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## Improving Electrochemical Devices via Increased Charge Density and Ceramic Nanoparticles

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# **Improving Electrochemical Devices via Increased Charge Density and Ceramic Nanoparticles**



Honors Thesis

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Department: Mechanical Engineering

Advisor: Binod Kumar, Ph.D., Human Rights Center

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## Abstract

Challenges posed by climate change in conjunction with increasing global energy demand necessitate improved energy systems in both transportation and power delivery. These systems will require more advanced energy storage than current commercially available options. To enhance energy storage capabilities, supercapacitors were investigated to discover new mechanisms, materials, and fabrication techniques for developing electrochemical devices. In particular, methods for improving electrolyte performance were explored to enhance capacitance and conductivity. The results indicate that increasing charge density in the electrolyte via higher salt concentration or higher ionic charge of the solvated ions significantly increases capacitance. Specifically, a 0.1M solution of magnesium chloride yielded an average capacitance 12 times higher than sodium chloride in the same concentration at 20° C. In addition, electrolyte conductivity can be improved by adding ceramic nanoparticles (~18nm) in the form of titanium dioxide. In particular, titanium dioxide increases the conductivity of a 0.1M solution of magnesium chloride by over 10%.

## Acknowledgements

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## Background

Inexpensive, plentiful energy in the form of fossil fuels was critical to the social development, progress, and prosperity of the 20th century. However, the 21st century will require advanced energy solutions that can meet growing demand while also addressing the challenge of climate change. Climate change is considered by most scientists to be directly linked to human activity, with the burning of fossil fuel playing the predominant role in triggering global warming (Cook et al., 2014). Fortunately, renewables are projected to generate enough energy to meet future demand (Budischak et al., 2013). However, renewable energy sources cannot easily match energy production with demand due to the intermittent power generation of solar and wind. Thus better energy storage techniques are required to provide steady, reliable power. In addition to large scale energy storage systems, future transportation methods will also require better energy storage, the most obvious example being electric vehicles. Clearly, improving energy storage methods will be critical to a successful, clean energy future. While energy storage systems will employ multiple methods, this work investigates electrical energy storage in the form of supercapacitors due to their unique properties and potential applications in power delivery systems.

Supercapacitors share a similar physical configuration to electrochemical batteries but they possess unique properties that provide opportunities for more versatile power delivery. The high power density of supercapacitors distinguishes them from batteries, meaning they can deliver higher current per unit weight. The high power density of supercapacitors allows for charging and discharging about 100 times faster than conventional batteries (Lu, Pandolfo, Ruiz, Sivakkumar, & Nerkar, 2013). A major disadvantage of supercapacitors is their low energy density, meaning they do not store the same total energy as compared to batteries per unit weight. For this reason, energy storage research typically focuses on batteries with high priority placed on lithium ion technology. However, this work takes a different approach by focusing on the energy storage mechanisms in supercapacitors in order to discover new components and construction techniques for electrical energy storage. Specifically, two ideas were

developed, namely increasing charge density in the electrolyte to increase capacitance and improving electrolyte conductivity via the addition of ceramic nanoparticles.

## Charge Density

Capacitors provide an alternate approach to electrical energy storage in that charge is stored electrostatically rather than the redox mechanisms in batteries. Like traditional capacitors, supercapacitors store energy electrostatically but use an electrolyte to achieve capacitance values around 10,000 times greater than conventional capacitors (Lu et al., 2013). Rather than storing charge on two parallel plates, supercapacitors form an electric double layer, which is essentially the positioning of ions close to the surface of the electrode held in place by an electric field (Kötz & Carlen, 2000). This idea was first described by Helmholtz in 1853 but has been revised to include a diffuse layer of ions as described by Stern (Gao & Béguin, 2013). Figure 1 displays the various models for the electric double layer and shows the relative placement of ions in solution.

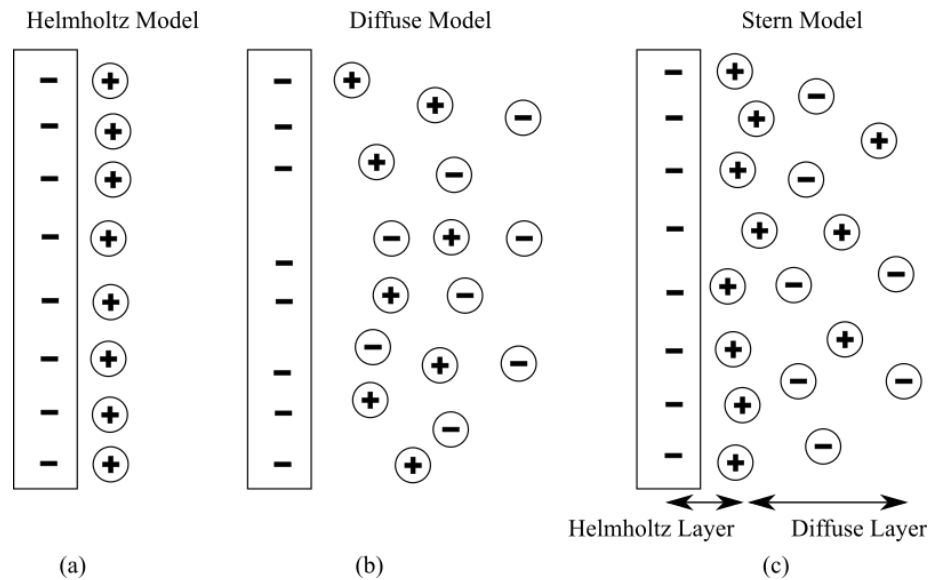


Figure 1: Electric Double Layer Models

The Helmholtz (Figure 1a) and Diffuse (Figure 1b) models combine to form the Stern model, Figure 1c. The overall capacitance of the electric double layer can be calculated by combining the capacitance of each layer in series as demonstrated by equation (1) (Gao & Béguin, 2013).

$$\frac{1}{C_{dl}} = \frac{1}{C_H} + \frac{1}{C_{diff}} \quad (1)$$

Where  $C_H$  is the capacitance due to the Helmholtz model,  $C_{diff}$  is the capacitance due to the diffuse layer, and  $C_{dl}$  is the capacitance of the Stern model (entire double layer). In contrast to the energy storage in supercapacitors, batteries store energy electrochemically via reduction-oxidation reactions between the electrolyte ions and the electrodes. In supercapacitors, high power density is achieved since chemical bonds are not formed between ions of the electrolyte and electrode. Instead energy is stored in the electric field between solvated ions and charges on the electrode, an electrical interaction which can more easily be formed and reversed.

Looking more closely at the construction of the double layer, it is clear that supercapacitor capabilities can be improved by increasing the strength of the electric field between the layer of ions and the electrode. The electric field in this region is due to coulombic attractions between charges, implying that it can be modeled with Coulomb's law by considering the attractive force of one ion in the double layer.

$$F = \frac{kQ_1Q_2}{r^2} \quad (2)$$

The equation for Coulomb's law includes the magnitude of each point charge in coulombs ( $Q_1$  and  $Q_2$ ) the distance between the charges ( $r$ ), and the Coulomb's law constant ( $k$ ). Coulomb's law clearly demonstrates that an increase in charge,  $Q_1$  and  $Q_2$ , will increase the magnitude of the attractive force. However, the equation usually describes the force between two charged particles, typically point charges. In the case of the electric double layer,  $Q_1$  and  $Q_2$  are the charges of the solvated ion and the resulting charge on the electrode. This relationship between the solvated ion and the electrode has been described as the "Image Force" (Donne, 2013, p. 47). The Image Force is described as "the force between a charge and its induced charge. It is always attractive" (Donne, 2013, p. 47). The IF force can be calculated using equation (3):

$$IF = - \frac{(ze)^2}{4\pi\epsilon\epsilon_0(2x)^2} \quad (3)$$

In this equation,  $z$  is the valence of the ion,  $e$  is the elementary charge of an electron in Coulombs,  $x$  is the distance from the ion to the electrode,  $\epsilon$  is the relative permittivity of the electrolyte to free space, and  $\epsilon_0$  is the permittivity of free space. This equation is a different form of Coulomb's law in that it describes the force between a solvated ion and its induced charge on the electrode. Based on this equation, the force between charges,

and consequently the electric field between the layers, can be strengthened by increasing the valence charge of the solvated ions. In other words, increasing the valence charge of the ions in solution should increase the overall charge density of the electrolyte allowing for a greater induced charge on the electrode. The total charge of the electrolyte can be determined by equation (4) (Donne, 2013, p.22).

$$\sigma = n_1 z_1 e + n_2 z_2 e + n_3 z_3 e + \dots + n_i z_i e = \sum n_i z_i e \quad (4)$$

Essentially, this equation is summing the total charge (Coulombs) in a given volume of electrolyte based on the valence charge and quantity of each ion. For example,  $n_1$  represents the number of ions with a valence charge of  $z_1$  where  $e$  is the charge of an electron in coulombs. Using this approach it is clear that higher elementary charge and higher concentration increase charge density. Based on these ideas, it was hypothesized that an increase in charge density should increase capacitance since higher charge in the electrolyte should theoretically induce more charge storage on the electrode. Using equation (4), the two methods for increasing charge density in an electrolyte are (i) increasing the concentration of the electrolyte and (ii) increasing the ionic charge of the charge carriers. Typically, supercapacitors use electrolytes with soluble salts dissolved in a liquid solvent leading to either +1 or +2 ionic charge when the salt is dissociated. This implies that improvements could be made with the addition of salts which yield higher valence ions. This work investigates salts with higher ionic charge and concentration to investigate the relationship between charge density and capacitance.

## Colloidal Particles

Besides investigating electrolyte charge density, charge mobility was also explored as an avenue for improving supercapacitor technology. Supercapacitors, as well as batteries, perform poorly at low temperatures due to the decreased conductivity of electrolytes. Previous work has shown that the addition of ceramic nanoparticles increases the conductivity of liquid electrolytes, especially at sub-ambient temperatures (Kumar & Rodrigues, 2006). They report that ceramic nanoparticles should help facilitate the charge and discharge process by improving ion mobility through a network of ceramic particles. In addition to Kumar's findings, Pfaffenhuber summarizes the same effect but describes the colloidal ceramics as "soggy-sand" electrolytes (Pfaffenhuber, Gobel, Popovic, & Maier, 2013). According to Pfaffenhuber, the colloidal particles offer



high lithium cation conductivity while improving mechanical stability and reducing flammability.

To explain the phenomenon of enhanced conductivity with colloidal particles, it is suggested that the ceramic particles form a space charge region that create pathways for the transport of ions in solution (Kumar, 2004). This region is supposedly due to higher electron concentration on the surface of the ceramic particles due to the presence of oxygen in the ceramic structure. When this negatively charged region interacts with the surrounding electrolyte it creates small “space charge” regions for ions to move through. This idea is illustrated below in Figure 2.

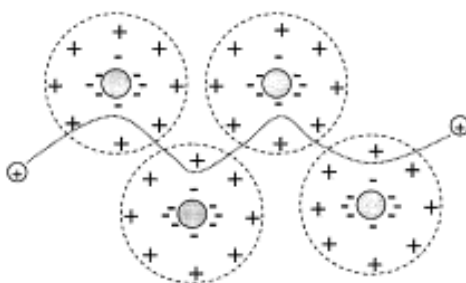


Figure 2: “Space Charge” effect allowing for transport of cations (Kumar, 2004)

Pfaffenhuber describes a similar idea where the ceramic nanoparticle exhibit acidic behavior while interacting with the ions of the electrolyte (Pfaffenhuber et al., 2013). This allows for the absorption of ions on to the ceramic nanoparticles, creating better salt dissociation and conductivity. However, it was observed that in the case of silica nanoparticles, large networks of particles were created since the particles typically coalesce and form aggregate (Pfaffenhuber et al., 2013). Due to the assembly of particles into large networks, the volume fraction of the silica network can become too high thus reducing the available pathways for transport. In other words, ion mobility is physically blocked by the ceramic particles, an idea originally described as the “blocking effect” (Kumar, 2004).

A recent work provides further evidence of improved conductivity with the addition of ceramic particles (Wu et al., 2016). In both Kumar, 2004 and Wu et al., 2016, titania is shown as a viable ceramic nanoparticle for improving conductivity. For this reason, titania was used in this investigation to improve the thermal capabilities of electrolytes thus enhancing performance of supercapacitors.

## Experimental Procedure

This section is divided into two experimental investigations, specifically a quantification of the effects of charge density on capacitance and effects of ceramic nanoparticles on the conductivity of aqueous electrolytes.

### Charge Density Measurement

Two factors impact the charge density of an electrolyte, namely the elementary charge of the solvated ions and the concentration of the ions in solutions. As such, the first experiment aimed to establish the relationship between the charge of solvated ions and capacitance. Three salts with increasing cationic charge were selected in the form of *NaCl*, *MgCl<sub>2</sub>*, and *FeCl<sub>3</sub>*. A 0.1M aqueous solution of each salt was prepared and then placed into a cell with a polyethylene separator. The cell electrodes were composed of stainless steel discs measuring about 7.5 mm in diameter yielding a surface area of about 44 mm<sup>2</sup>. Each salt was tested at -10, 20, and 50° C to determine the relationship between capacitance and temperature.

The testing procedure for each cell included multiple charge and discharge cycles comprised of current vs time measurements. The raw data were processed to yield capacitance as a function of salt concentration and temperature. First, to establish a constant temperature in the cell, it was exposed to the chamber temperature for one hour before applying any charging current or discharge load. Next, the cell was charged by increasing the applied voltage at 5 mV per second up to 1V. Subsequently, it was held at 1 V for five minutes. Similar to the charging process, the cell was discharged while decreasing voltage at 5 mV per second down to 0V. After completing the first discharge, the cell was charged again to 1 V and held for five minutes. Next, the cell was discharged to 0V at a constant current of 1μA per second. This procedure, which includes two charge and discharge cycles, was repeated 8 times at each temperature to ensure that the data were reproducible. After completing testing with aqueous cells, the procedure was repeated using an organic solvent in the form of propylene carbonate to compare results with the aqueous solvent. Furthermore, salt concentration was also varied in the organic solvent samples to determine the relationship between concentration and capacitance. The organic solvent electrolyte included 0.1M, 0.4M, and 0.7M solutions.

## Conductivity of Electrolytes with Ceramic Nanoparticles

Although many different ceramics have shown promise in improving conductivity, nano size titania was selected for all electrolytes in this work. In addition, two electrolytes were investigated, specifically potassium hydroxide and magnesium chloride solutions. To measure conductivity and temperature, a YSI 3100 conductivity meter was used to measure a 50 ml solution of each sample. Initially, a baseline curve was generated from a 0.1M solution of potassium hydroxide and magnesium chloride from  $-5^{\circ}\text{C}$  to  $50^{\circ}\text{C}$ . To generate the curve, the solution was placed in a freezer at  $-10^{\circ}\text{C}$  and then allowed to naturally warm up to room temperature while taking measurements every  $0.5^{\circ}\text{C}$ . Next, the solution was heated to  $50^{\circ}\text{C}$  and naturally cooled down to room temperature while making conductivity and temperature measurements from the probe. This procedure was followed for all samples, including a 1%, 0.5%, and 0.1% by weight of titania in 0.1M potassium hydroxide as well as a 0.5%, 1%, and 2% by weight of titania in 0.1M magnesium chloride.

## Results and Discussion

All of the experimental measurements in this section were conducted and completed by the author. Due to the time and laboratory constraints, measurements were conducted on a small sample size. However, the available data provides reproducible results that help establish certain trends. To verify these trends, further experimentation is advised.

### Charge Density Results

To calculate capacitance the current discharge curve of the cells were integrated to determine the total charge stored when the cell was charged to 1V. The results were averaged at each temperature yielding a typical curve as shown in Figure 3 for the three electrolytes containing sodium chloride, magnesium chloride, and ferric chloride solutes.

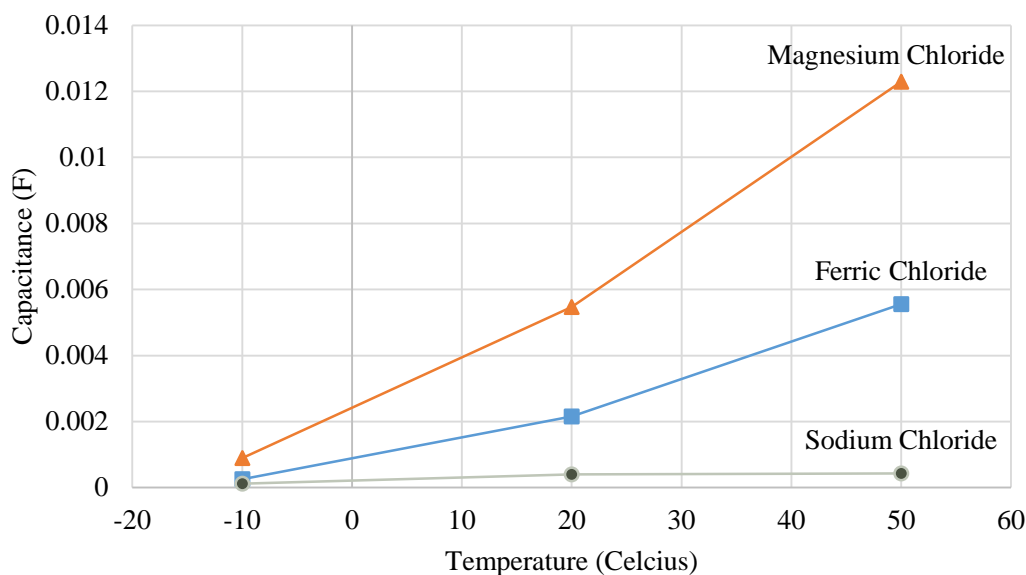


Figure 3: Capacitance of Aqueous Salt Solutions

In Figure 3, the lower, middle and upper curves present the temperature dependent capacitance of sodium chloride, ferric chloride, and magnesium chloride, respectively. It was hypothesized that ferric chloride would perform the best since the higher ionic charge of iron would yield higher charge density and thus greater capacitance. However, magnesium chloride clearly exhibited the highest capacitance at all temperatures, suggesting that other factors may be affecting the overall capacitance of electrolytes containing ferric chloride.

With the sodium chloride curve, it appears that the capacitance remains steady for all temperatures. However, the capacitance of sodium chloride actually triples from  $-10^{\circ}\text{C}$  to  $50^{\circ}\text{C}$ . This indicates that temperature plays a major role in the capacitance values since all solutions were shown to increase capacitance with increasing temperature. The increase in capacitance with temperature for all the salts can be explained on the basis of their dissociation constant as a function of temperature. Salts exhibit greater dissociation at higher temperatures, therefore providing more ionic species to form the double layer. In addition, the two salts with higher ionic charge yielded higher capacitance, indicating that charge density is a factor in improving capacitance, thus supporting the original hypothesis. However, the magnesium chloride unexpectedly yielded higher capacitance than ferric chloride, most likely due to the poor solubility of ferric chloride in water.

With the organic solvent, the results are more closely aligned with the original hypothesis. In this case ferric chloride generated the highest capacitance, especially at higher concentrations. For example, figure 4 displays the median capacitance of ferric chloride at 0.1M, 0.4M, and 0.7M concentration at 20° C. Median values were selected instead of average values since the samples included a scattering of data points.

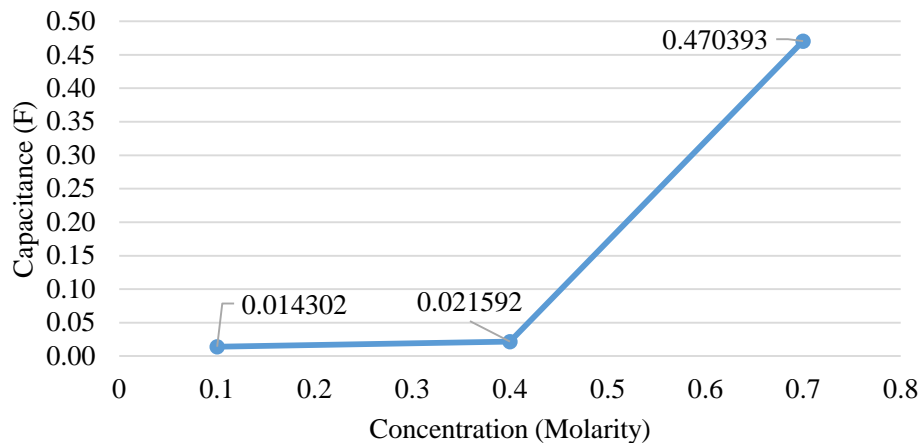


Figure 4: Capacitance vs concentration of Ferric Chloride in organic solvent

Figure 4 supports the original hypothesis in that additional concentration, and thus higher charge density in the electrolyte, increases capacitance. The magnesium chloride results reaffirm this idea where increasing concentration increases capacitance, as demonstrated by Figure 5.

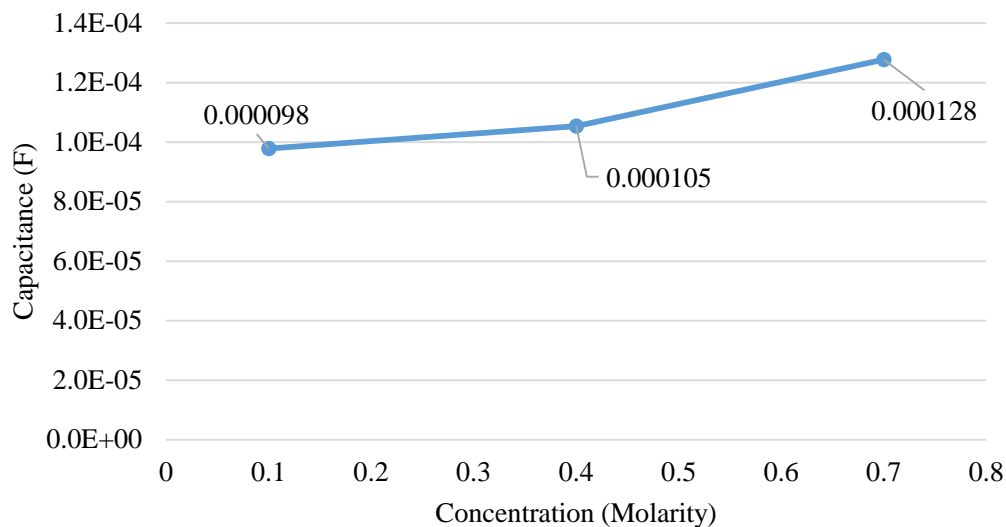
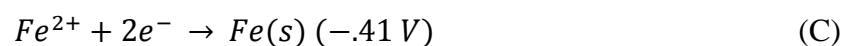
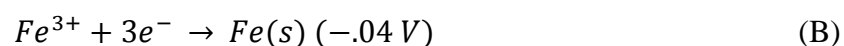
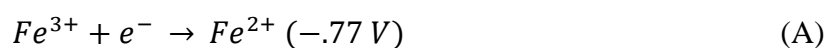


Figure 5: Capacitance vs concentration in Magnesium Chloride solutions

A comparison of Figure 4 and Figure 5 shows the large difference in capacitance between magnesium chloride and ferric chloride. Unlike the aqueous tests, the organic ferric chloride solutions yielded much higher capacitance than magnesium chloride, delivering values over 100 times greater at each concentration. Based on the disproportionate capacitance of the two salt solutions, it appears that the higher valence charge of ferric chloride is a factor in enhancing the capacitance. Overall, the organic solutions supported the original hypotheses in that increased concentration and ionic charge yielded higher capacitance in all cases.

However, when interpreting the data many factors must be considered. First, the capacitance of the 0.7M solution is uncharacteristically high suggesting the data may not be demonstrating purely capacitive behavior. Instead, additional reactions may be contributing to higher charge storage thus skewing the data. For example, the electrodes in the cell are composed of stainless steel providing a surface for iron deposits from the electrolyte. Iron displays the following half reactions when in solution.



Since the cell was charged to 1 V, each of the reactions listed in equations (A) through (C) can occur since they all exhibit a standard potential less than 1 V. Each of these reactions provides additional means of charge storage which is most likely contributing to the high capacitance values of ferric chloride.

Additional evidence of electrochemical reactions is apparent in the discharge curves of the ferric chloride samples. Figure 6 shows a typical constant current (1 $\mu$ A) discharge curve for both a 0.4M ferric chloride solution and 0.4M magnesium chloride solution at 20° C.

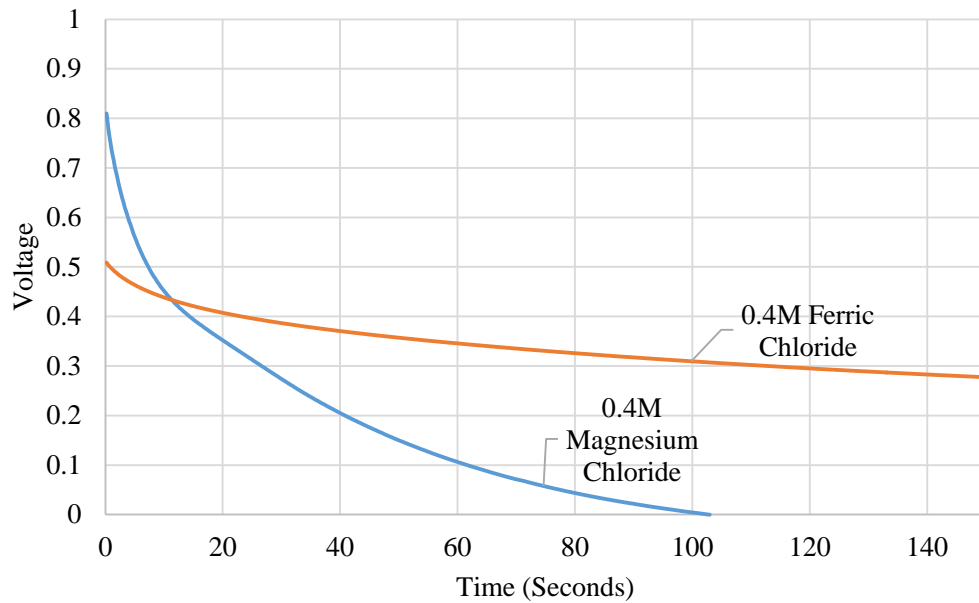


Figure 6: Discharge profiles of 0.4M Magnesium and Ferric Chloride at 20° C

With the magnesium chloride samples, the cell typically drops to less than 0.5 volts when discharge is initiated. After this drop, the cell outputs a gradual discharge indicating the charge was stored electrostatically. However, with the ferric chloride samples the cell dropped about 0.5 volts on average and then shows a nearly constant voltage, a characteristic of electrochemical discharge. For example, Figure 7 shows the entire discharge curve for ferric chloride along with the discharge curve of magnesium chloride.

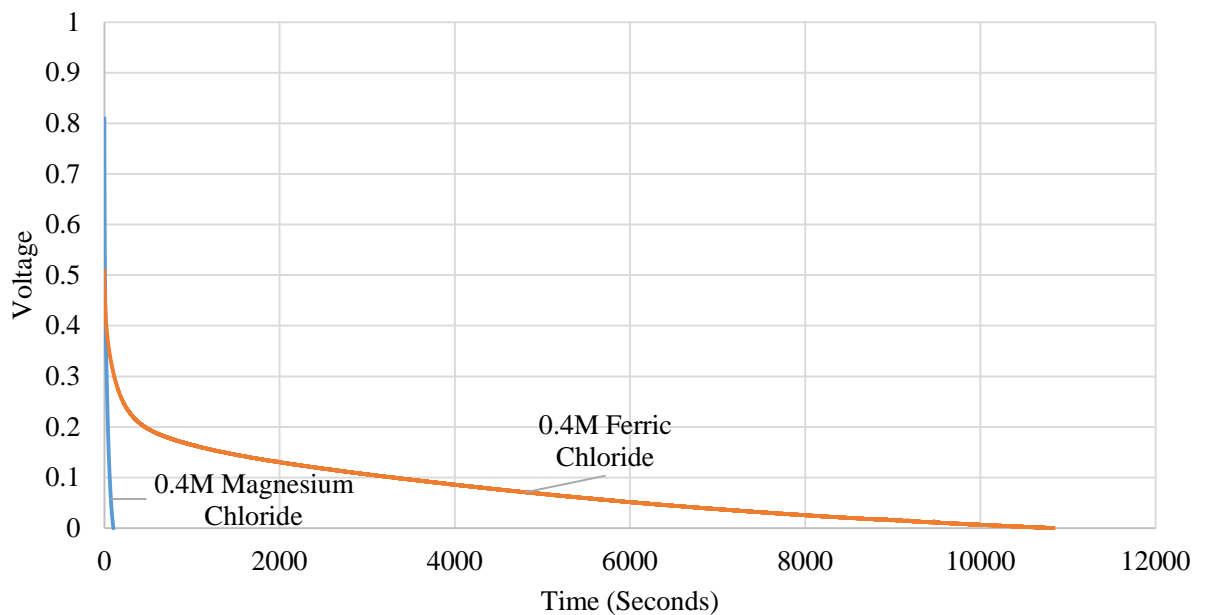
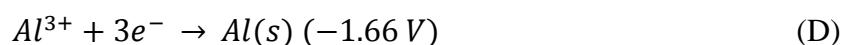


Figure 7: Total Curve of 0.4M Magnesium Chloride and 0.4M Ferric Chloride

In Figure 7, it is clear that a majority of the curve is under 0.2V and follows a nearly exponential shape. This is not typical capacitive behavior indicating the charge storage mechanism in the ferric chloride cell may be a result of an electrochemical reaction. Most likely, a combination of the reactions (A), (B), and (C) are maintaining the nearly linear voltage output under 0.3V.

To confirm that trivalent cations will provide high capacitance, additional testing should be conducted with a different salt such as aluminum chloride since aluminum should maintain its +3 ionic charge when charged to 1V. The half reaction for the oxidation of aluminum is shown in equation (D).



Furthermore, this data only includes one sample for each concentration of the salt solutions. With a small sample size, poor construction of certain cells may lead to incorrect results. For this reason, additional testing is necessary before the relationship between charge density and capacitance can be confirmed.

### Conductivity of Electrolytes with Titania Nanoparticles

Conductivity measurements were first conducted with potassium hydroxide due to its wide acceptance in electrochemical industries. To begin, a baseline curve was obtained for 0.1M potassium hydroxide without titania powder. The resulting curve is shown in Figure 9.

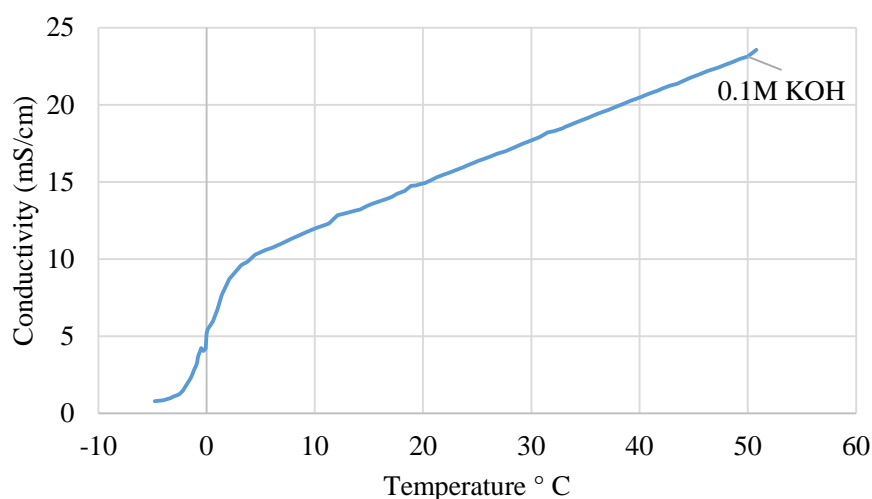


Figure 9: Baseline curve for 0.1M KOH (aq.)



This curve clearly shows the temperature dependence of conductivity, especially around the freezing point of the solution. It appears that conductivity is nearly linear with decreasing temperature until the freezing point of the electrolyte is approached where it drops precipitously. At temperatures less than 3° C, the conductivity again becomes linear and shows a conductivity trend typical of solids.

Subsequently, various amounts of titania were added to the 0.1M solution of potassium hydroxide and compared with the baseline curve. Figure 10 displays the baseline curve compared with a 0.1M KOH solution with 0.1% by weight of titania.

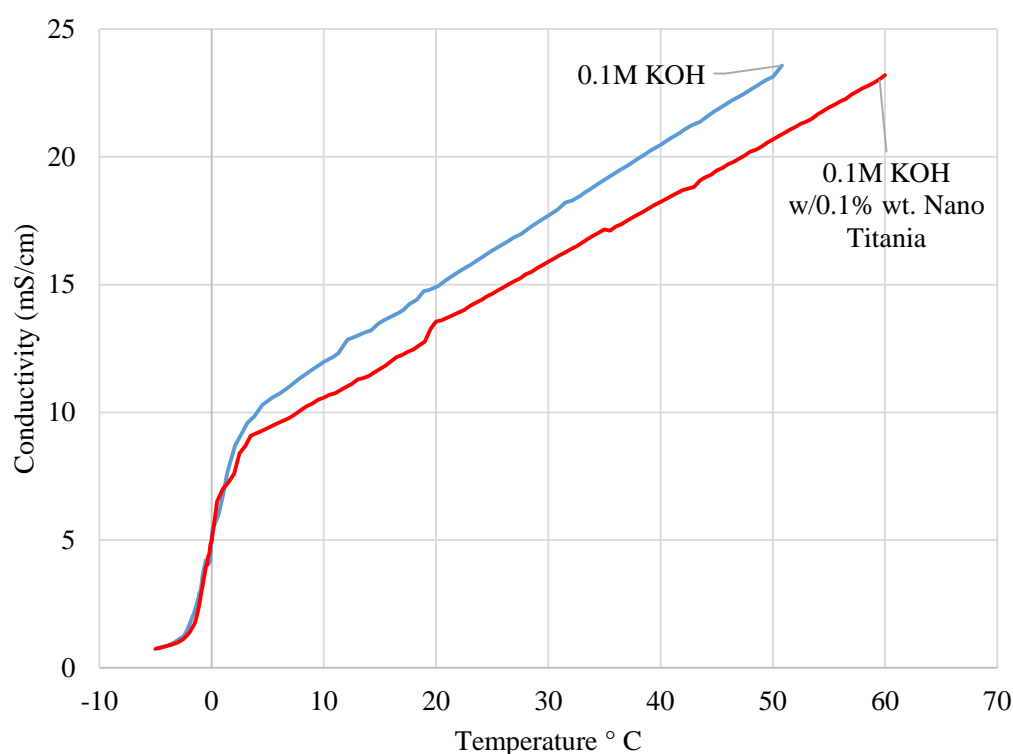


Figure 10: 0.1% wt. Titania in 0.1M KOH (aq.) vs Baseline

Interestingly, the conductivity of the 0.1M KOH solution with titania was less from about 2° C to 50° C but was nearly identical at lower temperatures. If the titania were simply blocking the transport of charges, the conductivity should be less at all temperatures. This indicates that the titania must be improving conductivity at lower temperatures to overcome the blocking effect seen at higher temperatures.

As concentration of the titania increases to 0.5% by weight, the conductivity increases, more closely resembling the baseline curve, as presented in figure 11.

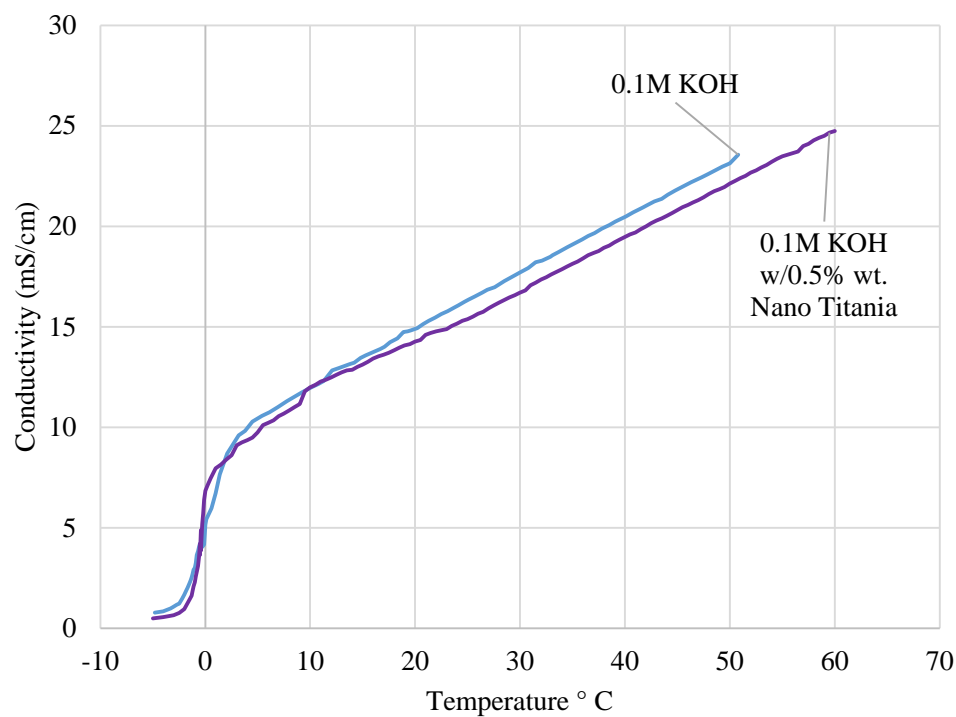


Figure 11: 0.5% wt. Titania in 0.1M KOH (aq.) vs Baseline

In this case, the titania appears to actually improve the conductivity of the KOH electrolyte at lower temperatures, specifically in the 0° C to 5° C range.

However, when concentration is increased to 1% the conductivity is less at all temperatures, Figure 13.

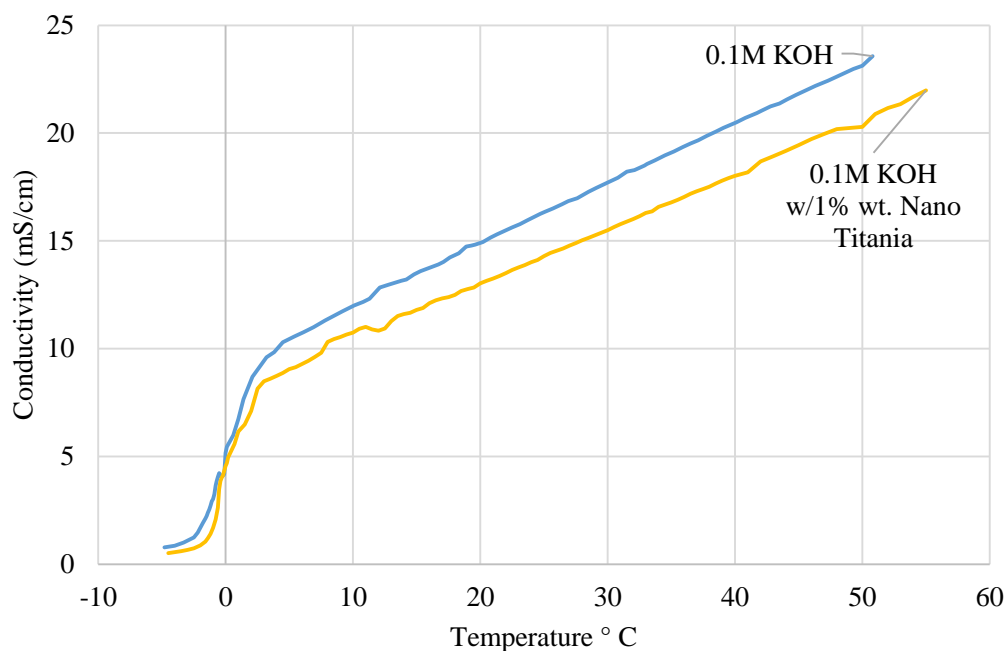


Figure 12: 1% wt. Titania in 0.1M KOH (aq.)

As shown in Figure 12, the blocking effect becomes too great at concentrations reaching 1% by weight of titania in 0.1M KOH, thus reducing the overall conductivity most notably at higher temperatures above 5° C.

To explore the effects of titania on electrolytes of other salts, magnesium chloride was selected for the subsequent series of tests. Following the same procedure, a baseline conductivity curve for a 0.1M solution of magnesium chloride was obtained. The magnesium chloride curve, like the potassium hydroxide electrolyte, demonstrates nearly linear behavior above 5° C but significantly drops around the freezing point of the solution, Figure 13.

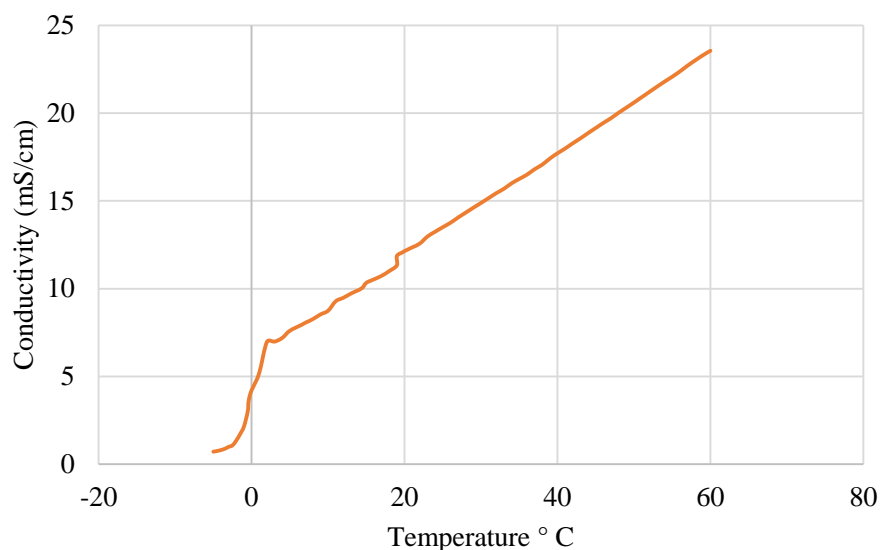


Figure 13: Baseline curve for 0.1M Magnesium Chloride

Subsequently, various amounts of titania were added to the 0.1M magnesium chloride solution and compared with the baseline curve for conductivity. Figure 14 displays the baseline curve compared with a 0.1M solution of magnesium chloride with 0.5% by weight of titania.

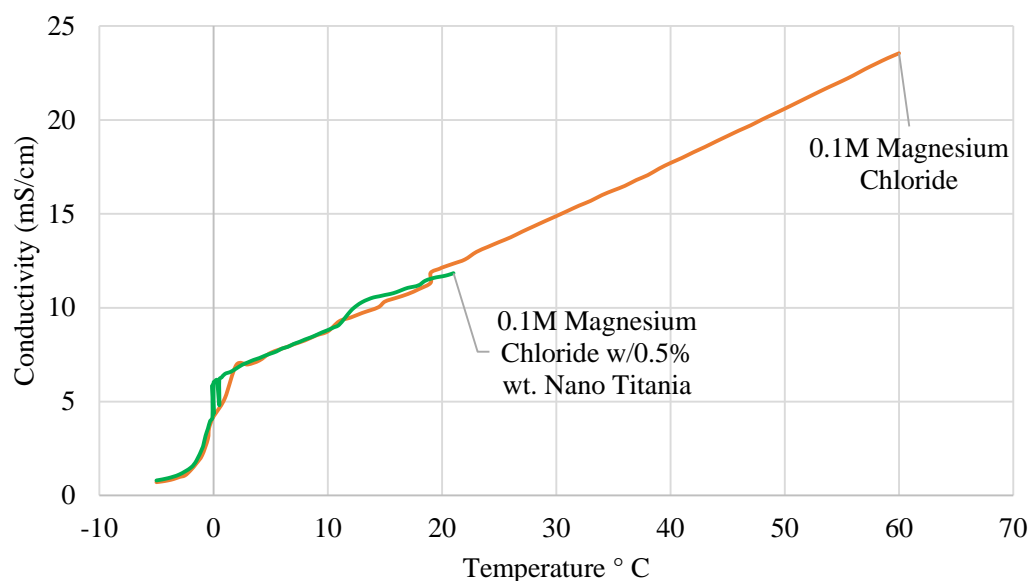


Figure 14: 0.5% by wt. titania in 0.1M Magnesium Chloride

Unlike potassium hydroxide, the magnesium chloride electrolyte did not show a significant decrease in conductivity when titania was introduced. This observation

suggests that the titania is improving conductivity to the extent that it overcomes the blocking effect.

With the 1% by weight solution, the conductivity is actually improved at all temperatures as demonstrated by figure 15.

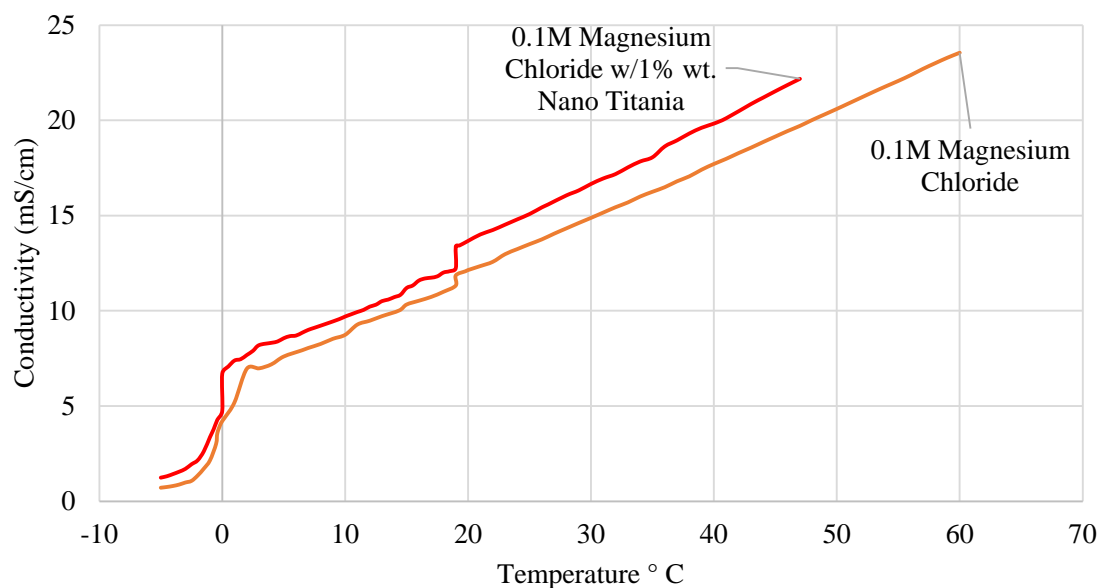


Figure 15: 1% by wt. titania in 0.1M Magnesium Chloride (aq.)

These results are particularly interesting because they demonstrate an improvement in conductivity across all temperatures in an aqueous solution. It is possible that the higher ionic charge (2+) of the magnesium ion is more conductive towards space charge mediated transport as described by Kumar (Kumar, 2004).

In the case of magnesium chloride, the 2% titania solution yielded slightly lower conductivity as shown in Figure 16.

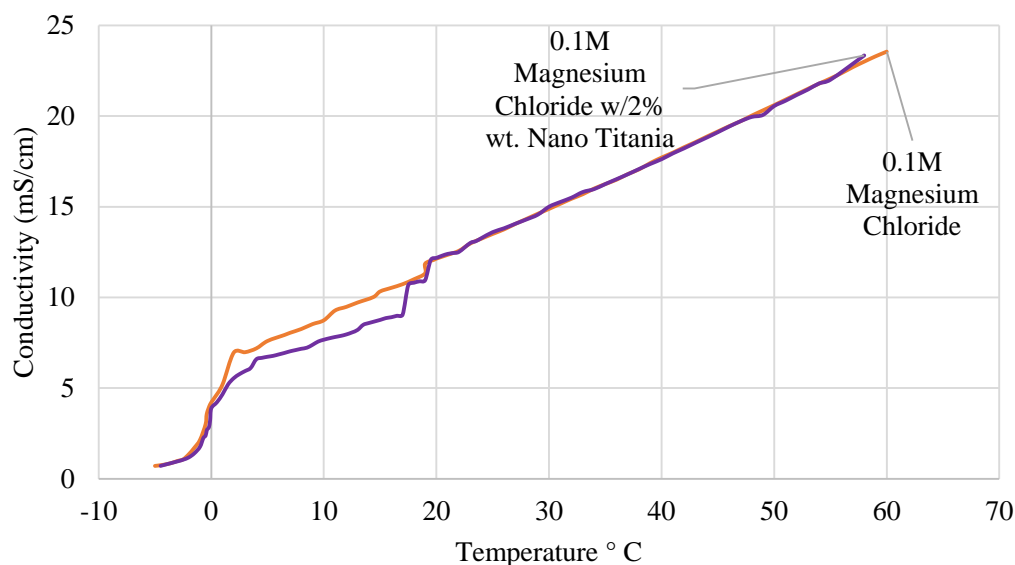


Figure 16: 2% by wt. titania in 0.1M Magnesium Chloride

While this is a small sample size, the data indicate that conductivity of titania doped electrolytes can be improved in aqueous solutions of magnesium chloride. This is significant considering previous work with ceramic nanoparticles usually involves more expensive and flammable organic electrolytes.

When interpreting the conductivity data, certain characteristics must be considered. First, the sudden jump in temperature around 18° C is a result of thermal hysteresis. This is an effect where the recorded value lags behind the actual physical property. For this reason the conductivity curves are slightly different when heating or cooling the sample. In other words, the data from -5° C to about 18° C was collected while the frozen specimen was heated whereas the data from 18° C to 50° C was collected while the solution was cooled. With this method, the heated curve and the cooling curve did not match around 18° C as one should expect. However, this jump is consistent throughout the experimental measurements of ceramic nanosize particle containing electrolytes, indicating that each sample can still be compared. Besides the effects of hysteresis, the data may also be affected by buildup of nanosize ceramic materials on the conductivity probe. Testing completed after the magnesium chloride tests using a different powder tended to show decreasing conductivity with each test, regardless of powder concentration. While the additional particles buildup most likely did

not affect the earlier tests, it is important to note the observation in later tests for scientific accuracy.

Additional conductivity measurements were also conducted with different titania powders. For example, a micro size titania powder was used in early tests but tended to yield poor conductivity results. For this reason, nano size titania powder is most likely the best candidate for improving conductivity. Specifically, the samples presented in this work used powder with an average size of 18 nm. While 18 nm is not a requirement for improved conductivity, powders around this size will likely perform best since they provide a large surface area for space charge effects to occur. Besides powder size, optimal powder concentration is likely different for each electrolyte. For example, the potassium hydroxide electrolyte yielded the highest conductivity with 0.5% by weight of titania whereas magnesium chloride performed best with 1% by weight. This suggests that in order to attain improved conductivity with ceramic nanoparticles, the electrolyte may need to be optimized where different concentrations of ceramic nanoparticles are tested until the desired conductivity is achieved.

## Applications

The results of this investigation have important implications in the development of supercapacitor and battery technology. Specifically, capacitance may be improved with the addition of salts such as magnesium chloride. The high charge density of magnesium chloride electrolytes paired with the high surface area of activated carbon or graphene electrodes will yield more energy dense supercapacitors. These supercapacitors could be used in applications like electric vehicles and consumer electronics to provide greater power density than current electrochemical methods of energy storage. Furthermore, the improvement in capacitance was observed in both aqueous and organic solvents indicating that the addition of salts can be applied to many types of solvents. In addition to improvements to supercapacitors, batteries could also utilize high charge density electrolytes to exhibit pseudo-capacitive behavior (Frackowiak, 2013). In other words, fast charging could be achieved via electrostatic charge storage while high capacity is still maintained via oxidation reduction reactions. To achieve pseudo-capacitive characteristics the cell would initially store charge electrostatically by forming

a double layer on the electrodes. However, an increase in charge voltage would trigger oxidation reduction reactions at the electrode, thus storing energy electrochemically.

In the case of ceramic nanoparticles, potential applications may be even broader than the use of magnesium chloride or similar salts. If conductivity is improved via the addition of ceramic nanoparticles, many applications for these electrolytes would emerge. For example, batteries and supercapacitors would exhibit higher efficiency and better mechanical properties. Additionally, ceramic nanoparticles may improve performance at low temperatures as well as safety associated with dangerous solvents. Specifically, flammability is reduced, a key concern with many organic solvents.

## Conclusion

Overall, the experimental investigations explored two objectives. First, capacitance was improved with the addition of salts, especially at higher concentrations. In particular magnesium chloride was shown to be a viable additive for improving capacitance in supercapacitors. This effect is due to an increase in charge density within the electrolyte that generates a higher induced charge in the electrode. Additional testing, specifically with high surface area electrodes such as carbon should be carried out to confirm these observations. Second, the addition of ceramic nanoparticles appears to increase the conductivity of electrolytes at certain concentrations. The ceramic nanoparticle tests support earlier observations made by Kumar et. al. (Kumar, 2004) and Pfaffenhuber (Pfaffenhuber, Gobel, Popovic, & Maier, 2013) suggesting that further exploration of ceramics in electrolytes should be carried out.



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