Long-Term Performance of Activated Wood Carbon Printed Supercapacitors: A Sustainable Alternative to Conventional Activated Carbon

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Abstract— **Supercapacitors (SCs) exhibit high power density, rapid charge-discharge capability, and an extended lifecycle, making them highly promising candidates for energy storage applications. Biomass-derived activated carbon (AC) has gained increasing attention for use as an electrode material in SCs due to its sustainability and eco-friendly nature. In this study, activated wood carbon (AWC) is employed as a sustainable electrode material for printed SCs. The long-term performance of AWC-based printed SCs using two aqueous, environmentally friendly electrolytes (NaCl and $K_xH_yPO_4$) over 10,000 charge-discharge cycles is assessed and compared to that of printed SCs fabricated with commercially available Kuraray YP-80F.**

The results of this study confirm that the AWC printed SCs show comparable, or even superior, capacitance retention compared to YP-80F printed SCs, particularly when using $K_xH_yPO_4$ electrolyte. In particular, AWC 2-800 and 3-800 printed SCs demonstrate better capacitance retention at the end of 10,000 cycles, with 94.9% and 95.0%, respectively; while YP-80F printed SC exhibits 90% capacitance retention. These findings underscore the potential of AWC materials as a promising alternative to conventional AC materials, facilitating the development of effective solutions for high-performance and sustainable energy storage systems.

Keywords—Supercapacitors; Activated wood carbon (AWC); Sustainable energy storage; Biomass-derived AC; Long-term performance; Capacitance retention; NaCl electrolyte; $K_xH_yPO_4$ electrolyte; Printed electronics

I. INTRODUCTION

The overconsumption of fossil fuel resources and the excessive release of greenhouse gases have led to numerous challenges, including climate change and air pollution [1]. Hence, it is essential to transition to renewable energy sources such as solar, wind, and hydroelectric power [2]. However, these resources are intermittent by nature, and this would require the development of efficient and reliable energy storage system technologies [3].

Among all energy storage solutions, supercapacitors (SCs) have proven to be more promising candidates due to their higher power density, rapid charge-discharge capability, and extended lifespan [4]. These properties make SCs suitable for applications like artificial intelligence (AI) systems [5], energy autonomous Internet of Things (IoT) [6], and wearable electronic devices [7], and self-powered wireless sensor networks [8].

SCs can typically be categorized into two primary types: electrochemical double-layer capacitors (EDLCs) and pseudocapacitors [9]. EDLCs store energy through the accumulation of non-faradaic charge at the electrode-electrolyte interface, whereas pseudocapacitors employ rapid redox reactions at the surface or near-surface to achieve larger capacitance values [9]. In most cases, SCs are attributed to EDLC-type, and this is also the case in this research.

Activated carbon (AC) is at the forefront of materials utilized as SC electrodes due to its high surface area, superior electrical conductivity, and cost-effectiveness. Over the past decade, biomass-derived AC has gained growing interest as a promising sustainable material for SC electrodes due to its renewability, adjustable porosity, and minimal environmental impact [10].

As for the SC electrode applications, various biomass feedstocks, including wood waste [11], nutshells [12], and agricultural residues [13], have been investigated. Among them, carbonized wood (CW) has exhibited remarkable potential owing to its hierarchical porous structure, lightweight nature, and chemical stability [14]. The inherent anisotropic channels present in wood-derived carbon enhance ion transfer, establishing it as a promising material for high-performance energy storage applications.

In order to manufacture SCs, one of the most efficient, advanced, and promising methods in recent years has been the utilization of printing techniques, enabling lightweight, flexible, and customizable energy storage solutions [15]. Printing allows for precise control over the electrode architecture and minimizes material waste. Additionally, it supports roll-to-roll manufacturing for large-scale production. Furthermore, it would be feasible to integrate printed SCs into wearable electronics [16], IoT devices [17], and wireless sensor networks [18].

In this study, activated wood carbon (AWC) is utilized as the SC electrode material, and the performance of printed SCs fabricated using AWC is evaluated over long cycling periods.

The results are compared to printed SCs fabricated using commercially available AC (Kuraray YP-80F). Regarding the electrolytes, two types of aqueous electrolytes, NaCl and $K_xH_yPO_4$, are chosen for their environmental friendliness and compatibility with carbon electrodes. The electrochemical results of printed SCs fabricated using AWC materials have been previously published by the authors, demonstrating up to a 90% increase in specific capacitance and energy density compared to SCs fabricated using commercial YP-80F [19].

II. Materials and Experimental Methods

A. Materials

The electrode materials employed for the fabrication of printed SCs comprise four variations of AWC materials (AWC 2-700, 2-800, 3-700, and 3-800), as well as the commercially available Kuraray YP-80F for comparison. The activation method and material characterization data for the AWC materials have been documented in previous work by the authors [19]. In addition, AWC ink formulation and fabrication, electrolyte preparation, and the fabrication and characterization of printed SCs have also been reported in detail in [19]. However, Fig. 1 provides a schematic summary of the activation process of AWC materials and the fabrication of printed SCs. The abbreviated name of the material indicates the ratio of the activation agent (NaOH) and the activation temperature. For example, AWC 2-700 refers to a NaOH ratio to carbon of two and an activation temperature of 700°C, as described in [19].

B. Experimental Method

In order to evaluate the long-term performance of the printed SCs, they were charged and discharged at a constant current of 10 mA up to 1.2 V for 10,000 cycles, with capacitance measured and recorded at the end of every 100 cycles. Maccor 4300 workstation (Maccor Inc., USA) was used for the measurements.

III. Results and Discussion

A. Long-term Performance of YP-80F SCs with NaCl and $K_xH_yPO_4$

The initial capacitance of the YP-80F SC with NaCl electrolyte was 260.4 mF. After 2,000, 3,000, and 10,000 cycles, the capacitance decreased to 237.8, 236.1, and 235.4 mF, respectively (as can be seen in Fig. 2a), indicating 90.4% capacitance retention after 10,000 cycles.

For the YP-80F SC with $K_xH_yPO_4$ electrolyte, the initial capacitance was 274.8 mF. After 2,000, 3,000, and 10,000 cycles, the capacitance declined to 249.8, 248.1, and 247.4 mF, respectively, as illustrated in Fig. 2b. This indicates a capacitance retention of approximately 90% after 10,000 cycles.

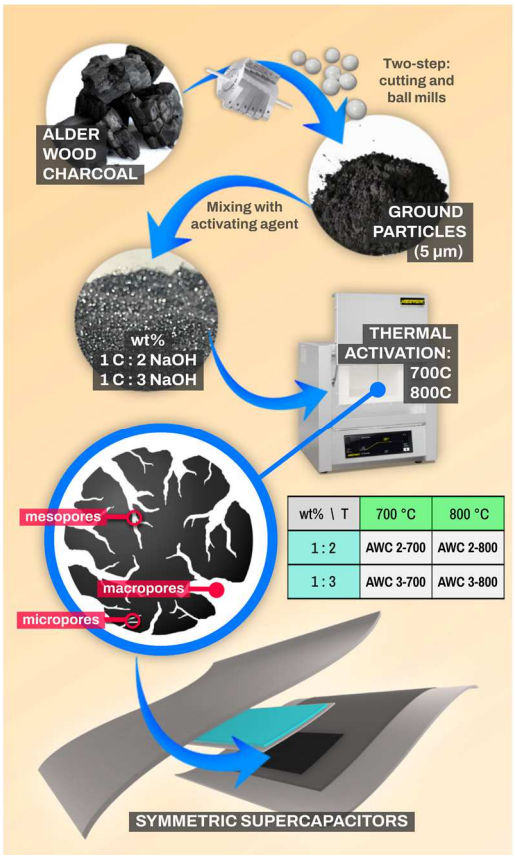

Fig. 1. Schematic summary of the activation process of AWC materials and the fabrication of printed SCs.

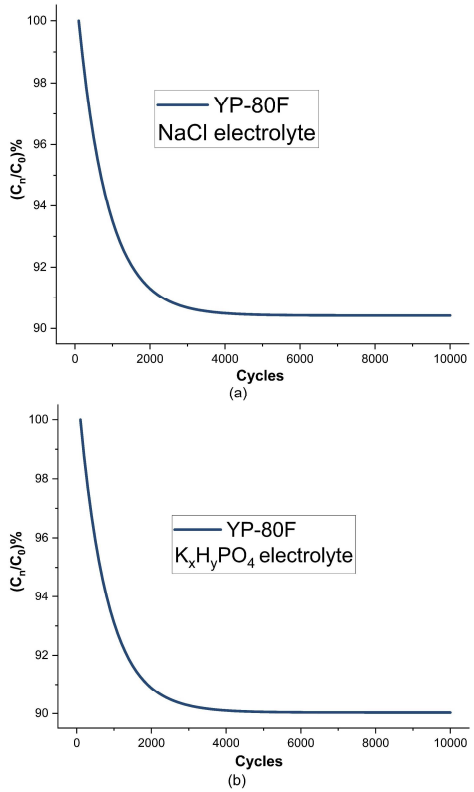

Fig. 2. Capacitance retention of YP-80F SCs with (a) NaCl, and (b) $K_xH_yPO_4$ electrolytes over 10,000 cycles.

B. *Long-term Performance of AWC SCs with NaCl*

The long-term performance of printed SCs fabricated using four variations of AWC materials and NaCl electrolyte is presented in Fig. 3. The capacitance retention values for AWC 2-700, 3-700, 2-800, and 3-800 after 10,000 cycles are 91.2%, 90.6%, 90.8%, and 91.3%, respectively, which is comparable to that of the YP-80F SC. Similar to the YP-80F SCs, the AWC SCs using NaCl electrolyte exhibited the most significant capacitance decline during the first 2,000 cycles. Beyond this point, the rate of capacitance decrease was minimal, making the reduction in capacitance from 2,000 to 10,000 cycles negligible.

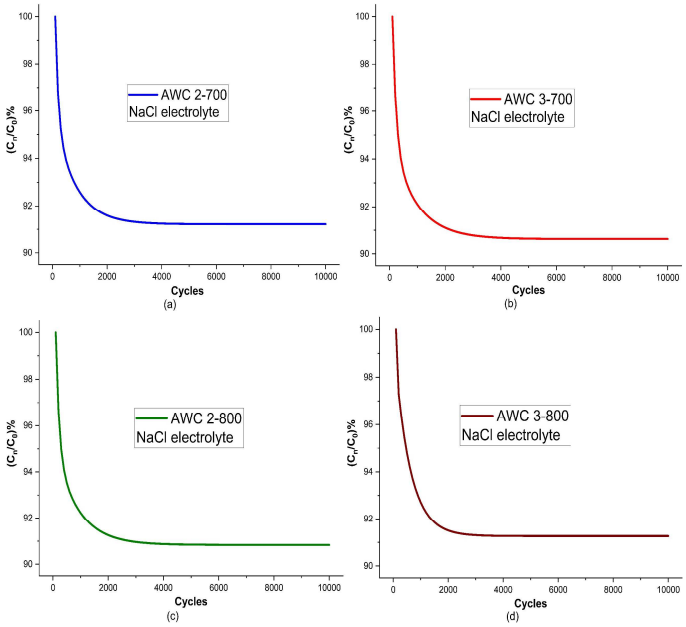

Fig. 3. Capacitance retention of AWC SCs with NaCl electrolyte over 10,000 cycles.

C. *Long-term Performance of AWC SCs with $K_xH_yPO_4$*

Fig. 4 presents the long-term cycling performance of AWC SCs fabricated with $K_xH_yPO_4$ electrolyte. The capacitance retention of AWC 2-700, 3-700, 2-800, and 3-800 after 10,000 cycles is 92.7%, 91.9%, 94.9%, and 95.0%, respectively, exceeding that of YP-80F SCs.

As demonstrated in Fig. 4a, and 4b, AWC 2-700 and 3-700 SCs exhibit similar long-term performance to YP-80F, as their capacitance declines more significantly during the first 2,000 cycles, and from 2,000 to 10,000 cycles, their capacitance values remain approximately constant.

However, AWC 2-800 and 3-800 SCs exhibit significantly better capacitance retention after 10,000 cycles compared to YP-80F SCs. Moreover, their long-term performance differs from that of YP-80F SCs, as their capacitance does not remain nearly constant between 2,000 and 10,000 cycles. The initial capacitance of AWC 2-800 is 488.9 mF. After 2,000, 5,000, and 10,000 cycles, it decreases to 476.4, 472.5, and 464.2 mF, respectively, as presented in Fig. 4c. For AWC 3-800, the initial capacitance is 356.3 mF. After 2,000, 3,000, and 10,000 cycles, it drops to 344.1, 341.5, and 338.5 mF, respectively, as shown in Fig. 4d.

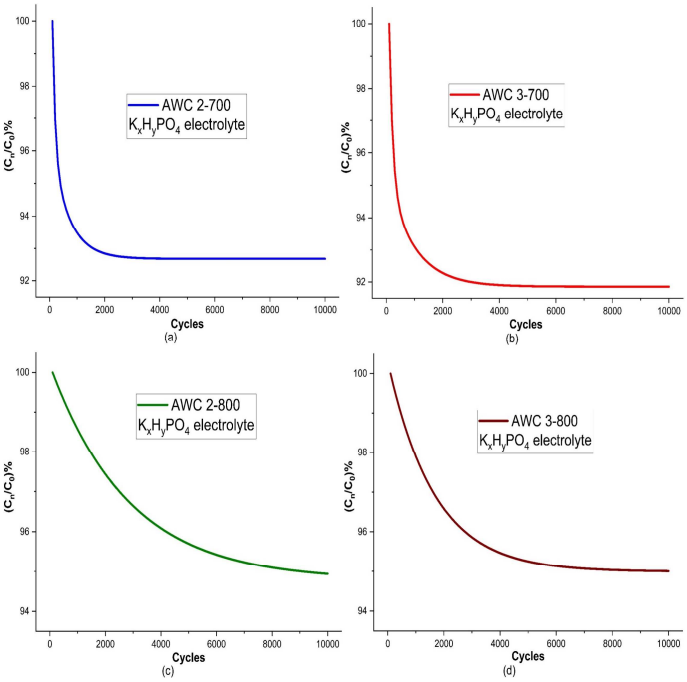

Fig. 4. Capacitance retention of AWC SCs with $K_xH_yPO_4$ electrolyte over 10,000 cycles.

The outstanding capacitance retention of AWC 2-800 and 3-800 over the long term is most likely attributed to their reduced surface oxygen content and enhanced graphitization degree. A higher activation temperature (800°C) decreases oxygen functional groups and contributes to structural stability by mitigating electrode degradation and suppressing parasitic redox reactions. In addition, enhanced graphitization improves electrical conductivity and mechanical integrity, resulting in reduced resistive losses and preventing structural collapse over extended cycles.

IV. Summary and Conclusion

This paper examines the long-term performance of AWC-based printed SCs employing two eco-friendly aqueous electrolytes (NaCl and KxHyPO4) in comparison with commercial Kuraray YP-80F printed SCs. The results demonstrate that AWC printed SCs maintain excellent capacitance retention after 10,000 charge-discharge cycles, indicating comparable or even superior long-term performance relative to YP-80F printed SCs.

Notably, AWC 2-800 and 3-800 printed SCs attain remarkable capacitance retention of 94.9% and 95.0%, respectively, when utilizing the KxHyPO4 electrolyte. In contrast, YP-80F printed SCs retain only 90% of their initial capacitance under similar conditions. The long-term performance of AWC printed SCs with NaCl electrolyte is also analogous to that of YP-80F SCs, presenting capacitance retention above 90% for all four AWC variations. These results emphasize the potential of AWC materials as a sustainable

alternative to conventional AC materials, providing superior performance and a longer lifetime in printed SC applications.

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