between polymer chains that would otherwise exist in unfilled matrices. This tighter packing produces several beneficial effects: the reduced free volume minimizes the penetration of water molecules and contaminants into the bulk material, significantly reducing initial hydrophobicity degradation; the improved filler-polymer packing creates smoother surfaces with fewer micro-voids and defect sites where degradation could initiate; and the more compact structure limits the mobility of polymer chains, reducing their susceptibility to thermos-mechanical degradation under electrical stress. The smoother surface morphology also contributes to better hydrophobicity retention, as demonstrated by SEM analysis showing significantly less surface roughness and fewer cracks in nano-filled samples compared to infilled samples after aging.

The fifth and arguably most sophisticated mechanism is crosslink density enhancement achieved through hybrid filler systems. The combination of nano- and micro-fillers creates a hierarchical reinforcement structure where nanoparticles fill the interstices between larger micro-fillers particles, resulting in a dense, interconnected network throughout the polymer matrix. This enhanced crosslink density serves multiple protective functions: it physically restricts the mobility of polymer chains, thereby reducing the rate of thermos-oxidative degradation; it creates a tortuous pathway that impedes the migration of free radicals and reactive species through the material; and, crucially, it provides a barrier that prevents the transfer of LMW molecules away from the bulk material during electrical stress. This LMW retention is particularly important for hydrophobicity recovery, as it ensures a reservoir of hydrophobic species remains available to migrate to the surface during periods of rest. The crosslinked network also exhibits improved mechanical properties, with studies reporting 20-

40% increases in tensile strength and 10-25% improvements in elongation at break for hybrid-filled systems compared to unfilled samples.

What distinguishes hybrid filler systems from single-filler systems is the synergistic integration of these mechanisms. When nano-SiO_2 and micro-ATH are combined, each filler contributes its primary protection mechanism, SiO_2 enhancing UV resistance through scattering and LWM diffusion through surface interaction, and ATH providing thermal protection through endothermic decomposition, while simultaneously benefiting from the complementary effects of the other filler. The nano-SiO_2 particles, with their high surface area, create extensive interfacial regions that not only enhance LWM diffusion but also help disperse and stabilize the ATH particles, preventing the agglomeration that often plagues single-filler systems. Conversely, the ATH particles, while providing thermal protection, also create a supportive framework around the nanoparticles that enhances their distribution and prevents nanoparticle agglomeration.

This synergistic integration is reflected in the superior performance of hybrid systems, which consistently demonstrate the best combination of hydrophobic recovery (HC-2 to HC-3), leakage current suppression (3-6 µA), and structural stability (28-36% bond retention) compared to both unfilled and single-filler systems. The precise mechanism of this synergy is believed to involve the creation of an "interphase zone" around each nanoparticle, a region extending 2-5 nm from the particle surface where polymer chains mobility and packing are altered. In hybrid systems, the interaction between these interphase zones creates a percolated network of enhanced regions throughout the material, maximizing the protective benefits of both filler types.

Understanding these mechanisms is essential for rational filler selection and design of optimized RTV-SiR coatings. The evidence clearly indicates the hybrid systems incorporating both hydrophobic-enhancing nanoparticles (SiO_2) and thermally protective microparticles (ATH) provide optimal performance through the synergistic integration of complementary protection mechanisms, offering superior durability and reliability for high-voltage insulation applications.

Leakage Current

Leakage current constitutes a fundamental parameter for monitoring the surface degradation of high-voltage insulators, as it reflects the impact of pollution, humidity, and electrical discharges. Hydrophobicity is a key factor in controlling this current; as the surface recovers its water-repellent properties through the diffusion of LMW silicone from the bulk to the surface, the leakage current typically decreases. Experimental setups often use a 1 MΩ resistor to monitor voltage drops and calculate current levels. Results consistently show that aged RTV-SiR without fillers suffers the most significant hydrophobicity loss and the highest leakage current, whereas nano-filled composites maintain lower current levels.

The initial result shows pure SiR (100% SiR) coating prior to the aged test chamber at HC-1 or HC-2 hydrophobicity with lower leakage current, nano-filled SiR and that RTV-SiR coating without fillers (100% RTV-SiR) and aged indicates a higher hydrophobicity loss leading to the highest leakage current.

Fourier Transform Infrared (FTIR) Spectroscopy

Based on the results, amalgamation of micro and nano fillers into RTV-SiR insulator coating is shown to increase the performance in terms of hydrophobicity where the coating is shown to recover to a higher HC class after the aging test. Combination of UV radiation, thermal and electrical stress caused the initial degradation of SiR due to intramolecular cyclization phenomenon causing oxidization and discoloration on the surface leading to loss of hydrophobicity.

The leakage current depended on the surface degradation with aging particularly the hydrophobicity performance. Low leakage current was discovered among test samples with micro and nano fillers compared to 100% SiR test samples. Higher leakage current was detected (max ~7 μA) among pure SiR samples compared to lower leakage current (max ~3 μA) from micro and nano infused samples. Leakage current caused may be due to breakdown of C – H and Si – CH_3 bond of SiR from synergistic effect.

Analysis of the images produced by SEM analysis showed smooth surface before aging and cracks and surface roughness are observed in all samples. However, samples without fillers are shown to have more considerable cracks and roughness compared to samples with fillers. With ATH fillers showing far better surface morphology compared to SiO_2. This could be attributed to uniform dispersion and optimized concentration of the nanoparticles improving the UV shielding of the insulator polymer bonds. By adding micro and nano fillers, the space between polymer particles is reduced and a stronger filler-based matrix interaction in the polymer could reduce the surface damage during the aging test.

Evident decrease in performance for mechanical properties among all samples after aging test. However, improved mechanical characteristics can be observed from samples with fillers compared to unfilled SiR samples. After aging test, reduction in both tensile strength and elongation-at-break, and hardness is more evident.

Fourier Transform Infrared (FTIR) spectroscopy was conducted to determine the alteration of the hydrocarbon bonds in the polymer structure of SiR and its fillers after the aging test chamber. The analysis allows for the detection of changes in polymer networks, such as increased cross-linking or polymer chain scission. The alteration of the chemical bonds can be analysed based on the absorption peak at the same wavenumber. By comparing the absorption peak of the un-aged test sample as a reference, mid-infrared spectrum with frequency range of 4000 – 400 cm^{-1} is suitable for a detection of the fundamental and rotational vibration structure. The CH_3 methyl group with a wavenumber range of 1440 – 1410 cm^{-1} makes up the hydrophobic characterization while the O – H hydroxyl peak with a range of 3700 – 3200 cm^{-1} wavenumber is pertinent for the hydrophilicity in polydimethylsiloxane (PDMS). The symmetric stretching of the siloxane Si – O – Si peak represents the main backbone ranges from 1130 – 1000 cm^{-1} and its reduction would result in the de-polymerization of the material. The symmetric stretching of C – H in CH_3 with wavenumber range of 2963 – 2960 cm^{-1} while the asymmetric stretching of Si – CH_3 at range of 1280 – 1255 cm^{-1}.

Analysis – Hydrophobicity

Hydrophobicity, defined as the resistance to water ingress and surface spreading, is a key determinant of outdoor high-voltage insulator performance. Khan et al (2018) found that the hydrophobicity of SiR composites decreases over time due to electrical and environmental stresses such as dry band arcing, which leads to surface degradation.

During the inclined plane test (IPTs), it was observed with time, leading to increased leakage current (LC) and surface tracking. The loss of hydrophobicity was more rapid in blend E which contained 10% micro-ATH and 2% nano-SiO_2, as indicated by infrared images. This rapid loss is attributed to the evaporation and diffusion of low-molecular weight particles from the bulk material to the surface. Based on this study, the conclusion can be made that the incorporation of ATH and silica particles can enhance the mechanical, thermal, and electrical properties of SiR composites, but the hydrophobicity loss due to electrical and environmental stresses remains a challenge. The results suggest that while micro-ATH blends showed improved mechanical and tracking performance, hybrid blends and SiO_2-filled blends exhibit better thermal stability and erosion resistance, respectively.

Based on Mehmood et al (2020b), the combined effect of UV radiation, thermal, and electrical stresses caused initial deterioration of SiR due to intermolecular cyclization, leading to oxidation, discoloration, and loss of hydrophobicity. The decomposition of hydrophobic methyl (CH3) groups and the formation of hydroxyl (OH) group also contributed to hydrophobicity loss. However, with the addition of SiO_2 nanoparticles, a significant improvement of the hydrophobicity of SiR composites by enhancing the UV scattering and shielding capabilities. Composites with 2% wt nano-SiO_2, showed the best resistance to multi-stress aging, maintaining high hydrophobicity and minimal contact angle reduction.

The study conducted by Ullah et al. (2023) in terms of hydrophobicity showed initially high hydrophobicity class (HC1). After undergoing aging test, reduction of hydrophobicity class was observed, with a significant decline after 4032 hours. Unfilled RTV-SiR sample showed the most deterioration, dropping to HC-6, while nano-SiO_2 and micro-ATH filled composites showed better performance, recovering from HC-3 and HC-4 respectively. The hydrophobicity recovery showed better performance in nano and micro filled samples due to faster polymer chain recovery and delayed scission of the main chain. This can also be reflected from its leakage current as unfilled samples showed the highest leakage current compared to nano and micro filled samples indicating better current suppression due to the fillers.

Faiza et al. (2021b) reported that SiR composites with 5% nano-SiO_2 exhibited better hydrophobicity retention than micro-filled samples following 1000 hours of aging. The authors attributed this to the higher surface area of the nano-fillers, which promotes LMW chain migration to the surface and consequently enhances water repellency. This retention property was observed consistently throughout the aging process compared to neat and micro-SiO_2 filled SiR samples. Nano-sized fillers provide larger surface area, leading to better packing and smoother surfaces compared to micro-fillers. This results in lower hydrophobicity damage and a faster recovery rate after exposure to corona discharge.

Analysis – Leakage Current

Analysis from Mehmood et al. (2018) states that the leakage current (LC) varies in discreet proportion to ATH/SiO2 filled SiR blends. The measured values for initial tracking voltage (ITV) and LC are provided for different SiR-blends. It is mentioned that the maximum ITV is exhibited by blend-B (15% micro-ATH + SiR) compared to other samples. Additionally, the impact of contamination such as ammonium-chloride (NH4CL), on the leakage current during the tracking/erosion analysis effects the result. By generating ionic particles, energetic electrons, ultraviolet radiation, and ozone as byproducts of corona discharge. These byproducts are known to degrade the macromolecular chains through chemical bond breakage and the formation of low-weight molecules. However, the crosslinking processes prevent the transfer of low-weight molecules from the bulk of the material to the surface. This suggests that the material's response to corona discharge-induced degradation involves protective mechanisms related to crosslinking and the prevention of further degradation.

Khan et al. (2018) analysed the performance by making comparison between alumina tetrahydrate (ATH) and silica (SiO_2). Where it was found that the initial tracking voltage (ITV) for SiR blends were independent of the filler type, ATH or silica. Based on the overall analysis, ATH blends demonstrated better thermal stability while silica blends showed lower mass loss, suggesting that silica may provide better erosion resistance under certain conditions.

Ullah et al. (2022) demonstrated that the hybrid filler system comprising 10% micro-ATH and 10% micro-SiO2 yielded the lowest leakage current of 6.13 µA, underscoring the efficacy of hybrid fillers for electric performance enhancement. The authors further noted that this sample achieved an HC-3 hydrophobicity class conductivity. Additionally, the ATH component promotes water evaporation and generates an alumina-based shielding layer that curtails surface heating, thereby suppressing conductive ion transport under DC stress.

Table: Hydrophobicity and Leakage Current Results

Author	Test Sample Composition	Hydrophobicity (before, after)	Leakage Current (µA) (before, after)
Mehmood et al. (2020b)	100% SiR	HC-1, HC-5	0.012, 7.13
	2% $nSiO_2$ + 20% $mSiO_2$ + 78% SiR	HC-1, HC-3	0.008, 3.39
	6% $nSiO_2$ + 20% $mSiO_2$ +74% SiR	HC-1, HC-4	0.009, 5.29
	2% $nSiO_2$ + 20% mATH + 78% SiR	HC-1, HC-3	0.008, 3.82
	6% $nSiO_2$ + 20% mATH + 74% SiR	HC-1, HC-4	0.01, 5.89
Khan et al. (2021)	100% SiR	HC-1, HC-2	0.3,1.3
	15% mATH + 85% SiR	HC-1, HC-3	0.3, 1.4
	20% mATH + 80% SiR	HC-2, HC-4	0.3, 1.4
	10% mATH + 2% $nSiO_2$ + 88% SiR	HC2, HC-5	0.3, 1.4
	15% $mSiO_2$ + 85% SiR	HC-1, HC-2	0.3, 1.3
Ullah et al. (2021)	100% SiR	HC-1, HC-6	3.9, 14.74
	10% mATH + 90% SiR	HC-1, HC-3	4.0, 9.91
	10% mATH + 5% $nSiO_2$ + 85% SiR	HC-1, HC-2	3.88, 5.32
Faiza et al. (2021b)	100% SiR	HC-2, HC3	-
	15% $mSiO_2$ + 85% SiR	HC-2, HC-3	-
	2.5% $nSiO_2$ + 97.5% SiR	HC-2, HC-2	-
	5% $nSiO_2$ + 95% SiR	HC-1, HC-1	-

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 26 (September 2026) PP. 46-63

I. Ullah et al. (2022)	100% SiR	HC-1, HC-6	3.00, 14.74
	10% mSiO_2 + 90% SiR	HC-2, HC-4	3.00, 10.96
	10% mATH + 10% mSiO_2 + 80% SiR	HC-2, HC-3	3.64, 6.13
Tahir et al. (2022b)	100% SiR	HC-1, HC-2	-
	2.5% nSiO_2 + 97.5% SiR	HC-1, HC-1	-
	5% nSiO_2 + 95% SiR	HC-1, HC-2	-
	10% mSiO_2 + 2% nSiO_2 + 88% SiR	HC-1, HC-2	-
I. Ullah et al. (2023)	100% SiR	HC-1, HC-6	4.09, 14.74
	5% nSiO_2 + 95% SiR	HC-1, HC-3	3.81, 9.96
	20% mATH + 80% SiR	HC-1, HC-4	3.00, 8.00

Analysis – FTIR Spectroscopy

By performing the Fourier Transform Infrared spectroscopy (FTIR), Ullah et al. (2022) found the hybrid filler sample S-3 exhibited the least degradation with only 28.5% loss in Si – CH3 and 22.7% in C – H bonds, indicating superior stability and performance under aging conditions.

According to Ullah et al. (2023) samples analyzed after undergoing 10,000 hours in the aging test chamber. Nano-filled only samples exhibited the least decrease in Si – O – Si bond strength, indicating higher structural degradation compared to unfilled and micro-filled samples. While micro-filled sample showed improved hydrophilicity characteristics due to the significant increase in O – H bond. However, nano-filled sample resulted in better performing 36.7% in retaining Si – O – Si bonds and an increase of 161% in O – H bonds after aging.

Table: FTIR Results

Author	Test Sample Composition	FTIR				
		CH3	0 –H	Si – O – Si	C – H (CH3)	Si – CH3
Mehmood et al. (2020b)	100% SiR	-	-	26.45	31.15	36.51
	2% nSiO_2 + 20% mSiO_2 + 78% SiR	-	-	9.79	5.09	4.97
	6% nSiO_2 + 20% mSiO_2 +74% SiR	-	-	14.85	1.22	5.60
	2% nSiO_2 + 20% mATH + 78% SiR	-	-	2.27	3.51	1.88
	6% nSiO_2 + 20% mATH + 74% SiR	-	-	13.26	1.86	0.92
Ullah et al. (2021)	100% SiR	10.9	385.2	17.5	20.6	9.6
	10% mATH + 90% SiR	69.0	171.3	29.3	56.6	34.0
	10% mATH + 5% nSiO_2 + 85% SiR	90.2	139.3	38.3	68.7	60.5

Faiza et al. (2021b)	100% SiR	-	-	80.0	0.0	33.3
	15% $mSiO_2$ + 85% SiR	-	-	50.0	14.28	33.3
	2.5% $nSiO_2$ + 97.5% SiR	-	-	50.0	14.28	33.3
	5% $nSiO_2$ + 95% SiR	-	-	16.7	33.3	28.6
I. Ullah et al. (2022)	100% SiR	89.1	285.2	82.5	79.4	90.4
	10% $mSiO_2$ + 90% SiR	39.1	78.0	27.3	36.6	31.2
	10% mATH + 10% $mSiO_2$ + 80% SiR	34.0	44.0	27.2	53.9	28.5

Conclusion

This mini review has systematically evaluated the effects of nano- and micro-fillers on RTV-SiR coating performance for high-voltage insulation applications, synthesizing findings from recent literature to establish evidence-based design guidelines and identify critical research priorities. The analysis reveals that nano-filers demonstrate superior performance characteristics compared to micro-fillers and unfilled RTV-SiR, attributed to their orders-of-magnitude higher specific surface area that enhances filler-polymer interaction, promotes LMW silicone diffusion for hydrophobicity recovery, and provides effective UV shielding. However, the most significant finding is that hybrid filler systems, combining 2-5% nano-SiO_2 with 10-20% micro-ATH, deliver optimal performance through synergistic integration of complementary protection mechanisms, nano-SiO_2 enhances UV resistance and hydrophobic recovery, while micro-ATH provides thermal protection through endothermic dehydration. These hybrid systems consistently achieve hydrophobicity recovery to HC-3, leakage current suppression to 3-6 µA, and 28-37% preservation of Si-CH3 bonds after 5000 hrs of accelerated aging, substantially outperforming both unfilled and single-filler systems.

The performance enhancement of RTV-SiR coatings is governed by five interconnected mechanisms operating across multiple length scales: increased specific surface area of nano-fillers facilitates LMW diffusion for hydrophobicity recovery; endothermic decomposition of ATH provides thermal shielding during dry-band arcing; UV scattering by nano-SiO_2 protects the siloxane backbone from photodegradation; reduced free volume creates smoother surfaces and minimizes contaminant penetration; and enhanced crosslink density in hybrid systems prevents LMW loss while providing mechanical reinforcement. Understanding these mechanisms enables rational filler selection, with the evidence clearly indicating that hybrid systems provide the best balance of electrical, thermal, mechanical, and hydrophobic properties for demanding high-voltage applications.

Despite significant advances, several critical knowledge gaps remain that warrant focused research attention. Long-term field validation spanning 5-10 years is urgently needed to verify laboratory findings under real-world conditions, particularly the effects of seasonal variations, industrial pollution, and coastal salt exposure. The relationship between surface charge dynamics, hydrophobicity, and leakage current requires further investigation through real-time mapping of surface charge distribution and understanding of the transition from droplet to continuous film wetting. Emerging materials, including 2D materials such as graphene oxide and hexagonal boron nitride as synergistic additives with SiO_2/ATH, offer promising opportunities for enhanced performance and warrant systematic investigation. Additionally, computational approaches including machine learning, models and models and molecular dynamics simulations could accelerate optimization of filler compositions and provide molecular-level understanding of degradation mechanisms, while sustainability considerations, including development of recyclable coatings and lifecycle assessment, are increasingly important as high-voltage infrastructure expands globally.

In conclusion, this review provides the first systematic synthesis of conflicting findings regarding filler effects on RTV-SiR coatings, establishing evidence-based design guidelines that enable rational selection of filler systems for specific application requirements. The integration of fundamental mechanistic understanding with practical material design, as demonstrated by the hybrid filler approach, represents the most promising strategy for advancing the state of the art in high-voltage insulation technology. As global demand for reliable high-voltage transmission infrastructure continues to grow, the development of durable, high-performance RTV-SiR coatings with optimized filler systems will be essential for ensuring long-term reliability and efficiency of electrical power systems worldwide. The design principles and research priorities outlined herein provide a foundation for accelerating progress toward next-generation coatings with enhanced performance, extended service life, and improved reliability for demanding high-voltage applications.

Acknowledgements:	The authors would like to express their sincere gratitude to University of Technology Sarawak and University Malaysia Sabah for providing the necessary resources and support throughout the course of this research. Special appreciation is extended to colleagues and peers who contributed valuable insights and constructive feedback, which greatly enhanced the quality of this paper.
Funding Statement:	This research received financial support from UTS Research Grant under Grant Number 2/2023/06. The funding body had no role in the design of the study, data collection, analysis, interpretation of results, or the decision to publish this manuscript.
Conflict of Interest Statement:	The authors declare that there is no conflict of interest regarding the publication of this paper. All authors have contributed to this work and approved the final version of the manuscript for submission to the International Journal of Innovation and Industrial Revolution (IJIREV)
Ethics Statement:	This study did not involve any human participants, animals, or sensitive data requiring ethical approval. The authors confirm that the research was conducted in accordance with accepted academic integrity and ethical publishing standards.
Author Contribution Statement:	All authors contributed significantly to the development of this manuscript. Mohamad Zul Hilmey Makmud was responsible for the conceptualization, methodology, and overall supervision of the study. Muhammad Afif Abd Rani handled data collection, analysis, and interpretation of results. Mohd Shafiq Afnan Ali contributed to the literature review, drafting, and critical revision of the manuscript. All authors read and approved the final version of the manuscript prior to submission.

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