Electrolytes for Electrochemical Supercapacitors

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Compatibility of Electrolytes with Inactive Components of Electrochemical Supercapacitors

Publication details
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Published online on: 06 May 2016

How to cite :- Cheng Zhong, Yida Deng, Wenbin Hu, Daoming Sun, Xiaopeng Han, Jinli Qiao, Jiujun Zhang. 06 May 2016, Compatibility of Electrolytes with Inactive Components of Electrochemical Supercapacitors from: Electrolytes for Electrochemical Supercapacitors CRC Press
Accessed on: 31 Jan 2020

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3.1 INTRODUCTION

As fully discussed in Chapter 2, the electrolyte has complex interactions with the electrode materials (active components) of electrochemical supercapacitors (ESs), which play an important role in the performance of ESs. Besides the active component of ESs, the compatibility or possible interaction between the electrolyte and inactive components such as current collectors, binders, and separators should also be considered. For example, the possible corrosion of current collectors in certain electrolytes could reduce the operative cell voltage and decrease the lifetime of ESs. Besides, the transfer of electrolyte ions across the separator could affect the equivalent series resistance (ESR) and the power performance of the ES. Therefore, the inactive components of ESs should be compatible with the electrolytes and electrode materials.

This chapter will provide a discussion of the compatibility issue or the possible interaction between electrolytes and inactive components of ESs including current collectors, binders, and separators.
3.2 CURRENT COLLECTORS

The chemical stability and electrochemical stability of current collectors in certain electrolytes have a profound influence on their performance characteristics such as the operating cell voltage, reliability, and lifetime of ESs. Besides, the contact between the active-electrode materials and the current collector may contribute a lot to the ESR of ESs in some cases. Furthermore, the loading amount and the utilization degree of active-electrode materials are also strongly dependent on the morphology of the current collectors.

For ESs using a strong acid electrolyte such as 1 M H$_2$SO$_4$, some metallic materials with high-corrosion resistance such as gold (Au) are traditionally used [1,2]. To save the cost of the current collectors, other materials, such as indium tin oxide (ITO) [3,4], carbon-based materials [5–7], and electrically conductive polymers (ECPs) [8], have been investigated as materials to fabricate the current collectors used in strong acid electrolyte-based ESs. The use of these recently developed current collectors may have other advantages. For instance, because of the relatively good conductivity and high transparency of ITO, transparent ESs can be fabricated with the use of ITO current collectors [3]. Noticeably, ITO may suffer from corrosion problems in some electrolytes. Folcher et al. [9] found ITO corroded in HCl solution at a potential of 0.9 V versus a saturated calomel electrode (SCE). This result was confirmed by quartz crystal microbalance (QCM), characterization of corrosion morphology, and electrochemical measurements. As the concentration of the HCl electrolyte increased from 0.04 to 1 M, QCM measurements indicated that the corrosion rate increased drastically from ≤5 to 3400 ng s$^{-1}$ cm$^{-2}$. Obvious dissolution of the ITO electrode was observed after a potential scan from 0.33 to 1.33 V versus SCE in 0.1 M HCl (Figure 3.1). An intergranular corrosion attack of ITO was found by transmission electron microscopy images. The authors proposed that the corrosion mechanism of ITO was related to the electrochemical formation of Cl$^-$ and OH$^-$ radical species that

![FIGURE 3.1 Scanning electron microscopy (SEM) image of an ITO layer immersed in a 0.1-M HCl solution after a potential scan from 0.3 to 1.2 V (SCE). (Reprinted from Anodic corrosion of indium tin oxide films induced by the electrochemical oxidation of chlorides, 301, Folcher, G. et al., Thin Solid Films, 242–248, Copyright 1997, with permission from Elsevier.)](image-url)
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destroyed the In–O surface bonds. In addition, using current collectors with carbon or ECP materials is beneficial for fabricating flexible ESs [5,8]. Furthermore, the use of free-standing electrodes such as the carbon-based composite paper for ESs has the benefit that it can be used without the use of additional current collectors [10].

In the case of ESs with alkaline electrolytes, nickel (Ni) current collectors have been extensively used owing to their good chemical and electrochemical stabilities in alkaline electrolytes, and the relatively low cost [11–17]. In some cases, Ni foam is used as the current collector to increase the total surface area, as well as the loading amount and utilization of the active-electrode materials [11,12,14,15]. However, it should be noted that the use of an Ni current collector may contribute to the additional pseudocapacitance due to the presence of Ni hydroxide/oxide on the surface, which can bring about an exaggerated capacitance value concerning the active-electrode materials, especially when the loading amount of the electrode material is small [18]. Therefore, Xing et al. [18] suggested the use of an electrochemically inert current collector such as titanium (Ti) and platinum (Pt) foil to characterize the true capacitive properties of active-electrode materials such as Ni and cobalt (Co) oxides/hydroxides. Apart from pure Ni, other types of metallic materials, such as stainless steel [19,20], Inconel 600 Ni-based alloy [21], and nanoporous Au [22], have also been explored to be used as current collectors in ESs using alkaline electrolytes. Owing to their good conductivity, high chemical, electrochemical, and thermal stabilities, lightweight, high flexibility, and good mechanical strength, carbon-based materials, such as carbon fibers [23], carbon fiber paper [24], carbon cloth [25], carbon nanotubes (CNTs) [26], and ultrathin-graphite foam [27], have all recently received growing interest.

Compared with strong acid and alkaline electrolytes, neutral aqueous electrolytes generally have much lower corrosiveness. Therefore, a wide variety of current-collector materials have been investigated for neutral aqueous electrolyte-based ESs. Some cited materials for current collectors are Ni [28–30], Ti [31], copper (Cu) [32], Ti oxynitride [33], stainless steel [34–38], modified TiO$_2$ [39], ITO [40], CNT [41,42], etc. It is interesting to note that Wang et al. [43] found the type and morphology of the current collectors (Ti mesh and Ni foam) to be affecting the performance of ESs greatly. The nature of the current collector has a profound influence on the impedance behavior of the MnO$_2$–CNTs composite electrode (Figure 3.2), as well as the galvanic charge/discharge profiles (Figure 3.3). Figure 3.3 shows the specific capacitance of ES using Ni foam as current collectors had the highest value, suggesting that the Ni foam exhibited a better current-collection property than the Ti mesh.

With the aim to enhance the performance of ESs such as lowering the contact resistance between the electrode materials and the current collector, it has been proposed to directly grow the electrode materials on the current collector [44–47]. Du and Pan [45] prepared multiwalled carbon nanotube (MWCNT) thin films on the Ni foil current collector by the electrophoretic deposition technique. The obtained ES showed near-ideal rectangular cyclic voltammograms even at a very high scan rate of 1000 mV s$^{-1}$, a high specific power density of more than 20 kW kg$^{-1}$, and an excellent frequency response. Miller et al. [46] reported that vertically oriented graphene nanosheets grown directly on metal current collectors (Figure 3.4) could minimize both electronic and ionic resistance, with resistance–capacitance (RC) time constants of less than 200 μs. This is beneficial for achieving ES with high-power performance.

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Regarding ESs with organic electrolytes, aluminum (Al) has been the most commonly used material for current collectors [48–57]. The degradation of Al current collectors was found to be related to the performance aging of the organic electrolyte-based ESs [55,56]. It has been found by Jänes et al. [56] that during the aging tests of a microporous carbide-derived carbon-based ES with 1.5 M (C$_2$H$_5$)$_3$CH$_3$NBF$_4$/ACN electrolyte, partial dissolution of Al current collectors from the positive electrode and the deposition of Al on the negative electrode occurred (Figure 3.5). Besides, Väli et al. [52] found that the electrochemical stability of the Al current collector was strongly dependent on the nature of the conducting salt in the organic solvent. The operative cell voltages of ESs were 3.4, 3.2, and 2.5 V for NaPF$_6$, NaClO$_4$, and NaFSI electrolytes, respectively. NaFSI electrolyte-based ES exhibited the lowest cell voltage due to the oxidation of Al current collector in this electrolyte.

To improve the performance of organic electrolyte-based ES, various surface treatment methods have been proposed for Al current collectors [48–51,54,57]. For example, Sato et al. [57] modified the Al foil surface with a thermocuring coating composed of glycol–chitosan, pyromellitic acid, and carbon powder. Compared with the unmodified Al foil current collector, the modified Al foil resulted in a much higher rate capability of the ES using the 1 M [DEME][BF$_4$]/propylene carbonate (PC) organic electrolyte. Lei et al. [49] found that the contact resistance of the carbon/Al in tetraethylammonium tetrafluoroborate (TEABF$_4$)/PC organic electrolyte greatly decreased by a carbon-modified Al current collector with Al$_4$C$_3$ nanowhiskers. Other methods, such as etching [48], sol–gel coating [48,54], and carbon modification [50]...
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FIGURE 3.5 Time-of-flight–secondary ion mass spectrometry (TOF–SIMS) spectra for titanium carbide (TiC)–CDC supercapacitor for (a, c) positive and (b, d) negatively charged electrode for (c, d) negatively and (a, b) positively charged secondary ions after 40,000 charge/discharge cycles. (e) Positive and negative ion-specific images of (i) CN$^-$ for negatively and positively charged TiC–CDC electrode; (ii) total ions and Al$^{3+}$ ions for positively and (iii) negatively charged TiC–CDC electrode. Image sizes are 400 $\times$ 400 $\mu$m$^2$. (Reproduced with permission from The Electrochemical Society from Jänes, A., J. Eskusson, R. Kanarbik, A. Saar, and E. Lust. 2012. Journal of the Electrochemical Society 159:A1141–A1147.)
for Al current collectors, have also been studied to decrease the contact resistance between the current collectors and the electrode materials. To decrease the interface resistance between the current collector and the electrode, hot pressing [58] and roll pressing [59] have been proposed for improving the contact quality between the current collector and the electrode.

For the ionic liquid (IL) electrolytes, Kühnel et al. [60,61] studied the anodic electrochemical stability of the Al current collector in three ILs with different anions: [PYR$_{14}$][FSI], [PYR$_{14}$][TFSI], and [PYR$_{14}$][FTFSI]. Figure 3.6 shows that after cyclic voltammetry (CV) tests, Al foil current collectors exhibit good passivation in [PYR$_{14}$][TFSI] IL, while pitting corrosion of the Al current collector was observed in [PYR$_{14}$][FSI] IL [61]. Interestingly, the authors also found that the anodic stability of Al current collectors in [PYR$_{14}$][FSI] could be improved remarkably by controlling the chloride impurities level to below 1 ppm [61]. Regarding the [PYR$_{14}$][FTFSI] IL electrolyte, the same group [60] found Al current collectors to exhibit excellent anodic corrosion resistance in this IL. The positive Al current collectors showed mild pitting corrosion only when electrical double-layer capacitors (EDLCs) were subjected to a constant cell potential of 3.2 or 3.5 V for 140 h. Brandt et al. [62] investigated the corrosion stability of Al foil current collectors in IL–organic electrolyte mixtures, that is, trimethyl-sulfonium bis(trifluoromethyl) sulfonyl)imide ([Me$_3$S][TFSI])–PC. Two different electrolyte mixtures were studied: one with 3.8 M [Me$_3$S][TFSI] in PC (86 wt% of [Me$_3$S][TFSI]) and another with 1.9 M [Me$_3$S][TFSI] in PC (50 wt% of [Me$_3$S][TFSI]). As shown in Figure 3.7, CV measurements have shown that the oxidative current of the Al foil current collector in 3.8 M [Me$_3$S][TFSI]–PC was one order of magnitude lower than that obtained in 1.9 M [Me$_3$S][TFSI]–PC. After the CV tests, the corrosion of the Al current collector was clearly observed in 1.9 M [Me$_3$S][TFSI]–PC whereas the Al current collector exhibited much less corrosion in 3.8 M [Me$_3$S][TFSI]–PC (see inset to Figure 3.7). As a result, EDLCs using the 1.9 M [Me$_3$S][TFSI]–PC electrolyte had a lower operating cell voltage and poorer cycling performance compared with EDLCs with 3.8 M [Me$_3$S][TFSI]–PC electrolyte.

![FIGURE 3.6](image_url) SEM images of Al electrodes taken after a CV experiment between 3.3 and 5 V in (a) PYR$_{14}$TFSI and (b) PYR$_{14}$FSI. (Reprinted from Comparison of the anodic behavior of aluminum current collectors in imide-based ionic liquids and consequences on the stability of high voltage supercapacitors, 249, Kühnel, R. S., and A. Balducci, *Journal of Power Sources*, 163–171, Copyright 2014, with permission from Elsevier.)
With regard to the redox-active electrolyte, Lota and Frackowiak \[63\] found the cycling stability of the electrode in the 1 M KI electrolyte to be significantly affected by the type of the metallic current collector. After 10,000 cycles, a moderate decrease of the specific capacitance \(<20\%\) was observed for the Au current collector, whereas an increase of specific capacitance from 235 to 300 F g\(^{-1}\) was found for the stainless-steel current collector. Meller et al. \[64\] also pointed out that it is not suitable to use an Au current collector in iodide electrolytes due to its reaction with iodides, while it is appropriate to use a stainless-steel current collector since it resulted in good long-term stability of ES.

In the case of solid- or quasi-solid-state electrolytes, there are other factors that need to be considered. For example, the choice of the current collectors should take into account the type of solid-state ES (i.e., whether it is flexible, stretchable, or transparent). For example, to meet the requirements of various solid-state ESs, a wide variety of carbon-based current collectors have been developed \[65–67\]. Notarianni et al. \[68\] found that for poly(vinyl alcohol) (PVA)/H\(_2\)PO\(_3\) hydrogel electrolyte-based ES, the performance of the ES based on CNT film as the current collector was comparable to the Au current collector, and the CNT film also provides a stronger binding to the graphene film electrodes. Niu et al. \[69\] reported a highly compressible, all-solid-state ES based on polyaniline (PANI)–single-walled carbon nanotubes (SWCNTs)–sponge electrodes, using PVA/H\(_2\)SO\(_4\) gel as the electrolyte. The performance of this all-solid-state ES could be largely maintained even when compressed under 60\% strain (Figure 3.8).

FIGURE 3.7 Cyclic voltammograms of the Al current collector in PC–Me\(_3\)STFSI(86) and PC–Me\(_3\)STFSI(50) at 20°C and at a scan rate of 0.5 mV s\(^{-1}\). The images show the recovered Al current collectors after 100 cycles (top PC–Me\(_3\)STFSI(50), bottom PC–Me\(_3\)STFSI(86)). (Brandt, A. et al. 2013. An investigation about the use of mixtures of sulfonium-based ionic liquids and propylene carbonate as electrolytes for supercapacitors. *Journal of Materials Chemistry A* 1:12669–12678. Reproduced by permission of The Royal Society of Chemistry.)
FIGURE 3.8 (a) Schematic diagram of an all-solid-state-integrated supercapacitor based on PANI–SWCNTs–sponge. (b–d) Real-time optical images of a supercapacitor showing the processes of compression and recovery, (e) CV curves, (f) galvanostatic charge/discharge curves, and (g) specific capacitances of a representative compressible supercapacitor at different strains. Scan rate: 10 mV s$^{-1}$, charge/discharge current: 0.64 A s$^{-1}$. (h) The Nyquist impedance plot of the compressible supercapacitor at different strains with frequency ranging from 10 kHz to 0.1 Hz. (Niu, Z. Q. et al.: Highly compressible and all-solid-state supercapacitors based on nanostructured composite sponge. 1–5. 2015. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.)
In addition, to simplify the fabrication process and also to avoid the potential problems associated with the use of additional current collectors, free-standing electrodes typically based on carbon-based materials have been developed [68–74]. ESs based on these free-standing electrodes have the advantage of avoiding the use of additional current collectors.

3.3 BINDERS

Electrode materials are generally composed of active particles or powders (e.g., AC powders) and binders. Binders can maintain the structural integrity of the active particles or powders and help electrode materials to adhere uniformly onto the current collector. To date, fluorinated polymeric binders, such as poly(vinylidene fluoride) (PVDF) and polytetrafluoroethylene (PTFE), have been extensively used for ESs.

The nature and the amount of the binders can also greatly influence the performance of the electrodes and the assembled ESs [75–78]. For instance, Tsay et al. [76] found that for Na₂SO₄ electrolyte-based ESs using carbon BP2000 electrodes, the maximum value of the specific capacitance was obtained when the PTFE binder content was 5 wt% (Figure 3.9). Decreasing or further increasing the content of PTFE decreased the specific capacitance. Since PTFE is hydrophobic, too large an amount of PTFE could inhibit the penetration of aqueous electrolyte ions into pores in the carbon electrode materials, resulting in a lower specific capacitance [76]. Paul et al. [79] added a small amount of polyvinylpyrrolidone (PVP) (3%) into the PTFE binder, and found it could effectively improve the wettability of the electrode materials in 1 M KCl aqueous electrolyte. The presence of binders was also found to change (usually decrease) the porosity of the porous electrodes, which affected the effective surface area and the ion diffusion in the pores [77]. Abbas et al. [77] demonstrated that such porosity change was also dependent on the nature of the carbon material and the property of the electrolyte. Timperman et al. [80] investigated two different binders for AC electrodes, that is, PVDF and carboxymethyl cellulose (CMC)–styrene–butadiene rubber (SBR). It was found that AC electrodes containing PVDF showed higher wettability in diisoproyl-ethyl-ammonium bis(trifluoromethanesulfonyl) imide ([DIPEA][TFSI]) IL compared with the electrodes containing CMC–SBR binders. However, AC electrodes containing PVDF or CMC–SBR binders exhibited similar wettability in pyrrolidinium bis(trifluoromethanesulfonyl)imide ([PYRR][TFSI]) IL. Owing to this different wettability behavior, the electrochemical performance such as the specific capacitance of the electrodes in certain IL electrolytes was also different.

Besides EDLCs, Liu and Pickup [81] found that adding a certain amount of Nafion® binder into the ruthenium (Ru) oxide powder-based electrodes was favorable for improving the power density of pseudocapacitors. As shown in Figure 3.10, the addition of an additional 5% Nafion binder led to a 39% increase in the average power density of the Ru oxide-based pseudocapacitor for full discharge at 1 A cm⁻². The high proton-conducting property could contribute to the improved power performance [81]. Cao et al. [78] compared the effect of PTFE and PVDF binders on the performance of lithium-ion capacitor (LIC) with the LiPF₆/ethylene
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**FIGURE 3.9** Specific capacitance and energy density of carbon BP2000 electrode material as a function of PTFE contents. (Reprinted from Effects of electrode layer composition/thickness and electrolyte concentration on both specific capacitance and energy density of supercapacitor, 60, Tsay, K. C., L. Zhang, and J. J. Zhang, Electrochimica Acta, 428–436, Copyright 2012, with permission from Elsevier.)

**FIGURE 3.10** Ragone plots for supercapacitors with different amounts of Nafion binder. Ru oxide loadings were 9.51, 10.35, 10.34, and 10.14 mg for 0%, 2.5%, 5%, and 10% Nafion, respectively. The discontinuities at high powers are due to the use of a different potentiostat (Solartron 1286) with lower lead resistances for experiments at currents >1 A. (Reprinted from Ru oxide supercapacitors with high loadings and high power and energy densities, 176, Liu, X., and P. G. Pickup, Journal of Power Sources, 410–416, Copyright 2008, with permission from Elsevier.)
carbonate–dimethyl carbonate (EC–DMC) electrolyte. It was found that the negative electrode containing the PTFE binder resulted in higher energy and power densities of LIC compared with that containing the PVDF binder.

With the environmental concern about the selection of ES components, environmentally friendly binders such as fluorine-free binders have attracted growing attention. For example, some researchers investigated other binder materials, such as natural cellulose [82,83], PVP [84], and polyacrylic acid (PAA) [85]. These binders may be used as alternatives to fluorinated polymeric binders. Aslan et al. [84] found that in comparison with the PTFE or PVDF binder, the application of the PVP binder resulted in a significantly higher pore volume and larger specific surface area of the AC-based electrodes (normalized to the amount of AC). Lee et al. [85] reported that the PAA binders could promote a uniform distribution of the electrolyte throughout the active-electrode layer because of their ability to adsorb and swell the electrolytes. Shin et al. [86] found that deoxyribonucleic acid (DNA) was also able to act as a mechanical binder for SWCNT-based electrodes in the 2 M NaCl electrolyte. Some promising results have also been obtained for natural cellulose binders [82,83]. For example, Varzi et al. [82] found that cellulose-based EDLCs with the [PYR][TFSI] IL electrolyte showed a much better performance compared with the PVDF-based ones after float voltage tests at 3.7 V. In addition, some ECPs, such as polypyrrole (PPy) [87], poly(3,4-ethylenedioxythiophene) (PEDOT) [88,89], and PANI [90], have also been proposed as binders to be used in electrode materials of ESs. In contrast with traditional binders such as PTFE and PVDF, ECP-type binders are electrically conductive and can also have additional pseudocapacitance.

However, to avoid some negative influences associated with the binders (e.g., decrease in the effective surface area and increase in electrode resistance), binder-free electrode materials have been investigated for ESs [91–93].

3.4 SEPARATORS

As shown in Figure 1.3, the separator is placed between the negative and positive electrodes of the ES to avoid contact and the electron transfer between the two electrodes. There are several critical requirements for the separators of ESs [94]: (1) good conductivity for the transfer of electrolyte ions through the separator, (2) high electronic-insulating property to prevent short circuits, (3) high chemical and electrochemical stability in the electrolyte used, and (4) sufficient mechanical strength to contribute to ES durability. Thin and highly porous insulating films are generally used to make the separators of ESs to meet the above requirements. Several factors, such as the type of ES, electrode materials, electrolytes, working temperature, and operative cell voltage, should be considered for the selection or development of appropriate separators. Typically used materials for separators include cellulose, a porous polymer membrane, and glass fiber. Bittner et al. [55] found that the performance aging of EDLCs using a paper separator could be accelerated by the trace water in the TEABF$_4$/acetonitrile (ACN) organic electrolyte. When ILs are used as electrolytes for ESs, due to the viscous nature of ILs, the ion transfer resistance through the separator becomes highly important [95,96].
Furthermore, the physical (e.g., thickness, porosity, and pore size distribution) and chemical (e.g., composition) properties of the separator play an important role in a series of performances of EDLCs, such as an ideal polarizability limit, specific capacitance, characteristic time constant, ESR, energy, and power densities [95,97–100]. For example, several studies found that separators are thinner or those with a higher porosity and higher pore size led to a better power performance, due to the lower ESR [97,100]. Karabelli et al. [101] reported that a PVDF separator provided higher ionic conductivity for a TEABF$_4$/ACN electrolyte compared with commercial cellulose and Celgard® (based on polyethylene [PE]/polypropylene [PP] separators). Besides, it should be noted that the influence of the separator parameters on the performance of EDLCs also depends on the investigated systems. For example, some studies [98,102] found there is a weak dependence of the separator parameters on the limits of ideal polarizability and the specific energy density whereas other studies [95] have shown a noticeable dependence. To increase the wettability and thus to improve the performance of polymer-based separators (e.g., PP) in aqueous electrolytes, surface modifications of the separators have been proposed [103,104].

Besides EDLCs, the performance of pseudocapacitors and hybrid ESs is also dependent on the properties of separators. Liu and Pickup [105] compared the effect of four different separators on the performance of RuO$_2$-based pseudocapacitors using the 0.5-M H$_2$SO$_4$ electrolyte. As shown in Figure 3.11, the value of the energy density of ES using Nafion-115 was the highest (31.2 Wh kg$^{-1}$ at 1 mA cm$^{-2}$), whereas the energy density value of ESs with Celgard separator was the lowest (23.4 Wh kg$^{-1}$ at 1 mA cm$^{-2}$). The other Nafion separators led to intermediate energy densities.

**FIGURE 3.11** Ragone plots for Ru oxide (ca. 10 mg) supercapacitors with different separators. Measurements were made by constant current discharge from 1.0 V. (Liu, X. R., and P. G. Pickup. 2008. Performance and low temperature behavior of hydrous ruthenium oxide supercapacitors with improved power densities. *Energy and Environmental Science* 1:494–500. Reproduced by permission of The Royal Society of Chemistry.)
As mentioned in Section 2.6, the selection of a suitable separator was also beneficial for reducing the self-discharge of redox-active electrolyte-based ESs [106,107].

Recently, researchers have developed some new separator materials for ESs, such as graphene oxide film [108] and eggshell membrane [109]. For example, Yu et al. [109] found the use of eggshell membrane as the separator for ESs gave a lower resistance, higher specific capacitance, quicker charge/discharge ability (4.76 s), and good cyclic stability (92% capacitance retention after 10,000 cycles) compared with the PE separator.

3.5 SUMMARY

Since the components of ESs are strongly coupled with each other, it is highly desirable to consider the compatibility or possible interactions between the electrolytes and both the active-electrode materials and inactive components of ESs. Several important aspects were discussed in this chapter to enable readers to (1) understand the compatibility issues or possible interactions between electrolytes and inactive components (current collector, binder, and separator) of ESs; (2) recognize how the interactions between electrolytes and inactive components affect the performance of ESs; (3) understand the importance of the compatibility of inactive components of ESs with the electrolytes and electrode materials; (4) understand the importance of designing or choosing appropriate inactive components according to the electrolyte systems and type of ESs; and (5) obtain an overview of choices or design strategies of inactive components of ESs to improve the device performance with a given electrolyte.

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