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Study on Two-Step and Low-Temperature Wet Activation of Residual Carbon Derived from Coal Gasification Fine Slag and Its Electrochemical Performance for Supercapacitor

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ABSTRACT: Supercapacitors are promising electrochemical energy storage devices because of their high power density, fast charge–discharge rate, and long cycle life. The development of low-cost and high-performance carbon electrode materials is crucial for improving their practical application. Herein, residual carbon (RC) from coal gasification fine slags (CGFSs) was used as a carbon precursor to prepare low-cost carbon electrode materials (RCHK-X) through HNO₃ pre-activation followed by KOH activation. HNO₃ treatment introduced abundant oxygen-containing functional groups, while subsequent KOH activation further enhanced the surface functionality and specific surface area, removed part of the nitrogen-containing species introduced during acid treatment, and generated more defects and electrochemically active sites. The optimized RCHK-3 sample exhibited a specific surface area of 775 m² g⁻¹ and a low contact angle of 35.0°, suggesting favorable ion accessibility and surface wettability. When used as a supercapacitor electrode, RCHK-3 delivered a specific capacitance of 155 F g⁻¹ at 0.5 A g⁻¹ and maintained 99.03% of its capacitance after 10,000 cycles. This work demonstrates an effective strategy for converting CGFS-derived residual carbon into value-added electrode materials and provides guidance for designing porous carbon materials for high-performance supercapacitors.

Key Words: Coal gasification fine slags; Wet activation; Electrochemical performance; supercapacitor.

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1. Introduction

China is a global leader in coal gasification, with a syngas production capacity exceeding 30 million m³/h^[1]. During coal gasification, inorganic minerals undergo a series of physical and chemical transformations, resulting in the formation of solid residues known as coal gasification slags (CGSs)^[2]. In recent years, with the rapid development of coal gasification technologies in China, the annual generation of CGSs has exceeded 60 million tons^[3]. However, only a very small fraction of this CGSs is effectively utilized, while the remainder is directly discarded or landfilled. This not only leads to a serious waste of land resources, but may also pose risks of soil and water contamination in the event of leachate leakage^[4]. Approximately 30% of CGSs is fine slags, which contains 20%-40% unburned RC^[5,6]. At present, the comprehensive utilization rate of RC in CGSs remains low, and it is mainly treated by co-combustion for energy recovery. This approach inevitably emits carbon oxides and may also result in adverse economic impacts^[7,8]. Against the backdrop of the global transition toward a green circular economy, the efficient and value-added utilization of CGFSs has become an urgent challenge in the field of coal chemical engineering.

Carbon-based materials have been widely applied in advanced electrochemical devices and environmental remediation owing to their excellent chemical stability, good electrical conductivity, abundant surface functional groups, and porous microstructures^[9]. The development of high-performance carbon materials via the activation of carbon-containing wastes is highly attractive from both scientific and practical perspectives, providing an effective strategy for addressing solid-waste disposal and energy-related issues^[10]. Due to its high residual carbon content, low cost, and inherent porous structure^[11], RC from CGFSs has been extensively investigated for applications such as CO₂ capture and wastewater purification. For example, Zhu et al.^[12] used RC from CGFSs as the precursor and KOH as the activating agent, and obtained porous materials with a high specific surface area after activation at 800°C for 1 h, which were applied for CO₂ adsorption. Luoyang et al.^[13] prepared carbon-based adsorbents from RC in CGFSs using a two-step acid-alkali treatment. Specifically, the

RC was first reacted with HNO_3 at 130°C for 150 min, followed by mixing with NaOH and reaction at 90°C for 6 h. The resulting adsorbent was used for methylene blue removal from wastewater, exhibiting a maximum adsorption capacity of 735.29 mg/g.

Nevertheless, the annual recycling and utilization rate of CGFSs remains below 30%^[14]. Therefore, it is necessary to further expand its utilization pathways to improve the overall recycling efficiency of CGFSs. In recent years, with the rapid development of the new energy industry, supercapacitors have attracted considerable attention due to their high power density and fast charge-discharge capability. Hybrid energy storage systems composed of supercapacitors and batteries play an important role in new energy vehicles and grid-scale energy storage systems^[15,16]. Carbon-based materials are currently the most widely used and technologically mature electrode materials for supercapacitors, and can be derived from diverse sources, including biomass, graphite, carbon nanotubes, and other carbonaceous precursors^[17]. Owing to its unique structure and low cost, RC from CGFSs can serve as an ideal precursor for supercapacitor electrode materials. Some studies have already reported the preparation of carbon-based electrode materials from coal gasification fine slag residual carbon for supercapacitor applications. Tian et al.^[18] used CGFSs as the carbon source. The CGFSs was first mixed with NaOH at 400°C to remove impurities and obtain RC, which was then mixed with KOH and activated at 800°C for 1 h under a nitrogen atmosphere. The prepared porous carbon exhibited a specific surface area of $2167.54\text{ m}^2/\text{g}$ and delivered a specific capacitance of 219.67 F/g at a current density of 1 A/g. Zhang et al.^[19] mixed CGFSs with KOH and activated the mixture at 850°C for 1 h, followed by washing and drying to obtain activated carbon. The resulting material had a specific surface area of $1464.39\text{ m}^2/\text{g}$ and achieved a specific capacitance of 226.9 F/g at 1 A/g.

These studies demonstrate the feasibility of using RC from CGFSs as a carbon source for preparing supercapacitor electrode materials. However, current activation strategies for coal gasification fine slag residual carbon are mainly based on high-temperature KOH activation. In contrast, the preparation of carbon-based electrode materials via low-temperature wet activation has rarely been reported. If high-performance carbon-based electrode materials can be prepared through low-

temperature wet activation, the energy consumption associated with high-temperature activation can be reduced, and the corrosion or damage of equipment caused by chemical reagents under high-temperature conditions can be alleviated. Therefore, in this study, CGFSs was employed as the precursor to prepare carbon-based electrode materials via low-temperature wet activation. The effects of activation temperature on the structure and electrochemical performance of the resulting carbon electrode materials were systematically investigated, with the aim of establishing the relationship among activation conditions, material structure, and electrochemical properties. This work provides a useful reference for the high-value utilization of CGFSs.

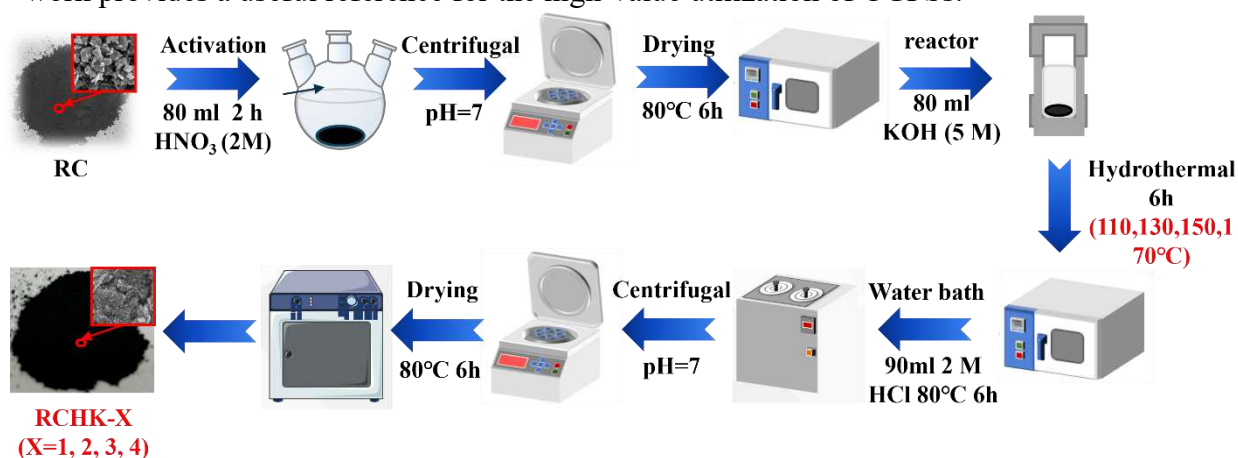


Fig. 1. Preparation route of RCHK-X.

2. Experimental section

2.1 Materials

The residual carbon (RC) was obtained by the gravity separation method from CGFSs. The process was completed by a coal chemical plant in Inner Mongolia. The obtained RC was utilized as the raw material in this experiment. The following reagents were bought from Shanghai Aladdin Biochemical Technology Co: potassium hydroxide (KOH, 85%), nitric acid (HNO₃, 65%), hydrochloric acid (HCl, 37%), acetylene black, and polytetrafluoroethylene (PTFE).

2.2 Preparation of porous activated carbon

After being pre-activated with HNO₃ for 2 h, 1 g RC (residual carbon) and 80 ml of 5 M KOH were placed into a high-pressure autoclave and then heated at activation temperatures of 110°C, 130°C, 150°C, and 170°C for 6 h. After cooling to room

temperature, the supernatant was decanted, and 90 ml of 2 M HCl was added to the precipitate at the bottom. This mixture was treated in an 80°C water bath for 6 h, followed by centrifugation with deionized water until the pH=7. The material was then vacuum-dried at 80°C for 6 h to obtain the carbon electrode materials. The activated carbon electrode materials were named RCHK-1, RCHK-2, RCHK-3, and RCHK-4, corresponding to the ascending order of activation temperatures.

To investigate the impact of the sequence of acid and alkali activation on the structure and electrochemical performance of the prepared carbon electrode materials, a process involving initial activation with KOH followed by HNO₃ activation was employed. The resulting carbon electrode materials were named RCKH-1, RCKH-2, RCKH-3, and RCKH-4, in ascending order of activation temperatures.

2.3 Structural characterization

N₂ adsorption-desorption isotherms were obtained at -196°C using an ASAP 2460 nitrogen analyzer to estimate the specific surface area. The structure and morphology of the materials were analyzed using a scanning electron analyzer (Regulus 8100, Hitachi, Japan). Thermal stability was analyzed by thermogravimetric analysis using an STA 449 F3 integrated thermal analyzer. HORIBA (HR800) Raman spectrometer analysis was done to determine the structural properties of the carbon material and to detect vibrational energy levels. X-ray photoelectron spectrometer, ESCALAB model 250XI, was used to determine the elemental types of the samples, as well as the chemical state of the elements. The X-ray analyzer D8 ADVANCE from Bruker AXS was used to obtain composition and crystal structure data based on X-ray patterns. The contact angles between the materials and the KOH aqueous solution were demonstrated using a HARKE-SPCA tester from Beijing HARKE.

2.4 Electrochemical measurements

The prepared carbon electrode materials (80%), acetylene black (10%), and PTFE (10%) were mixed in ethanol to form a uniform slurry. This mixture was then evenly coated on clean and dry nickel foam sheets. The electrochemical performance of the samples was measured using a CHI660E electrochemical workstation.

The assembly process for the symmetric supercapacitor was as follows: Circular nickel foam sheets were used as current collectors, and the superior performing RCHK-

3 material was prepared into a slurry as described above, then evenly coated on the circular nickel sheets. Two electrodes of equal mass were selected and assembled in the order of electrode, separator, and electrode to form a button-type supercapacitor (RCHK-3//RCHK-3).

The electrochemical properties of the samples were assessed using a CHI 660E electrochemical workstation in a three-electrode system with 6M KOH solution as the electrolyte. The specific capacitance per unit mass was calculated using the equation^[20].

$$C = \frac{I\Delta t}{m\Delta V} \quad (1-1)$$

Herein, C (F/g) is the specific capacitance, I (A) is the current, Δt (s) is the discharge time, m is the mass of the active electrode material, and ΔV (V) is the change in discharge voltage.

The specific capacitance per unit mass of electrode material in a two-electrode system is calculated according to the following equation^[21].

$$C = \frac{2I\Delta t}{m\Delta V} \quad (1-2)$$

Herein, C (F/g) is the specific capacitance, I (A) is the current, Δt (s) is the discharge time, m is the mass of the active electrode material, and ΔV (V) is the change in discharge voltage.

The energy density (E) and power density (P) of the capacitor are calculated according to the following equations^[22].

$$E = \frac{1}{2} C \Delta V^2 \frac{1}{3.6} \quad (1-3)$$

$$P = \frac{3600E}{\Delta t} \quad (1-4)$$

Herein, C (F/g) is the mass-specific capacitance of the symmetric capacitor, Δt (s) represents the discharge time and ΔV (V) refers to the change of discharge voltage.

3. Results and discussion

3.1 Structural characterization

XRD and Raman spectroscopy were used to investigate the microcrystalline structure of the materials. Fig.2(a) exhibits two diffraction peaks around $2\theta=23.5^\circ$ and 44° for five materials, correlating to the typical (002) and (100) planes of graphite carbon^[23]. Peaks corresponding to the (100) and (011) planes of SiO₂ are also present

in RC^[24]. XRD patterns indicate that SiO₂ is effectively removed through HNO₃ and KOH activation^[25]. Fig.2(b) displays the Raman spectra with two peaks at 1340 cm⁻¹ (D band) and 1594 cm⁻¹ (G band), representing the disordered graphite structures and *sp*² hybridized carbon structures^[26]. I_D/I_G ratios for five carbon electrode materials were measured as 1.193, 1.285, 1.304, 1.390, and 1.336. The highest I_D/I_G ratio in RCHK-3 indicates a substantial presence of structural defects within its carbon framework, resulting from the formation of amorphous carbon with more *sp*³ hybridization. The original ordered structure of the residual carbon particles is disrupted following activation with HNO₃ and KOH. The two activation methods are based on different mechanisms; HNO₃ activation introduces oxygen-containing functional groups that disrupt the regular structure and increase the polarity of the carbon material's surface, enhancing its wettability. KOH acts by intercalating K⁺ ions to more effectively adjust the pore structure of the residual carbon, forming a porous network^[27].

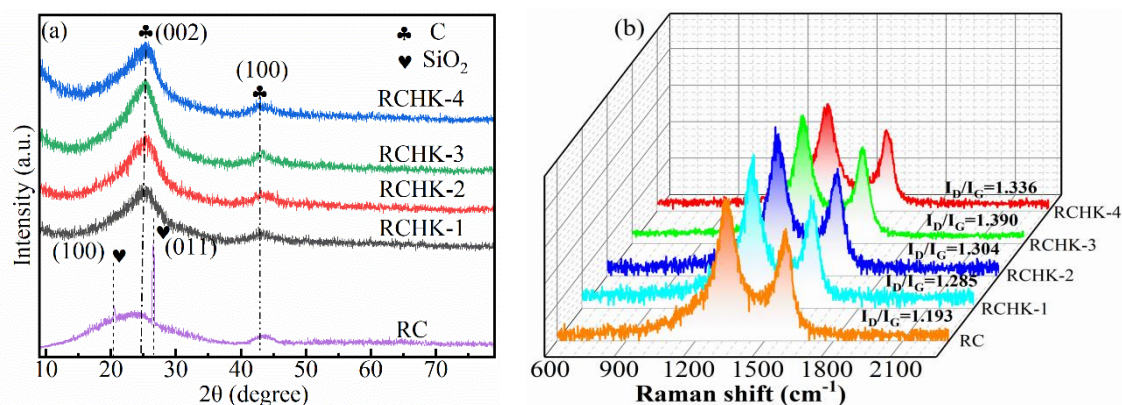


Fig.2. (a) XRD patterns, (b) Raman spectra of RC and RCHK-X (X=1, 2, 3, 4).

Fig.3 illustrates the morphology and microstructure of RC and RCHK-3. Fig.3(a) shows RC with amorphous flocculent carbon and spherical or irregular inorganic particles formed during the high-temperature gasification. The mapping inset of Fig.3(a) indicates that the spherical particles are composed of inorganic silicates, predominantly SiO₂, consistent with literature reports^[28]. The EDS spectrum in Fig.3(b) shows elements such as C, O, Si, Ca, Al, and Fe in RC. Fig.3(c) reveals spherical silica oxide particles in RC varying from 90-380 nm in diameter. After HNO₃-KOH activation, as shown in Fig.3(d) and (f), RCHK-3 is characterized by many highly dispersed porous structures on its surface, indicating that HNO₃-KOH activation has a significant impact on the surface morphology of RC^[29]. The EDS spectrum of RCHK-3 in Fig.3(e) shows

a reduction in silicon and metal impurities following the joint HNO₃-KOH activation. The combined HNO₃ and KOH activation results in a porous structure with numerous oxygen-containing functional groups, enhancing electrolyte ion pathways and improving electrochemical reactions and performance^[30].

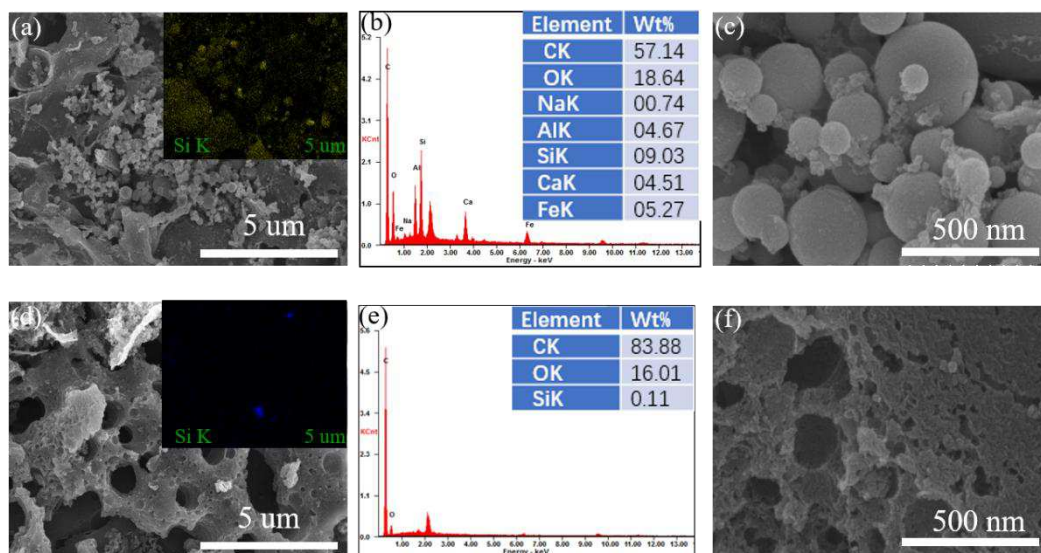


Fig.3. (a, b,c) SEM and EDS profiles of RC and (d, e, f) RCHK-3; insets for RC (a) and RCHK-3 (d) are mapping plots.

The specific surface area is a critical parameter for energy storage in electrode materials, where increased surface area and porosity enhance electrode-electrolyte contact, facilitating greater electrolyte penetration and boosting charge storage capacity. Fig.4(a) illustrates the N₂ adsorption/desorption isotherms for RC and RCHK-X (X=1, 2, 3, 4), conforming to Type IV isotherms as classified by IUPAC, indicative of primarily mesoporous structures^[31]. Analysis from Fig.4(a), along with Fig.4(b) and Table.S1, shows that the specific surface area and mesopore proportion of the materials initially rise with increasing activation temperature, peaking at 150°C with a maximum specific surface area of 775 m²/g and a mesopore proportion of 88.564%. Beyond this temperature, at 170°C, the specific surface area and mesopore proportion for RCHK-4 notably decline.

This trend may be due to the more intense and complete reaction between KOH, inorganic minerals, and reactive carbon as the activation temperature increases, exposing the carbonaceous surfaces previously occupied by inorganic minerals and expanding the pores occupied by reactive carbon. However, excessively high activation temperatures cause further reactions between KOH and the carbonaceous material forming the mesoporous

structure, leading to the collapse or even disappearance of mesopores^[32]. Thus, activation temperature is a key factor in adjusting porosity, and an appropriate activation temperature is necessary to achieve a higher mesopore proportion.

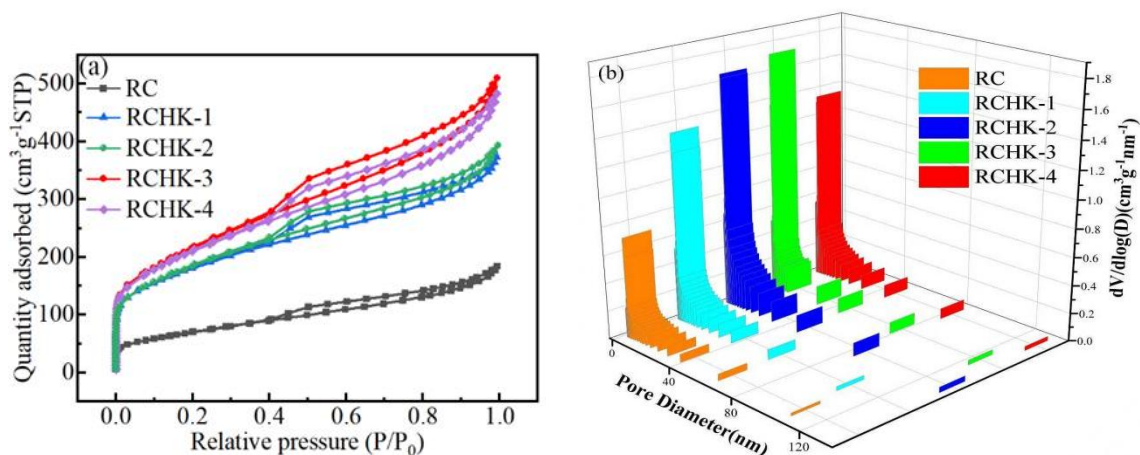


Fig.4. (a) N₂ adsorption/desorption isotherms, (b) pore size distribution of RC and RCHK-X (X=1, 2, 3, 4) .

The elemental composition and thermal stability of RC and RCHK-3 were examined using XPS and thermogravimetric analysis. Fig.5(a) displays the XPS spectra for RC and RCHK-3, showing dominant peaks for C1s (284.8 eV) and O1s (532.0 eV). Following the activation with HNO₃ and KOH, the relative contents of carbon and oxygen increased, while those of calcium, aluminum, and silicon decreased. The TG curves in Fig.5(b) reveal the pyrolysis behaviors of RC and RCHK-3 in an air atmosphere, where initial desorption of physically adsorbed water occurs below 200°C, followed by substantial weight loss between 520-720°C attributed to reactive carbon combustion. Above 720°C, non-combustible ash remains predominantly non-flammable carbon and inorganic minerals^[33]. These results indicate that compared to the unactivated RC, the activated RCHK-3 contained significantly higher amounts of reactive carbon and markedly lower amounts of inorganic minerals, consistent with XRD and EDS results.

The analysis of the specific surface area and pore size distribution from Fig.5(c, d) and Table.S2 shows that RCHK-3, activated by HNO₃-KOH, exhibits greater specific surface area, total pore volume, and mesopore proportion than RCHK-3, which is activated by KOH-HNO₃. This difference can be attributed to the removal of reactive nitrogen structures introduced by HNO₃ activation and the generation of new defects

and pores during KOH activation. Such enhancements in specific surface areas are crucial for double-layer capacitance due to vital electrode-electrolyte surface interactions. The co-activation with HNO₃-KOH not only enlarges the specific surface area of RCHK-3 but also improves its hierarchical pore structure, boosting ion storage and diffusion, enhancing electrolyte ion contact, and thereby improving the electrode's energy storage performance^[34].

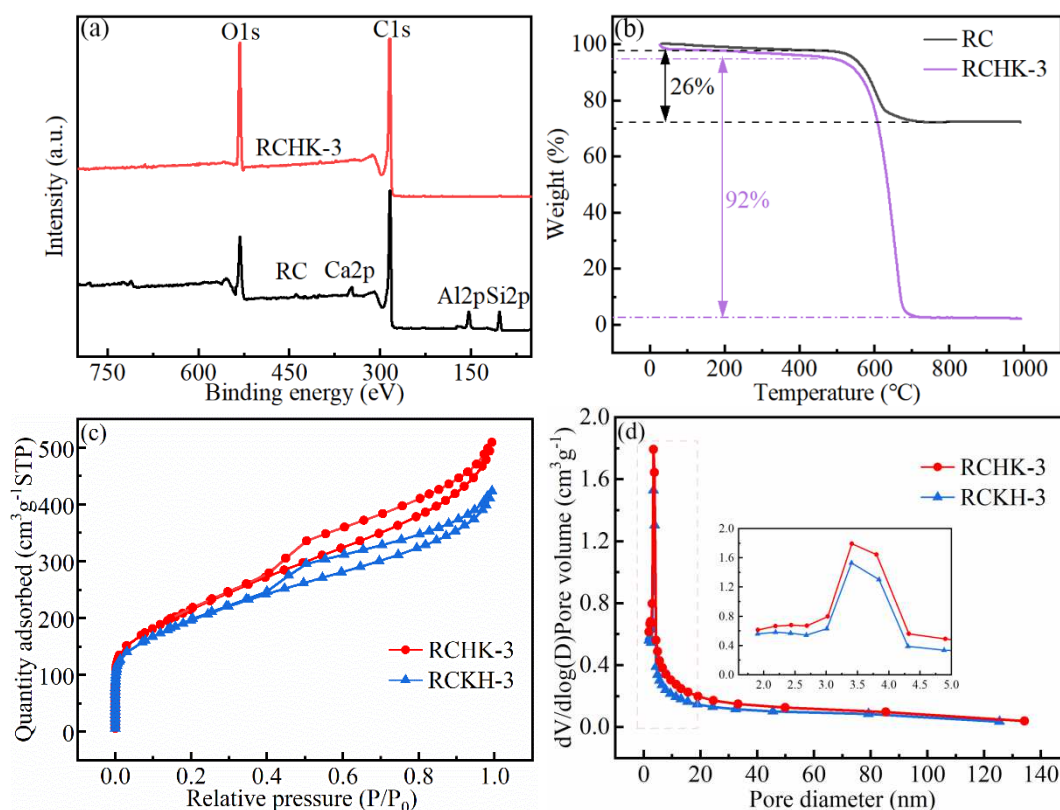


Fig.5. (a) XPS spectra of RC and RCHK-3, (b) TG spectra of RC and RCHK-3, (c) N₂ adsorption/desorption isotherms and (d) pore size distribution of RCHK-3 and RCKH-3.

To further explore why the electrochemical performance of RCHK-3, activated first by acid and then by alkali, is superior to that of RCKH-3, which is activated first by alkali and then by acid, a series of structural comparative characterizations were conducted on RC, RCHK-3, and RCKH-3. As illustrated in Fig.6(a), all materials display similar FT-IR spectra, indicating that they possess similar structures and functional groups. These include the O-H stretching vibration peak at 3400 cm⁻¹ and the C-O stretching vibration peaks between 1000 cm⁻¹ and 1250 cm⁻¹. Peaks at 1350 cm⁻¹ in both RCHK-3 and RCKH-3 indicate the presence of nitro groups (N=O)^[35].

Fig.6(b) shows that the raw materials and activated samples have similar XPS spectra, while the fine spectra of O1s and N1s for RCHK-3 are shown in Fig.6(c, d). The O1s spectrum includes peaks for C=O (531.3 eV), N=O (531.9 eV), O-H (532.9 eV), C-O (534.2 eV), and O-C=O (534.9 eV)^[36]. The N1s spectrum features pyridinic nitrogen at 398.3 eV, pyrrolic nitrogen at 399.9 eV, graphitic nitrogen at 401.0 eV, and N=O peaks at 402.2 eV.

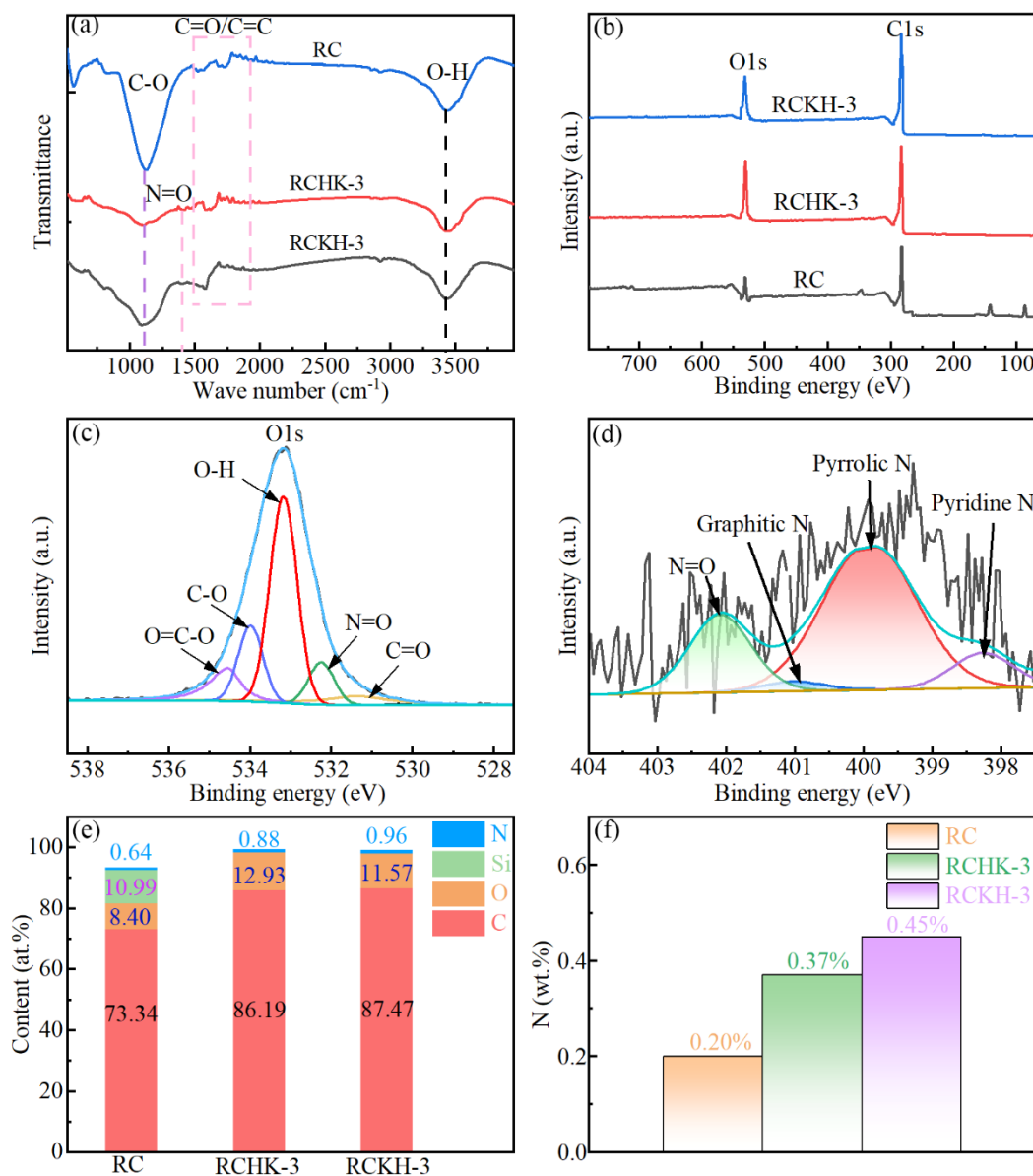


Fig.6. (a) FT-IR and (b) XPS spectra of RC, RCHK-3 and RCHK-3, (c) O1s and (d) N1s spectra of RCHK-3, (e) XPS peak area fitting elemental relative content plot and (f) N elemental analysis plot of RC, RCHK-3 and RCHK-3.

To compare the relative content of surface elements, bar charts of elemental

relative contents were derived from area fitting of peaks in the XPS spectra, as shown in Fig.6(e). Elemental relative content comparisons in Fig.6(e) show higher C, O, and N on RCHK-3 and RCKH-3 than RC, with RCHK-3 having lower surface N content than RCKH-3, indicating the effective removal of reactive nitrogen structures pre- HNO_3 activation by subsequent KOH treatment, as also supported by the trends in bulk nitrogen content in Fig.6(f)^[37].

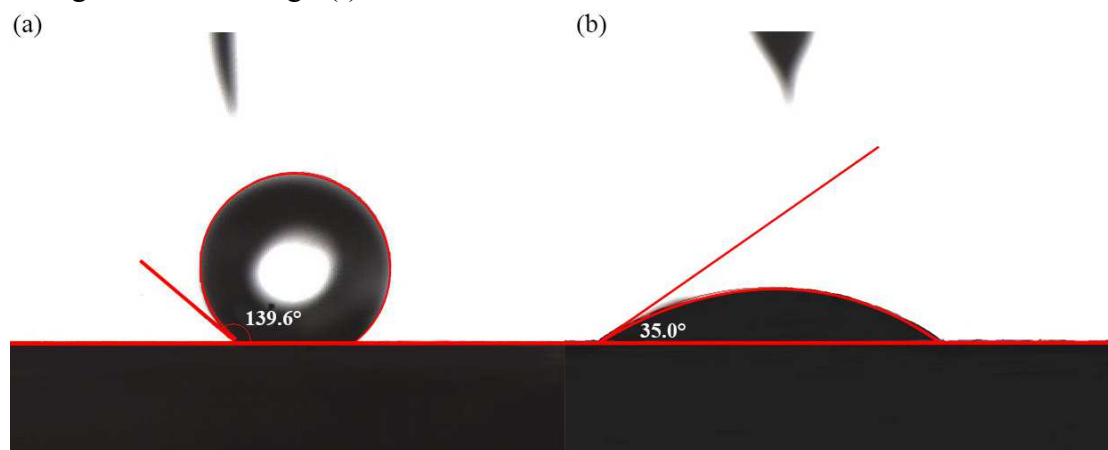


Fig.7. (a) Contact angle tests for RC and (d) RCHK-3.

To assess the enhanced hydrophilicity of the RCHK-3 electrode surface, contact angle measurements were conducted using a 6M KOH solution at ambient temperature. The results displayed in Fig.7(a, b) show that RCHK-3 has a significantly lower contact angle of 35.0° compared to RC's 139.6°, indicating increased hydrophilicity. This change is attributed to the presence of more hydrophilic oxygen-containing functional groups on the surface after HNO_3 and KOH activation. The improved wettability and porosity of RCHK-3 synergistically improve the diffusion of electrolyte ions, not only at the surface but also into deeper layers, enhancing the double-layer energy storage capacity of the carbon materials^[38].

3.2 Electrochemical characterization of the samples

The electrochemical properties of RC, RCH-3, RCK-3, and RCHK-X (1,2,3,4) were studied using 6 M KOH as the electrolyte in a three-electrode system. Fig.8(a) displays the CV curves for RC, RCH-3, RCK-3, and RCHK-X (1,2,3,4) at a scan rate of 20 mV/s. The curve for RCHK-3 encompasses the largest area, indicating it exhibits the best electrochemical behavior with the highest specific capacitance^[39]. Fig.8(b) illustrates that RCHK-3 maintains a quasi-rectangular CV shape across scan rates from

5 to 100 mV/s, suggesting effective double-layer capacitance with low ion diffusion resistance^[40]. GCD testing is frequently used to evaluate electrochemical performance. Fig.8(c) displays the GCD curves of RC and RCHK-X (1,2,3,4) within a potential window of -1.0-0 V at a current density of 0.5 A/g.

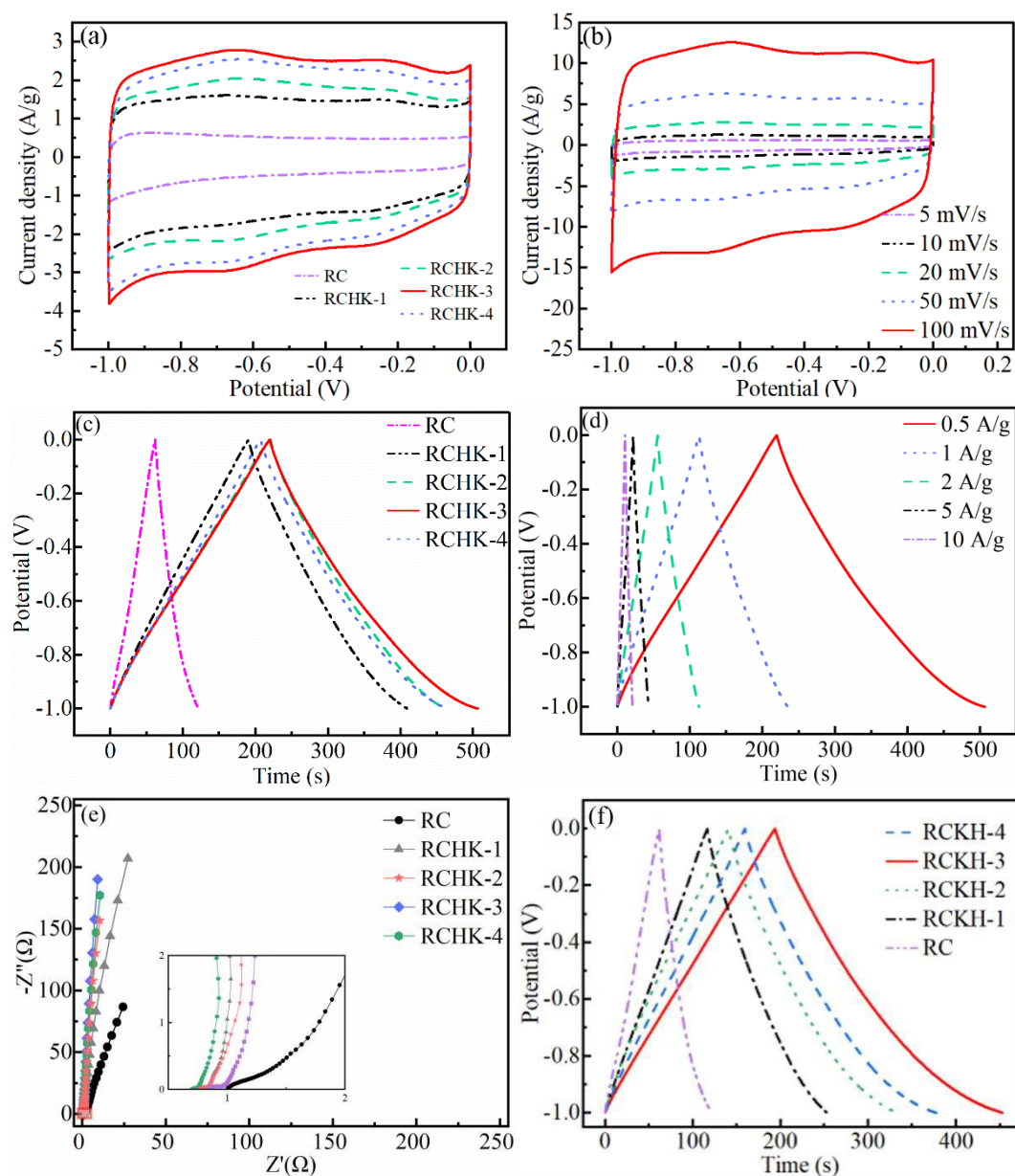


Fig.8. (a) CV curves of RC and RCHK-X (X=1, 2, 3, 4) at a scan rate of 20 mV/s, (b) CV curves of RCHK-3 at different scan rates, (c) GCD curves of RC and RCHK-X (X=1, 2, 3, 4) at a current density of 0.5A/g, (d) GCD curves for RCHK-3 at various scan rates, (e) EIS curves of RC and RCHK-X (X=1, 2, 3, 4), (f) GCD curves of RC and RCHK-X (X=1, 2, 3, 4) at a current density of 0.5 A/g.

All curves exhibit good isosceles triangular shapes, demonstrating excellent

symmetry and linearity, indicative of effective double-layer capacitance characteristics^[41]. The specific capacitances for RC and RCHK-X (1,2,3,4) are 36, 112, 125, 155, and 129 F/g respectively, with RCHK-3 showing the longest charge-discharge time, confirming its highest specific capacitance and best electrochemical performance. Fig.8(d) displays GCD tests for RCHK-3 at current densities from 0.5-10 A/g. With increasing current density, RCHK-3's specific capacitance slightly decreases, and the charge-discharge time significantly shortens. This reduction is likely due to the higher charge per unit time at elevated current densities, which hinders electrolyte ions from fully penetrating the carbon material, thus utilizing only a fraction of the active sites^[42].

To determine the resistance of the prepared samples, EIS tests were conducted. The results, as depicted in Fig.8(e) Nyquist plots, include a semicircle in the high-frequency region and a sloping line in the low-frequency region. A higher linear slope at low frequencies indicates that the supercapacitor is closer to an ideal capacitor, reflecting the better electrochemical performance of the electrode material^[43]. RCHK-3 exhibits a smaller semicircle diameter in the high-frequency region, indicating a lower ionic charge transfer resistance. The intersection of the semicircle curve with the horizontal axis reflects the equivalent series resistance of the supercapacitor electrode; a lower equivalent series resistance facilitates a higher specific capacitance for RCHK-3. The slope of RCHK-3 in the low-frequency region is significantly steeper than that of other samples, approaching 90°, indicating the fastest diffusion/migration process of electrolyte ions to the electrode surface. In the porous structure of RCHK-3, micropores provide a large specific surface area for ion storage, while mesopores offer effective ion transport channels, consistent with the analysis of the pore structure. RCHK-3 is one of the more promising candidates for supercapacitor electrode materials, as evidenced by CV, GCD, and EIS tests^[44].

Fig.8(f) presents the GCD curves at a current density of 0.5 A/g for RCKH-X (1,2,3,4) which were produced from RC with pre-KOH and then HNO₃ activation. Their specific capacitances are 70, 84, 129, and 107 F/g. It is observed that the specific capacitances from the HNO₃-KOH activation are higher than those from the KOH-HNO₃ activation, due to a larger specific surface area, pore volume, and greater

proportion of mesopores, facilitating more contact between the electrode and electrolyte ions, thus enhancing electrochemical performance^[45].

Table.S3 shows specific capacitance data for carbon electrode materials activated by a two-step activation method reported in the literature. The specific capacitance of the activated residual carbon RCHK-3 is on par with or even exceeds that of some biomass-derived carbon electrodes. Moreover, compared to its biomass precursors, the gasification fine slag residual carbon yields more and costs less.

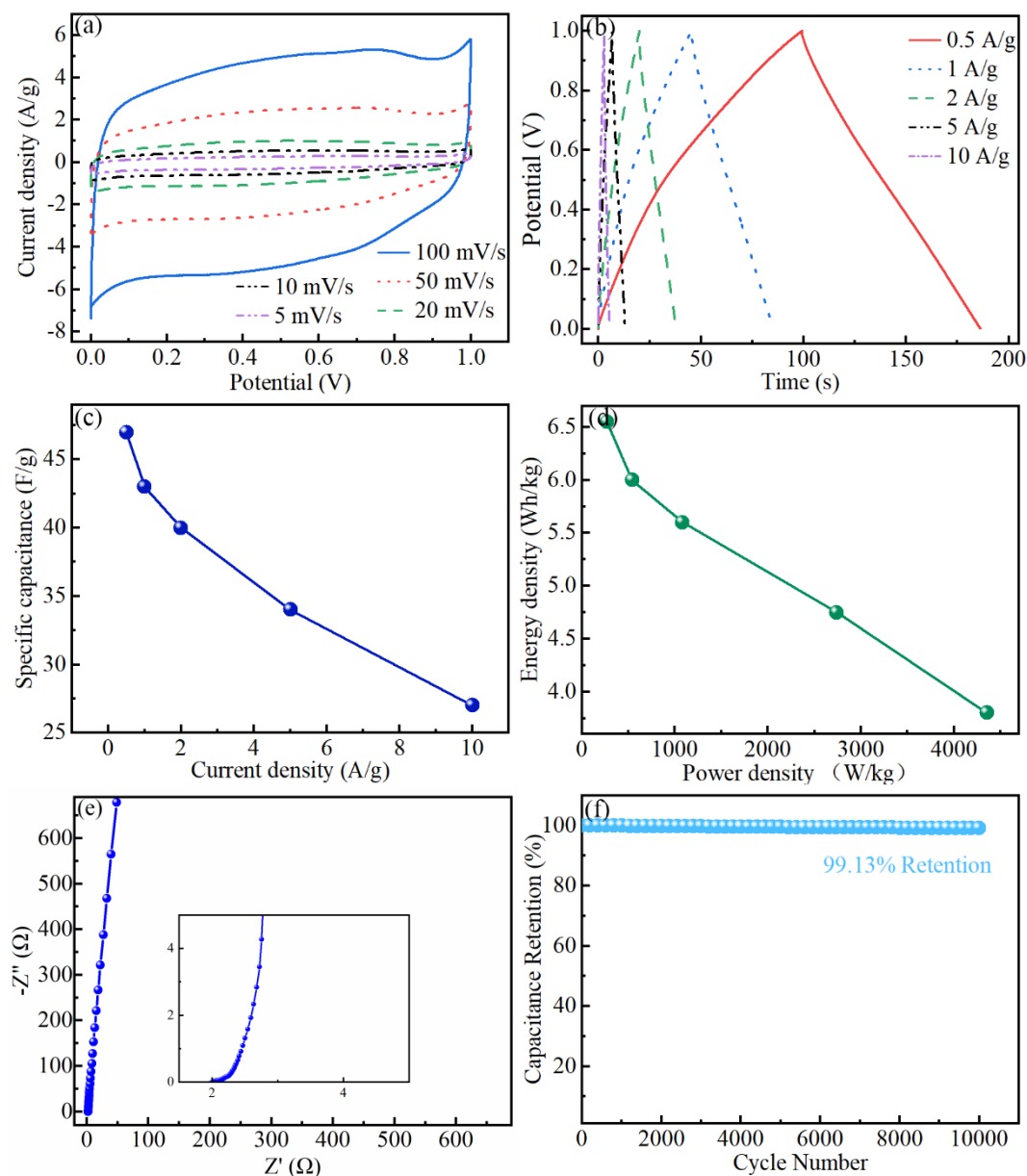


Fig.9. (a) CV curves of RCHK-3//RCHK-3 supercapacitors at various scan rates, (b) GCD curves at different current densities, (c) EIS spectra, (d) rate performance plots, (e) Ragone plots, (f) cycling stability.

In this study, the electrochemical performance of RCHK-3 was utilized to construct a symmetrical button-type supercapacitor, designated as RCHK-3//RCHK-3, and subjected to electrochemical testing. As shown in Fig.9(a), cyclic voltammetry (CV) tests conducted at scan rates between 5 and 100 mV/s produced relatively regular rectangular curves, demonstrating excellent rate performance and reversible charge-discharge capabilities.

Fig.9(b) presents the GCD curves at current densities ranging from 0.5 to 10 A/g, exhibiting good symmetry and indicating superior reversible charge-discharge properties^[46]. Specific capacitance was calculated according to Equation 2.3, yielding values of 47, 43, 40, 34, and 27 F/g at current densities from 0.5 to 10 A/g. Fig.9(c) illustrates the specific capacitances at different current densities, showing a decrease with increasing current density due to electrolyte diffusion. The capacitance retention of RCHK-3 at 10 A/g is approximately 58% of the maximum value observed at 0.5 A/g, confirming its excellent capacity retention and rate performance^[47]. Based on GCD tests, the energy and power densities were calculated using Equations 1-3 and 1-4, respectively, with the Ragone plot depicted in Fig.9(d) showing a maximum power density of 270 W/kg at an energy density of 6.6 Wh/kg.

EIS is a crucial technique for studying charge transfer and electrolyte diffusion at the electrode/electrolyte interface. As shown in Fig.9(e), the Nyquist plot for RCHK-3//RCHK-3 comprises a semicircle in the high-frequency region and an almost 90° line in the low-frequency region, indicating low resistance and good conductivity. Fig.9(f) addresses the cycle life, an important performance metric for supercapacitors^[48]. To evaluate the capacitive cycle life retention of RCHK-3//RCHK-3 under repeated charging and discharging at the same current density, a continuous test over 10,000 cycles at 2 A/g was conducted, achieving a capacitance retention of 99.13%, thereby demonstrating excellent cyclic stability of the capacitor.

4. Conclusion

This chapter combines the activation mechanisms of HNO₃ and KOH, employing an acid-base joint activation approach to modify the surface of residual carbon from gasified fine slag. Initially, using RCH-3 as the raw material, a series of carbon electrode materials (RCHK-X, X = 1, 2, 3, 4) were prepared through wet activation

with KOH at various activation temperatures (110°C, 130°C, 150°C, 170°C). Subsequently, by varying the order of activation and using RCK-3 as the raw material, another series of carbon electrode materials (RCKH-X, where X = 1, 2, 3, 4) were prepared through wet activation with at different temperatures (40°C, 60°C, 80°C, 100°C).

Systematic structural characterization and electrochemical performance testing revealed that the RCHK-3 material, activated by acid followed by base at 150°C, exhibited the best electrochemical performance, achieving a specific capacitance of 155 F/g at a current density of 0.5 A/g. Moreover, a symmetrical supercapacitor composed of RCHK-3 as the active electrode material (RCHK-3//RCHK-3) demonstrated an energy density of 6.6 Wh/kg and a power density of 270 W/kg. After 10,000 charge-discharge cycles, the capacitance retention of RCHK-3//RCHK-3 was 99.13%, indicating excellent cyclic stability. The favorable cyclic stability of RCHK-3 originates from the porous polar structure formed by the sequential acid-base joint activation, conducive to the storage and transport of charges and ions. This includes a high specific surface area (775 m²/g), high mesoporosity (88.564%), a large average pore size (4.982 nm), a high carbon content, and numerous oxygen-containing functional groups."

Declarations

Ethical Approval

This article does not address human and/or animal research.

Competing interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Authors' contributions

Jianan Wen: Complete experiments, test and analyze electrochemical performance, and write papers; Xiaotian Wang, Zhangcai Zhou, Guoxiang Xin, Jinxiao Bao, Jianmin Gao, and Yao Wang: Discuss and analyze the experimental results; Jinling Song: Determine the experimental plan, analyze and discuss the experimental results, and review and revise the paper.

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Availability of data and materials

All of the material is owned by the authors, and/no permissions are required.

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