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The influence of the type of conductive additive on the electrochemical properties of activated carbon material

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The present work investigated the electrochemical properties of activated carbon material/conductive additive composites as electrodes for electrochemical capacitors in an aqueous electrolyte. The influence of the type of conductive additive on the specific capacitance characteristics of the obtained activated carbon material has been established. The activated carbon material (ACM) was obtained by thermochemical activation of plant-based raw material using potassium hydroxide. The influence of the type of conductive additive on the electrochemical properties of the activated carbon material was studied by means of electrochemical impedance spectroscopy, cyclic voltammetry, and galvanostatic charge/discharge measurements.

The study demonstrated that the choice of conductive additive significantly affects the performance of electrochemical capacitors, particularly the specific capacitance of the electrode material and its stability during cycling. Among the tested conductive additives, Super-P carbon black proved to be the most promising, as its combination with the activated carbon material provides optimal electrochemical characteristics. The resulting composite exhibits the highest specific capacitance (~100-120 F/g), stable performance at high charge-discharge rates, and a significant reduction in internal resistance, which is crucial for enhancing the energy and power efficiency of electrochemical capacitors.

Keywords: activated carbon material, thermochemical activation, conductive additive, specific capacitance, internal resistance, impedance spectroscopy, cyclic voltammetry, galvanostatic charge/discharge.

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Introduction

Electrochemical capacitors (EC) represent an emerging energy storage technology associated with rapid power fluctuations, reduction of battery size, and decreased consumption of fossil fuels [1]. The electrode structure has a significant impact on the capacitance and power output of EC. Therefore, the appropriate selection of electrode materials and their preparation procedures is crucial for achieving high specific power and high specific energy. The porous structure of activated carbon material, which is widely used as an electrode material due to its high specific surface area, results in low electrical conductivity of the electrode and requires the addition of a conductive additive to reduce internal resistance [2, 3]. Carbon black is commonly employed as a conductive additive for this purpose [4]. In some cases, carbon nanotubes (multi-walled or single-walled), graphite, graphene, or graphene oxide are also used [5]. Carbon nanotubes possess a high aspect ratio, which enables the formation of an efficient conductive network within the electrode, thereby enhancing electron transport. However, difficulties arise in achieving their uniform dispersion in composites with ACM, along with their relatively high cost.

Graphene and graphene-like materials exhibit exceptional electrical conductivity, high specific surface area, and mechanical strength. They can significantly improve the capacitance and rate capability of EC. Graphite is characterized by high conductivity, stability, and good interfacial contact with ACM; however, it becomes less effective at very small particle sizes. One of the most common and cost-effective conductive additives (CA) is carbon black (e.g., Super-P, Ketjenblack EC-600JD). It provides good electrical conductivity and promotes the formation of a conductive network that improves contact between active materials.

In this work, the influence of the type of conductive additive on the specific capacitance characteristics of ACM and the internal resistance of electrochemical systems based on composite (conductive additive/ACM) electrodes is investigated.

I. Materials and methods of research

The activated carbon material was prepared by thermochemical activation. Crushed nut shells were carbonized in an autoclave at 300-350 °C for 30 min, after which the product was ground to a particle size of 500 µm and mixed with water and KOH in a mass ratio of 1:1:0.5. The resulting mixture was dried at 70-80 °C for 48 h and subsequently activated at 900 °C for 30 min. After cooling, the material was washed with distilled water until neutral pH was reached [6].

To improve the electrical conductivity of ACM, the following conductive additives were investigated: graphite (Aldrich), oxidized graphite, thermally expanded graphite, and carbon black (Super P, China). Based on the obtained ACM and the above-mentioned conductive additives, composite electrodes containing 75 wt.% ACM and 25 wt.% CA were prepared. Electrochemical studies of the ACM/CA composites were carried out using a two-electrode cell (Fig. 1) with an Autolab PGSTAT/FRA-2 potentiostat/galvanostat in a 33 wt.% aqueous KOH solution as the electrolyte.

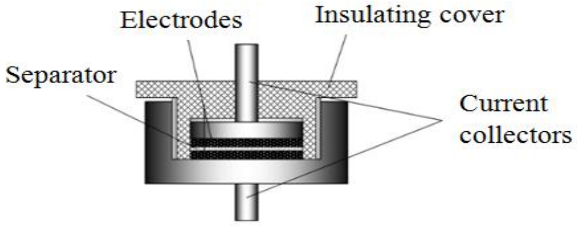

Fig. 1. Schematic diagram of a two-electrode cell for electrochemical research [7].

II. Results and discussion

Electrochemical impedance spectroscopy (EIS) is one of the most informative techniques for studying electrochemical systems. It is based on the application of a sinusoidal perturbation signal and the analysis of the system response, which enables the determination of resistance and the frequency dependence of capacitance. The frequency response is of great importance for the practical application of capacitors, and its evaluation is performed using mathematical and equivalent circuit modeling [8].

Figure 2 shows the Nyquist plots of electrochemical systems with composite ACM/CA electrodes at different charging voltages, which allow evaluation of the internal resistances of the electrochemical system and the charge storage mechanisms occurring within it.

As shown in Fig. 2, the impedance hodographs for all samples exhibit a shape typical of electrochemical capacitors. In the high-frequency region (105-104 Hz, left side), the impedance spectra display a small vertical linear "inductive" segment extending into the negative values of the -Z″ axis, which usually reflects the presence of current collectors and lead contacts. Subsequently, the curves intersect the Z′ axis at a point corresponding to the electrolyte solution resistance and/or the total contact and electrode resistance (Rs). In the presented plots, this point is located at approximately 0.1-0.25 Ω. This resistance is purely ohmic and does not depend on frequency. This indicates that at very high frequencies the capacitor behaves as a short-circuited element, and only the intrinsic system resistance is measured.

Immediately after the intersection with the Z′ axis, in the frequency range of approximately 104-800 Hz, a very small and slightly distorted semicircular segment is observed. This feature may indicate the presence of charge transfer resistance (Rct) and double-layer capacitance (Cdl) at the electrode/electrolyte interface. In electrochemical capacitors with high specific surface area and fast charge-discharge processes, this semicircle is often very small and barely distinguishable or even completely absent, since the Rct values are typically very low. In the presented impedance spectra, this region is not clearly expressed as a semicircle but rather appears as a smooth transition. The segment in the mid-frequency region corresponds to the transition from resistive to capacitive behavior. In the plot, this is observed as the onset of the upward rise of the curve along the -Z″ axis. At this stage, a transition occurs from kinetically controlled processes to capacitance-controlled processes. The nearly vertical line in the low-frequency region (the vertical segment on the right) is the most characteristic feature of the Nyquist plot for electrochemical capacitors. At low frequencies, all electrochemical systems behave as purely capacitive elements.

The imaginary part of the impedance (-Z″) increases sharply, while the real part (Z′) changes only slightly or remains nearly constant; for an ideal electrochemical capacitor, this behavior would be represented by a perfectly vertical line at an angle of 90° to the Z′ axis. However, in the presented plots (Fig. 2), the line is nearly vertical but shows a slight inclination toward higher Z′ values. This indicates the presence of a certain ohmic resistance associated with electrode pores (mass transport effects) or energy losses in the system at low frequencies, commonly described as the equivalent series resistance (ESR). The closer the line is to the vertical direction, the closer the system is to an ideal capacitor. The length of the vertical segment reflects the capacitance of the electrochemical system: the longer and more vertical this segment, the higher the capacitance of the device.

It should be emphasized that the highest values of specific capacitance are typically observed at very low frequencies; therefore, electrochemical capacitors are most effectively operated at low frequencies or under direct current (DC) conditions [9, 10].

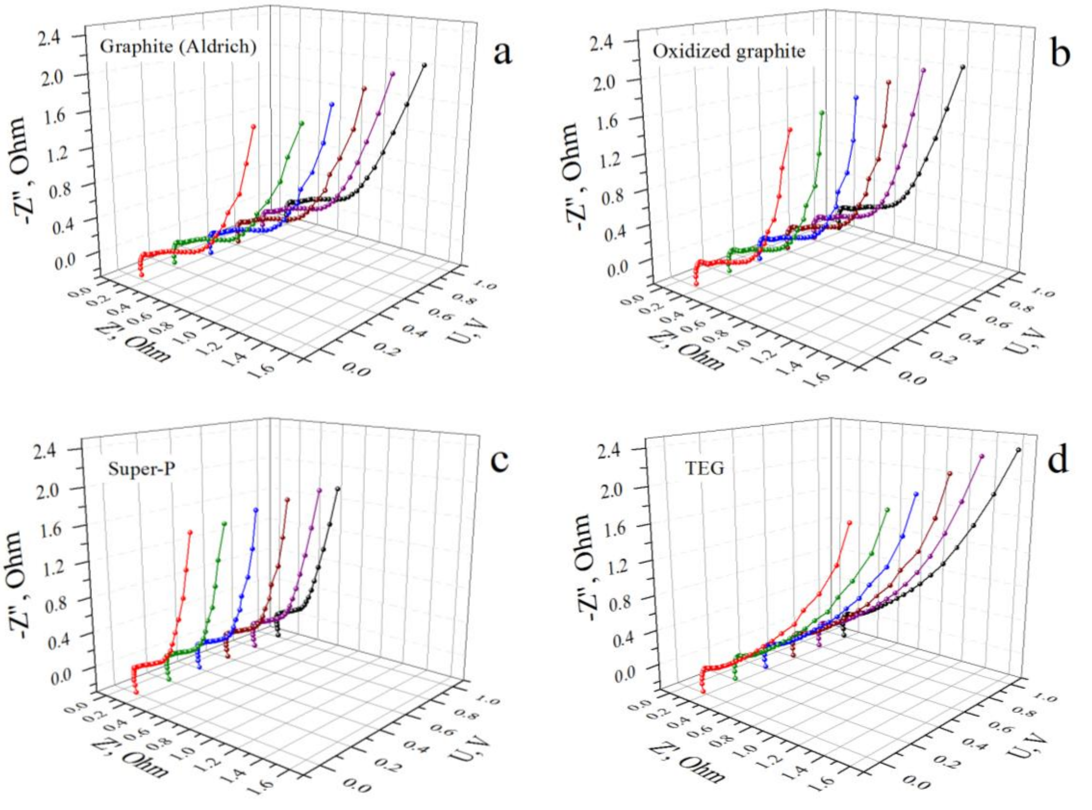

Fig. 2. Nyquist plots of the electrochemical system ACM/CA.

Thus, based on the visual analysis of the impedance spectra (Fig. 2), it can be concluded that all investigated conductive additives provide a low internal resistance, indicating good contact between the electrodes and the electrolyte, as well as a low charge-transfer resistance, which indicates the good electrochemical activity of the ACM surface. The electrochemical behavior of the systems is typical of electrochemical capacitors with double-layer capacitance. The absence of a clearly pronounced large arc indicates the lack of significant Faradaic reactions, i.e., the capacitive charge storage mechanism predominates in the electrochemical system.

Based on the analysis of the Nyquist plots (Fig. 2), the capacitance of all electrochemical systems with composite (ACM/CA)/electrolyte configurations was calculated. The capacitance was determined using the value of the imaginary component of impedance (Z'') at a frequency of f = 10 mHz, according to the following equation [10].

$$C = \frac{1}{2\pi \cdot f \cdot Z''}$$

Figure 3 presents the dependence of capacitance (C) on the applied voltage (U) for four systems with different types of conductive additives. As can be seen from the figure, all systems exhibit a slight decrease in capacitance with increasing voltage, which is typical behavior for electric double-layer capacitor (EDLC) systems. The general tendency toward decreasing capacitance with increasing applied voltage may be associated with limitations of ion transport within the pores of ACM, changes in the structure of the electric double layer, or other electrochemical effects.

The results (Fig. 3) show that the EC utilizing Super-P carbon black as the conductive additive demonstrates the highest capacitance among all investigated systems, starting at approximately ~9.5 F at 0 V and maintaining relatively high capacitance values over the entire voltage range (0-1 V), with only a slight decrease. This indicates high capacitance stability of the corresponding composite electrode under applied load. It should also be noted that Super-P is one of the most widely used conductive additives for supercapacitors. This material is known for its high electrical conductivity and its ability to form an efficient conductive network even at low concentrations. In addition, it has a relatively small particle size and good dispersibility [11].

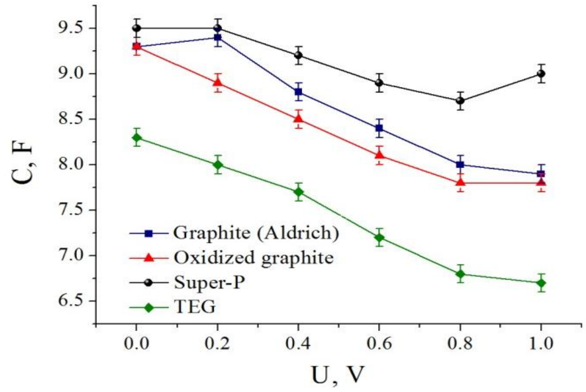

Fig. 3. Dependence of capacitance on applied voltage for an electrochemical system ACM/CA calculated from EIS data.

The initial capacitance of EC based on graphite (Aldrich) and oxidized graphite is slightly lower than that of the EC with Super-P, amounting to approximately 9.3 F at 0 V. Similar to the previous case, the capacitance decreases noticeably with increasing voltage, reaching about 7.8 F at 1 V. This capacitance drop is more pronounced than that observed for the Super-P based EC, indicating lower stability of the capacitive characteristics with increasing voltage. The lowest initial capacitance is observed for the EC based on thermally expanded graphite (TEG) (~8.3 F at 0 V), which decreases more rapidly with increasing voltage compared to all other investigated systems, reaching approximately 6.7 F at 1 V. This indicates the poorest capacitance stability under applied voltage for this conductive additive. Thus, the type of conductive additive affects both the absolute capacitance value and its voltage-dependent stability. This highlights the importance of selecting an appropriate additive for optimizing electrode performance.

For visual comparison and identification of changes occurring in EC during the charging process from 0 to 1 V, (Fig. 4. a, b) presents Nyquist plots for the four investigated electrochemical systems. The obtained impedance spectra are well described by the equivalent electrical circuit (EEC) shown in Fig. 4, c. It should be noted that, in this case, the element L1 represents the inductance associated with current collectors, contacts, and the metallic casing of the test cell. The series equivalent resistance Rs includes the resistance of the electrolyte, the electrode material, and the resistance due to the cell design features (Fig. 4. c). The C1‖R1 branch models diffusion processes occurring in the macropores of the porous electrode, as well as charge accumulation on its surface. The CPE1‖R2-C2 combination describes charge storage processes in meso- and micropores. The use of CPE elements in the circuit is required to provide greater flexibility in modeling. In particular, CPE1 is a diffusion-type constant phase element that reflects the limited diffusion of K+ and OH- ions within the meso- and microporous structure of ACM. The resistances R1 and R2 correspond to charge-transfer resistance within the pores of the carbon material, while the C2 element characterizes the capacitance accumulated in meso- and micropores [12].

The parameters corresponding to the EEC (Fig. 4. c) are presented in Table 1. During the fitting of the experimental EIS spectra, the χ^2 values did not exceed 0.005, confirming the reliability of the obtained parameters and their physical significance. As shown in the table, the inductance L1 values for all EC range from 0.390 to 0.442 μH, which are relatively low and indicate a negligible influence of inductance within the measured samples. This is important for EC, as high inductance can limit their high-frequency performance. The equivalent series resistance is critical for EC performance, since high Rs leads to significant energy losses (due to heating) and limits charge/discharge power. The Rs values range from 0.099 Ω (Super-P at 1 V) to 0.199 Ω (graphite Aldrich at 0 V).

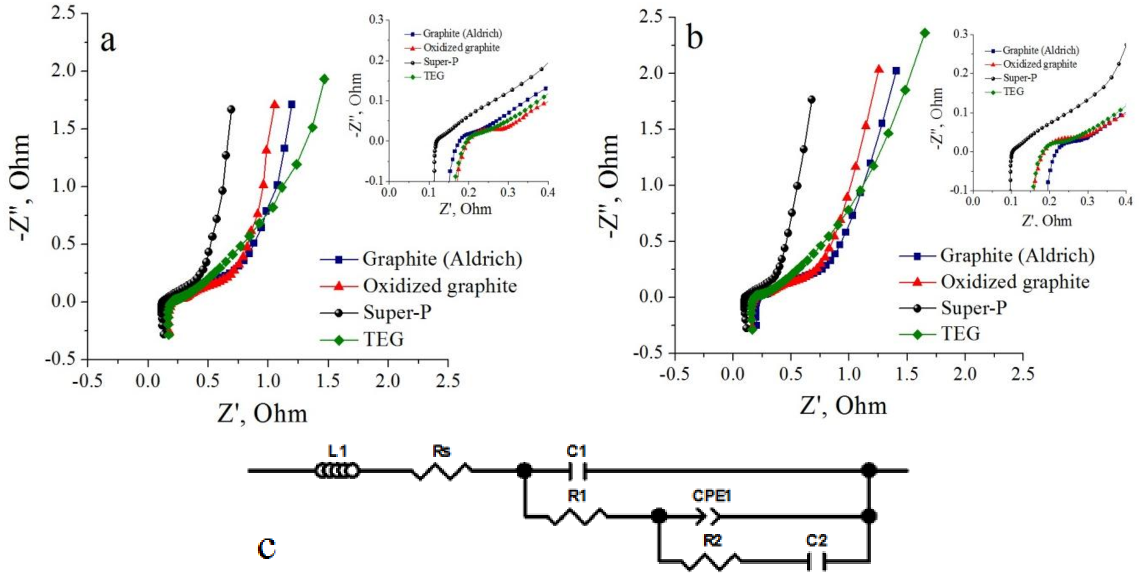

Fig. 4. Nyquist plots of the electrochemical system ACM/CA obtained at 0 V (a), 1 V (b), and EEC (c).

Table 1.

EEC parameters for EC based on ACM/CA composite

CA / Element	Graphite (Aldrich)		Oxidized graphite		Super-P		TEG	
	0 V	1 V	0 V	1 V	0 V	1 V	0 V	1 V
L_1, μH	0.390	0.393	0.397	0.403	0.440	0.432	0.437	0.442
R_s, Ohm	0.152	0.199	0.174	0.165	0.116	0.099	0.171	0.163
C_1, mF	0.288	0.364	0.237	0.291	6.810	8.407	0.392	0.423
R_1, Ohm	0.052	0.057	0.082	0.079	0.019	0.016	0.058	0.072
CPE_{1T}	0.929	0.791	0.934	0.821	1.369	1.385	1.294	1.116
CPE_{1P}	0.453	0.447	0.468	0.443	0.572	0.584	0.465	0.484
R_2, Ohm	1.281	1.219	0.897	0.954	0.594	0.491	1.820	1.745
C_2, F	3.949	3.398	4.426	3.549	4.613	4.452	1.265	1.232

Composite electrodes containing Super-P carbon black exhibit lower Rs values, which may indicate better conductivity of the composite or a more optimized interaction with the electrolyte. As mentioned above, the capacitance C1 reflects charge accumulation in macropores and on the electrode surface. The C1 values range from 0.237 μF (for oxidized graphite) to 8.407 μF (for Super-P). Higher C1 values, as observed for Super-P, indicate greater effectiveness of this conductive additive in forming a surface capable of efficient charge storage. The resistance R1 is associated with diffusion processes and charge transfer within the macropores. The R1 values lie in the range of 0.019-0.082 Ω. Lower R1 values, such as those obtained for the Super-P samples, are desirable, as they indicate easier ion diffusion and faster charge transfer.

The values of the CPE1P exponent are close to 0.5, which is characteristic of a Warburg-type diffusion element, confirming that CPE1 models diffusion-controlled processes. The CPE1T values are higher for carbon black (~1.36-1.38), indicating more active diffusion processes. The resistance R2, together with C2, describes charge storage processes in meso- and micropores. The R2 values vary from 0.491 to 1.820 Ω. Lower R2 values indicate more efficient charge transport within smaller pores.

Electrodes based on graphite (Aldrich) and oxidized graphite generally exhibit higher R2 values. The capacitance C2 represents a significant contribution to the total capacitance of EC, since meso- and micropores provide a large surface area for charge accumulation. The C2 values range from 3.398 to 4.613 F. Samples containing Super-P carbon black show higher C2 values, demonstrating their effectiveness in forming a well-developed porous structure for charge storage.

Thus, the analysis of the obtained data demonstrates that different conductive additives significantly affect the EEC parameters of electrochemical capacitors. In particular, Super-P carbon black generally exhibits superior performance, namely: lower equivalent series resistance (Rs), indicating reduced energy losses; higher capacitance values accumulated both in macropores (C1) and in meso- and micropores (C2), reflecting more efficient charge storage; and lower charge-transfer resistance values (R1, R2), which promote faster charge/discharge processes in EC. These results emphasize the importance of selecting an optimal conductive additive to enhance the electrical characteristics of electrochemical capacitors, particularly with regard to their capacitance and charge-transfer efficiency.

A comprehensive approach that provides a complete picture of the electrochemical behavior of EC – allowing evaluation of their potential for specific applications, optimization of materials and design, and clarification of the mechanisms of energy storage and release – is the performance of galvanostatic charge/discharge measurements at different current densities. Deviations from the ideal triangular shape of charge/discharge curves (e.g., curvature or plateaus) may indicate the presence of Faradaic processes (pseudocapacitance), self-discharge, or other side reactions that can affect the performance and stability of the capacitor. Testing at different current densities facilitates a more accurate differentiation of these phenomena.

To evaluate the influence of the type of conductive additive on the efficiency, stability, and specific capacitance of ACM, galvanostatic testing of EC was performed at charge/discharge currents ranging from 10 to 200 mA under conditions close to practical operation.

The presented discharge curves (Fig. 5) exhibit the nearly linear voltage-time behavior characteristic of supercapacitors, indicating that charge storage is predominantly governed by the electric double-layer capacitance (EDLC) mechanism. For all samples, a decrease in discharge capacitance is observed with increasing current from 10 mA to 100 mA. This behavior is typical for EC and reflects limitations in ion transport kinetics and/or an increase in internal resistance at higher current densities.

At 10 mA (Fig. 5. a), the discharge curves are more gradual, indicating a slower discharge process and, consequently, a longer discharge time. This enables a more complete utilization of the material capacitance. For the EC based on the ACM/Super-P carbon black composite, the longest discharge time is observed (~1200 s). EC based on composites with graphite (Aldrich) and oxidized graphite exhibit intermediate discharge times, while the shortest discharge time is recorded for the composite containing thermally expanded graphite (TEG). This behavior is likely associated with differences in the electrical conductivity of the investigated composites.

At 100 mA (Fig. 5. b), the discharge curves become significantly steeper, indicating a faster discharge process.

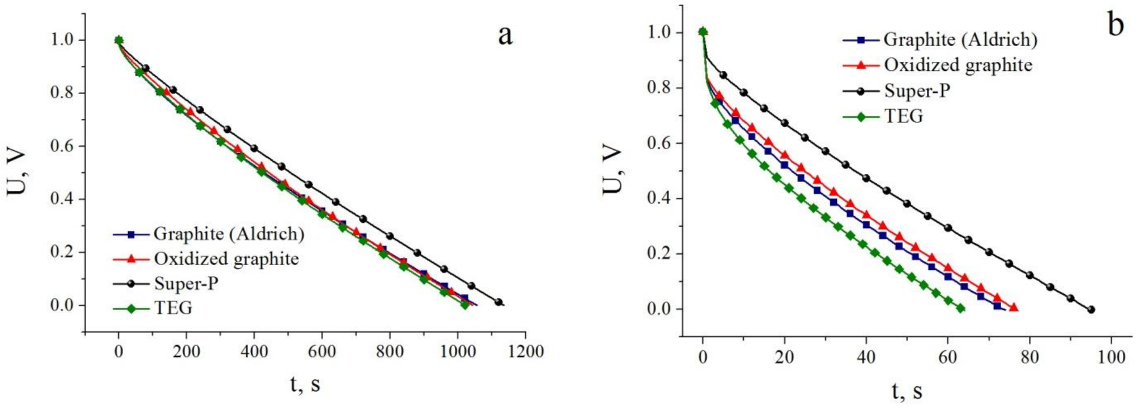

Fig. 5. Discharge curves for EC based on ACM/CA composites obtained at charge/discharge currents of 10 mA (a) and 100 mA (b).

This behavior is typical at higher currents, where kinetic limitations and internal resistance effects become more pronounced. The differences between EC fabricated from various composites become more evident under higher current conditions, as electrical conductivity and the efficiency of charge distribution exert a greater influence on performance. The discharge curves obtained at 100 mA (Fig. 5. b) exhibit a more pronounced instantaneous voltage drop (IR-drop) at the beginning of discharge for all samples compared to those recorded at 10 mA (Fig. 5. a). This indicates a higher equivalent series resistance at elevated currents, which is an expected behavior. The most pronounced IR-drop is observed for the composite containing TEG, indicating a higher ESR compared to the other additives at this current. The composite with Super-P carbon black demonstrates the best performance in terms of discharge time (and, consequently, capacitance) at both low and high charge/discharge currents, confirming its high efficiency as a conductive additive in ACM-based composites.

Testing at different current densities (from low to high) makes it possible to evaluate the ability of EC to rapidly store and deliver energy. This is critically important for applications requiring high power output, such as rapid acceleration or regenerative braking. If the capacitance decreases significantly at high currents, this indicates limitations related to the material properties or device design.

The obtained constant-current charge/discharge curves were used to calculate the specific capacitance of ACM (Fig. 6) and the voltage drop across the EC (Fig. 7), which, in turn, allowed evaluation of the influence of the type of conductive additive on the corresponding performance characteristics. The specific capacitance (Csp) of ACM was determined according to the following equation:

$$C_{sp} = \frac{2 \cdot I \cdot \Delta t}{\Delta U \cdot m},$$

where I is the current (A), Δt is the discharge time (s), ΔU is the voltage change during discharge (V), and m = 0.1875 g is the mass of ACM in a single electrode.

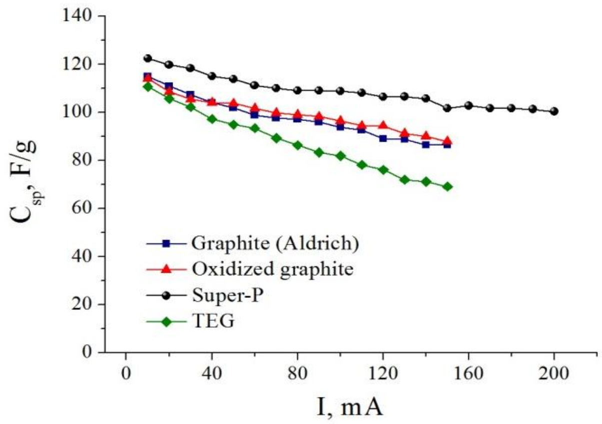

Fig. 6. Specific capacitance of ACM at different galvanostatic charge/discharge currents.

As shown in Fig. 6, all composites exhibit a general tendency toward decreasing specific capacitance with increasing charge/discharge current. This behavior is expected for EC, since at higher currents kinetic limitations, internal resistance, and ion diffusion constraints within the porous carbon structure become more significant, preventing full utilization of the available capacitance.

The composite containing Super-P carbon black exhibits the highest specific capacitance (100-123 F/g) over the entire current range. The corresponding curve is the least steep, indicating good rate capability and relatively low capacitance loss with increasing current. This behavior confirms the high electrical conductivity of the composite. Composites containing graphite exhibit slightly lower specific capacitance values (85-115 F/g); however, their capacitive behavior remains relatively stable. The decrease in capacitance with increasing current is more pronounced than that observed for the Super-P based composite. This behavior may be attributed, for example, to the presence of oxygen-containing functional groups in oxidized graphite, which can affect its electrical conductivity and interaction with the electrolyte.

The composite containing TEG exhibits the lowest specific capacitance values (70-110 F/g) among all investigated conductive additives. The Csp – I dependence for the TEG-based composite is the steepest, indicating the most significant decrease in capacitance with increasing current, i.e., the poorest rate capability. This behavior may be related to its morphology, structural features, or lower electrical conductivity under the given experimental conditions.

From the galvanostatic charge/discharge curves, the internal resistance of the device – representing the sum of all internal resistances (electrodes, electrolyte, and contacts) – can be estimated. The equivalent series resistance manifests as an instantaneous voltage drop (IR-drop) at the start of discharge or a voltage rise at the start of charge. At higher current densities, the IR-drop increases. A low ESR is desirable, as it ensures high power capability and reduced energy losses. Increasing the current enables a more pronounced evaluation of the ESR contribution.

For all EC, a linear increase in the voltage drop (ΔU) with increasing charge/discharge current is observed (Fig. 7. a). This behavior fully complies with Ohm's law (ΔU = I·R), indicating the presence of internal resistance in the device. The smaller the voltage drop, the better the material performance in terms of power capability and efficiency, as energy losses associated with internal resistance are minimized. Such behavior is observed for the EC based on the ACM/Super-P composite, for which ΔU does not exceed 0.15 V within the discharge current range of 10-200 mA.

Similarly, for most EC, the ESR exhibits relatively stable behavior or only slight decrease/increase with increasing current (Fig. 7. b). This is typical for supercapacitors, where the ESR remains relatively constant within a certain current range. However, it should be noted that the dependence of ESR on current is not always strictly linear, as it may be influenced by various factors, such as electrode polarization, electrolyte resistance, and other interfacial effects. The data obtained from the voltage drop (ΔU) and the calculated ESR values show good correlation. EC exhibiting a smaller voltage drop correspondingly demonstrate lower ESR values, which is consistent with expectations.

Detailed information on process kinetics, charge storage mechanisms, and internal device limitations can be obtained through potentiodynamic investigations (cyclic voltammetry, CV) performed at different scan rates Fig. 8.

At low scan rates, electrolyte ions have sufficient time to penetrate all pores and access the electrode surface, enabling full utilization of the material capacitance. With increasing scan rate (s), the time available for ion diffusion and for Faradaic reactions (if present) decreases. If the material exhibits good rate capability, its capacitance (or the enclosed CV area) will not significantly decrease with increasing scan rate. A pronounced reduction in capacitance at higher s values indicates kinetic limitations associated with ion transport or electrical resistance. An increase in internal resistance leads to distortion of the CV curve shape at high scan rates (e.g., increased separation between anodic and cathodic peaks or deviation from an ideal rectangular profile).

Peak shifting and peak broadening are also indicators of kinetic limitations and increased ESR. For an ideal electrochemical capacitor, the CV curve exhibits a rectangular or quasi-rectangular shape, and the current at a given potential is directly proportional to the scan rate. The area enclosed by the curve (charge) increases linearly with scan rate, while the capacitance remains relatively constant. However, most real EC materials demonstrate a combination of electric double-layer capacitance and pseudocapacitance. CV measurements performed at different scan rates enable quantitative evaluation of the relative contribution of each charge storage mechanism to the overall capacitance.

The experimental CV curves presented in Fig. 8 exhibit a quasi-rectangular shape, which is typical of EC where charge storage is dominated by the electric double-layer mechanism. The absence of distinct Faradaic (redox) peaks indicates a minimal contribution of pseudocapacitance or its complete absence. The measurements were carried out within a potential window from 0 V to approximately 1 V to prevent water electrolysis reactions. For all EC, as the scan rate increases (from 1 mV/s to 30 mV/s), the width of the CV curves (i.e., the absolute current value) increases, which is

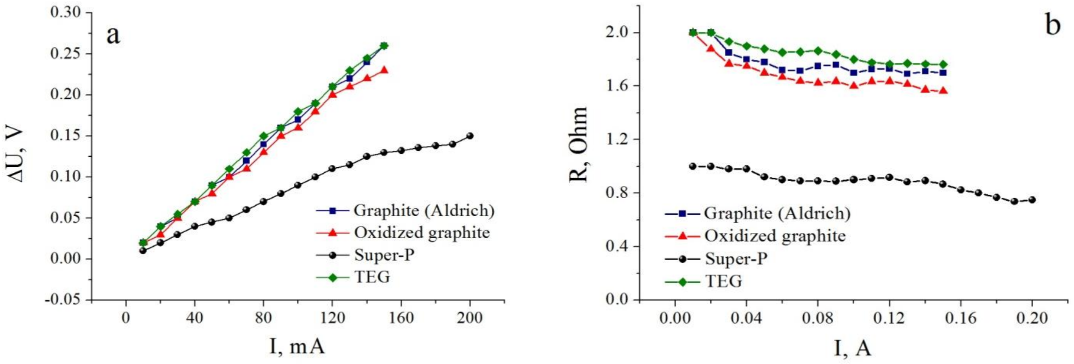

Fig. 7. Voltage drop across the EC (a) and ESR (b) at different charge/discharge currents.

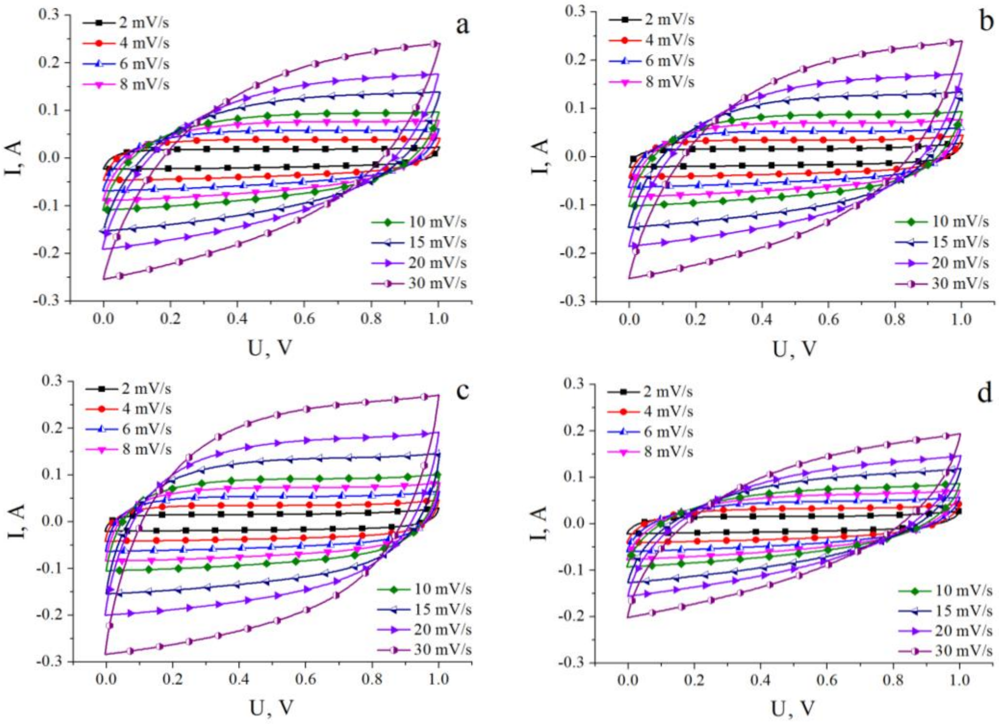

Fig. 8. CVA curves for EC made on the basis of ACM/CA composite: a – graphite (Aldrich), b – oxidized graphite, c – Super-P carbon black and d – TRG.

expected, since at higher scan rates a larger current flows through the electrode.

At high scan rates (especially 15-30 mV/s), the rectangular shape of the curves becomes slightly distorted, appearing more "stretched" along the current axis. This indicates an increase in ESR and kinetic limitations (ion diffusion constraints) under rapid potential changes. Although the absolute current increases, the relative area enclosed by the curve (integrated charge) per unit time may decrease, leading to a reduction in capacitance at high scan rates.

Based on the cyclic voltammograms (Fig. 8), the specific capacitance of the investigated ACM was calculated. The dependence of specific capacitance on the potential scan rate for these samples is presented in Fig. 9. In all cases, a decrease in specific capacitance with increasing scan rate is observed. This behavior is typical for electrochemical capacitors and is associated with kinetic limitations at higher scan rates.

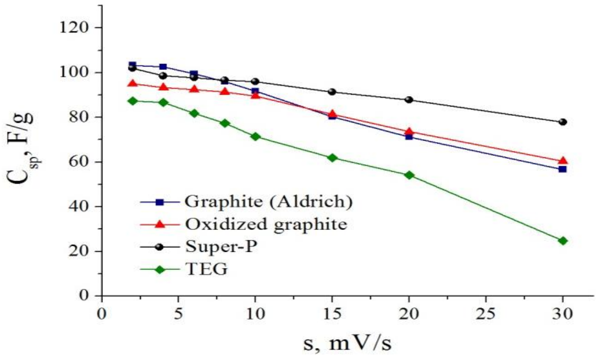

Fig. 9. Dependence of specific capacitance on scanning speed for ACM.

The highest specific capacitance values (~102-88 F/g) across the entire scan rate range are exhibited by the ACM in combination with the conductive carbon black Super-P. Its curve is the flattest, indicating the best rate capability. This means that the capacitance of this composite decreases the least (only ~10% loss) with increasing scan rate, confirming its low ESR and efficient charge transport.

The ACM in combination with graphite (Aldrich) and oxidized graphite exhibits somewhat greater capacitance losses with increasing scan rate (over 25% and 30%, respectively), indicating their more limited rate capability compared to Super-P. The most pronounced capacitance drop (over 65%) with increasing scan rate is observed for the ACM composite with TRG, suggesting its unsuitability for applications requiring high power density and rapid charge/discharge performance.

The obtained CV results, presented as the dependence of specific capacitance on scan rate (Fig. 9), are fully consistent with the galvanostatic measurements (Fig. 6), where the ACM composite with Super-P carbon black exhibited the highest capacitance and the best stability at different charge/discharge current densities. This also agrees with the ESR analysis (Fig. 7), in which the ACM composite with Super-P demonstrated the lowest internal resistance.

Conclusions

An activated carbon material was obtained by thermochemical activation of plant-based raw material using potassium hydroxide. Composites based on this material were fabricated using different conductive additives. The influence of the type of conductive additive on the electrochemical properties of the activated carbon material was investigated.

It was shown that the type of conductive additive significantly affects the performance of the electrochemical capacitor and the absolute value of the electrode material's specific capacitance. Acetylene carbon black stands out as the optimal choice for the composite with the carbon material, providing the highest specific capacitance (~100-120 F/g), high power capability, and minimized internal resistance of the electrochemical capacitors.

The impedance spectroscopy results indicate a nonlinear dependence of specific capacitance on the applied potential. The maximum capacitance is observed at 0 V, corresponding to a potential close to the point of zero charge. As the potential increases, the capacitance decreases, which can be attributed to compression of the electric double layer and the orientation of electrolyte ions.

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Вплив типу струмопровідної добавки на електрохімічні властивості активованого вуглецевого матеріалу

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У роботі досліджено електрохімічні властивості композитів на основі активованого вуглецевого матеріалу та струмопровідної добавки як електродів електрохімічних конденсаторів у водному електроліті. Встановлено вплив типу струмопровідної добавки на питомі ємнісні характеристики отриманого електродного матеріалу. Активований вуглецевий матеріал отримано шляхом термохімічної активації рослинної сировини з використанням гідроксиду калію. Вплив типу струмопровідної добавки на електрохімічні властивості вуглецевого матеріалу вивчали за допомогою електрохімічної імпедансної спектроскопії, циклічної вольтамперометрії та гальваностатичного заряд/розряду.

Дослідження показали, що вибір струмопровідної добавки суттєво впливає на ефективність електрохімічних конденсаторів, зокрема на величину питомої ємності електродного матеріалу та її стабільність під час циклічного заряд/розряду. Серед протестованих струмопровідних добавок найбільш перспективною виявилася сажа Super-P, яка в поєднанні з активованим вуглецевим матеріалом забезпечує оптимальні електрохімічні характеристики. Такий композит демонструє найвищу питому ємність (~100-120 Ф/г), стабільну роботу при високих швидкостях заряд/розряду та значне зниження внутрішнього опору, що є ключовим для підвищення енергетичної та потужнісної ефективності електрохімічних конденсаторів.

Ключові слова: активований вуглецевий матеріал, термохімічна активація, струмопровідна добавка, питома ємність, внутрішній опір, імпедансна спектроскопія, циклічна вольтамперометрія, гальваностатичний заряд/розряд.