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Unveiling the Super-Hydrophobic and Self-Cleaning Properties of CaO Nanoparticles Derived from Oyster Shell for Electrical Sheathing Insulator Applications

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Abstract

This research set out to examine a variety of variables for a full determination of the effects of all factors pertaining to deposition techniques and interactions between nanoparticles and substrates on the hydrophobicity and wettability of surface materials. The hydrophilic and hydrophobic effects on the super-hydrophobic and self-cleaning properties of Calcium Oxide nanoparticles (CaOnp) were examined. The deposition was done on glass and silicone rubber (PDMS) substrates. The microstructure, contact angle hysteresis (CAH), and static contact angle (SCA) were all used to evaluate the characteristics. The results demonstrate that the hydrophobic CaO nanoparticles and PDMS substrate interact synergistically to produce more advantageous hierarchical topologies with lower surface energy. The results show that PDMS in combination with hydrophobic CaO nanoparticles as well as horizontal and vertical drying procedures both satisfy the two requirements for a self-cleaning surface and super-hydrophobic surface.

Keywords
CaO nanoparticles, microstructure, self-cleaning and very hydrophobic surfaces, contact angles

1. Introduction
The distribution and transmission lines in insulating materials have a direct influence on how well power is distributed (Sethi and Manik, 2018). Extreme weather can have an impact on the characteristics of insulating materials used in outdoor applications, leading to surface flashover, insulation failure, and electrical line disconnections from the electrical grid (Ahmad-Kamal et al. 2021; Beitollahpoor et al. 2022). This civilization should use more renewable energy sources and improve its energy net distribution to make the most of its resources.
Due to their high hydrophobicity, polymeric composites have recently taken the role of glass or ceramics in the manufacture of insulator sheathing for outdoor applications (Mendoza et al. 2019; Pierce et al, 2019). High temperature, properties independence, silicone rubber ancestryand poly-dimethyl siloxane (PDMS) has demonstrated practical importance and property in the production of insulators sheath applications. This has been traced to its low surface energy, high flexibility and excellent weather resistance (Miyama et al. 1997; Aigbodion, 2022). The PDMS composites are potentially useful because of their inherent hydrophobicity and strong recovery characteristics (Aigbodion, 2022). These qualities increase environmental resistance to contaminants and boost long-term performance and durability (Miwa et al., 2000), as well as improve lighter weight. Reduced weight lowers transportation and construction costs, strengthens mechanical properties, and decreases conductivity (Elbourne et al., 2017).
However, throughout the course of their useful lives, silicone rubber composite insulators may experience a decline in the ability to act as electrical insulators, which results in the emergence of unfavorable electrical phenomena. Due to the increasing silicone rubber, electrical insulation is lost, which encourages the growth of water layers and conductive dust. Unlike other materials that fall short, the surface characteristics of PDMS enable the restoration of hydrophobicity after corona effects throughout the course of a recovery period. The literature claims that several techniques have been used to ostensibly add various nanoparticles to the silicone rubber's surface. Nanocomposites are of great interest (Elbourne et al., 2017; Nguyen-Tri et al., 2019).Oxides of certain elements, for example; ZnO, SiO_2, Al_2O_3, and MgO have all been combined with silicone rubber to create various nano-sized fillers. Tian et al. (2016) created silicone rubber composites by dip-coating ZnO, Fe_3O_4, and Al_2O_3 onto a variety of surfaces. The major goal of this work was to develop surfaces that were super-hydrophobic and self-cleaning by combining various CaO nanoparticles (CaOnp) produced from oyster shells (hydrophobic and hydrophilic) with the PDMS surface. The use of spraying deposition techniques, horizontal and vertical drying methods; PDMS; and glass substrate was chosen as the operating strategy. The CaOnp derived from oyster shell was used in this work because past researchers has demonstrated the potential of using CaOnp derived from oyster shell as an electroplating material for mild steel (Adams et al., 2022; 2023). The utilization of CaOnp produced from oyster shell can advance understanding in the innovative field and this has not been documented.

2. Materials and Method
Before being placed into teflon molds that were 70 x 20 x 1 mm in size, the PDMS slurry was vigorously stirred for one minute. The PDMS mixture-filled molds were completely cured for 2 hours at 80 °C in an oven after being degassed for 30 minutes under vacuum. The PDMS substrates were cooled to room temperature before being gently taken out of the molds. Prior to the deposition of nanoparticles, the PDMS substrates were washed with isopropanol at 35°C for 20 minutes. The CaOnp was developed from the oyster shell using sol-gel method. Details of the production process are reported elsewhere (Adams et al., 2022; 2023).

In order to create the hydrophilic and hydrophobic CaO nanoparticle solutions, Ebert and Bhushan (2012) methodology was used in a modified form. Hydrophilic and hydrophobic CaO nanoparticles were identified based on the evaluation of contact angle and surface roughness. 30 ml of 96% ethanol were mixed with 35 mg/ml of CaOnp to get a 4.3% yield concentration. The suspensions were treated with an ultrasonicator (VCX 750) for five minutes, PDMS and glass substrates were coated with the two different nanoparticle solutions utilizing the spray deposition experimental techniques and were applied within a 20-minute time window to guarantee that the samples were dried at the same temperature. Two drying techniques—vertical and horizontal drying—were used to simulate and evaluate the different positions of the central body and sheathing HV insulator designed for outdoor use. In order to ensure that the silicone rubber oligomers fully encased the nanoparticles and allowed the solvent to entirely drain from the samples, drying them for a full day was necessary. Surface energy measures, static contact angle measurements, and dynamic contact angle measurements, which included both the changing volume drop and the plane-tilted techniques, were used to evaluate wetability. Five distinct readings were obtained. Equations (1-3) were used to calculate the work of adhesive (Wpw), free energy of surface (Xp), and free energy of interfacial (Xpw).

$$X_p = X_w \frac{(1+Cos\vartheta)^2}{4} \tag{1}$$

$$X_p = X_{pw} + X_w Cos\theta \tag{2}$$

$$X_{pw} = X_p + X_w - W_{pw} \tag{3}$$

The static contact angle is θ, and water surface free energy (Xw) is 72.8 erg/cm^2
A VEGA 3 TESCAN scanning electron microscope was used to evaluate the different morphologies of the coated samples.

3. Results and Discussion

Figures 1-2 show the different microstructures that were developed to explain the samples' superhydrophobicity. It was evident that the structures in Figures 1 and 2 had significant morphological variations. When compared to the blank substrate samples (Figure 1), the PDMS structure (Figure 2) had higher particle roughness and dispersion. In comparison to a blank surface, the silicone rubber helps to promote particle dispersion and roughness, which creates more air holes. This is congruent with what obtains in literature (Ebert and Bhushan, 2012). The hydrophobic properties of the HB caused an increase in the roughness of the surfaces.

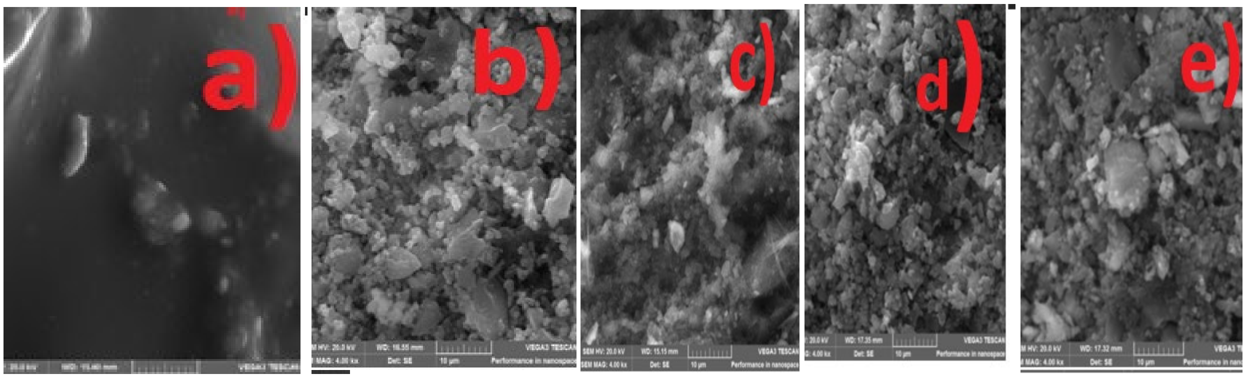

Figure 1: SEM images of Glass sample, a) Glass Blank(GB) b) HP vertically dried (GHPV) c) HP horizontally dried (GHPH) d) HB vertically dried (GHBV) e) HB horizontally dried (GHBH)

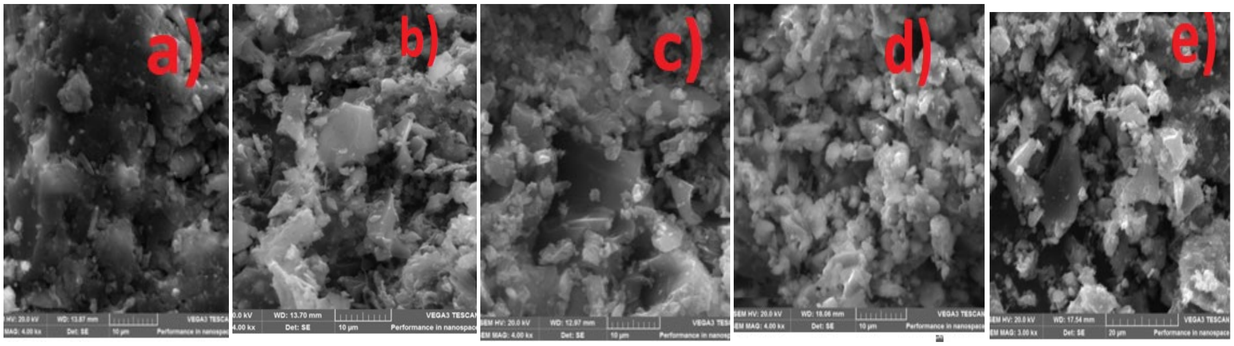

Figure 2: SEM images of PDMS sample, a). PDMS Blank (PB), b). HP vertically dried (PHPV), c). HP horizontally dried (PHPH), d). HB vertically dried (PHBV), e). HB horizontally dried (PHBH)

Figure 3 displays the results of the static contact angle. In contrast to samples with glass substrates, those with hydrophobic (HB) CaOnp showed higher static contact angles, as seen in Figure 1. Hydrophilic (HP) nanoparticles reduce the SCA of the glass substrates for both drying procedures. The hydrophobic nature of the HB resulted in an increase in SCA (Figure 3) and a decrease in surface free energy (Figure 4), when compared to the hydrophilic surface. With a PDMS substrate, SCA increases for both kinds of nanoparticles.

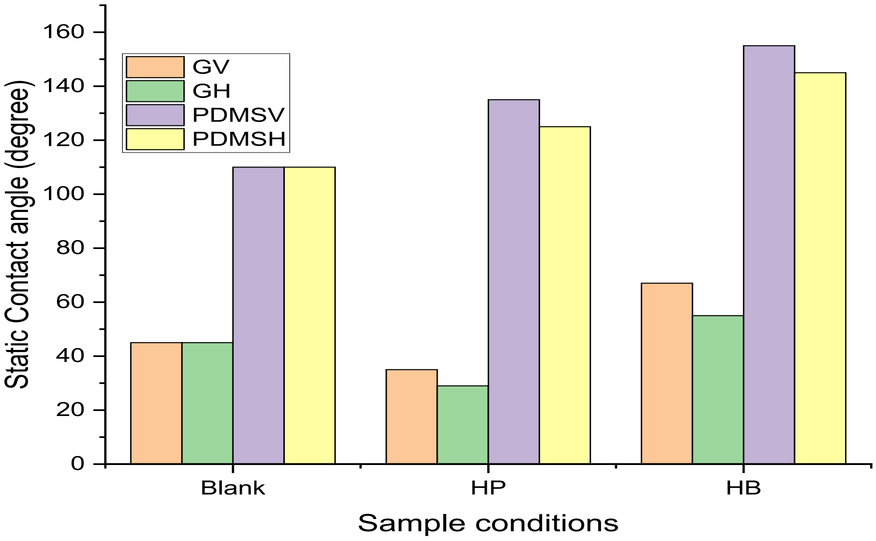

Figure 3: The static contact angle with sample conditions

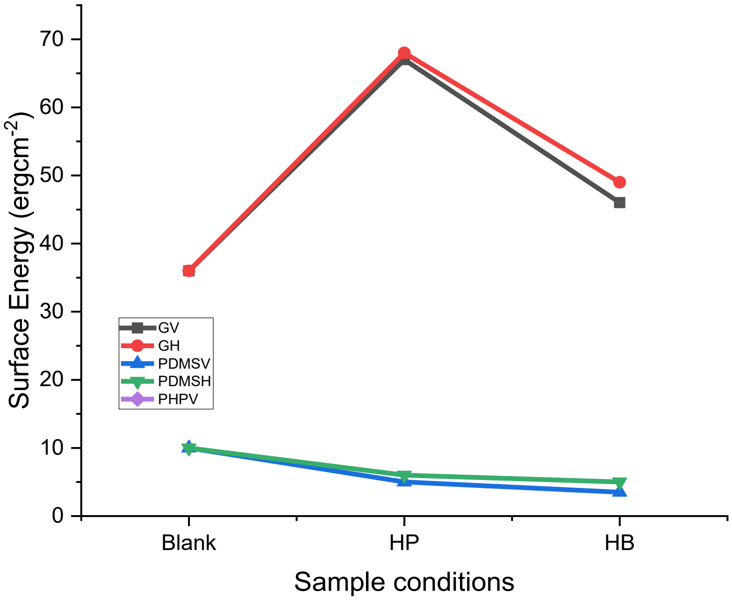

Figure 4: The surface free with sample conditions

According to the SEM pictures, air voids and uniform surface roughness were responsible for the increase in the hydrophobicity of the HB and HP (PDMS) samples. Additionally, the PDMS's low-molecular-weight oligomers serve to cover the CaOnp's whole surface, which aids in the PDMS's ability to regain its hydrophobicity over time (Miyama et al., 1997). Both kinds of CaOnp had different effects on the substrates depending on the deposition process and drying technique; in contrast to the control sample, the HP-containing samples that were dried vertically showed a little increase, but those that were dried horizontally showed a decrease. Improvement in SCA of the vertical dried samples was attributed to the creation of a more uniform, rougher surface that aids in the dispersion of the nanoparticles to cover the entire surface, resulting in high air cavities, and hence the regime of Cassie-Baxter wetting behavior of hydrophobic surfaces. The increase in SCA with HB samples was due to the enhanced compatibility of the PDMS substrate with the covering oligomers of the nanoparticles. The dynamic contact angle (CAH) of each surface was calculated using the receding and advancing contact angles, for super-hydrophobic surfaces without the capacity to self-clean (CAH > 5°), in order to evaluate each surface's ability to clean itself. When a surface has self-cleaning characteristics, the CAH is less than 5°, which macroscopically demonstrates that there is no pinning to the surface and the droplet baseline disappears as soon as liquid withdrawal begins. The contact angle of dynamic (CAH) findings for the samples under investigation is shown in Figure 5. In contrast, the addition of HP to the glass substrates prevented the materials from acting as self-cleaning surfaces. This was ascribed to surface air pockets packed with water that had held the droplets to the surface. This was caused by the hydrophilic nanoparticles' (HP) high wettability, or the strong adhesion between the solid and aqueous surfaces (Ebert and Bhushan, 2012).

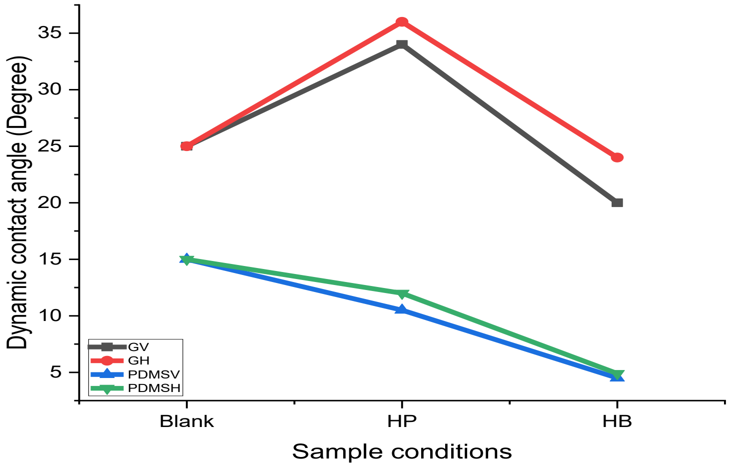

Figure 5: The dynamic contact angle with samples condition

However, after spraying PDMS with HB, the decrease abruptly started to recede, and the CAH was found to be less than 5° (Figure 5). This is because the droplet of the surface was pinned in the samples of sprayed HP on PDMS that had been dried both horizontally and vertically. Similar to how a droplet of water on a leaf lotus only faintly adhered to the surface, the surface is capable of self-cleaning. This behavior is shown by the water droplet in a Cassie-Baxter setting (Ebert and Bhushan, 2012). The only PDMS surfaces that met the two requirements for a self-cleaning surface and super-hydrophobic surface were those made using the spray deposition method in conjunction with hydrophobic CaO nanoparticles and both horizontal and vertical drying techniques (Ebert and Bhushan, 2012).

4. Conclusion

In order to define the adaptive production parameters for generating self-cleaning and very hydrophobic surfaces for sheathing electrical insulators, the effects of CaO nanoparticle generated from oyster shell were explored in this study for the first time. The following conclusion may be drawn from the work: In general, the hydrophobic CaO nanoparticles and the PDMS substrate collaborated to develop more advantageous hierarchical topologies with lower surface energy. The PDMS substrates led to the highest super-hydrophobicity (SCA > 150°). It was therefore shown that the materials' ability to self-clean and exhibit superhydrophobicity was significantly influenced by surface chemistry, drying and CaOnp types. The innovative coating's super-hydrophobic and self-cleaning qualities should be investigated for long-term stability or durability.

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Professor Charles Mbohwa is the Pro Vice Chancellor of the University of Zimbabwe, Harare, Zimbabwe. He obtained B. Sc. Honours in Mechanical Engineering in 1986 from Department of Mechanical Engineering of the same University. He later bagged M. Sc. in Operations Management and Manufacturing Systems with a distinction in 1992, from Department of Manufacturing Systems Engineering, University of Nottingham, UK. He obtained PhD in Engineering (Production Systems focusing on Energy and life cycle assessment) from Tokyo Metropolitan Institute of Technology, Tokyo, Japan in 2004. Professor Mbohwa is an NRF-rated established researcher. In January 2012 he was confirmed as an established researcher making significant contribution to the developing fields of sustainability and life cycle assessment. In addition, he has produced high quality body of research work on Southern Africa. He is an active member of the United Nations Environment Programme/Society of Environmental, Toxicology and Chemistry Life Cycle Initiative, where he has served on many taskforce teams. He has published over 600 research articles in leading international Journals and Conference Proceedings. Prof Mbohwa had been keynote speaker in many international conferences and has supervised many local and international postgraduate students while playing host to several international postdoctoral fellows. He is a visiting Professor to the University of Johannesburg, South Africa, where he had served in various capacities; including Dean of Postgraduate Studies and Executive Dean of Faculty of Engineering and the Built Environment.