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Optimizing Performance of PVC Gel Actuators: Temperature Influence and Characterizations

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Abstract:

Polyvinyl chloride (PVC) gels are in high demand for actuators, so choosing the optimal route for preparing PVC gel is crucial. In the current research work, the PVC gels are prepared from polymer PVC, plasticizer Di-butyl adipate (DBA), and solvent tetrahydrofuran (THF). The temperatures used for the preparation of the PVC gel samples are ranging from 40°C to 70°C. The samples obtained at different temperatures were labeled as PVC40, PVC50, PVC60, and PVC70. Rheological properties of all PVC gel samples were analyzed, revealing that the rheological behavior of the PVC70 gel sample differed significantly from the others due to THF evaporation at 70°C, resulting in inadequate PVC gel preparation. However, PVC40, PVC50, and PVC60 gel samples were chosen for further characterizations, including scanning electron microscopy (SEM), actuation, and mechanical properties evaluation. Moreover, a self-assembled setup was fabricated using electrodes and PVC gel to test the performance of the planar actuator. The maximum displacement of PVC60 was measured at approximately 0.74 mm, and a response time of 0.75 sec under an applied voltage of 1000V. It was observed that the homogeneity of the gel and the solubility of the raw materials, based on resin were influenced by the reaction temperature, suggesting that uniformity could be achieved through dipole-dipole interactions or hydrogen bonding between PVC and DBA (Cl-H…. O=C). Finally, our findings have the potential to contribute to the development of innovative PVC gel actuators.

Keywords: *PVC Gel; Preparation temperature; Characterizations; planar Actuator*

1. Introduction

Electroactive polymers play integral roles in numerous applications, functioning as actuators or resonators and enduring cyclic loading. Consequently, understanding the dynamic response and material failure under varying stimuli becomes paramount. For example, certain polymer gels can undergo shifts in their physical form when exposed to changes in external factors like an electric field, temperature fluctuations, and pH variations, ultimately leading to adjustments in their mechanical energy [1,2]. Electro-stimulation relies on the polar and non-polar properties of the polymer-based gels as well as on the formulating materials i.e. solvents and plasticizers. Notably, PVC Gels demonstrate a remarkable responsiveness to DC voltage, further enhancing their utility in various applications [3]. The low price of raw materials makes PVC gels much more economical. Several factors contribute to PVC gels standing out in the field of flexible actuators.

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PVC gels exhibit an excellent response to DC voltage. A notable phenomenon occurs when the PVC gel is subjected to a DC voltage applied to its surface within a well-designed driving structure. Plasticizer particles and polar molecules, influenced by their inherent polarity, migrate toward the anode within the gel. This migration process leads to the emergence of a surface deformation of the anode that is creeping, as evidenced by previous research [4–7]. It's worth noting that the cost-effectiveness of raw materials employed in this process significantly bolsters its economic viability. Several factors converge to illuminate the prominence of PVC gels within the realm of flexible actuators. Notably, PVC gel stands as a softer iteration of the conventional PVC material, rendering it particularly well-suited for applications in which flexibility is paramount [8]. Despite the widespread interest in soft electro-responsive composite gels for actuator measurements, they have several disadvantages that have restricted their use in practical applications [3,9]. These include factors related to the characteristics of both the polymeric materials, such as physicochemical interactions, response time, deformation, and flexibility, and the filler materials, such as low electrical conductivity and deterioration of mechanical properties [10]. However, when the polymer, such as PVC and filler materials, are combined, an electrical response filler particle network forms, the deformation resulting in actuation [11,12].

PVC gel deformation was assessed by measuring changes in Maxwell and interfacial adhesion forces. The corresponding displacements were measured with great care using image analysis software. Basic tests were carried out to further support the gel's deformation under the influence of an electric field. These studies included measuring forces operating between PVC gel and electrodes and monitoring the motion of chemical ingredients [13]. PVC gel was recently made from electroactive polymer PVC resin using a unique injection molding technique. The solvent-free method produces an environmentally friendly PVC gel product [14]. Our previously reported work highlighted that temperature plays an essential part in manufacturing PVC gels for various applications devices. Inadequate temperature chosen was directed to inadequate resolution, uneven surfaces, low light transmission, and several issues with optical devices. Apart from these applications, the high actuation performance of PVC gel is also important [15]. The polymer PVC, plasticizers, nanofillers, solvents, and electrode materials are essential for an improved electrical response [16,17]. However, the temperature for preparation of PVC gel is key to obtaining the actuator's required various characteristic properties. Therefore, increased deformation could potentially address some of the challenges associated with stimuli-responsive gels. This study primarily focuses on a fundamental approach to enhancing the PVC gel deformation under applied electric forces, aiming to provide a solution to some of the challenges associated with stimuli response gels. More specifically, this study reports the effect of temperature on gel formation. Furthermore, this research reports rheological and morphological analysis results to provide a more in-depth insight into the gel deformation mechanism by understanding the fabricated gels' structure-property correlations. This concept holds significant potential for actuators, artificial muscles and soft robotics applications.

2. Experimental section

2.1. Materials

PVC resin powder with characteristics polymerization degree (n=3000), CAS number 9002-86-2, melting point 170-195 °C), boiling point 0.100 °C, density 1.4 g/mL at 25 °C (lit.), refractive index 1.45, storage conditions 2-8 °C. The DBA plasticizer, CAS number 105-99-7, melting point -32.4 ℃, density 0.962, boiling point 305 ℃, flashpoint >110 in liquid form. The THF solvent with properties CAS number 109-99-9, boiling point 66 ℃, water solubility soluble, density 0.89 g/cm^3, flashpoint -14 ℃ and in liquid form.

2.2. Preparation of PVC Gels

The PVC gel samples were made using PVC resin powder, plasticizer Di butyl adipate (DBA), and tetrahydrofuran (THF). The soft PVC gel samples had a mass ratio of PVC: DBA: THF = 1: 9: 27 and were made from raw materials using the solution casting techniques. The total four PVC gel samples are made at four different range temperatures to examine the impact of reaction temperature on soft PVC gel. The water bath heating device was heated to 40°C, 50°C, 60°C, and 70°C for stirring, with a mixing speed of 1000 rad/min. After thorough mixing, the PVC gel solution was transferred into a 100 mm Petri dish glass. As the solvent was eliminated by drying it for three days at room temperature. Finally, a soft and flexible PVC gel was obtained. The samples were labeled as PVC40, PVC50, PVC60 and PVC70 according to their preparation temperature. Figure 1 illustrates the possible interaction mechanism (hydrogen bonding) between PVC and DBA.

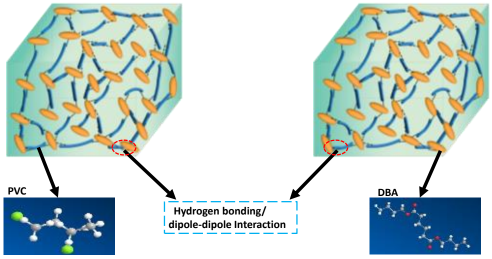

Fig. 1. *The interaction mechanism of physical bonding (hydrogen bonding or dipole-dipole) between PVC and DBA.*

2.3. Charazateration

2.3.1. Rheological

The rheological properties of polymers are important determinants of good interactions within the polymer system. In this study, a torque rheometer was chosen to test PVC gel's rheological properties/Tg. In this test, lower torque values indicate better rheological properties. The testing procedure followed the standard outlined in GB/T34917-2017, utilizing the Torque Rheometer machine (HAAKETM Rheomix OS, Thermo Fisher Scientific Company).

2.3.2. Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) is an electron microscope technology applied to detect the surface structure of powders or films. Thus, provides information on particle morphology, texture size, surface defects, and surface structure [18]. It has a higher resolution and depth of field of view than optical microscopy and is an effective tool for direct observation of surfaces. The electron source and control consolation are two major parts of the SEM. The electron source comprises of an electron gun and two or more electron lenses, which stimulate the electrons to travel along the vacuum tube. Controlling consolation consists of a cathode ray tube, display screen, and computer to generate an electron beam. The gun's job is to produce a stable beam of electrons. In order to obtain a good photomicrograph by SEM recording, it is better to reduce the charge of the conductive sample. In this study, scanning electron microscopy (JEOL jsm-6700f) was used [19,20].

2.3.3. Universal testing machine (UTM)

The mechanical characterizations of polymers, such as the stress-strain response, are largely determined by the interfacial adhesion of the constituent gels. Polymers exhibit three primary types of stress-strain properties: brittle stress-strain, characterized by high strength but very low strain to failure. The rectangular dog-bone shaped samples were cast following ASTM D638-02, a standardized procedure outlining specific methods and specimen geometries for tensile testing. This not only prescribes the sample shape suitable for testing in the Instron, but it is also commonly utilized for typical polymer tension testing [21].

2.3.4. Actuation measurement setup

Figure 2 illustrates the setup schematic to record planar PVC gel actuators' displacement and response time. The displacement of the single-layer actuator is recorded by a laser displacement meter. The glass pasted with soft copper (Cu) tape functions as an anode and a cathode.

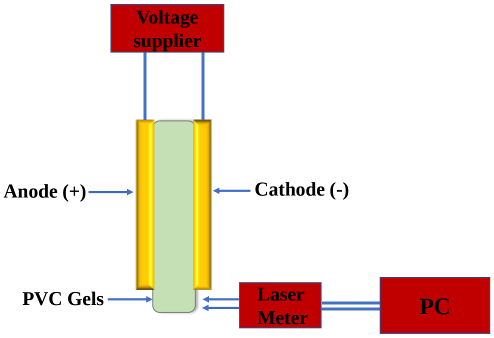

Fig. 2. *Schematic illustration of testing set up for recording the displacement of single layer actuator.*

3. Results and Discussion

3.1. Rheological Properties

The rheological properties of polymers are important determinants of good interactions within the polymer system. For rheological properties analysis, a torque rheometer was chosen to test PVC gel's rheological properties/Tg. In the testing process, the gel samples were cut into small pieces and put into the torque rheometer's rotating chamber with a rotational speed of 50 r/min and a testing temperature of 180°C. The torque parameters of the materials were determined under the above conditions. The specific test results are shown in Figure 3. The torque parameters of the PVC40, PVC,50, PVC60, and PVC70 were obtained as 1, 0.9, 0.4, and 0.5 N.m, respectively. However, PVC60 gel samples exhibit a very low torque (0.2 N-m), proving that the PVC60 group gel has good rheological properties. In this test, the smaller the torque means, the better the rheological properties. Hence, it demonstrated the excellent interaction between DBA and PVC materials when mixed at 60°C.

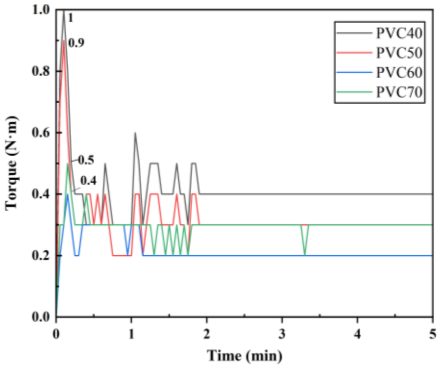

Fig. 3. *Rheological properties of PVC gel samples*

3.2. Surface Morphology Analysis

The surface properties of PVC gels were examined using SEM at different temperatures. The PVC gel samples have been frozen for 12 hours at -20 °C and then dried for 24 hours in a vacuum freeze-drying oven. The surface morphology of the dried PVC gels was studied using gold spraying; the outcomes are shown in Figure 4. Some agglomerations were visible because there was slightly less particle dispersion on the PVC gel samples' PVC40 and PVC50 surfaces. However, it was observed that in comparison to the other two PVC gel samples, the sample PVC60's surface morphology is more standardized and very few PVC agglomerates. As reported in previous work the PVC70 gel sample had poor surface characteristics due to the solvent evaporation and insufficient PVC particle breakdown caused by THF's 66°C boiling point [22]. As confirmed by the SEM pictures, the soft PVC gel developed at 60°C, was an excellent reaction temperature point. Hence, it was also proved that good surface morphology drastically impacted the PVC gel's mechanical and deformations characteristics properties.

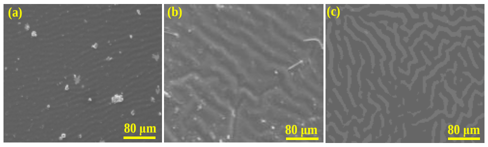

Fig. 4: *SEM images of PVC gel samples (a) PVC40, (b) PVC50, and (c) PVC60*

3.3. Mechanical Properties

In Figure 5, the typical stress-strain relationship obtained from the tensile tests is depicted. The strain and stress of the PVC40, PVC50, and PVC60 samples were obtained as 2.73, 3.25, 3.92 mm and 0.43, 0.42, 0.66 MPa. The first region exhibits a nearly linear behavior up to 0.3% strain, making the modulus measurement possible. The nonlinear behavior of the irregular curve in the second region is likely caused by the occurrence and buildup of potential damage other than fibre breaking [11]. In comparison to area I, the diagram's slope steadily drops. The curve abruptly drops off when the load reaches the breaking point, and the elongation at break may be calculated appropriately. Each tested composite exhibited a strain to failure of less than 5%, indicating the potential for brittle failure. Additionally, the areas under the curves for the treated and untreated fibre composites were 10.45 and 16.85, respectively, indicating that the fibre surface treatment boosts the composite's toughness [23].

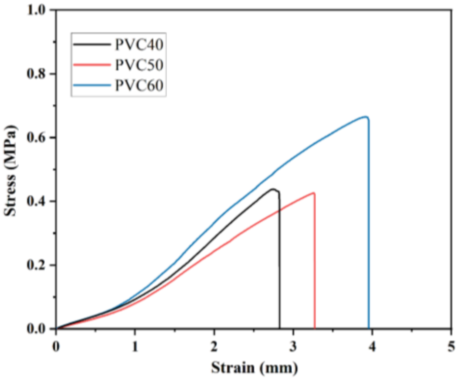

Fig. 5: *Stress and Strain properties of PVC gel samples*

3.4. Performance of PVC gel-based planar actuator

The performance of PVC gel-based planar actuator was analyzed from the parameters such as deformation and response time. The performance parameters of self-fabricated planar actuator were recorded using a displacement meter. Figure 6(a) shows the displacement under applied voltages of PVC40, PVC50, and PVC60 samples, which were recorded at approximately 0.69, 0.74 mm, and at 1000V. However, figure 6(b) shows that the response time of gel samples PVC40, PVC50, and PVC60 were recorded approximately 0.92, 0.85,0.75 sec at an applied voltage of 1000V. The highest displacement of PVC60 is about 0.74 mm, and the response time was 0.75 sec at a given voltage of 1000V. The charge of plasticizer DBA molecules upon the application of voltage was identified as the cause of the deformation induced by the Maxwell stress effect. These results are subjected due to the plasticizer DBA polarization, which caused the PVC matrix chains are opened and allowed DBA to move freely across the PVC gel structure. The cathode's negative charges migrated toward the anode whenever voltage was supplied, resulting in bending deformation. Figure 7 illustrates the bending deformation mechanism of plasticized PVC gels. As seen in Figure 7, PVC60 had the largest displacement and the fastest response time compared to PVC40, and PVC50. This rapid response and high deformation indicate a strong interaction between PVC and DBA. Moreover, because of this deformation, the PVC60 actuator is an excellent choice for planar actuators and artificial muscles.

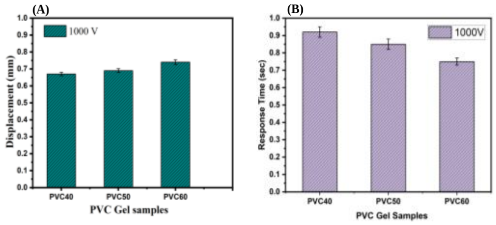

Fig. 6: (a) *Deformation and (b) Response Time of PVC gel samples*

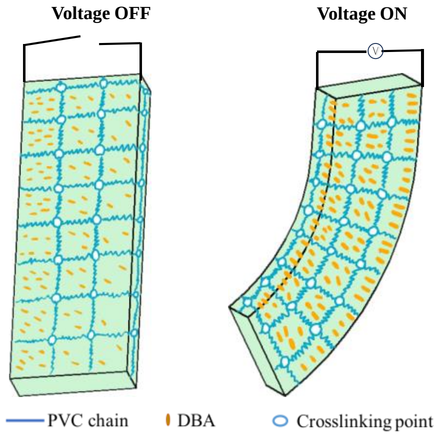

Fig. 7: *The actuation mechanism of PVC gel planar actuator under an induced voltage*

4. Conclusions And Future Recommendations

In this study, we have successfully prepared PVC gels from PVC, DBA, and THF at different reaction temperatures. This research advances the knowledge of electrical responsiveness in polymer PVC gels and the phenomenon of actuation. Particular attention is given to elucidating the role of matrix and DBA materials, physicochemical interactions, and deformation. Latter effects have been parametrically investigated by characterizing the PVC gel's morphology, electro-response, thermal, and mechanical properties. SEM images noted some agglomerations on the PVC40 and PVC50 gel surfaces. As compared to the PVC40, PVC50 gel samples, the PVC60's gel surface morphology is highy uniform and very low PVC agglomerates. As confirmed by the SEM results, the PVC gel fabricated at 60°C was an excellent reaction temperature point. The rheological properties of the materials were examined by torque rheometer, and the results showed that the gels in the PVC60 group had better rheological properties. The achieved results reflect the better interaction between PVC matrix and DBA plasticizer at a reasonable reaction temperature. The PVC60 gel sample showed highest stress and strain compared to PVC40, PVC50, and PVC60. The highest displacement of PVC60 gel sample was about 0.74 mm, and the response time was 0.75 sec at an electric field of 1000V. From the outcomes of current research work, it is anticipated that the major contributions made will be practically more supportive for commercializing prototypes of soft gels-based devices, and robots. Finally, it is suggested that the lifetime or durability of soft actuators, particularly gel-enabled, their structures, and other associated assemblies be increased for future work. The minimal power consumption, practical design approaches, and other issues to meet the required elevated rate of response using biomimetic actuators are also interesting and support the design optimization issue of soft gel products.

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