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2024

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The Development of the Novel Pseudo-Solid Electrolyte (Ionogel) for Lithium Metal Batteries

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Abstract

Humanity's quest for improved energy storage solutions has led to significant strides in battery technology, particularly in the realm of lithium metal batteries (LMBs). LMBs benefit many technologies due to their high energy density, high capacity (the total amount of electricity generated due to electrochemical reactions in the battery), and rechargeability. However, their usage is limited by major safety issues: flammability, short lifespans, and high risk of short-circuiting. One notable innovation to solve the issues of LMBs is the integration of solid electrolytes, primarily using the sol-gel method, which offers enhanced safety by limiting the likelihood of malfunctions. However, such methods gain this safety at the expense of performance, significantly limiting the battery's usability.

This study introduces a novel method for fabricating pseudo-solid electrolytes (ionogels) to bridge the gap between safety and performance. These ionogels combine the advantages of both solid and liquid electrolytes, offering significant improvements in longevity, cycling stability, and safety when compared to conventional electrolytes.

Utilizing scanning electron microscopy (SEM), Brunauer-Emmett-Teller (BET) Surface Area Analysis, Pore Size/Volume Testing Technique, and Fourier transform infrared spectroscopy (FTIR), along with a simple comparison to the plating and stripping of liquid electrolyte batteries, this study elucidates the microstructure and solvent exchange completeness of ionogels, confirming their potential as a safer and more efficient alternative to conventional electrolytes. These results, while preliminary, suggest that broader application of such ionogels may be seen in the future.

Future research will include testing the ionogel thickness, testing the electrolyte degradation, and evaluating the possibility of macropore presence in ionogels to revolutionize energy storage systems. These examinations will pave the way for safer and more durable batteries in diverse applications past what they are used in now.

Keywords: Ionogel, Batteries, Electrolyte, Pseudo-Solid, Pore Size, Safety, Lithium batteries

Introduction

The Evolution of Energy Storage and Its Impact on Society

Compared to most of human history, the pace of change in daily life has accelerated dramatically over the past few hundred years. This acceleration in scientific exploration coincides with humanity's increasing ability to exploit energy resources for its benefit. Some of the most profound inventions were created during the Industrial Revolution, such as Alessandro Volta's first battery (Piccolino, 2000). Built-in 1800, Volta's battery was the first practical device to store electrical energy, and since then, batteries have become essential to everyday life. Though dramatically improved from the stack of disks created by Volta, batteries today are still limited by factors like energy density, sustainability, and cycle life (Choi & Aurbach, 2016; Chu et al., 2016). These limitations have inhibited the wider application of batteries, specifically in the transition to batteries as a replacement for fossil fuels.

Lithium-ion batteries (LIBs)

Invented in the 1970s, the lithium-ion battery (LIB) earned Drs. Yoshino, Whittingham, and Goodenough the Nobel Prize in Chemistry (Azemtsop Manfo, 2023). The LIB has many various subtypes, but it generally consists of the anode, cathode, electrolyte, separator, and container. LIBs are notably different from other batteries due to their energy density, lasting power, long cycle life, and relatively low environmental impact and cost. They are also rechargeable, making them ideally suited for electric devices and machinery (Manthiram, 2017). Even though these batteries are widely utilized, they are still generally limited by their low

energy density, safety, and degradation in capacity when compared to gasoline or other fossil fuels. (University of Washington, 2015).

Lithium Metal Batteries (LMBs)

Another widely investigated battery is the lithium metal battery (LMB), which, due to its high energy density, is notably different from LIBs. LMBs utilize lithium as the anode as opposed to LIBs, which simply use lithium ions and no metal. Another difference is the distinct use of graphite as the anode in LIBs, compared to the LMBs that consist solely of lithium, a very unstable metal. LMBs are used more in research and are seen as very high-performing batteries with increased energy density, fast rechargeability, and large capacity. However, these batteries have limitations, such as their tendency to short-circuit and safety issues regarding the interactions between the lithium metal and the electrolyte (e.g., dendrites (needle-shaped structures that damage the protective layers between the anode and cathode and short-circuit the battery); Wang, 2021).

Mitigating LMB Limitations

Researchers have focused on overcoming the limitations of LMBs, leading to improvements in all areas of their composition, especially the electrolyte. A key area of research is the use of the sol-gel method to enhance energy density and conductivity (Dunn et al., 1994). (Dunn et al., 1994). The sol-gel method turns electrolytes into a glass-like texture through chemical synthesis (i.e., polymerization of chemicals using wet chemical methods). This method is used as a replacement for the liquid electrolyte in LMBs and is safer than the flammable liquid

electrolyte. However, one challenge with solid electrolytes is the contact between the anode and the electrolyte. The interface between the solid electrolyte and solid anode tends to be less effective compared to the liquid-solid interface (Yim et al., 2023).

Silicon as an Anode Material

Other research explores the use of silicon as the anode (Zhou et al., 2015). Silicon can store up to ten times more lithium than graphite and provides a higher energy density due to the high percentage of lithium in silicon-lithium alloys. Furthermore, the smaller size of silicon anodes compared to graphite anodes makes the former more space-efficient as they are generally more compact. Despite these advantages, the silicon battery has limited capacity, resulting from the volume expansion that occurs each time the silicon alloys are combined with lithium. The alloying forces cause the silicon anode to fracture and degrade over time, decreasing battery capacity and overall performance.

Ionogels

Modern LMBs are limited by their capacity, energy density, and the dangers of the liquid electrolyte (Deng et al., 2023). Recent advancements in electrolytes include the creation of ionogel, which improves not only the safety but also the capacity and energy storage properties of the battery. This advancement is due to the ionogel being a pseudo-solid electrolyte, which replaces the spacers, separators, and liquid electrolytes. The pseudo-solid electrolyte forms from a mixture of chemicals, creating a porous, light gel that completely separates the anode and cathode, ensuring the battery does not short-circuit or set aflame (Huang, H. et al., 2023; Huang,

J. et al., 2023). The ionogel functions the same as an electrolyte but is safer than LMBs with liquid electrolytes. (Chen, 2018).

Research Focus

This research explores advancements in battery technology, focusing on the development and application of pseudo-solid electrolytes, specifically ionogels, in improving battery performance. It will also explain the process of making ionogels, the resulting improvements in battery function, and their future use in research. This work introduces a pseudo-solid-state electrolyte that, when combined with copper foil, achieves high energy density in lithium metal batteries (LMBs), offering a safer alternative to liquid-state batteries due to its non-flammable nature. The pseudo-solid state also provides better wetting between the electrolyte and anode in comparison with solid-state electrolytes. Overall, this battery will be compared to standard liquid electrolyte batteries through many tests to prove that it is a superior device.

Methods

Materials

The precursors used in this experiment are methyltrimethoxysilane (MTMS), tetramethyl orthosilicate (TMOS), Formic Acid, and Ionic liquid (PYR14FSI or 1-Butyl-1-methylpyrrolidinium bis(trifluoromethyl sulfonyl)imide). Mixing 150 microliters of MTMS, 200 microliters of TMOS, and 200 microliters of formic acid creates the pseudo-solid part of the electrolyte, leaving pockets to be filled later with 800 microliters of ionic liquid, creating a soft gel with a solid exterior and liquid interior. The equipment used in this experiment

includes a stir plate to mix the precursors, a desiccator with a vacuum line to remove air bubbles while drying the ionogel, and a fume hood to protect researchers from exposure to toxic chemicals. Additionally, two types of convection ovens are used to dry the electrolyte, and a glovebox is employed to assemble the coin cell while keeping air-sensitive components in a controlled environment. A supercritical dryer – complete with a pressure chamber, heating and cooling system, and attachment to a CO₂ tank– is also needed to solvent exchange liquid CO₂ in the ionogel and reach the supercritical state. Other components used include: copper foil in a 1mm by 1mm square to add to the electrolyte, ethanol to presoak the copper, and finally, 1,3-dioxolane and 1,2-dimethoxyethane or DOL and DME to solvent exchange with the ionic liquid in the copper foil and pseudo-solid electrolyte. A setup to test the conductivity of the ionic liquid was premade by cutting a hollow plastic tube into a one-inch cylinder and poking a very small hole in the center of the tube. Along with this tube, two metal pins and alligator clips were used to attach the tube. Finally, the conductivity was measured for both the ionic liquid and the ionogel.

Design

BioLogic Potentiostat Software

BioLogic Potentiostat software was used to gather all the data needed to test the ionic liquid or batteries. This program was accessed via computer and connected to clips, which could be attached either to the homemade conductivity tester or to the coin cells.

Conductivity Calculation

$$\sigma = \frac{1}{\rho} = \frac{l(m)}{R(\Omega)A(m^2)}$$

Above is the resistivity to conductivity equation used to calculate the conductivity of the ionic liquid and ionogel. The σ represents conductivity (i.e., the variable being solved for); ρ is the resistivity; R is the resistance (i.e., given in ohm); A is the area given in meters²; length (l) is given in meters. The resistivity was determined by running the BioLogic Potentiostat program and other necessary values were gathered through measurements of the length and diameter of the ionic liquid being tested.

BET

Brunauer-Emmett-Teller (BET) surface area analysis is measured as a function of relative pressure using a fully automated analyzer and is commonly used alongside the Barrett-Joyner-Halenda (BJH) Pore Size and Volume Analysis Testing Technique. In this study, BET was used to determine the pore sizes in the ionogel after the supercritical drying process. Finding the pore sizes is crucial as ionogel is an intrinsically porous material and quantification of the ratio of microscopic to macroscopic pores in the ionogel directly relates to battery performance.

Supercritical Drying

Solvent exchanging with liquid CO₂ and turning it into a supercritical fluid is an essential step in creating and testing the ionogel. Creating the supercritical fluid allows the PYR14, or ionic liquid, to completely leave the pores in the gel without destroying the structure or the pore size distribution. Because the capillary forces associated with drying are minimized when the supercritical state is reached, pore collapse is prevented and the porous network is maintained in the supercritical fluid state.

FTIR

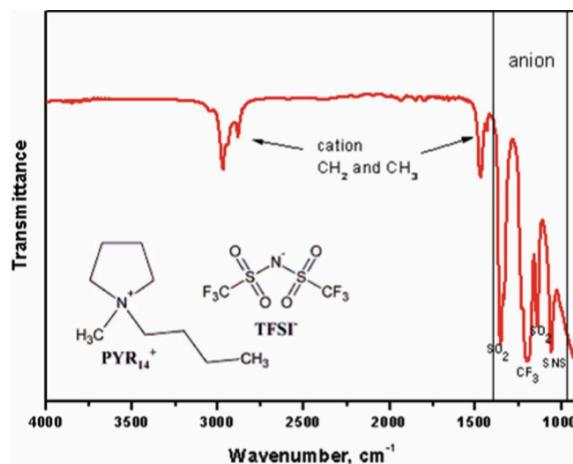


Figure 1: Normalized Fourier Transform Infrared Spectroscopy (FTIR) for PYR14 (ionic liquid) with characteristic peaks noted. (Mozhzhukhina, Nataliia, et al. 2017)

FTIR (Fourier Transform Infrared Spectroscopy) is a specialized form of infrared spectroscopy optimized for material analysis. FTIR works by bombarding a sample with infrared light, measuring the absorbance and emittance of the sample at various wavelengths. These

absorption profiles are highly specific to the functional groups present in the material, such as cation groups in ionic liquids. In this case, the cation groups are typically organic structures like methyl groups (CH_3) or pyrrolidinium groups in ionic liquids. The vibrations and rotations of bonds within these functional groups absorb energy at characteristic infrared wavelengths, creating distinct peaks in the FTIR spectrum. By analyzing the intensity and position of these peaks, the quantity of these functional groups can be determined. In this experiment, FTIR was used to determine whether the ionic liquid PYR14 (1-Butyl-1-methylpyrrolidinium bis(trifluoromethyl sulfonyl)imide) was completely removed from the ionogel. The CH_3 group in the PYR14 cation absorbs infrared radiation, producing peaks that signal the presence of the ionic liquid. If these peaks are absent or diminished, it indicates that PYR14 has been removed from the ionogel.

Procedure

Mixing the chemicals

Place chemicals MTMS (methyltrimethoxysilane), TMOS (tetramethyl orthosilicate), formic acid, and ionic liquid-PYR14FSI (1-Butyl-1-methylpyrrolidinium bisimide) inside a fume hood (keeping the ionic liquid on the side for later use). Begin by taking a small container, big enough to hold a little over 1 milliliter of liquid, with a corresponding lid, and adding a stirring rod to the bottom of the container. Place a container in the center of a stir plate inside a fume hood, setting the stir plate to a constant speed of 500 rpm. With the container on the stir plate, add 2520 microliters of MTMS to the container using a pipette that can measure up to 800 microliters. After changing the pipette's tip (and disposing of the used tip properly), add 300

microliters of TMOS to the MTMS solution. Finally, after changing the tip once more, add 300 microliters of formic Acid to the solution. Place the lid back onto the container and leave the solution stirring for 1 hour to allow the gel-like solution to form and mix properly.

Copper Foil

While the solution is stirring in the fume hood, cut a piece of copper foil into a 1-millimeter by 1-millimeter square and place it into a separate small container about 65 millimeters wide. Pour ethanol over the copper foil until completely covered. Then, take the container with the copper foil and ethanol and leave it in a desiccator for at least 10 minutes; this process ensures all air is gone from the ethanol and around the foil.

Conductivity Testing

Wait for the solution to mix, then place a small amount of the ionic liquid into a disposable pipette and set up the custom ionic conductivity tester using a plastic cylinder, metal pins, and alligator clamps. To begin assembly, cut plastic tubing to around an inch lengthwise and poke a small hole in the center of the tubing on one side. Then, place a metal pin inside one side of the tube, leaving just enough space to cover the small hole in the center of the tubing. Place a minimal amount of the ionic liquid into the tubing, leaving enough room to place the other metal pin into the other side while the ionic liquid is in the center. Then, carefully push the pin covering the hole to the side and remove any air bubbles in the ionic liquid through the hole to complete the setup of the ionic liquid conductivity tester. Once ready, connect alligator clips to

either side of the tubing and run the program. Then, measure the diameter, length, and area of the setup created to use in the resistivity and conductivity formula.

Finished Solution

After around 10 minutes, take the copper foil out of the desiccator and place it under the fume hood with the rest of the supplies. Wait for the solution to mix properly, then remove the lid and add 800 microliters of ionic liquid to the solution, allowing it to stir for around 1 minute. While waiting, use a disposable syringe to remove as much of the ethanol in the container with the copper foil as possible, leaving just the copper behind. Next, take the solution off the stir plate, uncap the container, and add the solution on top of the copper foil using a syringe. Once completed, put the container back into the desiccator and allow all remaining air bubbles to rise for at least 10 minutes. Then, remove the container from the desiccator and allow the solution to dry overnight under the fume hood.

Drying Stage

The next day, set a convection oven to 80 °C and place the solution into the oven to dry for around 24 hours. The following day, place the container into a vacuum oven at 120 °C and leave the container in there for exactly 6 hours (any longer and the ionogel will become too dry and collapse). Once the gel is dry, remove the container from the vacuum and place it aside for the solvent exchange process and supercritical drying process.

Solvent Exchange - Acetone

To begin the solvent exchange, submerge the gel in acetone and leave it on a stir plate overnight. After the overnight incubation, remove the acetone with a pipette and repeat the process four more times, for a total of five acetone exchanges. Once these steps are completed, remove the acetone one final time and prepare the supercritical dryer to transfer the ionogel inside. This solvent exchange process replaces the ionic liquid in the pores of the ionogel entirely with acetone, and it typically takes about 12 hours.

Supercritical Drying

Place the container with the ionogel inside the supercritical dryer and securely close the chamber. Begin by adding CO₂ gas to the chamber. Gradually increase the pressure while decreasing the temperature to convert the CO₂ into a liquid phase, which is necessary for performing the second solvent exchange. Continue to raise both the pressure and temperature until the supercritical state is achieved. Refer to Figure 2 for the exact pressure and temperature conditions required to reach the liquid CO₂ phase and the supercritical state. At this point, the solvent exchange process occurs as the liquid CO₂ replaces the acetone inside the pores of the ionogel. Because CO₂ has low surface tension and is a supercritical fluid, it can efficiently penetrate the gel's porous structure, facilitating the removal of residual acetone while preventing the collapse of the ionogel's framework during the drying process.

Trimming

Once the solvent exchange with liquid CO₂ is complete, place the container with the ionogel on a table alongside a sharp razor and an extra spacer to cut the ionogel to the correct size. First, cut off all the edges of the container leaving just the ionogel and a small bit of the container underneath. Then, remove any film on the top of the ionogel and trim the gel to around 2 millimeters thick. Trim the gel to the appropriate radius by placing a spacer on top and cutting it to that size.

Additional Materials

Once all of the previous steps are completed, place the ionogel into a container with a lid (with small holes in the lid). Then, transfer the container into the glovebox through the side door, along with a container filled with DOL/DME, small 1 mm lithium circles, XL gloves, and lithium polishing tools.

Solvent Exchange - DOL/DME

Once proper PPE is on, including gloves and a lab coat, and once inside the glovebox, move the containers to the center of the workspace. Take the lid off the ionogel and the container of DOL/DME and, using a syringe, complete a solvent exchange by filling the container with DOL/DME until the gel is fully submerged. Set the gel aside for two nights on a stirrer to make the solvent exchange more thorough. Once the solvent exchange is completed twice (for a total of four nights), gather the rest of the components to make a coin cell and place them into the glovebox, which includes the top and bottom parts of the coin cell, spring, and spacer.

Creating the Coin Cell

First, place a Kim wipe on the floor of the glovebox and place the bottom part of the coin cell onto the wipe with a spring inside the bottom part. Make sure to center all of the components in the battery as best as possible to make it easier to close later. Next, place a spacer on the side in an easily accessible place and put gloves on over the glovebox gloves to prevent contamination with the lithium metal used. Using flathead tweezers, place the lithium onto the rough polishing surface and drag it back and forth across the surface until the lithium shines. Repeat this process for each side of the lithium and use the same process for the fine-polishing tool. Once completed, take the spacer kept on the side and place it onto the polishing tool. Then, carefully place the lithium into the center of the spacer (make sure to be as centered as possible). To ensure the lithium stays where it was placed, press a finger onto the spacer and the lithium, which is fairly sticky (and will stay in place once firmly pressed onto the spacer). Once stuck, place the lithium and spacer on top of the spring with the lithium facing upwards and away from the spring. Finally, remove gloves and place them along with all of the lithium tools to the side, away from any other items in the glove box to prevent contamination. Next, take the ionogel out of the container by detaching the lid and removing as much of the liquid as possible from the container (disposing of it properly). Then, carefully tap the electrolyte to the side of the glass vial; this leaves a gap on the bottom of the electrolyte where flathead tweezers can be used to grab around the solution and remove it from the container. Next, with the side with more electrolyte facing the lithium, and the copper foil facing upwards, gently place the ionogel into the coin cell, making sure to center it and not move any of the pieces underneath. Finally, add a

spacer on top of the copper foil and place the top of the battery over all of the components. The easiest way to place the top on the whole coin cell is to use fingers or tweezers to gently drop it into place so the other components inside do not move. Then, once the top is on, carefully move the battery to *plastic* tweezers without squeezing the battery too tightly to avoid compressing the pseudo-solid electrolyte inside. Lastly, carefully place the coin cell into a hydraulic press, allowing the cell to be closed using the same plastic tweezers and ensuring that the coin cell will not short-circuit. Pull the handle of the hydraulic press to 500 PSI and, after reaching the desired pressure, release the hydraulic press and clean the excess liquid off with a Kim Wipe. Then, carefully take the battery out of the hydraulic press and out of the glovebox.

Testing

Take the freshly-made battery out and place it to the side. Using the same program that tested the conductivity of the ionic liquid, test the coin cell by attaching alligator clips to the corresponding positive and negative sides of the battery. Record the results of the conductivity test and begin the process of making the ionogels and coin cells over again.

Results & Discussion

Pore Size

The scanning electron microscope (SEM) was used to evaluate the microstructure of the ionogel (Figure 3) and revealed a sphere-like shape of SiO₂ particles with scattered areas of larger porosity. BET was used to determine the size distribution of these pores after supercritical drying was completed. Pore size distribution effectively represents the number of pores within a

certain range of dimensions. This is critical information as pore size can be related to battery performance. BET found a high pore volume at 2 nanometers in diameter, indicating a significant number of micropores (Figure 4). However, because BET testing only evaluated for pores under 100 nanometers, there is a chance of missing larger pores in the ionogel. To better evaluate this missing data, the anticipated density of the sample (using the known density of SiO₂ and the anticipated total micropore volume) was compared to the actual density. The comparison of the anticipated density of the sample to the actual density showed an unaccounted-for pore volume of approximately 70%, suggesting that 70% of pores were macropores. It was also observed in SEM that there were macropores in the sample. The synergistic effect of micropores and macropores enhances battery performance by leveraging micropores to mitigate dendrite growth and macropores to facilitate efficient ion transport.

Solvent Exchange Completeness

After quantifying the pore size, FTIR was utilized to determine if the solvent exchange was complete. Running FTIR revealed a lack of peaks at CH₂/CH₃, indicating an absence of the PYR14⁺ cation and a complete solvent exchange (Figure 5). Solvent exchange completeness is crucial to determine if the electrolyte was correctly changed to a more conductive solution, which effectively increases the conductivity of the ionogel and decreases the cell resistance.

Plating and Stripping

After the cells were created, lithium plating and stripping experiments were conducted to determine the coulombic efficiency (meaning the charge efficiency by which electrons are

transferred in batteries), measured at a current density of 4 mA/cm^2 and an areal capacity of 1 mAh/cm^2 . Together, these values represent the amount of lithium that can be plated and stripped, indicating the efficiency of the process. The ionogel immediately became stable at around 98% coulombic efficiency whereas the liquid electrolyte was volatile. This instability is seen as the liquid electrolyte exhibited periodic coulombic efficiency of over 100%, indicating that the battery had short-circuited (Figure 6). Over many cycles, the ionogel's coulombic efficiency remained at around 98%, only falling off a small amount as it neared 100 cycles. Proportionally, the liquid had a widely variable coulombic efficiency as seen through the sharp increases and decreases of coulombic efficiency as more cycles were performed. This suggests that ionogels offer superior plating and stripping performance, likely due to SiO_2 particles' ability to inhibit dendrite growth and promote more uniform deposition. This will be investigated more with SEM and discussed in a later section.

Conclusion

This experiment demonstrates the creation of an ionogel for LMBs and the feasibility of using an ionogel as an alternative to traditional liquid electrolytes. Ionogels are superior to the liquid electrolytes commonly used within commercial LMBs for several reasons. They are safer and provide better wetting between the anode and the electrolyte, a common problem among other electrolyte types, such as solid-state electrolytes. After testing the capacity, cycle rate, and stability of the ionogel it was determined that while they demonstrated superior electrolyte performance and properties when compared to other electrolytes, they have potential limitations that require further investigation. However, these findings showcase the potential applications for

ionogel in many electronic devices, owing to its demonstrated superiority in capacity, safety, and overall improved electrolyte properties.

Pore size

A potential barrier for ionogels had previously been pore size, as the pore size ratio is directly related to the battery's performance, with increased macropores correlating to worse performance (Beuse, et al., 2021). SEM analysis revealed that this project achieves an adequate pore size, which may help overcome the short-circuiting issues previously observed with liquid electrolytes. However, further investigation is required to determine the true pore size range within the ionogel. It is unclear if pores over 100 nanometers exist currently in the ionogels, as BET was used to search for pores up to this threshold only. One potential example of a larger-than-threshold pore (over 100 nanometers) is seen in Figure 3. Consequently, testing of the ionogels pore size larger than 100 nanometers is needed to fully evaluate the reason for the observed battery performance.

Solvent Exchange Completeness

Through FTIR testing and comparison of the electrolyte before and after solvent exchange, it can be concluded that full solvent exchange occurred, as there was no PYR14 left in the ionogel. This can be seen through the lack of peaks in CH₂ and CH₃ vibrations when tested with FTIR (Figures 1 & 5). Such complete solvent exchange is a marker for better electrolyte conductivity relative to current LMBs.

Plating and stripping

Battery durability and longevity limitations are currently seen as some of the major obstacles to the greater applicability of batteries. To help address these limitations, advancements in plating efficiency have been proposed. The data shown in Figures 6 & 8 (the cycling stability and SEM photos of liquid versus ionogel) indicate that the plating of the lithium and the battery's efficiency have significantly improved from the liquid electrolyte. This is supported by the uniformity throughout the battery over many cycles at a high rate compared to the opposing liquid electrolyte. This same consistency is observed in its coulombic efficiency over time, especially when compared to the fluctuating performance of liquid electrolytes (Figure 6). Such uniformity is expected to enhance the longevity of batteries produced using the pseudo-solid electrolyte method. Though the early cycle data indicates that the ionogel is already superior to the liquid electrolyte, the coulombic efficiency drops rapidly over time, specifically towards the end of cycling. Though the underlying reasons for this are not presently well understood, potential causes might include short circuits, a common reason for LMBs to fail. Another potential cause is the gradual depletion of the liquid in the electrolyte over time. Based on our observations, we anticipated that short-circuiting as the underlying cause is less likely, which led to an investigation of causes for electrolyte depletion, including testing ionogels of different thicknesses. After testing ionogel in 1-millimeter and 2-millimeter thicknesses (Figure 7), it was confirmed that electrolyte depletion was the underlying cause of the coulombic efficiency drop over cycles, as the thickness of the ionogel directly related to the rapid plummet of the electrolyte; however, additional investigation into this topic will be required and is forthcoming.

Future Research

The ionogel method has demonstrated the potential to be a superior solid-state electrolyte for LMBs, especially when compared to previous electrolytes, because of its many promising properties. However, future lines of investigation are required to fully evaluate the possibility of this electrolyte for further use. This includes evaluating the possibility of macropores in the ionogel and ionogel decay over time, specifically regarding the significance of ionogel thickness. Additionally, a more detailed SEM evaluation will be undertaken to ensure that the lithium is growing underneath the ionogel (similar to Figure 9) and behaving in the way theorized. Better characterization of these potential issues can further inform the creation of superior batteries that are safer and maintain better contact between the electrolyte and anode, yet still possess the benefits of other LMBs. This will, in turn, yield smaller, lighter, and safer devices that can further support the ongoing conversion to battery-powered systems such as electronic devices, cars, and other electrical energy storage systems.

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Figures

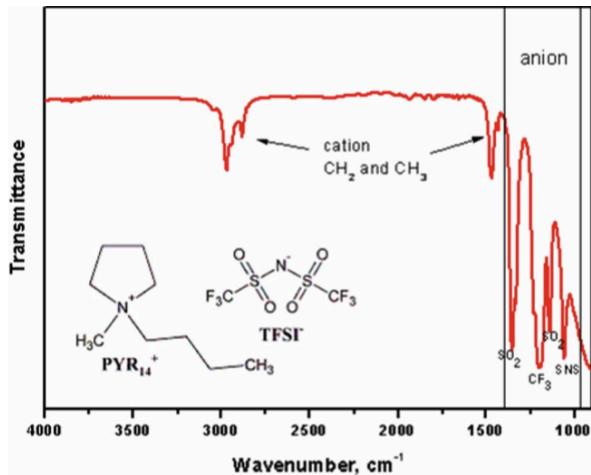


Figure 1: Normalized Fourier Transform Infrared Spectroscopy (FTIR) for PYR14 (ionic liquid)

with characteristic peaks noted. (Mozhzhukhina, Nataliia, et al. 2017)

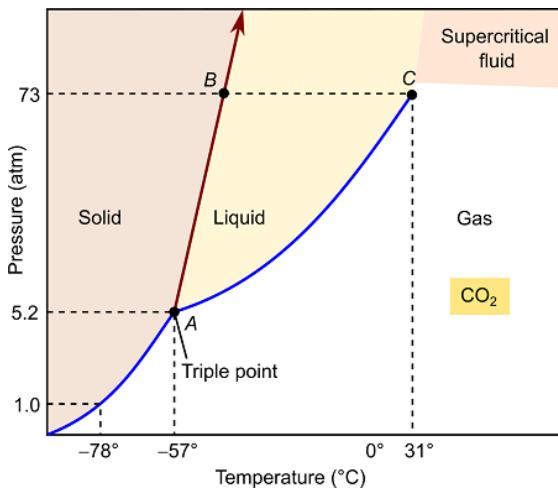


Figure 2: Diagram depicting a phase diagram for CO₂ highlighting the conditions required to obtain a supercritical state.

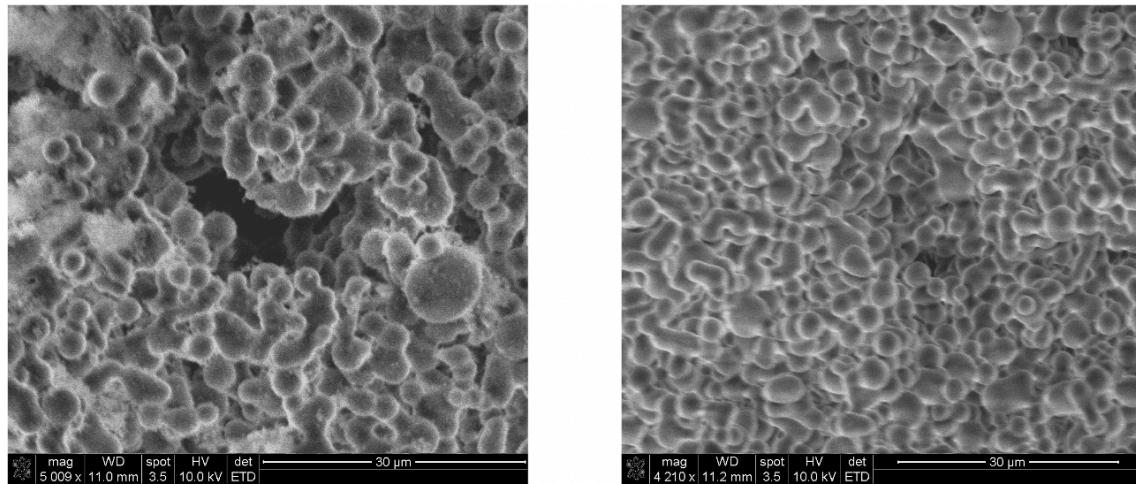


Figure 3: Topview SEM photos of Ionogel at 30 micrometers.

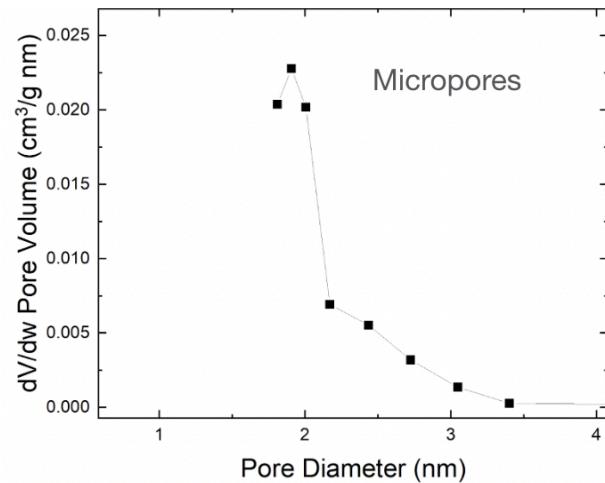


Figure 4: BET Surface area analysis and pore size analysis of Ionogel after supercritical drying.

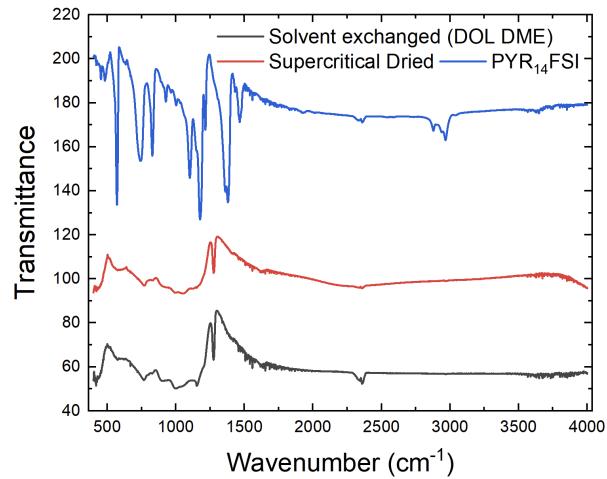


Figure 5: FTIR results for First Stage Ionogel, Supercritical Dried Ionogel, and Solvent Exchanged Ionogel (DOL/DME).

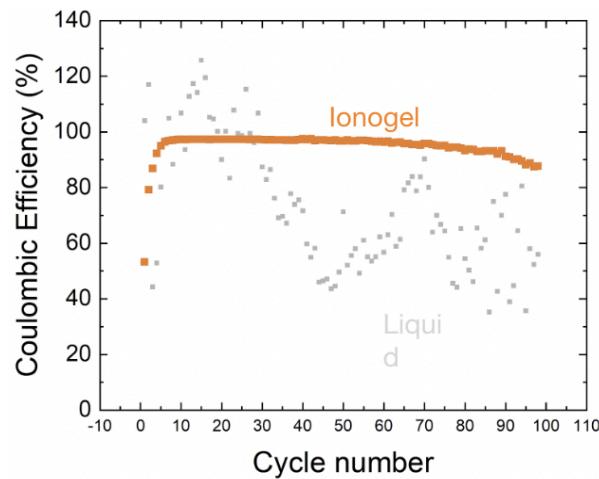


Figure 6: Cycling stability between Ionogel cell and liquid cell.

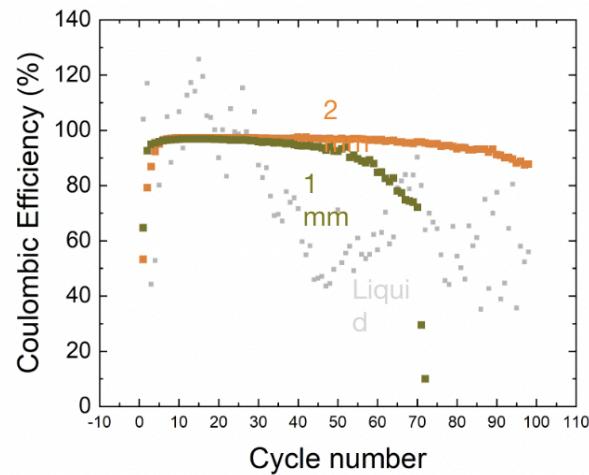


Figure 7: Cycling stability between Ionogel cell at two different thicknesses and a liquid cell.

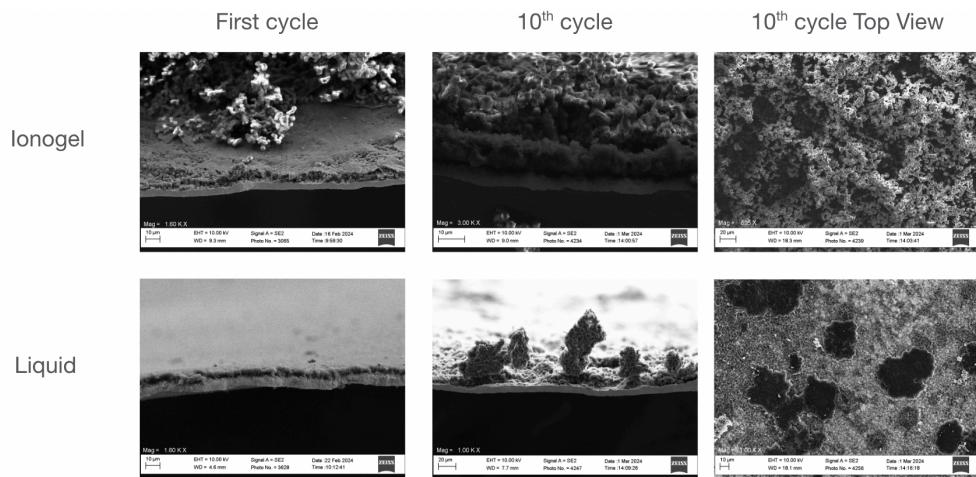


Figure 8: SEM photos of Ionogel versus liquid electrolyte before and after cycling.

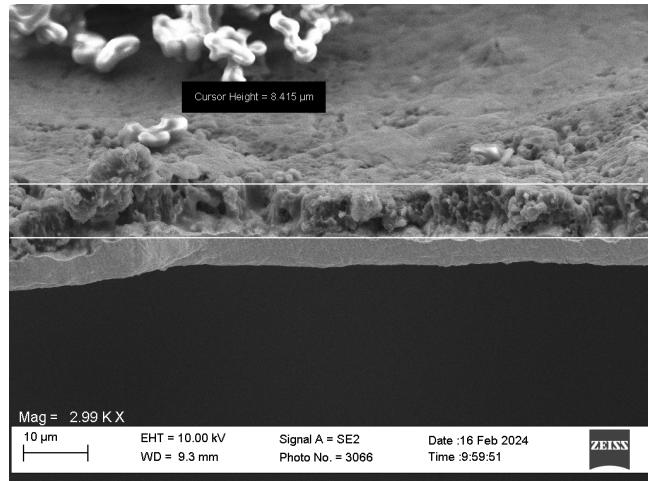


Figure 9: SEM photo of Ionogel highlighting the lithium layer that grows underneath.