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Synthesis, characterization, and electrochemical observation of PVC-supported strontium tungstate inorganic precipitated composite membrane

Mohd Arsalan[a], Shahla Imteyaz[a], Mohd Zeeshan[b], Rafiuddin[a,*]

[a]*Membrane Research Laboratory, Department of Chemistry, AMU, Aligarh 202002, India, emails: mohdarsalan.chem@gmail.com (M. Arsalan), shahlaimteyaz18@gmail.com (S. Imteyaz), Tel. +91 571 2703515; Fax: +91 9760229165; email: rafi_amu@yahoomail.co.in (Rafiuddin)*
[b]*Analytical and Polymer Research Laboratory, Department of Applied Chemistry, AMU, Aligarh 202002, India, email: mohd.zee2010@gmail.com (M. Zeeshan)*

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ABSTRACT

PVC-supported strontium tungstate composite membrane was prepared by the cast die frame of membrane preparation. The strontium tungstate material was qualitatively synthesized by sol-gel method of material synthesis. The membrane was characterized by SEM, XRD, FTIR, and simultaneous TGA/DTA studies. These characterizations demonstrated the material nature, functional groups, surface texture, porosity, thermal stability, ion-exchange property etc. The electrochemical properties have been studied by TMS theoretical approach which easily determines the important parameters of membranes like transport number, mobility ratio, charge density, charge effectiveness etc. The theoretical and observed electrolyte potential calculations get the values of charge density. The observed ionic potential and graphical fixed-charge density of both the membranes follows $CaCl_2 < MgCl_2 < BeCl_2$ and $CaCl_2 > MgCl_2 > BeCl_2$ order, respectively.

Keywords: PVC-supported strontium tungstate composite material; Thermal and chemical stabilities; TMS theoretical equation; Observed potential and surface charge density; $CaCl_2$, $MgCl_2$, and $BeCl_2$

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1. Introduction

The composite membranes have been designed by a uniform mixing of both the used organic and inorganic materials through an important cast die method. The inorganic materials of membrane like metal phosphate, tungstate, and arsenate have been easily synthesized by the qualitative sol-gel method of material synthesis. Nowadays, such type of hybrid materials indicate the prime outlook for intensive research, through which they merge in a single solid with much smart properties of used organic plus inorganic materials. Such composites are also used to modify the characteristics of organic and inorganic materials that show very different property from their original component [1–4].

The inorganic materials are very important due to their thermal stability and ion-exchange property, whereas the organic polymers have indicated much flexibility and mechanical stability [5]. The combined characteristic of fused materials shows various applications which attract great attention in the field

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*Corresponding author.

of material, medicinal, biological, and separation sciences. Such type of excellent materials have been synthesized and designed successfully into the form of an ion-exchange membrane, used in many separation and purification processes and electrodialysis for brackish water desalination [6–8]. Due to their multipurpose nature, such membranes have found applications in foods, drugs, chemical industries, and in wastewater treatments. It is also being used in many other processes like fuel cell, power generation, energy saving, electrodialysis, membrane electrolysis, electro deionization etc. [9,10].

In this experiment, PVC-supported strontium tungstate composite membrane has been prepared by the homogenous mixing of organic and inorganic materials. It has been noticed that the concerned material shows mechanical stability, chemical stability, good ion-exchange capacity (IEC), electrochemical property, and unique selectivity for heavy toxic metals and electrolyte ions [11–13]. In order to measure chemical stability, the examined membrane should not be affected by extreme pH solutions. The electrochemical observation depends on the physical characteristic of membrane parameters like porosity, thickness, water absorption, transportation, IEC, thermal plus chemical stabilities etc. [14,15].

The electrochemical observations are studied by observing the potential across the membrane and this is the most effective and simple method used to examine the transport of electrolyte solutions as well as ions. It is theoretically calculated by Teorell, Meyer and Sievers (TMS) [16–18], Khan and Rafiuddin [19], Arsalan and Rafiuddin [20,21] as well as the most new one is Beg et al. and Nagarale et al. [22,23]. In this study, TMS approach which is based on Donnan equilibrium and Nernst Planck equation has been used and the experimental and theoretical values of the potential has been compared and electrochemical parameters of the membrane like surface charge density, transport number, mobility ratio, charge effectiveness etc. have been calculated by using the method [24]. Therefore, the parameters of membrane determined the nature and environmental application of membrane [25].

2. Experimental

2.1. Materials, reagents, and instruments

Solutions of Be^{2+}, Mg^{2+}, and Ca^{2+} chlorides of different concentrations were made. 0.2 M Na_2WO_4 and $SrCl_2$ solutions of 99.90% of purity were prepared to make the $SrWO_4$ precipitated material. All these reagents were of analytical grade and double distilled water was used to prepare the solutions. Polyvinyl chloride (PVC) in the powder form of 200 mesh size was used.

Scanning electron microscopy (SEM) by "Leo-4352", Fourier transform infrared (FTIR) by "Interspec-2020" FTIR-Spectrometer", X-ray diffraction (XRD) by "Miniflex-II X-ray Diffractometer", thermogravimetric analysis/differential thermal analysis (TGA/DTA) by "Shimadzu DTG-60H", were done for the characterizations of the material and potentiometer by "Electronic India-118" with SCE as reference electrode were used for the measurement of the potential across the membrane [14].

2.2. Synthesis of strontium tungstate material

Strontium tungstate has been synthesized by the sol-gel method of material synthesis. First, 0.2 M Na_2WO_4 and $SrCl_2$ solutions were prepared separately in 100 ml distilled water and then the solutions were mixed with each other. The steady mixing of the solution gives a fine precipitation, while the mixing with heating process gets a fine and homogenous precipitation of the solution. The mixing of solution along with a maintained pH has been completed after vaporizing the water which changes the solution into strontium tungstate gel material. The water present in the material can easily be evaporated by the heating process and it is also separated by using Whatman filter paper. The important criterion is that the mixing of the solution should be homogenous and uniform. After this process, the gel material was placed into an oven for 2–3 h at 100°C temperature [26,27]. Material was then made into powder form by pestle and mortar of about 200 mesh.

2.3. Ion-exchange capacity

The IEC of composite material was evaluated by titration method in which the material was first treated with HNO_3 for 24 h and then it was washed 3–4 times by double distilled water. Thereafter, about 1 gm of material was filled into the buret for the titration with 0.1 M $NaNO_3$ solution which resulted in H^+ release by Na^+ ions in an ion-exchange reaction. The collected effluent was further titrated with 0.1 M NaOH solution and 3–4 drops of phenolphthalein was mixed into the collected effluent which was used as an indicator. NaOH was passed into the effluent until the color of it has turned into pink which gave the reading of consumed NaOH. The IEC of the material was determined with the help of the following equation IEC = volume of consumed NaOH × molarity of NaOH/weight of dried material [28].

2.4. Design the membrane through cast die method

A qualitative IEM has been designed by a homogenous mixing of organic and inorganic materials in a particular ratio. This ratio of materials may be 1:1, 1:2, and 1:3. The mixing must be done cautiously and homogeneously until the binders get totally mixed with inorganic materials. Then, the composite mixture of organic polymer with inorganic tungstate material was transformed into a cast die of 2.45 cm diameter. This was then kept in a furnace by maintaining 200˚C temperature to equilibrate the reaction mixture. Thereafter, a pressure of 100 MPa was applied using a pressure device of "SL-89 UK" which results a good membrane fabrication. 1:3 ratios of binder and inorganic materials have given the best mechanical and morphological stability to the membrane. If it is exceeded or lowered from the above-mentioned ratio, it never shows the same stability and functions. Now this membrane has been subjected to microscopic observations to see the cracks and homogeneity on its surface. Finally, the potential of the prepared membrane was measured using different electrolyte solutions, and various electrochemical parameters including charge density were calculated [29].

2.5. Chemical stability of membrane

By "ASTM D543–95" procedure the morphological changes in the membrane, where the alteration in color, texture, brightness, decomposition, splits holes, bubbles, curving, and stickiness have been carefully observed.

2.6. Electrochemical observation

The electrical potentials of electrolyte solutions across the synthesized membrane were measured by using the digital potentiometer. The electrolyte solutions of $CaCl_2$, $MgCl_2$, and $BeCl_2$ have been used to obtain the potential which were prepared by double distilled water. It was observed by saturated calomel electrodes dipped into one of the collared chamber of the glass cell having different concentrated electrolyte solutions. The membrane has incubated at the center of a two-chambered glass cell having 35 ml capacity. The temperature preferred for the best potential observation was maintained in the range of 25–28˚C. The charged property of membrane affects the potentiometer response due to unequal concentration of ions like Ca^{2+}, Mg^{2+}, and Be^{2+}. The setup used for electrochemical potential measurement is shown by Fig. 1 [14,15].

3. Characterization

In order to judge the performance of a membrane, the complete physicochemical characterization have been done and these includes the determination of parameters like membrane thickness, diameter, percentage of water content, porosity, swelling etc. These influence the electrochemical properties of membrane [20,21].

3.1. Diameter, thickness, and swelling of membrane

By using screw gauze, the diameter, thickness, and swelling of membranes were calculated. The swelling

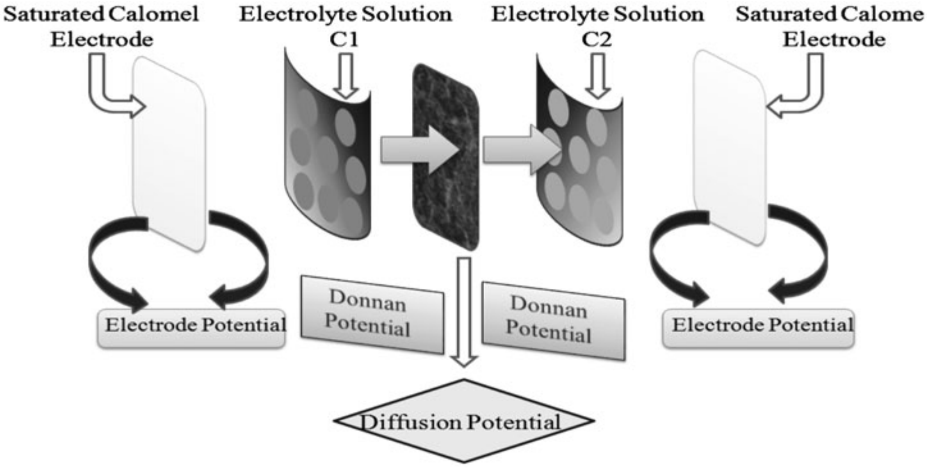

Fig. 1. Electrochemical setup for ionic potential measurement.

of membrane has been measured by taking the difference between average thickness of membrane that has equilibrated in 1 M NaCl solution and the dry membrane.

3.2. Water absorption percentage

The water absorption or percentage of water in membrane is measured by the following equation:

$$\text{Water absorption}\,(\%) \;=\left[\frac{W_{\text{wet}}-W_{\text{dry}}}{W_{\text{dry}}}\right]\times 100 \qquad (1)$$

W_{wet} is the weight of swollen membrane which is obtained by soaking in above salt solutions for 5 h, and W_{dry} is the weight of dry membrane.

3.3. Membrane porosity

The porosity of membrane is calculated very easily through using the following equation:

$$\text{Porosity}\,(\%) \;=\left[\frac{W_{\text{w}}-W_{\text{d}}}{AL_{\rho\text{w}}}\right]\times 100 \qquad (2)$$

where A = area of membrane, L = thickness, and ρw = density of water.

3.4. SEM analysis

SEM is a type of electron microscopy that produces images of a sample by scanning it with a focused beam of electrons. This technique is used to identify the morphology, topography, surface defects, and inclusions etc. SEM characterization was performed at an accelerating voltage of 20 kV. The sample was mounted on a copper stub and sputter coated with gold to minimize the charging.

3.5. XRD analysis

XRD is a technique used for identifying the atomic and molecular structure of a crystal, in which the crystalline atoms cause a beam of incident X-rays to diffract into many directions. By using this technique, the mean positions of the atoms in the crystal can be determined, as well as their chemical bonds, their disorder, and various other information also.

3.6. FTIR analysis

By FTIR spectrum, the chemical structure, existence of hydrogen, or covalent bonding between the phases as well as the present functional groups of composite material has been easily characterized.

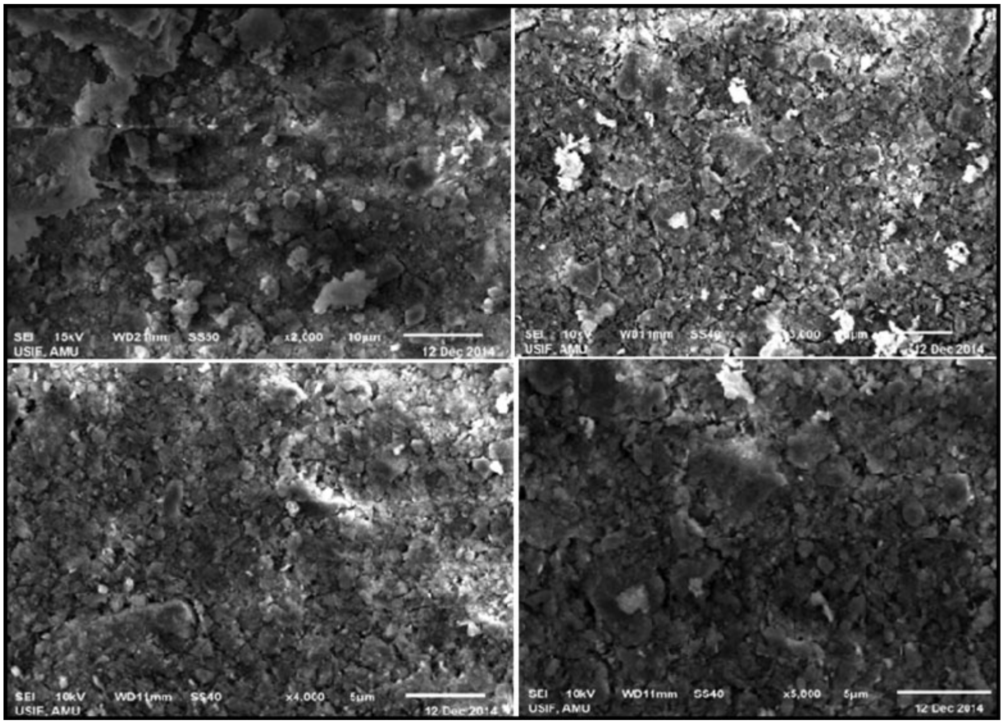

Fig. 2. SEM images at different magnifications of PVC-supported strontium tungstate composite membrane.

3.7. TGA/DTA analysis

TGA/DTA analyzes the rate of weight change either as a function of increasing temperature or time. At the same time, it can also determine the endothermic or exothermic behavior of used material.

4. Result and discussion

The SEM images of PVC-supported strontium tungstate composite membrane are shown by Fig. 2. Through which it is clear that the mixing of organic and inorganic materials has been very uniform, which results to show a porous surface texture of the membrane. The SEM images show neither any visible breakage nor cracks on the surface of the membrane, which prove the excellent binding nature of PVC with strontium tungstate material [30]. The FT-IR spectrum of PVC-supported strontium tungstate composite material is indicated by Fig. 3 which shows the presence of different functional groups in composite material. The small peaks at the range of 1,630.39 cm^{-1} and at about 3,435.22 cm^{-1} are assigned to –OH– bending and stretching vibrations, respectively, while 2,927.22 have detecting the NH$_2$ group of used ammonia gas. The absorption peaks at about 410.46 cm^{-1}, 472.10, and 562.52 cm^{-1} are attributed to O–P–O and O=P–O bending vibration as well as the peak at about 1,093.67 cm^{-1} is due to the P–O stretching vibration of phosphate group. The peak at more than 1,200 is attributed to the bending bond of C–H near Cl. The C–C stretch bond of the PVC backbone chain occurs in a range of 808.49–1,000 cm^{-1} [31].

The XRD spectra of PVC-based strontium tungstate composite material is indicated by Fig. 4 which shows intense peaks of different intensity at different values of 2θ range. All high and less intense peaks are found from the range of 20–80˚ values which indicated the examined compound corresponds to some planes at different ranges. This analysis indicated that the PVC-based strontium tungstate composite material has crystalline nature [32].

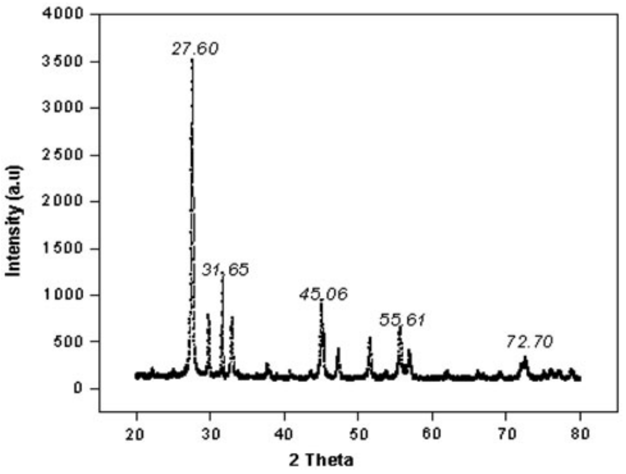

Fig. 4. XRD spectra of PVC-supported strontium tungstate composite material.

Thermogravimetric graphical analysis is represented by Fig. 5, which confirmed the degradation process of PVC-based strontium tungstate composite material at different temperature ranges. It shows only one time near about 0.411 mg of (6.610%) weight loss up to 600˚C, whereas the above weight loss has been measured by the midpoint of 59.84˚C. So it is clear that the increase of temperature leads to slight weight loss by materials. Therefore, it is clear that the material has some hydrophilic nature that could absorb moisture from the surrounding atmosphere.

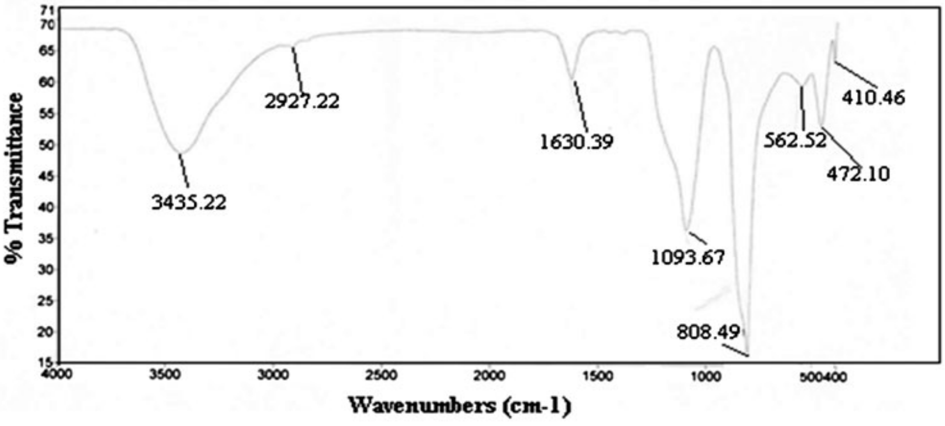

Fig. 3. FTIR Spectra of PVC-supported strontium tungstate composite material.

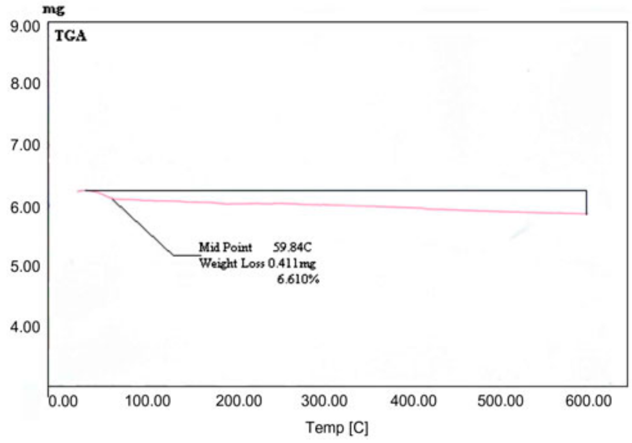

Fig. 5. TGA spectra of PVC-supported strontium tungstate composite material.

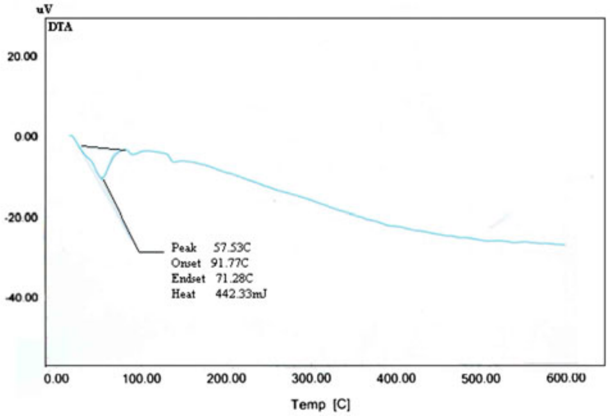

Fig. 6. DTA spectra of PVC-supported strontium tungstate composite material.

There is also DTA curve which shows by Fig. 6 has indicated only one time temperature reduction at 57.53–71.28˚C of (442.33 mJ). The PVC-based strontium tungstate composite material shows only one time downwards curve. It indicates that the used composite material of membrane has weight deduction at the temperature increment up to 600.00 that shows the endothermic characteristic of material which means that the heat changes must be there by deducing the temperature [33].

The chemical stability which has been done by "ASTM D543–95" method through which the prepared membrane was tested in 1 M acidic, basic, and alkaline solutions. The observation indicated that with the passing of time from 36 to 48 h, the membrane has become weak due to the solutions of harsh pH range. So, it is clear that the membrane becomes exhaustive in such solutions either by passing more time or increasing the concentration of solutions which results to get loses their mechanical stability. Therefore, one of the exclusive features of membranes is that it must have high thermal and chemical stability [34].

The diameter, porosity, water content percentage, and swelling of membrane are represented in Table 1. The membrane produced ionic potential due to their charges as well as unequal concentrations of electrolyte solutions. Through these characteristics, it transforms cations from higher to lower concentration and adsorb the respective anions on their surface. The cations are affecting the potentiometric response whereas anions do not influence as such. Therefore, the positive potential is observed and it obeys Nernst equation. The observed potential data represented by Table 2 and also by graph Fig. 7 indicate that the

Table 2
The observed potential as well as surface charge density of PVC-supported ST composite membrane in contact with various 2:2 electrolyte solutions of different concentrations at 25 ± 1˚C

Applied pressure 160 (MPa) Conc. (mol/L)	Observed potential (mV)		
	$CaCl_2$	$NaCl_2$	Be Cl_2
1	9.0	12.5	17.5
1×10^{-1}	13.3	16.7	21.5
1×10^{-2}	18.6	23.6	29.3
1×10^{-3}	24.9	31.7	36.4
1×10^{-4}	31.5	38.6	47.9
1×10^{-5}	36.5	42.3	53.2
Charge Densities ($D \times 10^{-3}$ eq/L)	2.12	1.80	1.64

Table 1
Thickness, diameter, water content property, porosity, and swelling properties of PVC-supported ST composite membrane

Applied Pressure (Mpa)	Diameter (cm)	Thickness of membrane (cm)	Water content as % weight of wet membrane	Porosity	Swelling of % wet membrane
160	2.45	0.0580	0.046	0.0016	No swelling

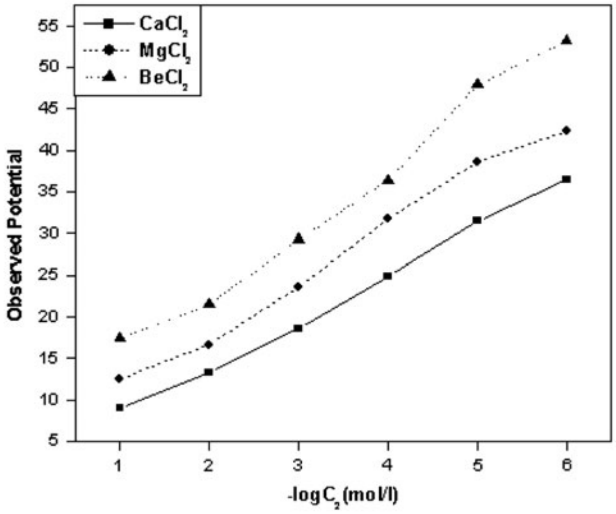

Fig. 7. Plots of observed potentials against logarithm of concentration for PVC-supported strontium tungstate composite membrane.

potential readings are directly increased by reducing the concentrations of electrolyte solutions which suggest that the membrane is negatively charged and cation selective. The ion selectivity is created due to charged surface of membrane and it shows more flourished property in high concentrated solutions over the diluted one [35].

In all membranes, the most important electrochemical property is the differences in permeability of co-ions, counter ions, and neutral molecules. Membrane charge is very essential to generate the ionic potential which depends on their pore sizes. If pores are broad, a lot of charges are required to generate potential while in narrow porous membrane, it shows an opposite behavior. The electrochemical studies can’t be completed without evaluating the thermodynamically effective fixed charge density of membrane. By graphical representation, it has obtained through the coinciding point which shows in the combined graphical image of dark and broken line represented in Fig. 8. The values of charge density show $D \leq 1$ which depends on the initial stage of material preparation and in this experimental observation it follows $CaCl_2 > MgCl_2 > BeCl_2$ order due to the sizes of electrolytes [36].

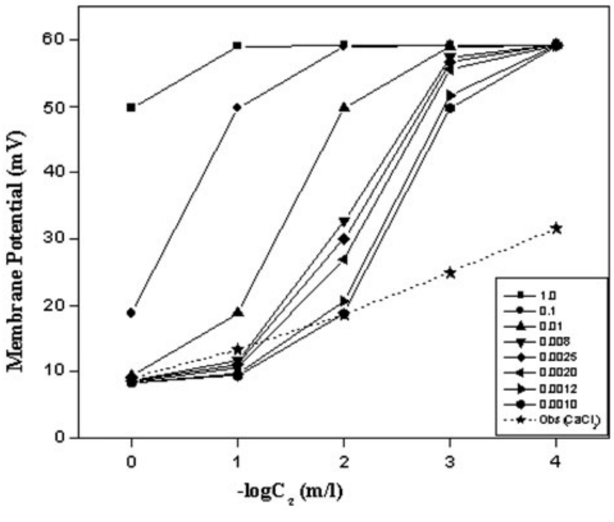

Fig. 8. Plots of theoretical and observed membrane potential against logarithm of concentration of KCl electrolyte for PVC-supported strontium tungstate composite membrane.

5. Teorell, Meyer, and Sievers

The electrochemical studies of composite membrane have been done by using TMS method which is very applicable and important. There must be an equilibrium development at both the interfaces of solution and membrane which has a suitable connection with the Donnan equilibrium. The assumptions made by the above discussions are as follows [37]:

1. It is found that the transference of water from either side of the membrane may ignore which indicated that it has not affecting the potentiometer response.
2. The ionic movements as well as the concentration of fixed charges are constant throughout the membrane matrix.
3. It is also independent on salt concentrations, while the activity coefficient is similar in both the solution as well as membrane phase.
4. It is found that there must be an equilibrium development at all the solution and membrane interfaces which have the proper similarity with Donnan equilibrium.
5. It stated that the activities of salt concentrations can only be agreed through Donnan potential either by using the Planck’s or Henderson equation.

The electrochemical setup shows two Donnan potentials at all the solution and membrane interfaces, whereas the membrane arise diffusion potential due to their charge property and unequal salt concentrations. The equilibrium development at interfaces has the proper similarity with Donnan equilibrium which results that there must be an internal salt diffusion potential is represented by Henderson and Planck expression. By the observation, it is clear that the TMS method is more applicable in high concentration range, but in low concentrated solutions it shows much deviation between the observed and calculated potential values [38].

TMS equation for obtaining the calculated potential is described as follows:

$$\delta\Psi_{\mathrm{m}} = 59.2\left(\log\frac{C_2\sqrt{4C_1^2 + D^2} + D}{C_1\sqrt{4C_2^2 + D^2} + D} + \bar{U}\log\frac{\sqrt{4C_2^2 + D^2 + UD}}{\sqrt{4C_1^2 + D^2 + UD}}\right) \tag{3}$$

where

$$\bar{U} = \bar{u} - \bar{v}/\bar{u} + \bar{v}$$

$\bar{u}$ and $\bar{v}$ are cationic and anionic mobilities, respectively, C_1 and C_2 are the solution concentrations of chamber 1 and 2 and D is charge density of membrane. Eq. (3) can also expressed by adding the Donnan and diffusion potentials

$$\Delta\Psi\mathrm{me} = \Delta\Psi_{\mathrm{don}} + \Delta\Psi_{\mathrm{diff}} \tag{4}$$

$$\Delta\psi_{\mathrm{don}} = -\frac{RT}{V_{\mathrm{k}}T}\ln\left(\frac{\gamma_{2\pm}C_2C_{1+}}{\gamma_{1\pm}C_1C_{2+}}\right) \tag{5}$$

F, R, and T have their standard meanings, $\gamma_{1\pm}$ and $\gamma_{2\pm}$ are mean ionic activity coefficients and C_{1+}, C_{2+} are cation concentrations on chamber 1 and 2.

$$C_{+} = \sqrt{\left(\frac{V_{\mathrm{x}}D}{2V_{\mathrm{k}}}\right)^2 + \left(\frac{\gamma_{\pm}C}{q}\right)^2} - \frac{V_{\mathrm{x}}D}{2V_{\mathrm{k}}} \tag{6}$$

V_{k} and V_{x} is valiancy of cations and fixed charge groups on the membrane, respectively, and q is the charge effectiveness of membrane.

$$q = \sqrt{\frac{\gamma_{\pm}}{K_{\pm}}} \tag{7}$$

Here $K\pm$ is distribution coefficient which is expressed as:

$$K_{\pm} = \frac{\bar{C}_i}{C_i},\ \bar{C}_i = C_i - D \tag{8}$$

$\bar{C}_i$ and C_i is the i^{th} ion concentration in membrane as well as external ionic solutions. The diffusion potential is predicted as:

$$\delta\psi_{\mathrm{diff}} = -\frac{RT\bar{\omega} - 1}{V_{\mathrm{k}}F\bar{\omega} + 1} \times \ln\left(\frac{(\bar{\omega} + 1)C_{2+} + (V_{\mathrm{x}}/V_{\mathrm{k}})D}{(\bar{\omega} + 1)C_{1+} + (V_{\mathrm{x}}/V_{\mathrm{k}})D}\right) \tag{9}$$

$\bar{\omega} = \bar{u}/\bar{v}$ is mobility ratio of cations to anions through membrane.

Therefore, the membrane potential can easily be obtained through addition of the Eqs. (5) and (9).

$$\delta\psi_{\mathrm{m}} = -\frac{RT}{V_{\mathrm{k}}T}\ln\left(\frac{\gamma_{2\pm}C_2C_{1+}}{\gamma_{1\pm}C_1C_{2+}}\right) - \frac{RT\bar{\omega} - 1}{V_{\mathrm{k}}F\bar{\omega} + 1} \times \ln\left(\frac{(\bar{\omega} + 1)C_{2+} + (V_{\mathrm{x}}/V_{\mathrm{k}})D}{(\bar{\omega} + 1)C_{1+} + (V_{\mathrm{x}}/V_{\mathrm{k}})D}\right) \tag{10}$$

$$\delta\psi^{\mathrm{m}} = \frac{RT}{F}(t_{+} + t_{-})\ \ln\frac{C_2}{C_1} \tag{11}$$

where

$$\frac{t_{+}}{t_{-}} = \frac{\bar{u}}{\bar{v}} \tag{12}$$

From the Eqs. (11) and (12), the values of t_{+} and $\bar{\omega}$ can easily be obtained. For satisfying the applicability of TMS equation, the diffusion and Donnan potential may be calculated separately by the observed potential data. The equation characters like $\gamma_{1\pm}$, $\gamma_{2\pm}$, C_{1+}, C_{2+}, $\bar{\omega}$, V_{x}, V_{k}, and $\gamma_{\pm}$ have their usual meanings. Experimental observation has indicated that higher transport numbers always follow the higher mobility ratio and it increases by decreasing the concentration of solutions. So it has indicated by Figs. 9 and 10 that the

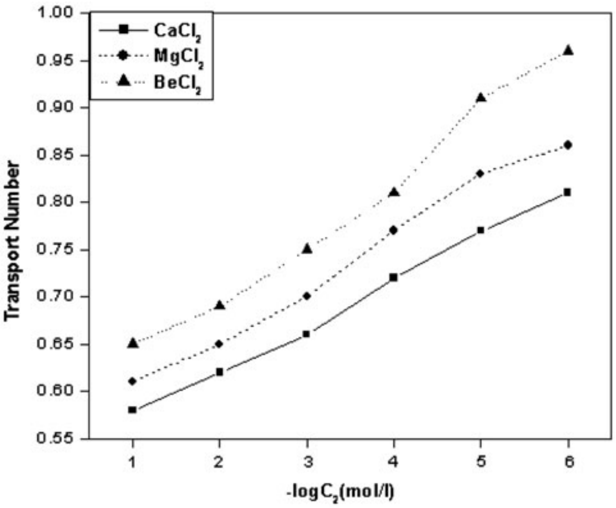

Fig. 9. Plots of transport number against logarithm of concentration for PVC-supported strontium tungstate composite membrane.

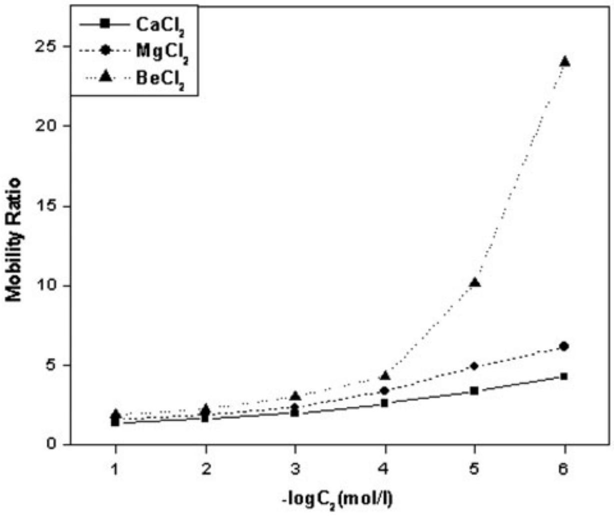

Fig. 10. Plots of mobility ratio against logarithm of concentration for PVC-supported strontium tungstate composite membrane.

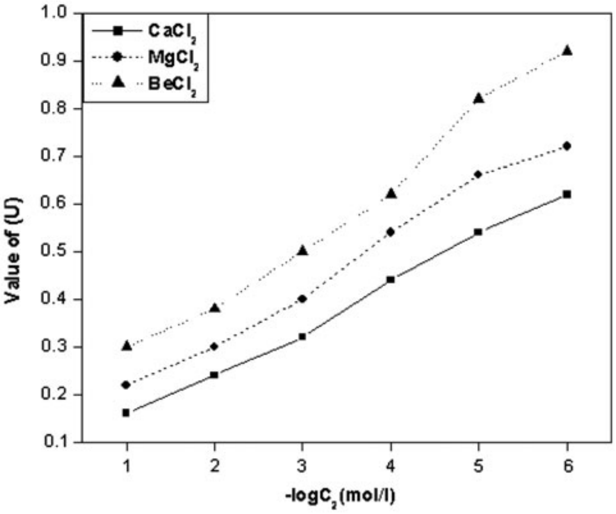

Fig. 11. Plots of (U) value against logarithm of concentration for PVC-supported strontium tungstate composite membrane.

transport number and mobility ratio, respectively, follows the $BeCl_2 > MgCl_2 > CaCl_2$ order. The important distribution coefficient also decreases by increasing the concentration of solutions and the graph is represented by Fig. 11. The most important property that is charge density of membrane is calculated by the Eqs. (5) and (9) and the values of charge density has also presented by the above Table 2 [39,40].

6. Conclusion

The PVC-based strontium tungstate prepared composite membrane shows mechanical, thermal, and chemical stabilities due to the good interaction of inorganic material with PVC. The inorganic material has been synthesized by sol-gel method of material synthesis. By studying the IEC, the composite material was found to be cation selective. The structural characterization of the synthesized membrane gives information about membrane thickness, porosity, diameter, water incorporation etc. The TMS theoretical calculations agreed well with the experimental observations and the charge density were calculated. The observed potential and charge density of some divalent electrolytes follows the order $CaCl_2 < MgCl_2 < BeCl_2$ and $CaCl_2 > MgCl_2 > BeCl_2$, respectively.

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Nomenclature

AR — analytical reagent
C_1, C_2 — concentrations of solutions on either side of the membrane (mol/L)
C_{2+} — cation concentration in membrane phase 2 (mol/L)
C_i — i^{th} ion concentration of external solution (mol/L)
$\bar{C}_i$ — i^{th} ion concentration in membrane phase (mol/L)
D — charge density in membrane (eq/L)
F — Faraday constant (C/mol)
100 MPa — pressure (MPa)
Q — charge effectiveness of the membrane
R — gas constant (J/K/mol)
SCE — saturated calomel electrode
TMS — Teorell, Meyer, and Sievers
t_+ — transport number of cation
t_- — transport number of anion
$\bar{u}$ — mobility of cations in the membrane phase (m^2/v/s)
$\bar{v}$ — mobility of anions in the membrane phase (m^2/v/s)
V_k — valency of cation
V_x — valency of fixed-charge group
$\bar{U}$ — $\bar{U} = (\bar{u} - \bar{v})/(\bar{u} + \bar{v})$

Greek symbols

$\gamma_{\pm}$ — mean ionic activity coefficients
$\bar{\omega}$ — mobility ratio
$\delta\psi_{m}$ — observed membrane potential (mV)
$\delta\psi_{m}$ — theoretical membrane potential (mV)
$\delta\psi_{Don}$ — Donnan potential (mV)
$\delta\psi_{diff}$ — diffusion potential (mV)

Abbreviations

SEM — scanning electron microscopy
XRD — X-ray diffraction
FTIR — Fourier transforms infra red spectroscopy
TGA — thermogravimetric analysis
DTA — differential thermal analysis
PVC — polyvinyl chloride
IEM — ion-exchange membrane

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