Electrical double layer capacitors (EDLCs) can serve as a clean energy storage system, in which charges are accumulated at the electrolyte/electrode interfaces. EDLCs are governed by the same fundamental principles of conventional capacitors, but utilizing higher surface area electrodes and thinner dielectric layers to achieve larger capacitance. This gives rise to energy densities greater than those of conventional capacitors and power densities greater than those of batteries. EDLCs are also rechargeable devices and can have a long cycle life. A typical EDLC consists of two porous activated carbon (AC) electrodes of high specific surface area soaked in an aqueous or organic electrolyte solution and prevented from contact with each other by a separator material. The electrolyte determines the usable potential window and stability of the EDLCs.11

Aqueous electrolytes have high conductivity and therefore are more effective in high power applications. However, the long-term stability of the capacitors is limited due to leakage and evaporation of the solvent in the electrolytes.8 The use of solid polymer electrolytes can solve some of the problems associated with liquid electrolytes. However, the use of solid polymer electrolytes in EDLCs is not widespread due to their relatively poor conductivity at ambient temperature and poor contact at the electrode/electrolyte interface.9 The conductivity of polymer electrolytes can be enhanced by increasing their amorphousness using either liquid plasticizers4 or ceramic fillers5 or salts with large anions.6 The polymer electrolytes are mostly ionic conductors, but for use in batteries and EDLCs the electrolytes should ideally have larger cation mobility and negligible anion mobility. The anion mobility can be minimized using larger anions7 or supramolecular anion trappers.8

A good example of a large anion lithium salt is lithium bis(oxalato)borate, LiBC4O8 (LiBOB) which was originally proposed by Angell and co-workers as the lithium salt for liquid electrolytes.9,10 LiBOB has been reported to give good conductivity with poly(ethylene oxide) (PEO)11 and poly(vinylidene fluoride-co-hexafluoropropylene) (PVdF:HFPe)12 polymer hosts. The large BOB anions are expected to disrupt the crystallization process of the polymer chains and increase the amorphous component of the polymer electrolyte. Apart from giving this plasticizing effect, LiBOB also does not generate harmful gases when in contact with traces of water as in the case of LiPF6, has good thermal stability up to 300°C and is environmentally friendly.13

The aim of the current work is to show that solid polymer electrolytes based on poly(acrylonitrile) (PAN) incorporated with LiBOB can be used as a membrane in EDLC. Thus, the focus of this paper is to investigate the properties of the PAN–LiBOB complexes in terms of conductivity, transference number, potential stability and its suitability as an electrolyte-cum-separator in an EDLC with two similar AC electrodes.
EXPERIMENTAL

Electrolyte preparation

Polyacrylonitrile (PAN) with molecular weight (MW) 150,000 g mol$^{-1}$ was supplied by Aldrich and used as received. LiBOB (MW = 193.79 g mol$^{-1}$) was obtained from Chemetall (Germany). N, N-dimethylformamide (DMF) was procured from Riendemann Schmidt. PAN–LiBOB-based polymer electrolytes were prepared by the solution casting technique. Desired amounts of polymer and salt with PAN:LiBOB weight ratios of 90:10 (S10), 80:20 (S20), 70:30 (S30), 60:40 (S40) and 50:50 (S50) were dissolved in DMF. Pure PAN film was designated S00. The mixtures were continuously stirred in a dry box at room temperature (RT) to obtain homogeneous solutions. The solutions were then cast into different glass Petri dish and dried at 60°C in an oven to form free standing films. Beyond 50 wt.% LiBOB, e.g. 60 wt.% and onwards, the polymer electrolyte was no longer mechanically stable and cracked.

Electrolyte characterization

Electrochemical Impedance Spectroscopy (EIS)

A HIOKI 3520 LCR Hi-Tester was used to measure the impedance of samples in the frequency range from 50 Hz to 100 kHz. Two stainless steel disc electrodes with 2 cm diameter were used to sandwich the polymer electrolyte film. The conductivity $\sigma$ was calculated using the equation

$$\sigma = \frac{d}{R_b A}$$

where $d$ is film thickness, $R_b$ is bulk resistance obtained from the Nyquist plot and $A$ is area of electrode–electrolyte contact.

Transfer number measurement

The Li$^+$ ion transference number in the present system was measured using the Bruce–Vincent method.[14] A voltage of 10 mV was used to polarize the cell at RT. Lithium foils were used as non-blocking electrodes to sandwich the polymer electrolytes.

Cyclic voltammetry test for electrolytes

The electrochemical stability window (ESW) of solid polymer electrolyte, S50, was determined using CH-Instrument Model 600D electrochemical analyzer. The S50 was sandwiched between two stainless steel electrodes and scanned at a rate of 10 mV s$^{-1}$ in the potential range of –2.5 and 2.5 V.

EDLC fabrication

The highest conducting PAN–LiBOB solid polymer electrolyte S50 was sandwiched between two identical AC electrodes. The AC electrode/S50/AC electrode configuration was sealed in a packaging bag with leads exposed for external connection. The solid polymer electrolyte in the EDLC also acts as a separator or spacer to avoid short circuit between the two symmetrical electrodes.

EDLC characterization

The performance of the EDLCs was evaluated using EIS, cyclic voltammetry (CV) and galvanostatic charge–discharge cycling. EIS was performed using the HIOKI 3522 LCR Hi-Tester with the sinusoidal signal amplitude of 10 mV over the frequency range from 100 kHz to 10 mHz. The CV test was performed using the Autolab PGSTAT12 potentiostat in conjunction with the General Purpose Electrochemical System software version 4.9.005. The galvanostatic charge–discharge characteristics were carried out using the Neware battery cycler and the software used was BTS version 5.3. For galvanostatic charge–discharge, a working voltage of 1.0 V and different currents from 0.2 to 1.5 mA and back to 0.2 mA were applied to study the effect of discharge current on the EDLC performance.

RESULTS AND DISCUSSION

Characterization of PAN–LiBOB solid polymer electrolytes (SPEs)

Impedance analysis of SPEs

The DC conductivity of PAN–LiBOB polymer electrolytes at RT is listed in Table 1.

A conductivity of $2.23 \times 10^{-10}$ S cm$^{-1}$ is obtained for PAN film without salt. The ionic conductivity of the PAN-based polymer electrolyte increases with increasing LiBOB concentration up to $2.55 \times 10^{-5}$ S cm$^{-1}$ at 50 wt.%. Hence, S50 was chosen for further characterization.

Transfer number analysis

Transfer number measurement was determined for the 50 wt.% PAN–50 wt.% LiBOB sample using the Bruce and Vincent method. In this method, the resistance of the passivation layer before and after DC polarization is obtained using

<table>
<thead>
<tr>
<th>Designation</th>
<th>LiBOB weight (wt.%)</th>
<th>Sample thickness (µm)</th>
<th>Bulk resistance, $R_b$ (Ω)</th>
<th>Conductivity (S cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S00</td>
<td>0</td>
<td>56</td>
<td>$8.00 \times 10^6$</td>
<td>$2.23 \times 10^{-10}$</td>
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<tr>
<td>S10</td>
<td>10</td>
<td>66</td>
<td>$1.74 \times 10^8$</td>
<td>$1.21 \times 10^{-7}$</td>
</tr>
<tr>
<td>S20</td>
<td>20</td>
<td>98</td>
<td>$9.40 \times 10^8$</td>
<td>$3.32 \times 10^{-7}$</td>
</tr>
<tr>
<td>S30</td>
<td>30</td>
<td>104</td>
<td>$1.08 \times 10^9$</td>
<td>$3.07 \times 10^{-6}$</td>
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<tr>
<td>S40</td>
<td>40</td>
<td>126</td>
<td>$4.80 \times 10^7$</td>
<td>$8.36 \times 10^{-6}$</td>
</tr>
<tr>
<td>S50</td>
<td>50</td>
<td>224</td>
<td>$2.80 \times 10^7$</td>
<td>$2.55 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

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Transfer number analysis

Transfer number measurement was determined for the 50 wt.% PAN–50 wt.% LiBOB sample using the Bruce and Vincent method. In this method, the resistance of the passivation layer before and after DC polarization is obtained using
EIS. The Li⁺ ion transference number can be calculated using the following equation\(^{14}\):

\[
t_{Li} = \frac{I_{SS}(\Delta V - I_0R_0)}{I_0(\Delta V - I_{SS}R_{SS})}
\]

In this equation, \(t_{Li}\) is the Li⁺ transference number, \(I_0\) and \(I_{SS}\) are the initial and steady-state currents, respectively, \(\Delta V\) is the potential applied across the cell, \(R_0\) and \(R_{SS}\) are the initial and steady-state resistance of the passivation layer, respectively. Figure 1(a) depicts the polarization current curve of Li/S50/Li configuration at an applied voltage of 10 mV.

The initial current \(I_0\) is found to be 9.8 μA while the steady-state current \(I_{SS}\) saturates at 7.8 μA after 10593 s. The comparison of the impedance plot before and after dc polarization is shown in Fig. 1(b). \(R_0\) and \(R_{SS}\) are observed to be 1570 Ω and 3500 Ω, respectively. As a result, the lithium ion transference number for 50 wt.% PAN–50 wt% LiBOB solid polymer electrolyte is calculated to be 0.25. This value is comparable to the literatures. Appetecchi and co-workers\(^{9}\) worked on PEO–LiBOB electrolyte and reported a Li⁺ transference number ranging from 0.25 to 0.30 using an applied voltage of 30 mV. On the other hand, Choe\(^{15}\) had reported a Li⁺ transference number of 0.25 in PAN-based electrolyte incorporated with lithium bis(trifluoromethane sulfonimide), LiN(CF₃SO₂)₂ as salt with a dc bias of 7.4 mV across the cell.

CV analysis for S50

Figure 2 shows the CV curve of electrolyte S50 that will depict the electrolyte ESW. The ESW is the working potential range in which an electrolyte remains stable and safe. The onset of the oxidation or reduction current has been observed from −1.6 to +1.6 V.

Characterization of EDLCs using 50 wt.% PAN–50 wt.% LiBOB (S50)

Impedance analysis of EDLCs

The complex impedance results can be presented as Bode plot and Nyquist plot. Bode plot illustrates the impedance–frequency dependence and distinguishes region that are resistive and/or capacitive dominant while the Nyquist plot shows the EDLC’s resistance. Based on the Nyquist plot, an equivalent circuit can also be drawn to represent the impedance data. The impedance is generally expressed as a complex number using the equation

\[
Z(\omega) = Z' - jZ''
\]

where \(Z'\) and \(Z''\) are the real and imaginary components, respectively. The parameter \(j\) is \(\sqrt{-1}\).

Alternatively, the impedance can be expressed as

\[
Z(j\omega) = |Z|e^{j\phi}
\]

Here, \(|Z|\) is magnitude of the impedance;

\[
|Z|^2 = (Z')^2 + (Z'')^2 = R^2 + X_c^2
\]

\(R\), \(X_c\) and \(\phi\) are equivalent series resistance (ESR), capacitive reactance and phase angle, respectively. Equation 3 represents impedance data in Nyquist plot; meanwhile, eqn 4 presents impedance data in Bode plot.

Phase angle \(\phi\) describes the phase difference between voltage and current and can be manipulated to convey the equilibrium between capacitive and resistive nature of the EDLC. The phase angle was obtained from \(\tan^{-1}(|Z'|/|Z'|)\).\(^{16}\) Theoretically, the EDLC is an ideal capacitor when phase angle is −90° and resembles a resistor when phase angle is zero. At −45° phase angle, the EDLC behaves in a way intermediate between a capacitor and a resistor. Figure 3 shows the (a) Bode plot, (b) Nyquist plot and (c) equivalent circuit of the EDLC.
Figure 3 (a) and (b). The parallel CPE1 and leaky capacitor (or a leaky capacitor) where its impedance can be represented by the following equation

\[ Z'' = R_1 + \frac{R_2 k_1^2 + R_2^2 k_1 \omega^p \cos \left( \frac{\pi}{2} \right)}{k_1^2 + 2k_1 R_2 \omega^p \cos \left( \frac{\pi}{2} \right) + R_2^2 \omega^{2p}} + \frac{k_2}{\omega^{p_2}} \left[ \cos \left( \frac{\pi}{2} \right) \right] \]

\[ -Z' = \frac{R_2^3 k_1 \omega^p \sin \left( \frac{\pi}{2} \right)}{k_1^2 + 2k_1 R_2 \omega^p \cos \left( \frac{\pi}{2} \right) + R_2^2 \omega^{2p}} + \frac{k_2}{\omega^{p_2}} \left[ \sin \left( \frac{\pi}{2} \right) \right] \]

(7)

Here, \( \omega \) is angular frequency, \( k_1 \) and \( k_2 \) are coefficient of CPE1 and CPE2, respectively. \( p_1 \) represents the fraction of right angle the diameter of the semicircle makes with the vertical axis and \( p_2 \) is the fractions of right angle the tilted spike makes with the horizontal axis.\(^{[12]}\)

The simulated impedance plot is shown as the solid line in Fig. 3(c). It can be seen that the simulated data fits well with the experimental data. The extracted parameters such as \( R_1, R_2, k_1, k_2, p_1 \) and \( p_2 \) are obtained to be 12 Ω, 75 Ω, 2.5 × 10\(^{-5}\) F\(^{-1}\), 2.37 × 10\(^{-6}\) F\(^{-1}\), 0.83 and 0.89, respectively. As observed in the Bode plot, \( R_1 \) dominates the impedance at high frequencies. Hence, \( |Z| = R_1 \) (12 Ω). Before the end of region II at intermediate frequencies, \( R_2 \) exists and therefore \( R_1 + R_2 \) can be obtained by extrapolating the horizontal line to the y-axis. Hence, \(|Z| = R_1 + R_2 \) (87 Ω), which matches the simulated value. \( R_1 \) represents the ohmic resistance of the bulk electrolyte\(^{[2,21]}\) and \( R_1 + R_2 \) or so-called ESR is due to electrolyte resistance, the collector/electrode contact resistance and the electrode/electrolyte interface resistance.\(^{[17]}\)

In this work, \( p_2 \) is 0.89 indicating that CPE2 is more capacitive than resistive. The deviation from being parallel to the vertical axis of the spike is attributed to the resistance emanating from contact between different components in EDLC or the electronic resistance of carbon materials.\(^{[23]}\) According to Emmenegger and co-workers,\(^{[24]}\) the non-vertical slope at low frequency is a typical feature of electrochemical charging process for real EDLC and is caused by a non-uniform distribution of active layer or surface roughness.

Figure 3 (a) depicts a phase angle of −69° at 10 mHz, indicating that the EDLC is not perfectly capacitive. At 100 kHz, the phase angle reduces to −18° and this implies a resistor-like behavior at high frequencies. Hence, in the frequency range between 100 kHz and 10 mHz, the present EDLC behaves as a “leaky” capacitor. The frequency dependence of the impedance modulus can be divided into two regions. Region I is the low-frequency region, between 30 Hz and 10 mHz while Region II is the high-frequency region, between 100 kHz and 30 Hz. These low- and high-frequency regions correspond to the Nyquist plot in Fig. 3 (b), the tilted spike and depressed semicircular arcs, respectively. According to Portet,\(^{[17]}\) the theoretical Nyquist plot for an electrochemical capacitor should show a 45° impedance line at high frequencies and an almost vertical line at low frequencies. However, many experimental results\(^{[18–20]}\) demonstrated a semicircle arc and tilted spike in which the semicircle arc can be contributed from the contact resistance between current collector and AC electrode.\(^{[18,20]}\) Gu and co-workers\(^{[21]}\) have represented the semicircle arc with a capacitor parallel to a resistor, where the high-frequency intercept with real axis gives the value of the polymer electrolyte bulk resistance.

Figure 3 (c) reveals the equivalent circuit model to simulate the impedance data in Fig. 3(b). \( R_1 \) and \( R_2 \) can be obtained from Fig. 3 (a) and (b). The parallel CPE1 and \( R_1 \) represent the semicircle arc at intermediate frequencies. CPE2 corresponds to the tilted spike at low frequencies. CPE is a constant phase element (or a leaky capacitor) where its impedance can be represented by the following equation

\[ Z_{\text{CPE}} = k(j\omega)^p \]

where \( 0 \leq p \leq 1 \). The parameter \( k \) is CPE coefficient and inverse of \( k \) corresponds to the value of the capacitance involved. The parameter \( p \) is dimensionless indicating the tilting of the spike to the horizontal axis. The overall impedance of the equivalent circuit in Fig. 3 (c) is then given by equation

- \( k_1 \) and \( k_2 \) are the fractions of right angle the diameter of the semicircle makes with the vertical axis and \( p_1 \) and \( p_2 \) are the fractions of right angle the tilted spike makes with the horizontal axis.\(^{[12]}\)

- \( k_1 \) and \( k_2 \) are the fractions of right angle the diameter of the semicircle makes with the vertical axis and \( p_1 \) and \( p_2 \) are the fractions of right angle the tilted spike makes with the horizontal axis.\(^{[12]}\)

- \( k_1 \) and \( k_2 \) are the fractions of right angle the diameter of the semicircle makes with the vertical axis and \( p_1 \) and \( p_2 \) are the fractions of right angle the tilted spike makes with the horizontal axis.\(^{[12]}\)
The variation of specific capacitance, \( C \) as a function of frequency, \( f \) was calculated from the imaginary part of impedance \( Z'' \) using eqn 8 and is shown in Fig. 4

\[
C = \frac{1}{2\pi f Z''} \times \frac{1}{m}
\]  

(8)

Capacitance can be related to the mass of electrode (excluding mass of current collector) or to the mass of active materials. In this work, \( m \) is mass of single electrode (including CB and binder). It can be observed that, the capacitance is high at low frequencies (35 F g\(^{-1}\) at 10 mHz) and decreased with increasing frequency up to 100 kHz. The capacitance curve levels off to small values at high frequencies indicating that resistive behavior exists in the EDLC.

CV analysis

CV is also one of the popular methods to study the characteristics of EDLC as it gives capacitive behavior, reversibility and the rate of electron transfer in EDLC. An ideal EDLC often shows a rectangular CV. However, most EDLCs do not exhibit a perfect rectangular CV due to some resistive element in the electrode–electrolyte system. Figure 5 depicts the cyclic voltammograms of EDLCs at scan rate 10 mV s\(^{-1}\) with various potential windows, from 0 to 1 V, 0 to 1.5 V and 0 to 2 V. Both specific current and specific capacitance are depicted. The specific capacitance was calculated from the following equation

\[
\text{Specific capacitance, } C_s = \frac{i}{mv}
\]  

(9)

where \( i \) is current in unit ampere, \( m \) is the mass of the single electrode in unit grams and \( v \) is the scan rate in unit volt per second.

No redox peak is observed in Fig. 5 indicating that Faradaic process does not occur in the present system. This is expected as the storage mechanism of EDLC is by accumulation of ions in the electrical double layer and not by charge transfer of electrolyte into the electrode. Figure 5 also shows that rectangular shape CV is more likely to occur with narrower potential window. This is related to stability of the solid polymer electrolyte as shown in Fig. 2. The present electrolyte is stable only up to 1.6 V thus explains why potential window 0 to 1 V demonstrates the most rectangular shape. Hence, potential window between 0 and 1 V is chosen for further investigation as it exhibit good capacitive behavior. The effect of scan rate is tested and shown in Fig. 6.

Figure 6 shows that lower scan rate gives better rectangular shape voltammogram. As current increases with increasing scan rates, CV begins to distort and deviate from rectangular shape due to the fast build-up of the electric double layer.\(^{25}\) Analyses of the scan rate dependence reveals that the specific capacitance decreases with increasing scan rate, as shown in Fig. 6 (b). According to Prabaharan,\(^{19}\) high IR drop is the cause of the imperfect rectangular shape. Similar finding was reported by Pandey et al.\(^ {25}\) where ohmic drop is the reason for poor capacitive behavior.

Tables 2 and 3 summarize the respective specific capacitance of EDLCs calculated from CVs according to equation 9, where \( i \) is an average charge or discharge currents. The slight difference between charge and discharge capacitance is due to the delay in charge distribution determined by the internal resistance of electrode and electrolyte.\(^{11}\)
Galvanostatic charge–discharge characteristics

Galvanostatic charge–discharge cycling was carried out in the potential range between 0 and 1 V. The charge–discharge currents were varied for every 5 cycles being 0.2, 0.5, 0.8, 1.0 and 1.5 mA and back to initial current, 0.2 mA for a total of 30 cycles to study the effect of capacitance retention in the EDLC cell. The relationship between energy and power was also studied. Figure 7 shows the galvanostatic charge–discharge curves of EDLCs at various constant currents.

A good capacitive behavior of the EDLC should display a triangular shape where the slope of the linear charge–discharge curves equal to the current divided by the capacitance. In the presented work, non-symmetrical behavior is observed in Fig. 7 where the linear-like behavior is depicted in the potential range from 0.28 to 0.71 V.

As seen in Fig. 7, at low constant current, the charge–discharge profile is more linear compared to high constant current, indicating that the capacitive behavior is good at low current, 0.2 mA. Higher current seems to cause a higher IR drop. There are many explanations about IR drop from the literature. According to Guo and co-workers,[27] the IR drop is expected to increase with increasing discharge current due to incomplete discharge occurring in the middle of the as-formed electric double layers. Both Pandey[25] and Morita[28] proposed that IR drop is caused by ohmic loss across the internal resistance, also referred as ESR. On the other hand, Matsuda[29] pointed out that IR drop is a dc resistance of the EDLC due to a leak current through the side area. Apparently, the contact resistance and resistance of electrolytes and electrode were the sources of electrical resistance in EDLC, thus resulting in IR drop at the beginning of discharge process. The variation of IR drop of EDLCs as a function of current is plotted as shown in Fig. 8.

As observed, IR drop is proportional to current. Hence, the resistance of EDLC can be determined from the slope of the IR drop versus current plot following the Ohms Law equation:

\[
R = \frac{V}{I} = \frac{IR_{\text{drop}}}{I}
\]

The potential V in volt, which is equal to difference between maximum voltage during charge and the first voltage during discharge, is also termed as IR drop / I is current in ampere. Hence, from Fig. 8, the overall resistance for the EDLC is 162 Ω.

### Table 2. Characteristic parameters obtained from CVs at a fix scan rate 10 mVs⁻¹ with different potential windows

<table>
<thead>
<tr>
<th>Potential window (V)</th>
<th>Average charge capacitance (F g⁻¹)</th>
<th>Average discharge capacitance (F g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–1.0</td>
<td>26.20</td>
<td>23.75</td>
</tr>
<tr>
<td>0–1.5</td>
<td>47.13</td>
<td>31.56</td>
</tr>
<tr>
<td>0–2.0</td>
<td>94.09</td>
<td>55.94</td>
</tr>
</tbody>
</table>

### Table 3. Characteristic parameter obtained from CVs with a potential window of 0–1 V at different scan rates

<table>
<thead>
<tr>
<th>Scan rates (mVs⁻¹)</th>
<th>Average charge capacitance (F g⁻¹)</th>
<th>Average discharge capacitance (F g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>26.20</td>
<td>23.75</td>
</tr>
<tr>
<td>50</td>
<td>21.87</td>
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<td>100</td>
<td>17.92</td>
<td>16.58</td>
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<tr>
<td>150</td>
<td>15.09</td>
<td>14.01</td>
</tr>
<tr>
<td>200</td>
<td>13.01</td>
<td>12.11</td>
</tr>
</tbody>
</table>

Figure 7. Galvanostatic charge–discharge curves of EDLCs at various constant currents (0.2, 0.5, 0.8, 1.0 and 1.5 mA).
From the charge–discharge profile in Fig. 7, the specific charge and discharge capacitance of the EDLC can be determined using equation (11)

\[ C_s = \frac{I}{(\frac{dE}{dt}) \times m} \]  

In this equation, \( I \) is constant charge–discharge current (in amperes, A), \( \frac{dE}{dt} \) is gradient of the linear portion of charge and discharge curves in the range of 0.28 and 0.71 V (in units of V s\(^{-1}\)) and \( m \) is mass of a single electrode, including binder and CB (in grams, g). Another important characteristic for EDLC is the efficiency of the cell and it can be evaluated using equation

\[ \eta = \frac{C_d}{C_c} \times 100\% \]  

Based on the characteristic parameters obtained from eqns (9) and (10), the performance of the present EDLC is displayed in Fig. 9.

In this experiment, the EDLC was charged from low (0.2 mA) to high current (1.5 mA) and back to low current (0.2 mA) after a few cycles. Charge and discharge capacitance is higher at low current and lower at high current. At low current, 0.2 mA, the time taken to store the energy is quite long (419 s) compared to that at higher current 1.5 mA (21 s). A longer cycle time indicates that a higher amount of electric energy is stored in the EDLC. The efficiency of the present EDLC is quite high because of the value of charge and discharge capacitance does not differ much. It may be implied that the EDLC can act as a memory back up. However, the efficiency is not 100% indicating that the charge and discharge process in the EDLC is not fully reversible.

The ability of capacity retention by the EDLC was studied and results are as presented in Fig. 10. It can be seen that, at high constant current, 1.5 mA, capacitance retention is ~ 50 % of the initial capacitance. After bringing the charge/discharge current back to 0.2 mA, the EDLC is able to regain its original capacitance value.

Energy and power are also important measurements of EDLCs. Energy delivered is a measure of the amount of charge/energy that can be supplied while power is a measure of the rate at which the stored energy can be delivered. Both parameters are given by the following equations

\[ E = \frac{CV^2}{2m} \]  

\[ P = \frac{V^2}{4mESR} \]  

Energy and power delivered by an EDLC are often limited by the operating voltage and the \( ESR \) value. The operating voltage is governed by the electrolyte potential window. The \( ESR \) may be related to the low cation transference number of 0.25 or to the minimal ionic conductivity of the S50 electrolyte. For an ideal case, \( ESR \) should be as low as possible while operating voltage should be high. Figure 11 shows the evolution of specific energy and power delivered of EDLCs versus cycle numbers at various constant currents.

As seen in Fig. 11, the specific energy is higher at low current and specific power is just the opposite giving low value at low current. When the discharge current increases from 0.2 mA to 1.5 mA, the time taken to store the energy is significantly reduced from 419 s to 21 s.

---

**Figure 8.** Variation of IR\(_{\text{drop}}\) of EDLCs as a function of current.

**Figure 9.** Evolution of charge–discharge capacitance and efficiency of EDLCs as a function of cycle numbers at various constant currents.

**Figure 10.** Capacitance retention of EDLCs during galvanostatic charge–discharge cycles at various constant currents.
The resistance and frequency-dependent capacitance of 1.6 V and is tested as the electrolyte-cum-separator for application. S50 also gives a cationic transference number of 0.25, an ESW of 5 Sc m$^{-1}$C$^0$, and electrochemical stability. The highest RT ionic conductivity have been investigated for ionic conductivity, transference number –

CONCLUSIONS

Lithium ion-conducting polymer electrolytes based on PAN–LiBOB have been investigated for ionic conductivity, transference number and electrochemical stability. The highest RT ionic conductivity is 2.55 x 10$^{-3}$ S cm$^{-1}$ in 50 wt.% PAN–50 wt.% LiBOB (S50) sample. S50 also gives a cationic transference number of 0.25, an ESW of 1.6 V and is tested as the electrolyte-cum-separator for application in EDLC. The resistance and frequency-dependent capacitance of the EDLC obtained from the impedance plot are 87 Ω and 35 F g$^{-1}$, respectively. This capacitance value is higher than that from CV and galvanostatic charge–discharge tests, which are 24 and 22 F g$^{-1}$, respectively. The present EDLC is not suitable to work at high voltage or high scan rate operations due to the high IR drop.

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Figure 11. Evolution of specific energy and power delivered of EDLCs versus cycle numbers at various constant currents.

1.5 mA, the specific energy decreases from 3.01 to 1.47 W h kg$^{-1}$ and the corresponding specific power delivered rises from 380 to 474 W kg$^{-1}$. 