

# Study on Cotton-based Porous Carbon Electrode Materials for Supercapacitors Based on Carbon Materials

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## Abstract

Supercapacitors are favored by researchers because of their high energy density, excellent cycle performance, low price and environmental friendliness. Supercapacitor is an advanced high-energy storage component with a cycle life of more than 10,000 cycles, higher power density than ordinary batteries, and longer cycle life than conventional rechargeable batteries. In order to solve the problems of energy shortage, environmental pollution and other issues, and to maintain the sustainable development of human society, in addition to changing the existing production and lifestyle, saving energy, we must vigorously develop and promote renewable green new energy. With the development of electrode materials and the development of manufacturing processes, the industrialization process of supercapacitors has been accelerating, and the global market is growing. In the near future, supercapacitors will play an extremely important role in the rapid development of renewable energy. Based on the characteristics of carbon materials, this paper studies cotton-based porous carbon electrode materials in supercapacitors.

## Keywords

Supercapacitor; Carbon material; Electrode material.

## 1. Introduction

In the 21st century, the world's population and social economy continue to grow, so the demand for energy is also increasing. Supercapacitor is an advanced high-energy storage component with a cycle life of more than 10,000 cycles, a higher power density than ordinary batteries, and a longer cycle life than conventional rechargeable batteries [1]. In order to solve the problems of energy shortage, environmental pollution and other issues, and to maintain the sustainable development of human society, in addition to changing the existing production and lifestyle, saving energy, we must vigorously develop and promote renewable green new energy, and gradually replace the traditional use. Non-renewable fossil energy [2]. Supercapacitor is a new concept energy storage device between battery and traditional electrostatic capacitor. Compared with traditional electrostatic capacitor, supercapacitor has higher specific capacitance [3]. In order to better meet the needs of clean, economical and efficient development of the future society, the research and application of new energy-saving materials and green energy has gradually become the focus of the world. With the development of electrode materials and the development of manufacturing processes, the industrialization process of supercapacitors has been accelerating, and the global market is growing in size [4]. Although its energy density is lower than that of lithium-ion batteries, its power density is much

higher than that of lithium-ion batteries, which can make up for the shortage of lithium-ion batteries in the high-power applications of electrochemical energy storage systems.

The supercapacitor mainly relies on static charge to store energy in the electric double layer formed between the electrode and the electrolyte interface. The specific surface size of the electrode material is the key to affect the energy storage capacity of the electric double layer, and the material with high specific surface area can be used as the electrode. The storage high-energy electrochemical energy storage and conversion system is mainly composed of batteries, electrochemical capacitors and fuel cells [5]. As a new type of energy storage component, supercapacitors are widely used in new energy vehicles, rail transit, wind power generation and military special equipment, and the demand for industrial production is also increasing [6]. If used in conjunction with a power battery, it can act as a large current or energy buffer, reducing the damage of the battery caused by large current charge and discharge, and prolonging the service life of the battery [7]. At the same time, it is better to recover the instantaneous energy in the supercapacitor through the regenerative braking system, thereby improving energy utilization. The electrode is the most important component of the supercapacitor and consists of the electrode material and the current collector, respectively. In addition to the characteristics of being stable in the electrolyte and not chemically reacting with the electrode material or the electrolyte, it is also desirable to select a current collector that is in complete contact with the electrode material and has the lowest contact resistance [8]. In the near future, supercapacitors will play an extremely important role in the rapid development of renewable energy.

Throughout the development of supercapacitors, electrode materials have always been a key factor in obtaining excellent supercapacitor performance, so they have received extensive attention [9]. Compared with the polymer electrode and metal oxide electrode materials, the carbon electrode has a large specific surface, excellent thermal conductivity and electrical conductivity. Its low density, good chemical corrosion resistance, small thermal expansion coefficient, can store more energy [10]. Supercapacitors do not undergo chemical reactions during energy storage and are electrochemically reversible. In order to develop supercapacitors with excellent performance, from the material point of view, it is crucial to research and develop carbon electrode materials with high specific capacity in different electrolytes for supercapacitor applications [11]. According to the energy storage mechanism, supercapacitors can be divided into two types of electric double layer capacitors and tantalum capacitors, which is the most common classification method. Although the specific surface area of the composite material is lower than that of the pure porous carbon foam, the doping of sulfur element eventually leads to a significant increase in electrochemical performance [12]. Hybrid capacitors can also be assembled using two different metal oxides or conductive polymers as electrode materials, and their performance is closer to that of batteries, showing higher specific energy and specific power [13]. Based on the characteristics of carbon materials, this paper studies the use of cotton-based porous carbon electrode materials in supercapacitors.

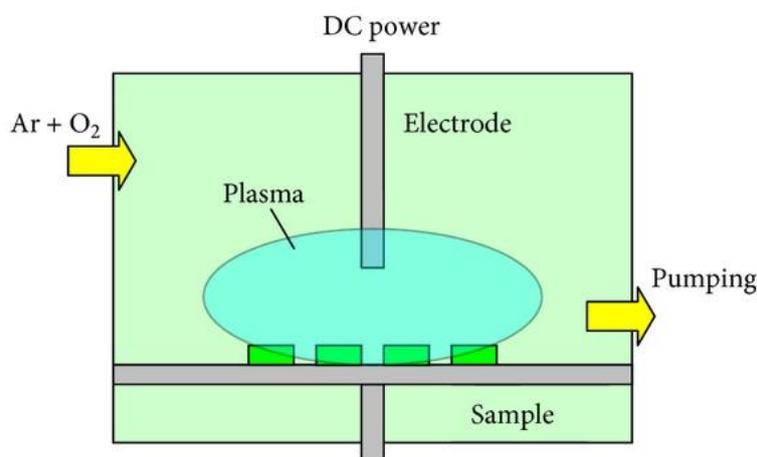
## 2. Supercapacitor Classification and Energy Storage Principle

Supercapacitors are also called super batteries. Unlike traditional electrostatic capacitors, they are mainly used to store electrical energy through the interface double layer. Through the cyclic voltammetry test, the electrochemical behavior of the electrode surface during charging and discharging can be visually displayed, reflecting the ease of electrode reaction, reversibility, oxygen evolution characteristics, charge and discharge efficiency, and adsorption characteristics of the electrode surface [14]. The structural porosity is to improve the specific surface area and pore state of the carbon-based electrode material, increase the contact area and the degree of infiltration of the electrode material with the electrolyte, and improve the

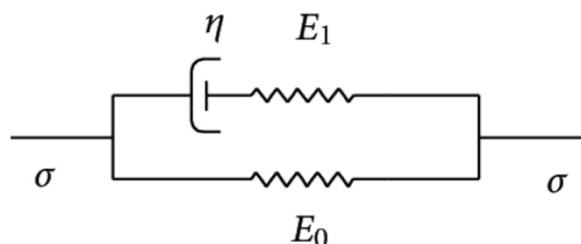
performance of the electrode material. Since the electrochemical potentials of the two phases of the electrode and the electrolyte solution are different, the electrostatic charge on the surface of the electrode attracts some irregular ions from the solution, so that they gather at a certain distance from the electrode at one side of the electrode solution interface [15]. From the perspective of the storage principle of capacitors, carbon nanotubes are ideal electrode materials. First, the carbon nanotubes are hollow tubes with large specific surface area, especially single-walled nanotubes, which is favorable for the formation of electric double layer capacitors. Although carbide-derived carbon is one of the research hotspots of porous carbon materials, its internal curved and irregular micropores account for the main part, and ions transport in such micropores are slow, even unable to reach some micropores.

As the current density increases, the discharge time decreases significantly, indicating an increase in the diffusion resistance of the electrolyte ions in the electrode material. The electrons flow from the negative electrode to the positive electrode through the external circuit, so that the potentials on the two electrodes are recovered, and the positive and negative ions in the electrolyte solution are respectively removed from the surface of the negative positive electrode and returned to the inside of the electrolyte. The capacitance of the supercapacitor is closely related to the effective area of the electric double layer and the thickness of the electric double layer. The outer surface of the nitrogen-containing carbon microsphere material retains the original rough surface after the high temperature treatment, which can increase the contact area of the carbon microsphere material with the electrolyte, so that it has good electrochemical performance. For carbon material electrodes, the effective area of the electric double layer is related to the specific surface area of the carbon electrode, and the thickness of the electric double layer is affected by the action of ions in the electrolyte [16]. Scale nanocrystallization can shorten the ion and electron transport paths and release cyclic stress while increasing the specific surface area of the material to obtain excellent electrochemical performance.

The specific surface area of carbon materials is an important indicator. Whether it is activated carbon powder or activated carbon fiber, there is a tendency that the specific surface area is large and the total mass ratio is large. Although some capacitor designers use reduced voltage to reduce leakage current, most researchers reduce leakage current by improving electrolyte purity and improving carbon electrode materials. Figure 1 is a schematic diagram of carbon material plasma treatment, and Figure 2 is a viscosity model of carbon material.



**Figure 1.** Principle of plasma treatment of carbon materials



**Figure 2.** Viscosity model of carbon material

Since the number of ions on the interface of the electric double layer is not satisfied and the capacity of the material is lost, the capacitance performance of the material is reduced to some extent as the sweep speed increases. A supercapacitor is a component that can discharge a large current instantaneously, which requires an internal resistance to be very small to reduce the partial pressure drop caused by the internal resistance. In carbon-based supercapacitors, the electrolyte is adsorbed into the pores of the electrode material, and the pore size of the electrode material required by different electrolytes is different [17]. In addition to the selection of a suitable carbon source for the preparation of activated carbon, post-treatment of activated carbon is also a way to improve its electrochemical performance. Through the qualitative study of the cyclic voltammetry curve, electrode materials suitable for supercapacitors can be selected [18]. The purpose of the template method for preparing porous carbon is to orient the design and improve the pore size, porosity and other structures of the carbon material, and improve the electrochemical performance of the carbon material. The cycle life of the electrode can be studied by observing the shape of the cyclic voltammetry curve of different cycles and calculating the change in specific capacity of different cycles. Generally, the ultra-high specific surface area carbon material is mainly microporous. For supercapacitors, it is desirable to have a larger mesoporous ratio, which requires improvement of the preparation process and method of the activated carbon material.

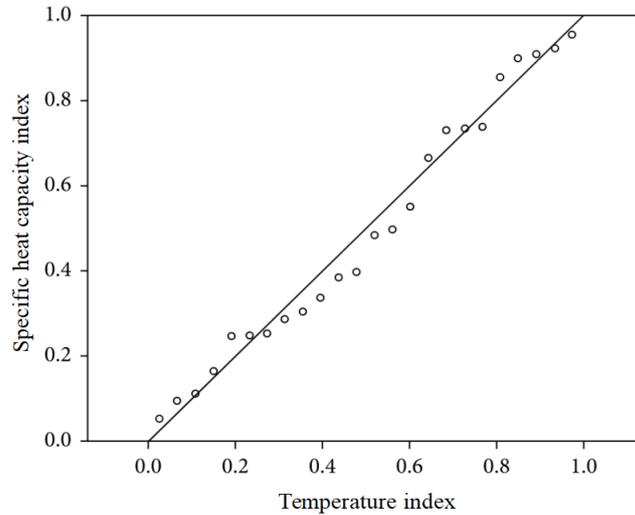
### 3. Electrochemical Capacitors for Carbon Materials

#### 3.1. Preparation and Testing of Carbon-based Electrode Materials

Exploring a simpler method makes it more meaningful to prepare a layered porous carbon material under milder conditions. Among porous carbon materials, carbon microspheres have gained more and more attention due to their high tap density, good sphericity and stable physicochemical properties. Carbon nanotubes have a relatively regular pore structure, a large specific surface area, high electrical conductivity and chemical stability, which facilitates ion diffusion and electron transport inside the electrode material. Due to the low price of activated carbon, electrodes made of powdered activated carbon with high specific surface area have been extensively studied and applied and popularized in the commercial production of electric double layer capacitors [19]. The conventional method for preparing carbon nanotubes is to grow carbon nanotubes using a non-conductive material as a matrix, and the carbon nanotubes and the matrix need to be separated first when the electrodes of the supercapacitor are fabricated. The ratio of the raw materials controls the network structure, density and density of the carbon aerogel. The catalyst concentration controls the size of the individual particles, and the particle size is small when the concentration is large. At a large current, protons cannot enter the inside of the electrode body phase in time, and the ion migration rate in the electrolyte is lowered, resulting in a greatly reduced utilization of the electrode active material.

Three tests were performed with the same test procedure for each sample, namely blank test, calibration test, and sample test. Combining these three experimental data, through professional software analysis, the final solid heat capacity data is obtained. The test results are

compared with the solids of the first and the 400th cycles of the analysis sample as shown in Fig. 3.



**Figure 3.** Comparison of solid heat capacity with temperature

Due to the activity of the chain, the winding easily reacts with water, carbon dioxide and oxygen, so for the cone air battery, the protection of the anode cone is very important. It is assumed that the filling factor of the window is  $m$ . Calculate the transformer here:

$$cell_{ps-1} = \arg \max_n \left( \sum_{m=1}^M P_{f-n_m} \right) \tag{1}$$

The core window area is:

$$cell_{ps-n_s} = \arg \max_{n, n \neq cell_{ps-1}, \dots, cell_{ps-(n_s-1)}} \left( \sum_{m=1}^M P_{f-n_m} \right) \tag{2}$$

Determine the minimum value of the winding voltage of the low-voltage side isolation transformer:

$$cell_{ps-n_{s1}} = \arg \min_{i, i \neq cell_{ps-1}, \dots, cell_{ps-n_s}} \left( \sum_{m=1}^M \sum_{l=1}^M P_{i_l} \left\| \mathbf{h}_{i, ps-1_m}^T \mathbf{W}_{i, i_l} \right\|_2^2 \right) \tag{3}$$

Substitute the parameters:

$$R_{n_i}^C = \log_2 \left( 1 + \frac{P_{mac, n_i} \left\| \mathbf{h}_{mac, n_i}^T \mathbf{W}_{mac, n_i} \right\|_2^2}{\sigma^2} \right) \tag{4}$$

The supercritical carbon dioxide density is about one-third that of a liquid, which is hundreds of times that of a gas. This gives it a liquid-like solvency, and this solvency varies with temperature and pressure. Table 1 shows the comparison of the properties of different states.

**Table 1.** Comparison of properties of different states

nature	Gaseous state	Supercritical state	Liquid
Density (g/cm <sup>3</sup> )	0. 0006-0. 002	0. 15-0. 45	0. 5-1. 5
Viscosity (mPa/s)	0. 02-0. 05	0. 02-0. 06	0. 6-2
Diffusion coefficient (cm <sup>2</sup> /s)	0. 3-0. 6	0. 006	0. 007-0. 02

The solidification of the crystal is usually carried out under normal pressure, and the solid-liquid two phases coexist during the solidification of the pure crystal. The degree of freedom is equal to zero, so the solidification temperature does not change. According to the second law of thermodynamics, under isothermal isostatic conditions, the spontaneous direction of the process is the direction in which the free energy of the system decreases. Freedom can be expressed as:

$$w = (w_{\max} - w_{\min}) \times \frac{I_{\max} - I_i}{I_{\max}} + w_{\min} \tag{5}$$

Can be expressed as:

The antenna is fabricated by using a microwave dielectric resonator, and then the antenna array can be widely used in other fields. The built-in antenna of the mobile phone and the antenna for the wireless local area network have been successfully developed and are being promoted and applied. If you design a 3-layer network, you have K input units and s output units. Then for the 3 layer network:

$$G_r(s) = \frac{K_r}{1 + T_r s} \tag{6}$$

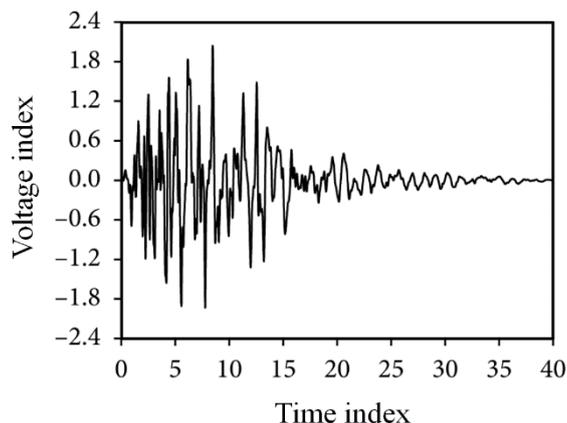
Calculate the output layer unit activation value:

$$Q(u_{ij}) = \sum_{i=1}^n \text{Max}_{1 \leq j \leq m} \{g_{ij}(T)\} \tag{7}$$

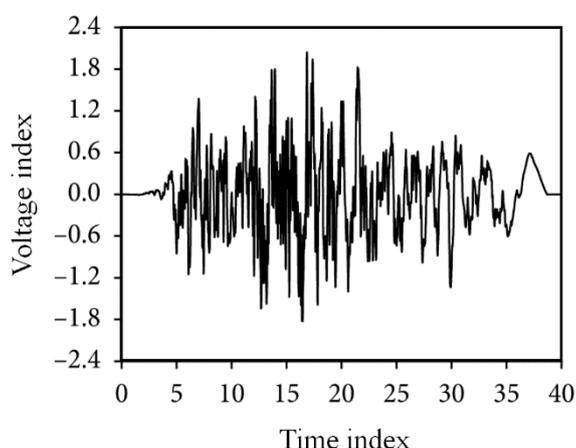
The sample is sent to the hidden layer unit by the connection weight, and the new activation value of the hidden layer unit is generated:

$$y_{f-n_m} = \sum_{i=1, i \neq n}^N \sum_{l=1}^M \sqrt{p_i} h_{i,n_m}^T W_{i,i_l} s_{i_l} \tag{8}$$

The specific surface area of the carbon material will have a relatively large effect on the performance of the air-encapsulated electric oil. The larger the specific surface area, the larger the reaction site that can provide oxygen. The more favorable the reaction is, the more time it will provide more storage space for the discharge product. There are two forms of constant current charging. One is a single constant current charging, as shown in Figure 4. The other is segmented constant current charging, as shown in Figure 5.



**Figure 4.** Single constant current charging voltage waveform

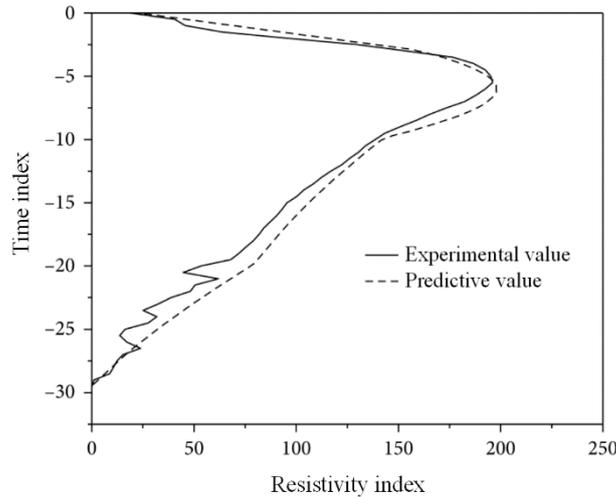


**Figure 5.** Segmented constant current charging voltage waveform

When the scanning rate is low, the penetration of the electrolyte in the electrode material is very sufficient, and it can enter into the internal cavity, so that the electrode material is in sufficient contact with the electrolyte, thereby generating a large specific capacity. For maintenance-free lead-acid supercapacitors, the common charging methods are constant current limiting voltage and constant voltage current limiting. However, one of the charging methods is used alone, and there is no dynamic tracking of the actual state of the battery and acceptable charging. The current size technique is not ideal for charging maintenance-free lead-acid supercapacitors. The experimental and predicted values of material resistivity are shown in Table 2 and Figure 6.

**Table 2.** Experimental and predicted values of material resistivity

Group No	Experimental value	Predictive value
1	185.32	185.47
2	195.86	184.81
3	230.59	231.88
4	198.34	198.74
5	217.62	217.69



**Figure 6.** Comparison of experimental values of material resistivity with predicted values

All test results are based on or parallel equivalent circuits. As the frequency increases, the inductance on the low-voltage side, the inductance measured on the high-voltage side, and the inductance measured on the high-voltage side and the low-side side are reduced. When the frequency rises, the measurement results have been rendered capacitive. The parasitic parameters of the isolation transformer are shown in Table 3.

**Table 3.** Separation transformer parasitic parameters

frequency	Low voltage side short circuit	Low pressure side open circuit	High voltage side short circuit	High pressure side open circuit
15kHz	66.82	112.59	3.462	7.492
25kHz	68.43	133.47	2.548	9.527
35kHz	71.69	126.68	2.355	8.773
45kHz	61.55	119.41	1.374	9.885
55kHz	72.86	146.86	2.531	9.496

A series of pulse sequences of equal amplitude and unequal width are output, and the width of the pulse is modulated according to a certain rule. You can change the output voltage or change the output frequency. Thereby greatly improving the dynamic response of the system. Calculate the comparison:

$$RSRP_{n_i,n} + (\lambda_j - \lambda_R) = RSRP_{n_i,m} \tag{9}$$

Number of turns of the low voltage side isolation transformer winding:

$$A^T G = \sum_i A_i^T G_i \tag{10}$$

Finally, calculate the number of turns of the winding on the high-voltage side isolation transformer:

$$S^* = \arg \{ f(S) \} = \sum_{i=1}^n \max \{ (T_{s_{m,j},m} - D_{s_{m,j}}), 0 \} \rightarrow \min \tag{11}$$

In addition to the selection of a suitable carbon source for the preparation of activated carbon, post-treatment of activated carbon is also a way to improve its electrochemical performance. Equivalent series resistance is one of the most direct factors affecting the power characteristics of capacitors, and it is also a direct indicator to evaluate the high-current charge-discharge performance of capacitors [20]. The electrolyte plays a role in transporting lithium ions in the operation of the air-filled pool. It is mainly composed of a solvent and an electrolyte [21]. Although there are many related studies, so far, the instability of the solvent is a major bottleneck in the electrification of lithium air. Each of the single cells is charged at a constant voltage, and the initial current of charging is large, and the current gradually decreases as charging progresses. Although catalytic activation is a better method for preparing mesoporous activated carbon materials, it is inevitable to introduce metals, which may cause some problems when applied in aqueous solution [22]. By connecting the mesoporous windows of adjacent large holes, the large holes in the next layer can be seen, indicating that the pore structures inside the material are interconnected. As the scan rate is further increased, the concentration polarization also increases, resulting in a decrease in specific capacity.

### 3.2. Improvement of Carbon-based Electrode Materials

The charging technology of the conventional lithium ion battery is constant current and constant voltage charging. The battery is first charged with a constant current, such as until the battery terminal voltage rises to the charge termination voltage. Then the battery enters the constant voltage charging phase, and when the battery drops to a preset small current, the charging is completed. Analyze the main circuit and control circuit of the design of the charging and discharging device to realize the dual functions of rectifying and reversing the battery. It solves the shortcomings of low power factor, serious harmonic pollution, large device volume and energy waste in the traditional charging and discharging device. The drive and protection circuits of the device are increasingly sophisticated and gradually modularized and integrated [23]. At present, most of power electronic converters are used for power conversion. In some conversion devices, it is possible to include more than two types of converters at the same time. The problem is that low-order harmonics are generated, and the power grid is a load with a lagging power factor. The rapid increase of such nonlinear loads has a serious impact on the power grid [24]. As a power conversion method commonly used in modern high-voltage electric pulse discharge devices, the basic working principle of pulse charge and discharge is to control the on and off of power devices. For solid crystalline compounds, the crystal structure and chemical composition of any two compounds are the same, and the diffraction data of the powders of crystals with different structures and compositions are different.

When the discharge transmits electrical energy to the grid, it operates in an active inverter operating state. It is necessary to continuously detect the terminal voltage of the battery. When the set maximum voltage value is exceeded, the charging process proceeds to the next stage. A skin effect occurs when an alternating current is passed through the wire. When the working frequency is , its skin depth is:

$$\mathbf{M}_{AB}(\psi) = \{ \psi_{j,\ell,k}(x) = |\det \mathbf{A}|^{j/2} \psi(\mathbf{B}^\ell \mathbf{A}^j x - k), j, \ell \in \mathbb{Z}, k \in \mathbb{Z}^2 \} \tag{12}$$

The window fill factor is:

$$\mu_{s,d} = \frac{1}{MN} \sum_{m=1}^M \sum_{n=1}^N |W_{s,d}(m,n)| \tag{13}$$

The inductor current is continuous, and the minimum value of the inductor current continuous is:

$$\sigma_{s,d} = \left[ \frac{1}{MN} \sum_{m=1}^M \sum_{n=1}^N \left| |W_{s,d}(m,n)| - \mu_{s,d} \right|^2 \right]^{1/2} \tag{14}$$

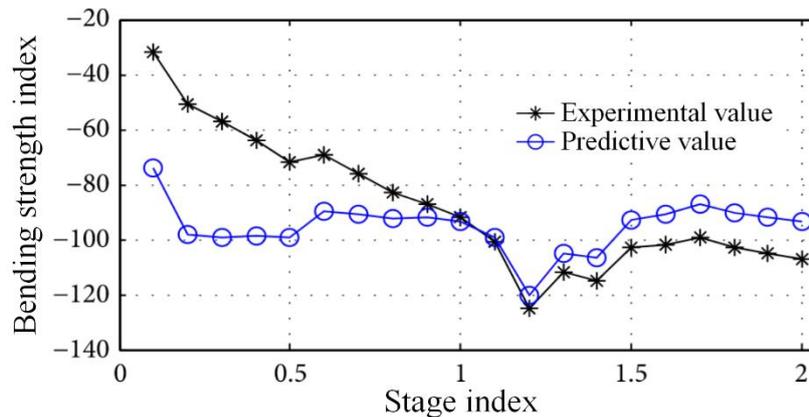
Substitute the parameters:

$$M(w) = \frac{w}{D} R_{ON} + \left(1 - \frac{w}{D}\right) R_{OFF} \tag{15}$$

The non-harmonic effect of the vibration of the carbon material can be simply described as a monophonic absorption peak accompanied by a fixed damping coefficient resulting in the existence of dielectric loss. The comparison between the learned value of the flexural strength and the experimental value is shown in Table 4 and Figure 3.

**Table 4.** Experimental and predicted values of carbon material flexural strength

Group No	Experimental value	Predictive value
1	68.42	67.53
2	69.57	58.25
3	53.78	54.51
4	56.34	59.47



**Figure 3.** Comparison of experimental values and predicted values of carbon material flexural strength

The charging system consists of a charging device and a battery. The charging device determines the charging parameter according to the state of the battery. The charging current is in the vicinity of the acceptable charging current curve of the battery, so that the battery is charged almost without gas precipitation, so as to save energy without damaging the battery [25]. Although the diode improves the grid-side power factor, it still produces grid-side harmonic currents that "contaminate" the grid. In addition, the deficiency of the diode is also due to the uncontrollability of its DC voltage. In response to insufficient appeal, pulse charging and discharging have completely improved the traditional phase control and diode. The key

improvement is to replace the semi-controlled power switch tube or diode with a fully-controlled power switch, replacing the phase-controlled rectifier or the uncontrolled rectifier with pulse-charge-charge-controlled rectifier [26]. The charging and discharging process of the supercapacitor charging and discharging device is required to maximize the chemical reaction speed of the battery, shorten the time for the battery to reach the full charge state, and increase the charging speed.

#### 4. Summary

In recent years, the widespread use of nanomaterials and new energy technologies has greatly promoted the development of supercapacitor energy storage technology. A porous carbon material having a larger mass than a large capacity is relatively easy to obtain, but a carbon material having a large volume specific capacity and a long-term application stability is difficult to obtain. Most of the current battery charging and discharging devices use thyristors, which cannot meet customer requirements in terms of function and performance. In order to coordinate and solve the two contradictory performance indicators of capacity and long-term stability, it is necessary to develop some new activated carbon materials and activation technologies. At present, the research on improving the performance of carbon-based electrode materials mainly focuses on the porous structure, scale nano-material and material composite of materials. In practical applications, these three aspects work together and work together. The nanometer scale material exhibits special physical and chemical properties, shortens the particle transport path and releases cyclic stress, and enhances the electrochemical reactivity of the electrode material. With the gradual depletion of the world's energy and the continuous expansion of the application of electrochemical capacitors, the development of carbon supercapacitors with practical prospects is an important work with theoretical significance and practical prospects.

#### References

- [1] Choi C, Lee J A, Choi A Y, et al. Flexible Supercapacitor Made of Carbon Nanotube Yarn with Internal Pores [J]. *Advanced Materials*, 2014, 26(13):2059-2065.
- [2] Wang G, Wang H, Lu X, et al. Solid-State Supercapacitor Based on Activated Carbon Cloths Exhibits Excellent Rate Capability [J]. *Advanced Materials*, 2014, 26(17):2676-2682.
- [3] Zhang Z, Chen X, Chen P, et al. Integrated Polymer Solar Cell and Electrochemical Supercapacitor in a Flexible and Stable Fiber Format [J]. *Advanced Materials*, 2014, 26(3):466-470.
- [4] Hou J, Cao C, Idrees F, et al. Hierarchical Porous Nitrogen-Doped Carbon Nanosheets Derived from Silk for Ultrahigh-Capacity Battery Anodes and Supercapacitors[J]. *ACS Nano*, 2015, 9(3):2556-2564.
- [5] Kouchachvili L, Ya?Ci W, Entchev E. Hybrid battery/supercapacitor energy storage system for the electric vehicles [J]. *Journal of Power Sources*, 2018, 374:237-248.
- [6] Bambang R T, Rohman A S, Dronkers C J, et al. Energy Management of Fuel Cell/Battery/Supercapacitor Hybrid Power Sources Using Model Predictive Control[J]. *IEEE Transactions on Industrial Informatics*, 2014, 10(4):1992-2002.
- [7] Hao P, Zhao Z, Tian J, et al. Hierarchical porous carbon aerogel derived from bagasse for high performance supercapacitor electrode [J]. *Nanoscale*, 2014, 6(20):12120-12129.
- [8] Li P, Shi E, Yang Y, et al. Carbon nanotube-polypyrrole core-shell sponge and its application as highly compressible supercapacitor electrode [J]. *Nano Research*, 2014, 7(2):209-218.
- [9] Kovalenko V L, Kotok V A, Sykchin A A, et al. Nickel hydroxide obtained by high-temperature two-step synthesis as an effective material for supercapacitor applications [J]. *Journal of Solid State Electrochemistry*, 2016, 21(3):683-691.

- [10] Devillers N, Jemei S, Marie-Cécile Péra, et al. Review of characterization methods for supercapacitor modelling [J]. *Journal of Power Sources*, 2014, 246(3):596-608.
- [11] Wang K, Li L, Zhang T, et al. Nitrogen-doped graphene for supercapacitor with long-term electrochemical stability[J]. *Energy*, 2014, 70:612-617.
- [12] Wang Q, Wang X, Xu J, et al. Flexible coaxial-type fiber supercapacitor based on NiCo<sub>2</sub>O<sub>4</sub> nanosheets electrodes [J]. *Nano Energy*, 2014, 8:44-51.
- [13] Xie L, Su F, Xie L, et al. Self-Assembled 3D Graphene-Based Aerogel with Co<sub>3</sub>O<sub>4</sub> Nanoparticles as High-Performance Asymmetric Supercapacitor Electrode [J]. *Chemsuschem*, 2015, 8(17):2917-2926.
- [14] Yang X, Xia H, Liang Z, et al. Monodisperse Carbon Nanospheres with Hierarchical Porous Structure as Electrode Material for Supercapacitor[J]. *Nanoscale Research Letters*, 2017, 12(1):550.
- [15] Zhang W, Zhu S, Luque R, et al. Recent development of carbon electrode materials and their bioanalytical and environmental applications [J]. *Chemical Society Reviews*, 2015, 45(3):715-752.
- [16] [16] General Strategy for Controlled Synthesis of Ni<sub>x</sub>Py/Carbon and Its Evaluation as a Counter Electrode Material in Dye-Sensitized Solar Cells [J]. *ACS Applied Materials & Interfaces*, 2017, 9(21):17949-17960.
- [17] Esat B, Bahceci S, Momchilov A A. Anthraquinone Functionalized Reduced Graphene Oxide As Electrode Material for Rechargeable Batteries[J]. *Carbon*, 2016, 116:154-166.
- [18] Liu W F, Yang Y Z, Liu X G, et al. Preparation and electrochemical performance of a polyaniline-carbon microsphere hybrid as a supercapacitor electrode[J]. *New Carbon Materials*, 2016, 31(6):594-599.
- [19] Porous N-doped carbon material derived from prolific chitosan biomass as a high-performance electrode for energy storage [J]. *RSC Adv.* 2015, 5(118):97427-97434.
- [20] Li J. Synthesis and characterisation of polyacrylonitrile and its derived carbon materials [J]. *Surface & Coatings Technology*, 2015, 261(8):436-441.
- [21] Lee K K, Chin W S, Sow C H. Cobalt-based compounds and composites as electrode materials for high-performance electrochemical capacitors [J]. *J. Mater. Chem. A*, 2014, 2(41):17212-17248.
- [22] Tan Q, Lv C, Xu Y, et al. Mesoporous composite of LiFePO<sub>4</sub> and carbon microspheres as positive-electrode materials for lithium-ion batteries [J]. *Particuology*, 2014, 17:106-113.
- [23] Talib E, Azam M A. An extensive study on carbon nanomaterials electrode from electrophoretic deposition technique for energy storage device [J]. *Journal of Materials Research*, 2016, 31(13):1972-1982.
- [24] Meng W, Chen W, Zhao L, et al. Porous Fe<sub>3</sub>O<sub>4</sub>/carbon composite electrode material prepared from metal-organic framework template and effect of temperature on its capacitance[J]. *Nano Energy*, 2014, 8:133-140.
- [25] Kaivosoja E, Sainio S, Lyytinen J, et al. Carbon thin films as electrode material in neural sensing [J]. *Surface and Coatings Technology*, 2014, 259:33-38.
- [26] Melke J, Jakes P, Langner J, et al. Carbon materials for the positive electrode in all-vanadium redox flow batteries [J]. *Carbon*, 2014, 78:220-230.