Fabrication of Silica-PS Self-cleaning Superhydrophobic Coating on Glass Substrate

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Abstract

In this study, a superhydrophobic coating was fabricated by spray-depositing a composite solution of Polystyrene (PS) and Methyltrichlorosilane (MTCS)-modified silica nanoparticles onto glass substrates. Initially, silica nanoparticles were synthesized via a sol-gel process in a basic condition using tetraethyl orthosilicate (TEOS) as the precursor. The resulting particles were subsequently functionalized with MTCS to introduce low-surface-energy methyl groups. These modified nanoparticles were then dispersed in a PS solution to formulate a sprayable suspension. Upon deposition and drying, the coated glass surfaces exhibited a high-water contact angle of 166°, indicating excellent superhydrophobicity. Furthermore, the coating demonstrated outstanding water jet impact resistance, highlighting its mechanical and chemical stability and potential for real-world self-cleaning applications.

Keywords: Superhydrophobic, silica coating, spray coating, self-cleaning

1. Introduction

Self-cleaning superhydrophobic coatings have attracted considerable scientific interest due to their exceptional water-repellent performance across a variety of substrates. Inspired by natural examples such as lotus leaves and insect wings, these coatings achieve their functionality through the integration of micro- and nanoscale surface textures with materials of inherently low surface energy. Superhydrophobicity is typically characterized by a water contact angle exceeding 150° and low contact angle hysteresis, enabling water droplets to bead up and roll off the surface effortlessly, removing dust and other contaminants in the process. This behavior is primarily governed by the synergy between surface roughness at multiple length scales and chemical modifications that reduce adhesion between water and the surface [1]. Achieving superhydrophobicity relies heavily on the presence of surface roughness. The Wenzel and Cassie-Baxter models explain how surface texture influences wettability, either enhancing or reducing it depending on the interaction between the liquid and the rough features. Superhydrophobic behavior is typically associated with the Cassie-Baxter state, where air pockets remain trapped beneath the water droplet, minimizing solid–liquid contact. This effect is most effectively achieved on hierarchical surfaces, where microscale structures are further decorated with nanoscale features. To complement this surface architecture, materials with inherently low surface energy such as fluorinated compounds or silicones are often used, as they reduce the attraction between water molecules and the surface, thereby enhance the water-repellent properties [2]. Because of their very special properties, superhydrophobic coatings have very broad applications. Notably, in self-cleaning surfaces, droplets roll off and take out dirt and contaminants [3].

Darmawan et al. [4] developed a thin hydrophobic silica layer by varying the concentration of the TMCS and TEOS precursors. This study reported that, higher concentration leads to elevation in WCA. Also, decrease trend in WCA was observed by elevating the calcination temperature. Kurbanova et al. [5] fabricated superhydrophobic coating of SiO_2/TMCS via spray deposition for self-cleaning application. The coating exhibited high WCA of 165° with SA less than 10° which showed excellent self-cleaning ability against sands during self-cleaning performance. Sutar et al. [6] developed PS/OTS coating on SS mesh to achieve superhydrophobic attributions via dip coating method. The consecutive layers of PS and OTS was able to generate hierarchical rough structure which exhibited high WCA of 157.5 ± 2° and SA of 6 ± 2°. In the present study, we have prepared a superhydrophobic coating on a glass substrate via facile spray coating technique. In a composite solution of TMCS modified silica particles and PS prepared sample exhibited high water contact angle of 166° and SA of less than 5°. Furthermore, to access the durability of the coating various mechanical and chemical tests were performed.

2. Experimental

2.1 Materials

Polystyrene (PS, Mw ~ 280000), Tetraethylorthosilicate (TEOS, 98%) and Trimethylchlorosilane (TMCS) were purchased from Sigma Aldrich. Hexane, toluene, ammonia solution (NH_4OH – 25%), ethanol (99.9%) was procured from Loba Chemie. Glass slides (CAT. No. 72900135) was obtained from Riveria, India.

2.2 Preparation of hydrophobic silica nanoparticles

In 20 mL of ethanol, 5 mL of distilled water and 4 mL of TEOS were added. This solution was stirred about 20 min then 5 mL of NH_4OH was added and stirring continued for 6 h. The white solution then aged overnight. The dried solution was ground to earn fine silica particles. The grounded silica nanoparticles were added in the 10 v/v% TMCS-Hexane solution and stirred for 2 h at 60 °C. Finally, these silica nanoparticles were grounded to earn hydrophobic silica nanoparticles.

2.3 Fabrication of superhydrophobic coating

A 16 mg PS was dissolved in 20 mL of toluene by stirring for 30 min. Then 200 mg as prepared silica particles were added in PS solution and further stirred for 30 min. The final solution was sprayed on clean glass substrate from a distance of 10 cm at a pressure of 2 bar. Finally, the spray coated glass samples dried at 100 °C for 1 h.

3. Results and discussion

Silica nanoparticles were successfully synthesized using the sol-gel method under basic conditions by utilising TEOS as the silica precursor. The alkaline environment facilitated controlled hydrolysis and condensation, yielding silica nanoparticles. These nanoparticles were subsequently modified using methyltrichlorosilane (MTCS), which reacts with surface silanol groups to introduce hydrophobic methyl (-CH_3) functionalities. The MTCS modification not only reduces the surface energy of the silica particles but also enhances compatibility with the hydrophobic polymer matrix of polystyrene. the sprayed coating formed a hierarchical surface topology. The micro/nanostructured roughness was generated by the random stacking of MTCS-modified silica nanoparticles embedded within the polystyrene matrix. This dual-scale roughness is essential for achieving the Cassie-Baxter wetting state, which traps air and minimizes water-solid contact.

The water contact angle (WCA) measured on the coated glass surface was found to be 166°, indicating outstanding superhydrophobicity. The high contact angle can be attributed to the synergistic effect of the low-surface-energy MTCS groups and the hierarchical roughness imparted by the silica nanoparticles. The sliding angle (SA) was observed to be below 5°, demonstrating excellent water repellency and low adhesion, allowing water droplets to easily roll off the surface. To evaluate the mechanical robustness of the coating, a water jet impact test was performed. The superhydrophobic surface retained its high contact angle and low sliding angle even after continuous exposure to a high-velocity water stream for several minutes. This indicates strong adhesion of the coating to the substrate and mechanical stability of the hierarchical surface features. The success in withstanding water jet impact demonstrates the potential application of this coating in real-world self-cleaning environments, where exposure to rain, spray, or washing is common.

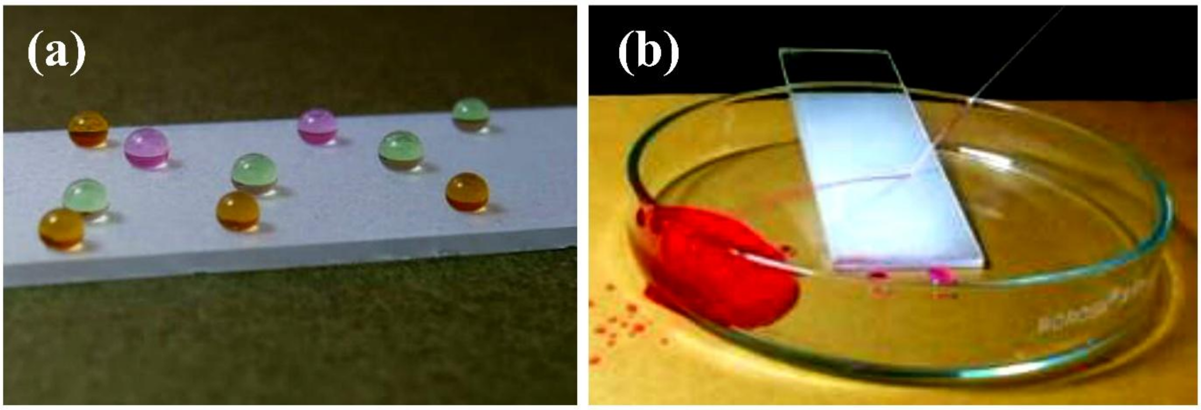

Figure 1. An optical image of (a) different colour water droplets and (b) water jet impact test on superhydrophobic sample.

To evaluate the mechanical and chemical robustness of the superhydrophobic glass samples, a series of durability tests were performed. The variation in water contact angle (WCA) was recorded as a measure of surface wettability. The adhesive tape peeling test (Figure 2a) was conducted to assess the mechanical adhesion and robustness of the coating under repetitive stress. The initial WCA of the pristine surface was 166°, indicating excellent superhydrophobicity. However, with each successive peeling cycle, the contact angle showed a gradual decline. After four tape peelings, the WCA dropped to around 91.2°, suggesting partial removal or deformation of the hierarchical surface structure responsible for hydrophobicity. In the sandpaper abrasion test (Figure 2b), the coated glass substrate was dragged over a standardized abrasive surface to simulate physical wear. The WCA decreased steadily from 166° to about 98° as the total dragging distance increased from 0 to 60 cm. This behavior confirms that abrasion deteriorates the surface texture, thereby reducing the air-trapping ability essential for sustaining superhydrophobicity. While the coating retained some hydrophobic character.

To further assess durability under fluid interaction, a water impact test was performed by continuously pouring water over the surface (Figure 2c). The contact angle remained relatively stable up to 400 mL of water but then exhibited a noticeable decline, reaching 112.4° after exposure to 1000 mL of water. This drop reflects partial damage to the micro/nanoscale roughness or possible leaching of the hydrophobic components, highlighting that prolonged exposure to dynamic water flow can compromise the superhydrophobic performance. In contrast, the coating demonstrated excellent chemical stability when exposed to aqueous water droplets of varying pH values ranging from 2 to 12 (Figure 2d). The WCA remained consistently high across the entire pH range, varying only slightly between 165° and 172°. This indicates that the surface chemistry of the coating is resistant to acidic and basic environments, thereby confirming the chemical robustness of the MTCS-polystyrene-based system.

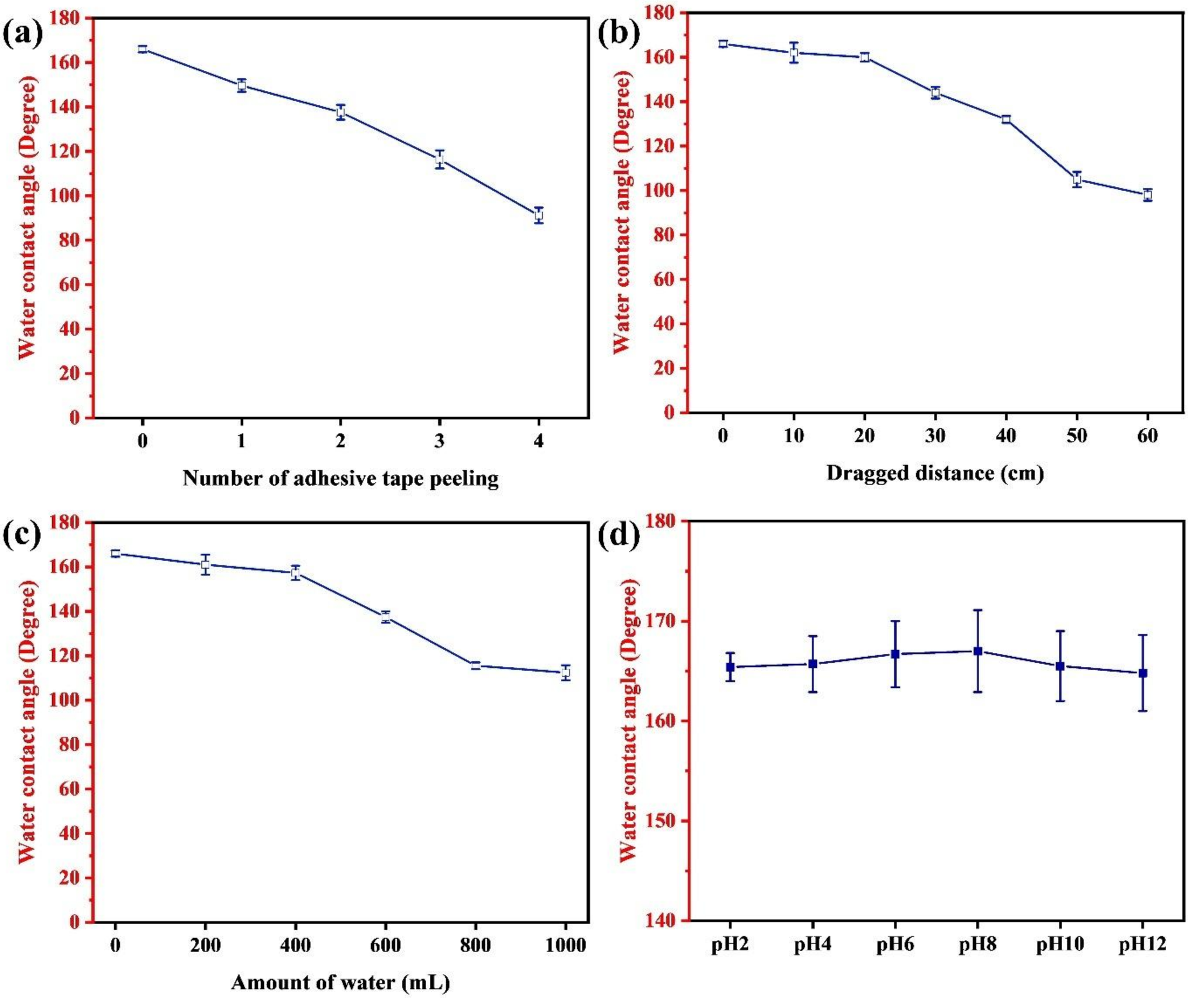

Figure 2. Water contact angle variations under (a) adhesive tape test, (b) sandpaper abrasion test, (c) water droplet impact and (d) different pH water droplets of the superhydrophobic coating.

4. Conclusion

This study reports a superhydrophobic coating by spraying a mixture of MTCS-modified silica nanoparticles and polystyrene onto glass. The surface showed excellent water repellency, with a contact angle of 166°, and stayed highly water-resistant even under strong water jet impact. Furthermore, the prepared sample exhibited good stability under mechanical tests such as adhesive tape test, sandpaper abrasion test and water droplet impact test. Also, excellent resistance to different pH water droplets. Therefore, this simple spray-based coating holds strong potential for real-world applications like self-cleaning glass.

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