

Requirements for Water-, Dust-, and Flame-Resistant Materials Treated with Silicon-Organic Compounds

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ABSTRACT: This study analyzes the main requirements for materials that are water-, dust-, and flame-resistant, focusing particularly on the chemical structure of hydrophobic coatings and the factors determining their efficiency. Hydrophobic coatings are characterized as systems that reduce the adhesion or penetration of water molecules onto the material surface. The degree of hydrophobicity is determined by the contact angle and depends on surface energy, molecular polarity, and the micro- and nanorelief structure. Coatings based on silicon-organic compounds (PDMS, methylsilane, ethylsilane) and fluorinated organics (PTFE, perfluoroalkyl silanes) exhibit high resistance to water, dust, and heat. Moreover, biomimetic approaches — such as nanostructured surfaces inspired by the lotus effect — are highlighted as a promising direction in modern materials science for developing self-cleaning surfaces.

KEYWORDS: Hydrophobic coatings, water repellency, silicon-organic compounds, fluoropolymers, surface energy, contact angle, nanostructure, biomimetic surface, PDMS, PTFE, lotus effect.

Chemical Basis of Hydrophobic Coatings: Hydrophobic coatings possess chemical structures that limit the adhesion, absorption, or wetting of water molecules on a material surface. Their performance primarily depends on surface energy, molecular polarity, and micro/nano morphological structure. The contact angle formed by a water droplet on the surface is a key parameter for determining hydrophobicity. If the angle exceeds 90° , the surface is considered hydrophobic; if it is above 150° , the surface is classified as superhydrophobic. On such surfaces, water droplets slide off almost without adhesion.

The mechanism of hydrophobicity formation is associated with the reduction of surface energy. To achieve this, nonpolar, low-energy atoms and groups such as methyl ($-\text{CH}_3$), trifluoromethyl ($-\text{CF}_3$), or siloxane ($-\text{Si}-\text{O}-\text{Si}-$) fragments are introduced into the molecular structure. These groups do not form hydrogen bonds with water molecules, thereby reducing surface polarity and minimizing water interaction.

Silicon-organic compounds play a crucial role among hydrophobic coatings. Coatings based on polydimethylsiloxane (PDMS), methylsilane, and ethylsilane possess low surface energy, enabling water droplets to easily roll off the surface. The high bond energy of the Si–O linkage enhances the chemical, thermal, and UV stability of such polymers.

Fluorinated organics — particularly polytetrafluoroethylene (PTFE) and perfluoroalkyl silanes — can reduce surface energy down to 18–20 mN/m, exhibiting strong repellence against water, oil, and contaminants. Due to the high electronegativity of fluorine and the strong C–F bond energy, these coatings are chemically and thermally inert.

In addition to chemical modification, altering the surface micro- and nanorelief plays a significant role in achieving hydrophobicity. Rough or porous surfaces reduce the actual contact area between water and the material, enhancing hydrophobicity according to Wenzel and Cassie–Baxter wetting models.

Typically, such coatings are produced in two stages: (1) activation of the surface (through oxidation, plasma treatment, or mechanical processing) and (2) chemical bonding with reactive

silanes or fluoropolymers. The resulting coatings demonstrate resistance to water, dust, corrosion, UV radiation, and chemical reagents. Currently, silicone- and fluoropolymer-based hydrophobic coatings are widely used in textiles, leather, construction, electronics, and optics, providing waterproofness, dust repellency, anti-contamination, and self-cleaning properties.

Nanostructured surfaces inspired by biomimetic principles — such as the lotus effect — represent one of the most promising trends in modern chemical materials science.

Stable Surface Structures Against Dust Particles: The development of flame-resistant and dust-repellent stable surfaces based on silicon-organic modified polymers is an important topic in modern materials science. Silicon-organic polymers (silicones) are widely used due to their unique physicochemical properties — high thermal stability, chemical inertness, hydrophobicity, elasticity, and dielectric performance. Coatings and composites based on these polymers are also environmentally friendly, mechanically durable, and have long operational lifetimes. However, their unmodified forms tend to degrade at high temperatures or under flame exposure and may not fully resist dust and oil particles. Therefore, recent research has focused on modifying silicon-organic polymers to create flame-resistant, dust-repellent, and durable surface structures.

Mechanisms of Flame Resistance in Silicon-Organic Polymers: Enhancing the fire resistance of silicon-organic polymers is achieved by modifying their structural composition. Flame-retardant elements such as phosphorus, boron, aluminum, titanium, or mineral fillers ($\text{Al}(\text{OH})_3$, $\text{Mg}(\text{OH})_2$, SiO_2) are introduced. These additives undergo endothermic decomposition upon heating, releasing water vapor or inert gases that cool the surface and limit oxygen access. Consequently, a carbonized or ceramic-like layer forms, protecting the underlying material from further combustion.

For instance, adding aluminum hydroxide to PDMS-based silicon-organic polymers increases heat resistance up to 250–300°C. The strong Si–O–Si bonds (bond energy 444 kJ/mol) contribute to the polymer skeleton's resistance to thermo-oxidative degradation. Incorporation of nanoparticles (SiO_2 , TiO_2 , Al_2O_3) further enhances the mechanical and thermal stability of the surface structure, forming an integrated network within the polymer matrix that minimizes deformation under heat exposure. This modification approach not only improves fire resistance but also increases the material's durability against UV radiation and oxidative agents.

Formation of Dust-Repellent Stable Surface Structures: Modified silicon-organic polymers provide both flame resistance and anti-dust functionality. Their efficiency is determined by a micro/nano relief and low surface energy. Such surfaces exhibit the lotus effect, where water droplets and dust particles have minimal contact with the surface and slide off easily, ensuring self-cleaning properties. Typically, these coatings are prepared from SiO_2 – TiO_2 –polysiloxane composites. TiO_2 acts as a photoactive component that oxidizes organic contaminants under UV radiation, while SiO_2 enhances mechanical stability, and the polysiloxane layer provides hydrophobicity and reduces surface energy. Experimental results show that such surfaces achieve a contact angle of 150–155°, confirming their superhydrophobic behavior.

Experimental Procedure for Surface Formation: In laboratory conditions, dust-resistant silicon-organic surfaces are synthesized using the sol–gel method. A mixture of tetraethyl orthosilicate (TEOS) and titanium isopropoxide undergoes hydrolysis and condensation in an ethanol medium. PDMS or methylsilanetriol is then added to the resulting SiO_2 – TiO_2 sol suspension. During drying, a firmly bonded silicon-organic layer forms on the substrate surface. This layer contains Si–O–Si linkages and a micro/nano-relief structure that drastically reduces dust adhesion.

Experimental Results: The resulting coatings demonstrate that:
A) They maintain structural integrity up to 250–300°C.
B) They exhibit strong repellency against water and oily contaminants.

- C) They retain performance under mechanical abrasion.
D) They are effective for optical surfaces, protective clothing, and industrial filters.

Structural Analysis: The obtained surface structures consist of three main layers:

Base substrate (fabric, leather, or glass) – provides mechanical support.

Inorganic nanoparticle network ($\text{SiO}_2\text{-TiO}_2$) – ensures mechanical and thermal stability. Silicon-organic modification layer (PDMS, methylsilanetriol) – lowers surface energy and forms a hydrophobic, dust-repellent barrier.

These layers are interconnected through covalent bonds, ensuring the surface's durability, chemical inertness, and long-term dust resistance. Currently, silicon-organic modified coatings are widely applied in aerospace technology, electronic devices, transportation, protective clothing, and architecture. They are distinguished by their stability against dust, water, oil, and heat. Their environmental friendliness and recyclability also provide industrial advantages.

Research findings indicate that such surfaces are also energy-efficient, as non-adherent dust maintains the performance of optical panels and solar cells over time. Flame resistance ensures safety in fire-prone environments.

CONCLUSIONS

- I. Modification of silicon-organic polymers is an effective method to enhance their thermal, fire, and chemical stability.
- II. Incorporation of nanoparticles and inorganic fillers strengthens the polymer matrix and increases the mechanical durability of the protective surface layer.
- III. Stable, dust-repellent surface structures result from micro/nano relief formation, low surface energy, and silicon-organic modification.
- IV. The superhydrophobic effect (contact angle $>150^\circ$) significantly reduces adhesion of dust, water, and oil particles.
- V. The developed surface structures are promising for creating flame-resistant, dust-repellent, waterproof, and environmentally safe materials.

Overall, coatings based on modified silicon-organic polymers belong to the class of multifunctional, durable, and highly efficient advanced materials. This direction lays the groundwork for the development of energy-efficient, fire-resistant, and self-cleaning technological surfaces in the future.

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