Effect of Fiber Amount on Piezoelectric Paper's Mechanical and Electro-mechanical Properties

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Abstract

Piezoelectric papers exhibit a coupling of mechanical and electric quantities, which makes them available for sensors. These papers are proven to be a promising substitute for current sensor materials due to their flexibility and environmental friendliness. In this research, we investigated the effect of fiber on mechanical and electro-mechanical properties to simplify the material selection for piezoelectric paper sensors. Piezoelectric papers with different amounts of fiber are tested and compared to determine how the change in fiber amount contributes to the difference in properties. We find that more fiber content increases the fiber network connections and make the physical structure stiffer. However, as the fiber content increases, the strength of the piezoelectric response reaches its threshold and then degrade. The findings provide insights into the material selection for piezoelectric sensors to balance the structure strength and sensitivity.

Keywords: Piezoelectric paper; Fiber amount; Piezoelectric Response; Stiffness

1. Introduction

Piezoelectricity is materials' ability to generate net charges on the surface under the application of external force. Due to this ability, piezoelectric materials are widely used in force sensors, which detect and convert mechanical forces to electric signals (Tressler et al., 1998). About a century ago, piezoelectric materials became a popular research topic (Sappati & Bhadra, 2018). At this stage, most researchers focused on piezoelectric ceramics (Sappati & Bhadra, 2018), which have solid structures and stable piezoelectric behavior. However, piezoelectric ceramics cannot be widely applied in many fields, especially in biomedical devices, since the ceramics are hard, nonbiodegradable, and expensive. To overcome these drawbacks of ceramics, researchers suggested piezoelectric papers as flexible, cost-efficient, and biodegradable substitutes (Mahadeva et al., 2016). Some recent research intends to characterize piezoelectric papers and optimize their performance. Studies on piezoelectric paper characterization have found that poling time and voltage have an important influence on the piezoelectric response (Mahadeva et al., 2013). However, the dependence of the papers' properties on fiber amount has rarely been investigated. We designed this study to give insights into the fiber amount effect on piezoelectric papers' mechanical and electro-mechanical properties. This study focuses on two research questions:

Q1. Is the papers' mechanical strength improved with more fiber?

Q2. How does fiber amount impact the papers' piezoelectric response?

These properties of piezoelectric papers with different fiber amounts are measured and compared. Our results indicate that the mechanical strength increases with fiber amount. However, the piezoelectric response reaches its threshold and decreases at a higher fiber amount. The results will allow developers to decide the appropriate amount of fiber to build devices with proper mechanical strength and piezoelectric response. The findings may also have important implications for optimizing piezoelectric paper fabrication.

2. Method

This study aims to evaluate the fiber amount effect on mechanical strength and piezoelectric response for piezoelectric papers. The piezoelectric papers are fabricated with different amounts of fiber. Their mechanical stiffness and piezoelectric response are evaluated and analyzed in relation to fiber amount.

2. 1 Piezoelectric Paper Fabrication

To study the fiber amount effect, we utilized fiber F300 from 300ml to 700ml to prepare the paper samples. First, the fiber was functionalized via the method proposed by Mahadeva et al. (2014) to obtain the paper substrates. Secondly, the paper substrates were treated in BaTiO3 suspension, which contains 300nm BaTiO3 nanoparticles purchased from US Research Nanomaterials Inc. This treatment would anchor BaTiO3 particles to the substrate. Thirdly, the papers were immersed in sodium carboxymethylcellulose (CMC, AF0705) for 10 hours to secure the anchored BaTiO3 particles. Finally, the papers were subject to corona poling for 4 hours at 122°C, which is around BaTiO3's curie temperature. After poling, which exerted an external electric field onto the papers, the BaTiO3 particles would get aligned and exhibit net piezoelectric behavior.

2. 2 Paper Characterization

Scanning electron microscopy (SEM) was applied to view the microstructure of the hybrid papers and check the attachment of BaTiO3 particles. The compressive modulus is defined as:

$$E = \frac{d\,\sigma}{d\,\varepsilon} \tag{1}$$

where E is the compressive modulus, σ is the stress on paper and ε is the strain. The compressive modulus of the papers was tested using dynamic mechanical analysis (DMA). In DMA testing, compressive loading that increases from 2 to 10N in 4 minutes was applied to 5mm-by-5mm square paper samples. The DMA test machine generated a stress-strain curve, in which the slope is determined as the compressive modulus (Equation 1). It should be noted that the slope generally drops as the loading increases. The overall slope of the curve is taken as the mechanical modulus. Therefore, the modulus cannot accurately demonstrate the papers' behavior at a specific loading.

The piezoelectric constants are also measured to show the strength of the piezoelectric response. The piezoelectric constants, d_{33}, are defined as:

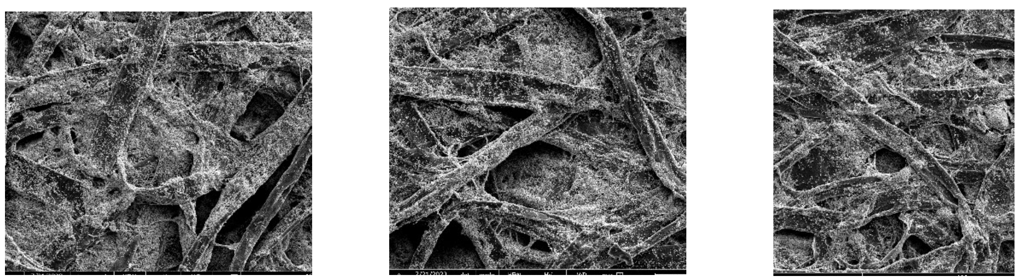
$$d_{33} = \frac{Q_3}{F_3} \tag{2}$$

where Q_3 is the induced charge on both sides of the paper and F_3 is the force normal to the paper surface. The d_{33} is examined by measuring the induced charge under loading. After applying loading to 20mm-by-20mm paper samples, the induced charge is measured using a charge meter. The piezoelectric constant is calculated as the ratio of the induced charge to the applied load.

All the tests above are performed in room environments at about 25°C and a relative humidity rate of around 50%.

3. Results and Discussion

The microstructure in the paper samples is examined via photos from SEM (Fig. 1). As shown in the microscopic images, BaTiO3 particles are anchored to the fiber network. The particles ensure that the hybrid papers can be rendered with piezoelectric properties after poling. The network has more fiber connections and less void space as the fiber amount increases, indicating a stronger and stiffer mechanical structure.



(a) (b) (c)

Fig. 1 SEM Images of Paper Composite with Different Fiber Amounts.
(a) 300 mL, (b) 400 mL, (c) 500 mL.

This observed tendency is confirmed by the results from DMA testing, where sinusoidal loading is exerted on the paper samples (Fig. 2). Papers with more fiber generally exhibit stiffer behavior. The results are consistent with Ham et al.'s (2020) findings, in which it is reported that increasing fiber amount helps improve the mechanical stiffness of the fiber network.

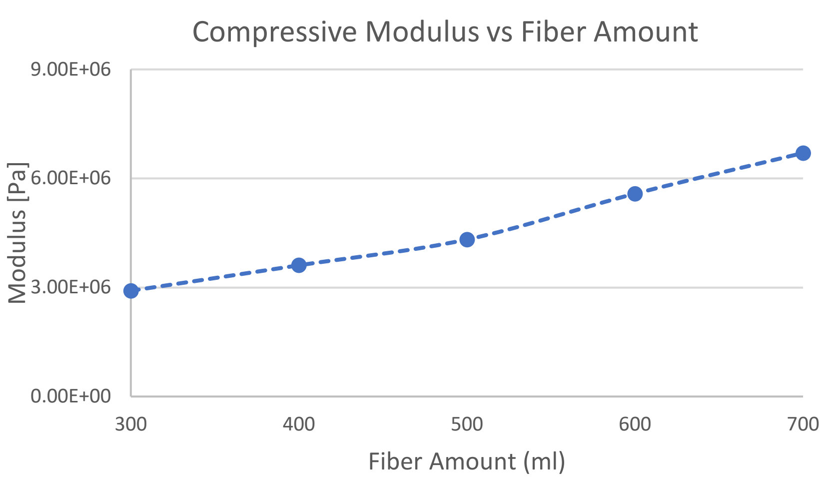


Fig. 2 Compressive Modulus at Different Fiber Amounts

The piezoelectric constants (d33), which indicate the strength of piezoelectric performance, are determined as the ratio of the induced charge to the applied loading. The piezoelectric constant (Fig. 3) reaches its threshold (17.5 pC/N) at 500ml fibers and then drops as the fiber amount increases. Our explanation of the curve is that more fiber can provide more surface area for anchoring the $BaTiO_3$ particles, improving the papers' piezoelectricity. However, after the fiber amount exceeds 500ml, the fiber network may get crowded and cannot provide much room for the nanoparticles.

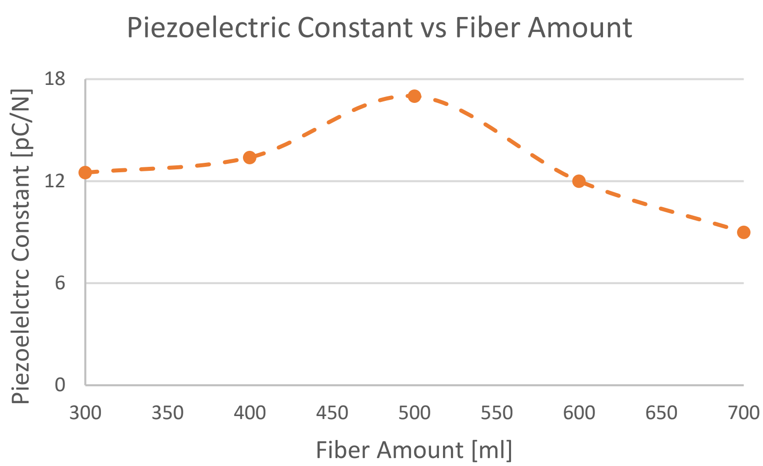


Fig. 3 Piezoelectric Constant at Different Fiber Amounts

We presented the piezoelectric constants immediately after poling to keep the results consistent. However, we noticed an interesting phenomenon that piezoelectric response varies with time. For instance, the paper with 600 ml fibers has a piezoelectric constant of 12.2 pC/N immediately after poling. The value degrades to 8.7 pC/N after 24 hours and then goes up to 14pC/N after one week. To explain this phenomenon, we hypothesize that the piezoelectric constant can be affected by temperature, humidity, or other environmental factors that change with time. The phenomenon could be a valuable topic for future research.

4. Conclusion

In this study, we measured the effect of fiber content on piezoelectric papers' stiffness and piezoelectric response. We found that the fiber amount positively affects the papers' stiffness. However, we found a threshold in the piezoelectric constant, after which increasing fiber content leads to degradation in the piezoelectric response. The finding could help the material selection for piezoelectric devices that require both piezoelectric response and mechanical strength. In following research, more electro-mechanical properties could be studied to evaluate the fiber amount effect. The evolution of piezoelectric properties over time could also be a valuable topic for optimizing piezoelectric papers.

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