Catalytic graphitization of resorcinol-formaldehyde xerogel and its effect on lithium ion intercalation

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A B S T R A C T

Resorcinol formaldehyde (RF) derived xerogels were synthesized by polymerization of resorcinol and formaldehyde using sol–gel method followed by sub-critical drying. Thus prepared RF xerogel samples were then pyrolyzed at different temperatures ranging from 900 to 1800 ºC with and without catalyst to understand the role of catalyst in graphitization while varying the temperature. These RF derived carbon xerogels were structurally characterized extensively by Raman spectroscopy, X-ray diffraction, high-resolution transmission electron microscopy and small angle X-ray scattering. Structural characterization studies confirmed that RF xerogels pyrolyzed at moderate temperatures in the presence of a catalyst were graphitized however the degree of graphitization achieved was only 10% in case of no catalyst even at elevated temperatures (2500 ºC). Later, these RF derived catalytically graphitized carbon xerogels were tested for their electrochemical performance as potential anode materials for rechargeable batteries. Galvanostatic charge discharge experiments were performed at 0.1C rate (37.2 mAh/g current density) to examine the effect of degree of graphitization on lithium ion intercalation. It was found that with increased degree of graphitization, specific capacity increased with decrease in irreversible capacity along with excellent cyclic stability and coulombic efficiency more than 97%.

1. Introduction

Carbon materials are widely used as anodes for lithium ion batteries due to their low cost and availability in various forms with reasonably good reversible lithium insertion/intercalation capacity. They are mainly classified as graphite, hard carbon and graphitizable soft carbon based on their crystalline structure. Among them, graphite is a natural allotrope of carbon with sp² hybridization (trivalent carbon atoms). Graphite is formed by stacking of graphene layers. These graphene layers consist of two dimensional network of regular hexagons with an interlayer distance of 3.354 Å between these sheets. This interlayer distance is higher than carbon–carbon distance (1.42 Å) of hexagonal rings as the sheets are weakly bonded in c-axis compared to strong carbon–carbon bonding in basal plane [1]. This interlayer bonding may further weaken thus losing the stacking and increasing the interlayer distance further. Thus in disordered carbons like hard and soft carbons, the interatomic spacing varies from 3.354 Å to 3.7 Å while basal plane carbon–carbon bonding maintains same interatomic distance [1,2]. Hard carbons contains few graphene layers arranged in a disordered manner like house of cards, and they cannot be graphitized even by heating as high as 3000 ºC while soft carbons show slightly higher degree of order and these carbons can be graphitized on heating at elevated temperatures over 2000 ºC [3]. Among these different types of carbons, graphite is most commercially used anode because of its flat charge discharge plateau below 0.2 V, good cyclic life and high coulombic efficiency [4]. Theoretical reversible capacity of perfectly structured graphite is 372 mAh/g with LiC₀ stoichiometry however most common graphitic materials that have been used extensively showed the capacity in the range of 215–370 mAh/g with good coulombic efficiency [5–8]. On the other hand, hard carbons synthesized form pyrolysis of organic compounds like epoxy novolac resins, phenolic resins, synthetic isotropic pitches, polymers and oxidized pitches [9–12] show higher capacity (400–700 mAh/g) than graphitic materials but find limited use due to high irreversible capacity that consumes more lithium in initial cycles [4,12].

Considering the limitations of both graphite as well as hard carbons, efforts have been made in literature to tune the properties of graphite. Synthetic graphite can be prepared commercially from graphitizable carbons using resistive heating above 3000 ºC [13]. However as compared to the cost of raw materials heating at elevated temperatures take more share in process cost [13].
Graphitization occurs due to displacement of layer of graphitic planes and grouping of such layers at elevated temperatures among parallel crystallites [14,15]. To reduce the energy penalty, graphitization can be achieved at lower temperatures by pyrolyzing carbon under high pressure or by introducing a metal or inorganic/organic additives to serve as a catalyst for graphitization [16–18]. Later is also known as catalytic graphitization. A number of carbon precursor materials such as polycrylonitrile, phenolic resins, furan resin, organic gels in the form of fibers and monoliths have been successfully graphitized in the presence of catalyst [19–26]. From these studies, it was observed that use of Ni and Fe as metal catalyst was more effective during graphitization [19,21–24].

Since its introduction by Pekala in 1989, [27] resorcinol-formaldehyde (RF) based organic gels have been widely used as precursor to carbon aerogels, cryogels and xerogels. RF derived carbon aerogels and cryogels have been widely used as anode materials for energy storage devices, mainly for supercapacitors due to high capacitance and interfacial resistance [28,29]. However the major limitation of RF derived aerogels and cryogels as anode materials for lithium ion battery is higher surface area and thus large irreversible capacity losses in addition to higher processing cost in synthesis. Non-porous carbon xerogels possess less surface area and hence shows comparatively less initial irreversible capacity compared to carbon aerogels when used as anode material in lithium ion battery [30,31]. In recent times, RF derived carbon xerogels have been successfully demonstrated as potential anode materials for lithium ion battery but reversible capacity reported for powder sample was only 145 mAh/g, which was lower than most of graphitic and hard carbon materials [31]. To improve this, doping with nitrogen is suggested as one of the approach in one of the recent literature [32].

However in this work, we focus on catalytic graphitization of RF derived carbon xerogel as an alternative approach to tailor their structural characteristics. Role of pyrolysis temperature and presence of catalyst on microstructures of RF derived carbon xerogel was studied in detail which further improved the electrochemical performance of these materials for their potential use of anode materials in lithium ion battery. Although RF derived carbon gels have been widely tested as anode materials for energy storage devices, to the best of our knowledge, this is first detailed study on the catalytic graphitization of RF derived carbon xerogels and paving the way to enhance their electrochemical performance by engineering their microstructure and thus crystallinity. In literature, there are only a few studies available on effect of catalytic graphitization on lithium ion intercalation moreover these studies are not only limited to PAN based electrospun fibers, carbon fibers grown by chemical vapor deposition and phenolic resin but also pyrolysis temperature is limited to less than 1000°C [33–35].

2. Experimental

2.1. Materials

Resorcinol (99% purity), formaldehyde (37% w/v; stabilized with about 10% methanol), potassium carbonate (98% purity), LP-30 electrolyte (1 M LiPF₆ in 1:1 v/v mixture of ethylene carbonate and diethyl carbonate) were purchased from Merck, India and used directly. Lithium foil (99.9% trace metal basis) and Iron (II) acetate was purchased from Sigma–Aldrich, India while stainless steel (SS) foil (polycrystalline SS 316, 100 μm thick) used as a substrate for cell testing was purchased from MTI corp., USA. Deionized water was used as solvent while making RF aqueous sol.

2.2. Preparation of RF sol

To prepare the RF sol, resorcinol and formaldehyde were first added in a molar ratio of 0.25 (Resorcinol to formaldehyde) followed by mixing using magnetic stirrer for 15 min. Thus prepared solution was then added to aqueous solution of potassium carbonate with the resorcinol-to-water and resorcinol-to-catalyst molar ratios 0.037 and 25 respectively. The graphitizing catalyst iron (II) acetate (1% w/w) was then added to as prepared RF sol and stirred for 15 min in an inert atmosphere inside the glove box. RF sol mixed with catalyst was then air dried at room temperature for 24 h followed by oven drying at 80°C to yield RF xerogel. The RF sol without catalyst was also stirred for 15 min followed by similar drying procedure as in previous case of with catalyst.

2.3. Pyrolysis

Dried RF xerogel blocks were pyrolyzed in graphitizing tubular furnace (Materials Research Furnace, USA). After introducing the sample into the furnace tube, the tube was evacuated to 100 m Torr pressure before purging with argon (Ar) gas. After purging the chamber twice, Ar gas flow was maintained throughout the pyrolysis process at the rate of 21/min. Initially the temperature was raised to 500°C at a ramp of 10°C/min to prevent cracks in RF xerogel blocks due to rapid mass loss. Then the furnace temperature was raised to final pyrolysis temperature with 20°C/min ramp followed by a dwell time for 1 h at respective final pyrolysis temperature. The samples were then cooled to room temperature in the presence of Ar flow. Hereafter, RF derived carbon xerogel samples without catalyst were denoted as RFC-T, while the RF derived carbon xerogel samples with 1% (w/w) graphitization catalyst were denoted as RFCC-T where T denotes final pyrolysis temperature in both the cases in degree Celsius.

2.4. Ball milling

RF derived carbon xerogel blocks were first crushed in a mortar for 15 min before milling it to get fine powder in a ball mill. Crushed samples were then filled into stainless steel bowl with 3 mm diameter SS balls. Sample to balls weight ratio was maintained to be 1:12 for all the samples. The samples were milled using planetary ball mill pulversette7 (FRITSCH).

2.5. Characterization

Powder X-ray measurements were recorded in scattering angle range of 10°–50° on PANalytical X-ray diffractometer with CuKα radiation while Raman spectroscopy measurements were performed with a 532 nm laser on Bruker Raman microscope (Model: Senterra). Small angle X-ray scattering (SAXS) (0.01–10 nm⁻¹) curves were recorded on point collimation SAXess (Anton-Paar) instrument in transmission mode to estimate the radius of gyration. The carbon xerogel powder samples were placed in between X-ray transparent Kapton films and packed between two copper windows with the help of a sample holder. X-ray path including sample holder maintained in vacuum of 1 mbar to prevent the absorption and scattering of X-rays (λ = 0.154 nm) with air. Further high resolution transmission electron microscopy (HRTEM) (FEI Tecnai G2S-Twin) operated at 200 kV was used to study the morphology of microstructure.

2.6. Electrode preparation

For electrochemical studies, SS foil was used as current collector. A slurry was prepared by dissolving 10% polyvinylidene difluoride (PVDF) and 90% carbon xerogel powder in N-methylpyrrolidone
Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>Degree of graphitization ( g = (0.344 - d_{200}/0.0086 )</th>
<th>Empirical parameter ( R )</th>
<th>Radius of gyration ( R_g ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFC-900</td>
<td>-</td>
<td>2.12</td>
<td></td>
</tr>
<tr>
<td>RFC-1200</td>
<td>-</td>
<td>2.19</td>
<td></td>
</tr>
<tr>
<td>RFC-1500</td>
<td>-</td>
<td>2.44</td>
<td></td>
</tr>
<tr>
<td>RFC-1800</td>
<td>-</td>
<td>2.70</td>
<td></td>
</tr>
<tr>
<td>RFC-900</td>
<td>-</td>
<td>2.95</td>
<td></td>
</tr>
<tr>
<td>RFC-1200</td>
<td>0.45</td>
<td>2.97</td>
<td></td>
</tr>
<tr>
<td>RFC-1500</td>
<td>0.66</td>
<td>3.16</td>
<td></td>
</tr>
<tr>
<td>RFC-1800</td>
<td>0.69</td>
<td>3.21</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Effect of pyrolysis temperature and catalyst on structural parameters of RF derived carbon xerogels.

(NMP) solvent. The working electrode was prepared by coating this slurry on SS foil followed by vacuum drying at 120°C and lithium foil was used as a counter electrode. Glass microfiber filter (Whatman, Grade GF/D) soaked with LP-30 electrolyte was used as separator between two electrodes and packed inside the Ar filled glove box using Swagelok cell assembly. Before electrochemical testing, the electrochemical cells were soaked for 12 h. Potentiostat/Galvanostat (Bio-Logic Science Instruments, Model VSP) was used to study the electrochemical performance of packed half-cells.

3. Results and discussions

3.1. Structural characterization

Raman spectrum of RF xerogel samples pyrolyzed at various temperatures with and without catalyst is summarized below in Fig. 1a and b. For RF derived carbon xerogels without catalyst (Fig. 1a), D-band at about 1345 cm\(^{-1}\) corresponding to edges of small crystallite edge motions and vibrations of tetrahedrally bonded (sp\(^3\)) carbon atoms, which are not located in graphite crystallite is dominating over G-band at about 1585 cm\(^{-1}\) that corresponds to two dimensional in-plane motion of strongly coupled sp\(^2\) bonded carbons (E\(_{2g}\) symmetry) in the hexagonal honeycomb network of graphite lattice [11]. This trend is same for all samples pyrolyzed from 900 to 1800°C. However in case of RF derived carbon xerogels pyrozed in the presence of catalyst (RFC), we observed significant changes in the intensities of G-band and D-band with varying temperature (Fig. 1b). Intensity of G-band increased significantly compared to D band intensity with increase in pyrolysis temperature. Beyond 1200°C, G-band peak intensity started dominating over D-band. Further we observed that for RFC samples (without catalyst), intensity ratio \((I_D/I_G)\) of these two characteristics bands decreased marginally from 1.8 to 1.2 and similarly in-plane crystallite width (in plane diameter) \((L_a = 4.4(I_0/I_G))\ nm\) also increased slightly from 2.3 to 3.4 nm as shown in Fig. 2a. In contrast, RFC samples (with catalyst) showed significant change in intensity ratio from 1.6 to 0.3 and in-plane crystallite width increased from 2.6 to 12.2 nm as shown in Fig. 2b. Graphitic G-bands of samples pyrolyzed above 1200°C were observed to be more intense than D-band indicating initiation of graphitization. D band and G band position also varied with heat treatment temperature, as temperature increases G band and D band position shifted towards lower wave number and G band approached 1582 cm\(^{-1}\) corresponding to E\(_{2g}\) mode of single crystal graphite [2]. In addition to D band and G band we can observe D' band for the samples RFC-15000 and RFC-1800. Further narrowing of G band and splitting in G band and D' band for the samples pyrolyzed above 1200°C clearly shows that the graphitization is enhanced in presence of graphitization catalyst [19]. In addition to D and G band, Raman spectrum also shows the second order peak (2D) near 2700 cm\(^{-1}\), which appears most commonly in graphene and graphitic carbon and often called as G' band. This band is frequently used to distinguish single layer, bilayer graphene, from multilayer graphite based on the shift towards smaller wavenumber as number of layers decreases [36]. In our study it can be observed that the second most prominent peak (G') of graphite materials is not appeared in samples without metal catalyst as shown in Fig. 1(a). A broad 2D band can be seen for the RFC-1200 sample, which is indication of beginning of graphitization. Further, intensity of this peak increased as graphitization increases with pyrolysis temperature. However, the shift in 2D band is very little towards higher wave number with increasing graphitization.

Along with in-planar crystallite width calculated from Raman spectroscopy, crystallite thickness and interlayer spacing are two other important parameters to study the extent of graphitization.

XRD patterns for RFC and RFC samples as shown in Fig. 3 were used to study these parameters. Fig. 3a and b shows the diffraction patterns of RFC and RFC samples prepared at different pyrolysis temperatures. Diffraction peaks at 2θ value of 25° and ~43.8° corresponds to (0 0 2) and (1 0 1) reflections respectively [22]. No clear signature of diffraction peak at 2θ = 25° for RFC sample pyrolyzed at 900°C reveals complete amorphous nature of these carbon xerogels. Even RFC samples pyrolyzed at higher temperature (equal or more than 1200°C), only a broad peak at 2θ = 24° was observed which still indicates the amorphous nature of carbon xerogels, although within short range. Interestingly for RFC samples, the diffraction peak at about 26° was found to be very sharp as compared to RFC samples. This observation clearly suggest the ordering of graphite layers at higher temperature in the presence of catalyst. Further using XRD data, we have calculated interlayer spacing and crystallite thickness using Scherrer formula as summarized in Fig. 4 [37]. The angle at which (0 0 2) plane diffracted was considered in this formula. For RFC samples, as shown in Fig. 4a, the interlayer spacing decreased from 3.61 to 3.49 Å while the crystallite thickness increased marginally from 7.7 to 11.4 Å on increasing the pyrolysis temperature from 900 to 1800°C respectively.

However in case of RFC samples as shown in Fig. 4b, interlayer spacing was reduced to 3.48 Å at 900°C to 3.38 Å at 1500°C which remained nearly same even at 1800°C. At the same time, the crystallite thickness increased significantly from 31 to 55 Å as shown in Fig. 4b. These observation suggested that in the presence of catalyst at higher temperature, there was long range of ordered graphitic layers within RF derived carbon xerogel samples. To support this further, we recorded XRD patterns for RFC at very high temperature 2500°C (given in the supplementary material) however a broad peak at 2θ = 25.9° with 3.43 Å interlayer spacing and 17 Å crystallite thickness suggests that RF derived carbon xerogel is non-graphitizable carbon without the use of catalyst [13].

In order to further understand the arrangement of graphene layers in RF derived carbon xerogels, we conducted small angle X-ray scattering measurements. The intensity versus scattering vector (q) plots obtained for RFC and RFC samples are shown in Fig. 5a and b.

Scattering vector q is defined as \( q = 4\pi \sin (θ/2) / λ \). As we observe in case of RFC and RFC samples both, there is a rise in scattering intensity of the carbon xerogel samples with pyrolysis temperature. This may be due to separation of graphite crystallites edges and voids at higher temperatures [38]. Further we estimated the radius of gyration form the slope \( \ln I(q) \) versus \( q^2 \) plot of the scattering data recorded for the carbon xerogel samples in Guinier region using following simplified equation [39].

\[
\ln I(q) = \ln I(0) - \frac{R_g^2 q^2}{3}
\]

Alignment of graphene layers at elevated temperature (graphitization) resulted in reduction in the number of voids/pores between...
Fig. 1. Raman spectrum of carbon xerogel pyrolyzed at different temperature (a) without graphitization catalyst and (b) with 1 wt.% graphitization catalyst.

Fig. 2. Effect of pyrolysis temperature on in-plane crystallite width and $I_p/I_G$ of RF derived carbon xerogel (a) without graphitization catalyst and (b) with 1 wt.% graphitization catalyst.

Fig. 3. XRD spectrum of RF derived carbon xerogel (a) without graphitization catalyst and (b) with 1 wt.% graphitization catalyst.
the graphene layers and therefore increase in pore diameter which was correlated to radius of gyration as summarized in Table 1 [40]. In case of graphitization without catalyst, radius of gyration increased from 2.12 to 2.7 nm while in the presence of catalyst, it increased from 2.95 to 3.21 nm from 900 to 1800 °C respectively. For any given temperature, RFC sample has less radius of gyration than corresponding RFCC samples. Not only that, even at the highest temperature (1800 °C), radius of gyration for RFC samples (2.7 nm) was less than RFCC samples at lowest temperature (900 °C). This observation was more profound while calculating the degree of graphitization.

We reported degree of graphitization based on a correlation between d-spacing (measured from XRD data), radius of gyration from SAXS analysis and an empirical parameter \((R)\) that corresponds to number of single graphene layers. Empirical parameter \((R)\) is the ratio of the height of \((002)\) diffraction peak and background of XRD pattern. It is inversely proportional to number of single graphene layers [12]. This empirical parameter value increased with pyrolysis temperature as summarized in Table 1. Finally the degree of graphitization values revealed that graphitization occurred only beyond 1200 °C that too in the presence of
catalyst. At 1500 °C, degree of graphitization achieved was 0.66 that further increased marginally to 0.69 at 1800 °C.

To further examine the microstructure of carbon xerogels with and without catalyst HRTEM micrographs were recorded for samples pyrolyzed at 1800 °C. Fig 6a and b reveals that RFC-1800 sample contains disordered carbon with very few layer of short graphene layers stacked without any well-ordered graphite domain. In contrast, graphitized RFCC-1800 sample is made up of graphitic carbon ribbon like structures. The shape of these ribbon like structures can be attributed to precipitation of graphitic carbon around the metal nanoparticles while cooling [23]. These ribbon like structures of size about 4–6 nm (40–60 Å) from HRTEM images are close to the crystallite thickness calculated from XRD using Scherrer equation. Improved graphitization observed in case of carbon samples at higher temperatures with metal catalyst (RFCC-1500 and RFCC-1800) can be ascribed to enhanced dissolution of amorphous carbon into metal nanoparticles at elevated temperature followed by precipitation of graphitic carbon during the cooling [15].

Once we studied the microstructure and crystallinity of RF derived carbon xerogel prepared with and without catalyst, we then examined their electrochemical behavior and explained it in terms of their structural parameters.

3.2. Electrochemical performance

3.2.1. Cyclic voltammetry

Fig. 7 shows the cyclic voltammogram of RFCC-1800 sample recorded at a scan rate of 0.1 mV/s in the voltage range of 0–3 V. It exhibited two cathodic current peaks, a broad peak at 0.6 V and
another sharp peak near 0 V. Broad peak at 0.6 V can be ascribed to SEI formation due to electrolyte decomposition and sharp peak at near 0 V attributed to lithium insertion into carbon xerogel samples [41]. Anodic broad peaks at about 0.2 V and 1 V corresponds to lithium extraction from carbon xerogel samples during charging. As there was no major change in chemical composition and surface area, all other samples (RFCC 1200 and RFCC 1500) show similar peaks in cyclic voltammetry.

3.2.2. Galvanostatic charge-discharge experiments

Galvanostatic charge-discharge experiments were carried out at 0.1 C rate (37.2 mA/g current density) in between 0.01 V and 3 V. Fig 8a and b shows the cyclic performance of RFC and RFCC samples pyrolyzed at different temperatures up to sixty cycles. For RFC samples (Fig. 8a), first cycle discharge capacity increased from 494 to 754 mA h/g with increase in temperature from 900 to 1800°C. Initial cyclic efficiency was also increased from 32 to 40% for RFC samples pyrolyzed at 900 and 1800°C respectively. For all RFC samples pyrolyzed at different temperatures, coulombic efficiency was observed to be more than 90% by third cycle of charge/discharge which further increased to nearly 97% after ten cycles. After sixty cycles of continuous charge and discharge, specific reversible capacities for RFC samples pyrolyzed from 900 to 1500°C were stabilized in similar range from 187 to 195 mA h/g with no significant increase with temperature. However at further higher temperature (1800°C), reversible capacity increased nearly 15% to 224 mA h/g. This electrochemical behavior was also in line with structural characterization for these samples in which there was no significant change observed in their crystallinity and internal microstructure.

Further more importantly in case of RF derived carbon xerogel samples prepared in presence of catalyst, we observed significant larger values of reversible capacities with much improved first cycle efficiency at higher temperature (Fig. 8b). For RFCC-900 sample, first discharge/intercalation capacity was found to be significantly higher (641 mA h/g) with 34% initial cycle efficiency. Interestingly, for RFCC-1800 sample, first discharge capacity increased further to 857 mA h/g while charge capacity was measured to be 385 mA h/g, larger than that of graphite, with sufficiently higher initial efficiency of 45%. For carbon materials in literature, lower first cycle efficiency (20–35%) can always be explained due to formation of solid electrolyte interface however for RFCC samples, we have shown a sufficiently high first cycle efficiency up to 45%. Further coulombic efficiency was increased up to 98% for RFCC samples at higher temperature, a further confirmation of excellent cycling behavior of these samples. After sixty cycles of charge discharge, reversible capacity was stabilized to 280 mA h/g for RFCC-1800 sample, a significant 25% increase to their corresponding RFC-1800 sample. Among all samples, RFCC-1800 sample showed best electrochemical performance with its specific capacity in the similar range of graphitic carbon materials. This behavior can easily be ascribed to higher degree of graphitization achieved that resulted in increased electronic conductivity of the sample. At the same time, we found an interesting observation. RFCC-900 sample showed higher capacity than RFCC-1200 and RFCC-1500 samples. This could be due to adsorption of lithium ions on surface of nanopores of disordered carbon of RFCC-900 sample compared to moderate graphitized samples with less number of nanopores of adsorption of lithium ions [12].

Reversible capacity and first cycle efficiency values reported here in this work are superior to what has been reported in literature for RF derived carbon xerogel powder samples [31]. Further a comparison of electrochemical performance of various other forms of carbon gel materials is summarized in Table 2. This confirms the enhanced reversible capacity and much improved cyclic stability in RF derived carbon xerogels. This enhancement can be attributed to catalytic graphitization which has improved the electronic conductivity in basal plane of stacked graphene layers. The electrochemical performance of thus prepared carbon xerogel samples is much better than cryogels and aerogels in terms of initial cycle coulombic efficiency and cyclic stability.

4. Conclusions

RF derived carbon xerogels with and without catalyst were prepared by pyrolyzing RF xerogel at different temperatures from 900 to 1800°C. A detailed structural characterization using Raman spectroscopy, XRD, SAXS and HRTEM suggested that RF derived carbon xerogels were non-graphitizable (hard) carbon which could be graphitized in the presence of metal catalyst at elevated temperature of 1200°C and beyond. On the other hand, there was no observed change in crystallinity and arrangement of graphene layers even at temperature as high as 2500°C without catalyst. Degree of graphitization and therefore crystallinity was found to be largely dependent on final pyrolysis temperature. These findings were further supported while examining the electrochemical performance of these materials. Galvanostat charge/discharge experiments suggested the use of RF derived graphitized carbon xerogel as efficient anode materials for lithium ion battery with excellent cycling behavior and cyclic stability. Graphitization not only improved first cycle efficiency and therefore reduced the irreversible capacity losses associated with SEI layer formation in carbon materials but also a significantly large first charge capacity was obtained in these materials.
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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jaap.2015.10.017.

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