



Quaternized poly(methyl methacrylate-co-butyl acrylate-co-vinylbenzyl chloride) membrane for alkaline fuel cells

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ABSTRACT

Instead of modification of pre-existing polymers, a new route of preparation of polyelectrolyte OH⁻ conductive membranes via copolymerization of selected functional monomers was reported in this study. A random copolymer of poly(methyl methacrylate-co-butyl acrylate-co-vinylbenzyl chloride) was synthesized via copolymerization, which was followed by quaternization and membrane casting. The intrinsic OH⁻ conductivity of the free-standing polyelectrolyte membranes can reach $8.2 \times 10^{-3} \text{ S cm}^{-1}$ at 80 °C. The alkaline fuel cells using copolymer polyelectrolytes demonstrated the feasibility of the preparation concept of these membranes.

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1. Introduction

Alkaline fuel cell (AFC) research has recently made a noticeable comeback from a proton exchange membrane fuel cell (PEMFC) dominant era. Despite the promises, lack of fruition of practical proton exchange membranes (PEMs) that is more cost-efficient than Nafion, is stirring renewed interest in AFC. AFC has already been proven as an important, usable fuel cell system with several intrinsic advantages over PEMFC: the activation loss is lower in alkaline medium [1], oxidant reduction kinetics is faster [2] and non-noble metal catalysts can be used [3]. However, the downfall of AFC, which eventually caused the shift to PEMFC, was the required use of liquid alkaline electrolytes. The alkaline solution electrolyte, which typically is highly concentrated KOH aqueous solution, can react with CO₂ to form carbonate salts that quickly contaminate the catalysts, causing the fuel cell to cease functioning. The CO₂ can come from the oxidant, such as air, or from the oxidation of hydrocarbon fuels, such as methanol. This problem must be solved in order to boost the widespread application of AFC. One possible solution is to replace the alkaline solution with a cation-free OH⁻ conducting solid polymer alkaline electrolyte membrane (AEM).

Early AEM research mainly focused on using polymer membranes as a solid matrix to hold alkaline solution. Hydrophilic polymers, such as poly(ethylene oxide) (PEO) [4–7], chitosan [8–11], polyvinyl alcohol (PVA) and polyacrylamide (PAA) or their copolymers [12–18], have been used to absorb the alkaline solution, and these polymers were generally cross-linked to obtain the required mechanical properties. However, these polymer membranes are not cation-free OH⁻ conductive, since they would not work without alkaline solution. Therefore, recent AEM studies have focused more on quaternizable polymers, which are categorized by containing chloromethyl groups that can be quaternized by tertiary amines. The quaternization of chloromethyl groups will result in dissociated Cl⁻ ions that can be replaced by OH⁻ ions through ion exchange to obtain an intrinsically OH⁻ conductive polymer. Some polymer AEMs were prepared via quaternization following chloromethylation of polymers containing phenyl structures on the backbone chains, such as polyethersulfone (PES) [19], poly(phthalazinone ether sulfone ketone) (PPESK) [20], polysulfone (PS) [21] and poly(2,6-dimethyl-1,4-phenylene oxide) (PPO) [22]. Other polymer AEMs were obtained via quaternization of polymers containing vinylbenzyl chloride (VBC) units. Varcoe et al. have carried out numerous investigations on grafting VBC monomers onto fluorinated polyethylene chains through γ -ray radiation, followed by quaternization [23–31].

The current methods for preparation of the aforementioned solid polymer AEMs mainly focus on modifications of pre-existing polymers. A disadvantage of this method is that it is difficult to achieve a balance between OH⁻ conductivity and mechanical prop-

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erties. For instance, every repeating unit on a PS polymer chain can be chloromethylized so that the entire PS polymer chain is consequently quaternized. The degree of quaternization can only be coarsely controlled by reaction time with the tertiary amines. If the degree of quaternization is high, despite high OH⁻ conductivity, the obtained polymer may suffer poor mechanical properties in an aqueous environment due to the strong hydrophilicity from the high degree of quaternization. Therefore, the authors report a new route to prepare polymer AEMs via polymerization of selected functional monomers. Using this procedure, OH⁻ conductivity and mechanical properties can be balanced by varying the ratio of supporting chain monomers to OH⁻ conducting monomers.

In this study, polymer AEMs based on a copolymer of methyl methacrylate (MMA), butyl acrylate (BA) and VBC, namely poly(methyl methacrylate-co-butyl acrylate-co-vinylbenzyl chloride) (PMBV), was synthesized through free radical copolymerization. Polymerized VBC can be quaternized to provide the OH⁻ conductivity because of its chloromethyl group. The quaternized VBC portion is expected to be hydrophilic and lack of mechanical strength in the aqueous environment. Therefore, polymer chain portion with good mechanical strength must be incorporated to balance the OH⁻ conductivity and mechanical properties. MMA was chosen to provide this function. Because both VBC and MMA polymers are in glassy state in ambient temperature, BA polymer which is a rubbery polymer in ambient temperature was also used in the copolymer to alleviate the brittleness so that the PMBV copolymer can retain the toughness and flexibility even after quaternization, and in the aqueous environment. Three different monomer ratios were used for the copolymerization to demonstrate the effect of monomer ratio on the OH⁻ conductivity and mechanical properties.

2. Experimental

2.1. Copolymerization

2.1.1. Materials

MMA (99%), BA (99%) and VBC (97%) were all purchased from Sigma–Aldrich. Monomers were passed through an inhibitor remover (Sigma–Aldrich) column before copolymerization. Initiator, 2,2'-azobis(2-methylpropionitrile) (AIBN) was purchased from Sigma–Aldrich and used as received. Toluene was purchased from VWR and used as received as the solvent for the copolymerization.

2.1.2. Synthesis

Three different molar ratios of monomers (MMA:BA:VBC = 50:40:10, 53:40:7 and 55:40:5) were used in copolymerization. A representative copolymerization process is as follows (for MMA:BA:VBC = 50:40:10): monomers (MMA: 0.15 mol, BA: 0.12 mol, VBC: 0.03 mol) were blended in 50 mL of toluene and put into a three-neck round bottom flask. The reactants mixture was heated using an oil bath, and vigorous stirring was provided by a magnetic stir bar. 5×10^{-4} mol AIBN was added when the temperature reached 50 °C to start the copolymerization. The reactants were kept in a nitrogen environment throughout the reaction, and a condenser was used to prevent evaporation. The reaction lasted 36 h and was stopped by quenching the flask in an ice water bath. After evaporation of solvent and unreacted monomers in the hood for 24 h, the copolymer was dried in a vacuum oven at 50 °C for another 24 h. Scheme 1 demonstrates the synthesis methodology of PMBV.

2.1.3. Characterization

Gel permeation chromatography (GPC, Waters 2410 Refractive Index Detector, Polymer Labs mixed-bed columns) using tetrahydrofuran (THF) as the carrier was used to determine the molecular weight (MW) and molecular weight distribution

(polydispersity index, PDI) of PMBV. Five standard polystyrene samples (Easical® from Polymer Laboratories) with different MWs (7.5×10^6 , 8.417×10^5 , 1.48×10^5 , 2.85×10^4 and 2930 g mol^{-1}) were used as the reference for GPC analysis. The GPC spectra of polystyrene standards were fitted using a third-order polynomial equation which was used to extrapolate the MWs of the obtained PMBV copolymers. Proton nuclear magnetic resonance (¹H NMR, Bruker DRX-400 high resolution) was used to determine the composition of the obtained PMBV using D-chloroform as the solvent. The NMR results revealed the actual VBC composition in the copolymer rather than the monomer in the reactants mixture. Differential scanning calorimetry (DSC, TA Instruments Q100) was used to determine the glass transition temperature (T_g) of PMBV. The heat-cool-heat procedure was applied between 120 and -20 °C at a rate of 10 °C min⁻¹.

2.2. AEM preparation and characterization

The obtained PMBV was dissolved in dimethylformamide (DMF) and quaternized through reaction with trimethylamine (Me₃N, Sigma–Aldrich) for 8 h at room temperature (Scheme 2). The quaternized PMBV (QPMBV) solution was then casted into a membrane on a leveled smooth surface and dried in the fume hood for 24 h and then in the vacuum oven at 60 °C for an additional 24 h. Fig. 1 shows a picture of as-prepared QPMBV membrane. All as-prepared membranes have uniform thickness around 120 μm. The obtained membrane was soaked in 6 M KOH solution overnight to exchange Cl⁻ to OH⁻. The OH⁻ exchanged QPMBV membrane was washed with de-ionized water until a pH of 7 was reached.

2.2.1. Mechanical property

The mechanical properties of pristine PMBV, dry QPMBV and wet QPMBV membranes were tested using a dynamic mechanical analyzer (DMA, TA Instruments Q800) by tensile tests at room temperature. The stretch rate was 1 N min⁻¹. Water uptake percentage of the wet QPMBV was determined by gravimetric method. The wet QPMBV membranes were first dried on the vacuum oven and then immersed in de-ionized water for 20 min for water uptake test:

$$\text{water uptake} = \frac{M_{\text{wet}} - M_{\text{dry}}}{M_{\text{dry}}} \times 100\% \quad (1)$$

2.2.2. Ion-exchange capacity

The ion-exchange capacity (IEC) of the QPMBV membrane was measured by acid-based back-titration. The dry QPMBV sample was immersed in 6 M KOH solution overnight to exchange into OH⁻ form. After washed with adequate amount of de-ionized water till pH value reaching 7, the sample was soaked in 30 mL of 0.01 M

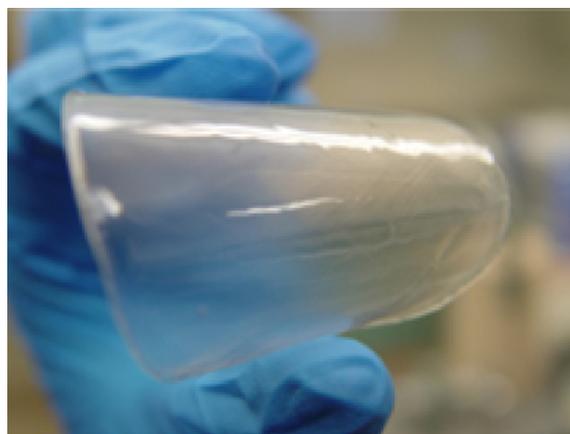
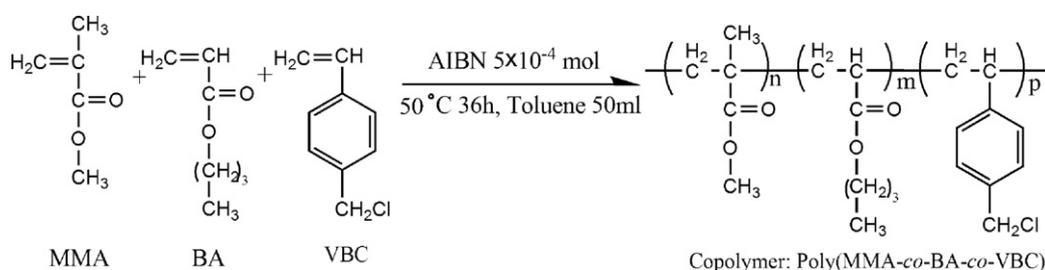
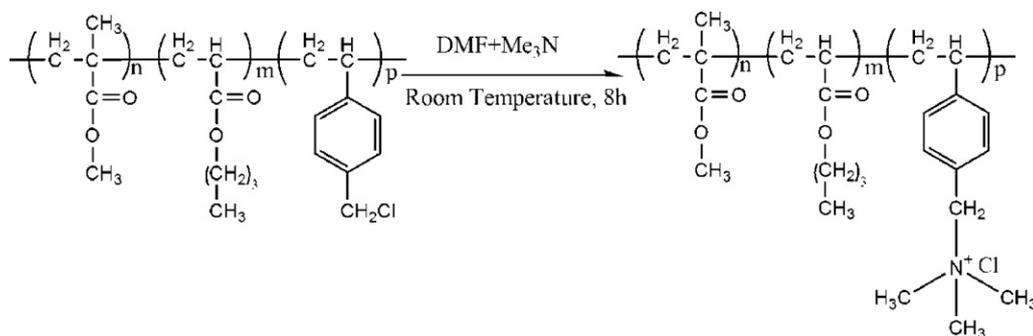


Fig. 1. Representative QPMBV membrane.



Scheme 1. Synthesis of poly (MMA-co-BA-co-VBC).



standardized HCl solution for 1 day to ensure the neutralization of OH⁻ in the membrane. The IEC value was then determined from back-titration of the excess HCl with 0.01 M NaOH solution, which can be calculated by

$$\text{IEC} = \frac{(V_{\text{HCl}} - V_{\text{NaOH}}) \times C}{m_{\text{dry}}} \quad (\text{mmol g}^{-1}) \quad (2)$$

where V_{HCl} is the volume of HCl solution for membrane soaking; V_{NaOH} is the volume of NaOH solution used in back-titration; C is the concentration of HCl and NaOH solutions (0.01 M). m_{dry} is the mass of the dry QPMBV sample.

2.2.3. Anion conductivity

The conductivities of the OH⁻ exchanged QPMBV membranes were measured using electrochemical impedance spectroscopy (EIS) (1287/1260 Solartron) with a standard four-probe conductivity measurement technique. The effects of temperature on conductivity were tested in an environment chamber (sub-zero) at a relative humidity (RH) of 80%. Conductivity σ was calculated by

$$\sigma = \frac{l}{Rab} \quad (3)$$

where l is the membrane thickness, a is the membrane width, b is the membrane length and R is the resistance obtained from EIS.

A few recent studies [32–35] suggested that exposure to CO₂ could have significant impact on the anion conductivity of the OH⁻ exchange membrane due to the neutralization by CO₂ producing HCO₃⁻ and CO₃²⁻ anions. In order to verify the effect of CO₂ on the conductivity of the QPMBV membranes, we carried out conductivity measurement before and after the CO₂ exposure. The specific experimental process is described as follows: a freshly prepared QPMBV membrane was exchanged to OH⁻ in 6 M KOH solution in a sealed container equipped with gas inlet and outlet. N₂ gas was used to bubble the KOH solution during the entire overnight OH⁻ exchange process. The OH⁻ exchanged QPMBV membrane was quickly transferred to a large sealed beaker containing N₂ bubbled de-ionized water to remove the KOH. The rinsing process was repeated for a few times until the neutral pH value was reached.

The conductivity was measured on the membrane soaked in the de-ionized water immediately following the rinsing process. After the conductivity (prior to CO₂ exposure) measurement, the container containing de-ionized water was exposed to the air for 12 h. Then the conductivity was measured again, which was considered as the conductivity after the exposure to the CO₂ in the ambient environment. The results will be discussed in Section 3.

2.3. Membrane electrode assembly (MEA) and fuel cell performance

The electrochemical performance of the QPMBV membrane was tested using a fuel cell test station (Arbin) at different temperatures with RH of 60%. Hydrogen and oxygen were used as the fuel and oxidant, respectively, at 80 sccm (standard cm³ min⁻¹) flow rate. MEA was prepared as follow: a mixture of 30 wt.% polytetrafluoroethylene (PTFE, suspension in de-ionized water) and 70 wt.% carbon black was brushed onto one side of a piece of carbon cloth, which was heated to 340 °C for 30 min. Catalyst Pt/C (20/80 wt.%) was sprayed onto the PTFE/carbon black coated carbon cloth surface. QPMBV membrane, which was soaked in 6 M KOH solution for ion exchange, was taken out and washed with de-ionized water prior to MEA assembly. The QPMBV membrane was sandwiched by two pieces of catalyst-loaded carbon cloth using a hydraulic press. Catalyst loading amount was 1.0 mg cm⁻² (based on Pt), and the surface area of MEA was 5 cm². The fuel cell was charged and discharged on an Arbin fuel cell test station between open circuit potential and 0.1 V at 5 mV s⁻¹.

3. Results and discussion

3.1. Copolymer characterization

GPC results of the obtained PMBV with different monomer molar ratios are shown in Fig. 2. MWs and PDIs of the copolymers are listed in Table 1. All three samples have MWs on the order of 10⁵ g mol⁻¹ and PDIs of about 3. The T_g of all obtained PMBV copolymers were around 40 °C, as indicated in Fig. 3.

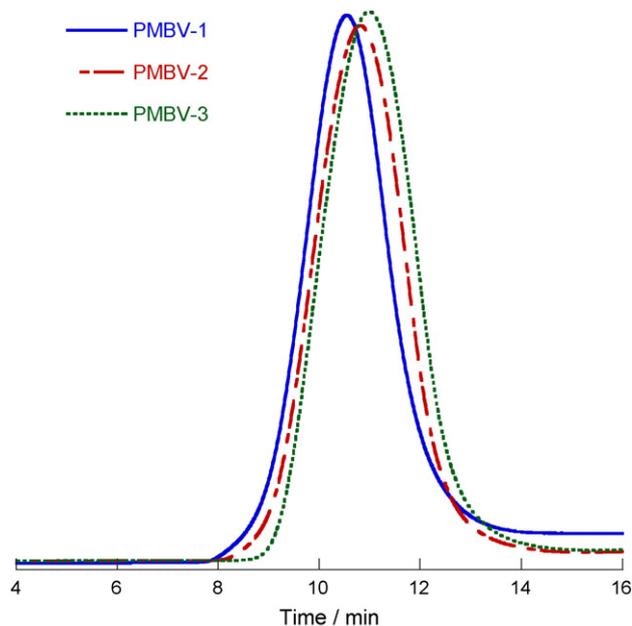


Fig. 2. GPC characterization of PMBV with different mole ratios.

Table 1
Composition, MW and PDI of PMBV.

	PMBV-1	PMBV-2	PMBV-3
Molar ratios (MMA:BA:VBC)% in monomers	50:40:10	53:40:7	55:40:5
Molar ratios (MMA:BA:VBC)% in copolymers	47:27:26	53:30:17	66:27:7
MW (Mn) (g mol ⁻¹)	2.9 × 10 ⁵	2.6 × 10 ⁵	2.5 × 10 ⁵
PDI	3.3	3.2	2.5

¹H NMR tests were performed to obtain the exact composition of the obtained PMBV copolymers, as shown in the representative spectra in Fig. 4. Chemical shifts (δ ppm) of 4.538 (s, 2H, -CH₂Cl in VBC) [36], 3.983 (s, 2H, -OCH₂- in BA) [37,38] and 3.588 (t, 3H, -OCH₃ in MMA) [37,38] are the characteristic peaks for VBC, BA and MMA, respectively. The molar ratio of components in the

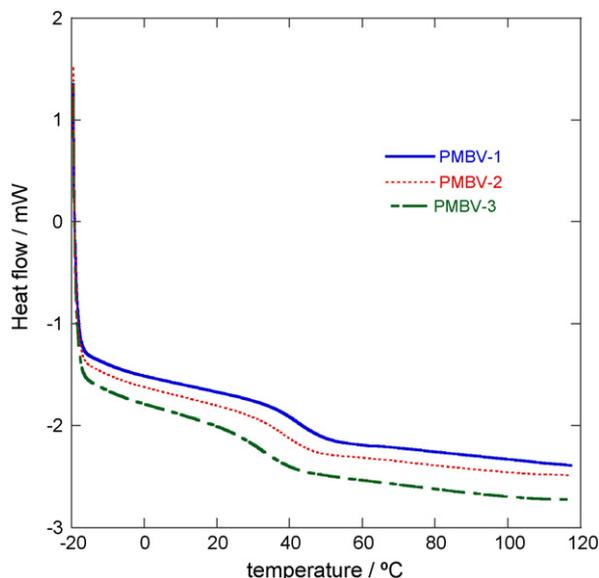


Fig. 3. DSC characterization of PMBV.

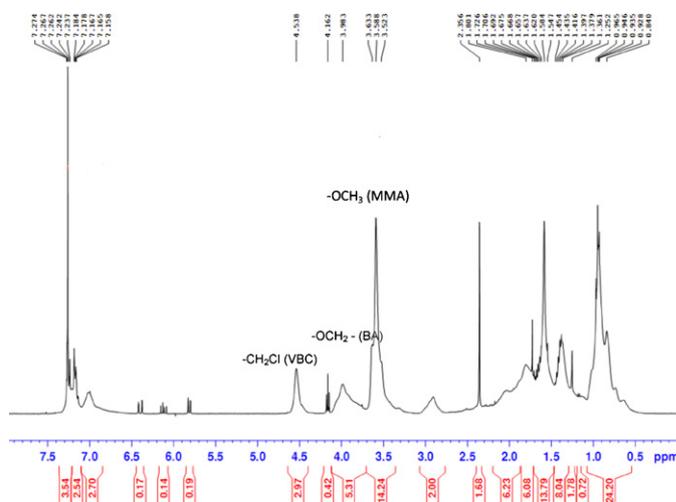


Fig. 4. ¹H NMR characterization of PMBV.

copolymer can be calculated from the integrals of the corresponding characteristic peaks. The copolymer compositions calculated from ¹H NMR results are listed in Table 1. From Table 1, it can be seen that BA incorporation in all three copolymers are similar, but considerably lower than their percentages in the reactants mixture. One possible explanation is that the reactivity ratio of BA is much lower than that of MMA and VBC [39,40] in this ternary monomer mixture. Therefore the incorporation of BA is unfavorable compared to copolymerization of MMA and VBC, which have comparable reactivity ratios [39,40]. As the copolymerization proceeded, it became more difficult for BA monomers to access the growing polymer chains. Therefore, when the reaction was stopped, a portion of BA monomers remained unreacted. Consequently, the percentage of VBC in the copolymers was higher than the corresponding composition in the reactant mixtures. The composition of PMBV copolymers followed the trend that higher VBC monomer composition in the reactant mixture results in higher VBC incorporation in the obtained copolymer. Therefore, the ¹H NMR results demonstrate that the composition of the PMBV copolymers can be designed by varying the monomer ratios so that the properties of the resulting QPMBV can be tailored as well.

3.2. Mechanical properties

Tensile tests were performed on PMBV and QPMBV (both dry and wet) membranes at room temperature to determine the Young's modulus and the tensile strength of the membranes which are listed in Table 2. The dry membranes refer to the ones that were completely dried in the vacuum oven and then exposed to the ambient environment during the tensile test. The wet QPMBV membranes refer to the ones that were dried on the vacuum oven and then immersed in de-ionized water for 20 min prior to tensile test. The water uptakes of wet QPMBVs are listed in Table 3 along with other main properties of the QPMBV membranes. Fig. 5 shows the stress-strain curves of dry PMBV membranes and Fig. 6 illus-

Table 2
Young's modulus and strength for PMBV and QPMBV membranes.

Sample	Young's modulus (GPa)			Tensile strength (MPa)		
	PMBV	QPMBV	Wet QPMBV	PMBV	QPMBV	Wet QPMBV
1	0.68	0.5	0.01	34	25	3.2
2	0.36	0.25	0.07	37	27.5	9.9
3	0.32	0.16	0.11	27	25.5	18.5

Table 3
Main properties of QPMBV membranes at room temperature.

Property	QPMBV-1	QPMBV-2	QPMBV-3
Thickness (μm)	120	120	120
Ion-exchange capacity (mmol g^{-1})	1.25	0.93	0.66
Anion conductivity ^a (mS cm^{-1})	5.3	4.3	2.9
Water uptake (%)	239	16.5	2.8

^a 80% relative humidity.

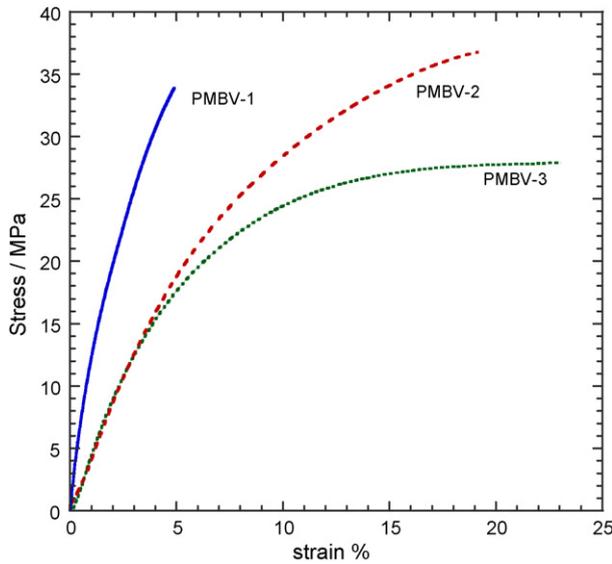


Fig. 5. Stress–strain curves for dry PMBV copolymer membranes.

trates the stress–strain performance of QPMBV membranes in dry and wet environment. Young's modulus is the slope of the initial linear portion of the stress–strain curve and represents the stiffness of the material, while tensile strength is the ultimate stress before the membrane fractures [41]. For the dry PMBV membranes (Fig. 5), Young's modulus increases with increasing VBC composition in the copolymer. Therefore, PMBV-1 is the stiffest membrane and fractured at an elongation of 5%. PMBV-3 is the most ductile membrane of these three, as it has the lowest Young's modulus and tensile

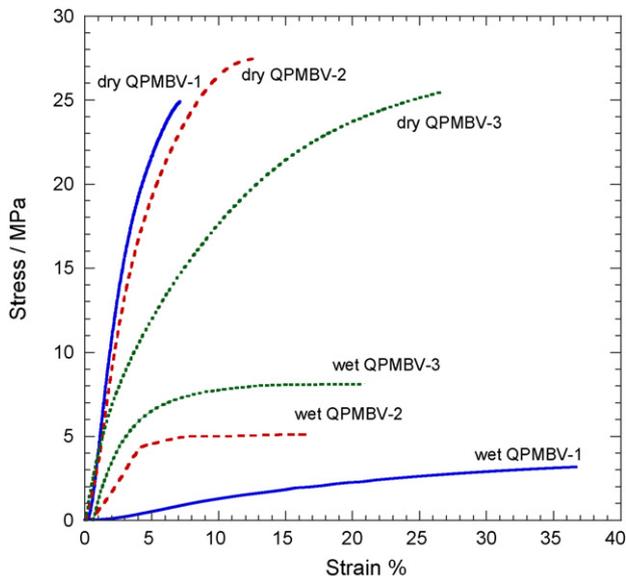


Fig. 6. Stress–strain curves for QPMBV copolymer membranes.

strength. VBC is more rigid than MMA, since the benzyl group in VBC has a large steric hindrance. Therefore, stiffness of dry copolymers increases with the increase in VBC composition. Compared to the PMBV membranes, the corresponding dry QPMBV membranes have lower Young's modulus and lower tensile strength. This observation suggests that the QPMBV copolymer slightly lost mechanical property during quaternization process, which is consistent with the ionomer nature of QPMBV. Like dry PMBV, stiffness of dry QPMBV copolymers increases with the increasing VBC composition. Young's moduli of the dry QPMBV membranes are comparable to that for dry Nafion used in PEMFC (300 MPa) [42]. The tensile strengths of the dry QPMBV membranes with different compositions remain close, meanwhile the elongation before fracture decreases with increasing VBC composition. Since AFC operates in wet condition, the properties of wet QPMBV are more important to achieve high fuel cell performance and long durability. Interestingly, after immersing the QPMBV membranes in de-ionized water for 20 min, completely opposite behaviors were observed in wet QPMBV membranes (as shown in Fig. 6), i.e. tensile strength decreases and elongation increases with increasing VBC composition. This is because quaternized VBC is hydrophilic so that higher VBC composition led to absorb more water as indicated in Table 3. On the other hand, MMA and BA portions of the copolymer still sustain reasonable mechanical properties of the membranes after wetting. The mechanical properties of wet QPMBV membranes increased with higher composition of MMA and BA with sacrificing ionic conductivity and vice versa. Therefore, a balance must be achieved to synthesize QPMBV membranes which have both high mechanical property and high ionic conductivity in wet condition through tuning the composition of QPMBV.

3.3. Conductivity measurement

The ion-exchange capacities of three OH^- exchanged membranes (denoted as QPMBV-1, QPMBV-2 and QPMBV-3 with 26, 17 and 7 mol.% VBC composition, respectively) are listed in Table 3. The increased ion-exchange capacity is consistent with the increasing VBC composition. Fig. 7 shows the anion conductivities of OH^- exchanged QPMBV membranes at various temperatures at 80% relative humidity. Increase in conductivity was observed when temperature was increased. Among three membranes, QPMBV-1

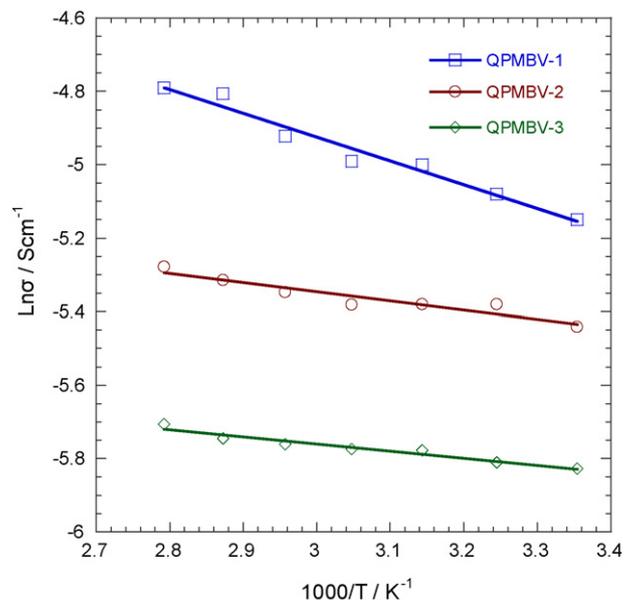


Fig. 7. Conductivities of QPMBV membranes a relative humidity of 80%.

Table 4
Conductivity of QPMBV membranes before and after CO₂ exposure at fully water-saturated state.

Condition	Anion conductivity (mS cm ⁻¹)		
	QPMBV-1	QPMBV-2	QPMBV-3
Before CO ₂ exposure	13.5	9.1	5.2
After CO ₂ exposure	6.7	4.6	3.1

has the best conductivity due to the highest composition of quaternized VBC groups. QPMBV-1 membrane could reach a maximum conductivity of $8.2 \times 10^{-3} \text{ S cm}^{-1}$ at 80 °C due to the high amount of water uptake. Although the high water uptake can enhance ionic conductivity, it also has detrimental effect on mechanical property and durability. The goal of anion conducting membrane is a material with high conductivity at minimum water uptake. It has been well recognized that CO₂ may have significant impact on the anion conductivity of the OH⁻ exchange membrane due to the neutralization reaction to produce HCO₃⁻ and CO₃²⁻ anions. Table 4 shows our measurement of the conductivities of OH⁻ exchanged QPMBV membranes before and after CO₂ exposure at fully water-saturated state. The distinct difference between these two sets of conductivities indicates the strong effect of CO₂ on QPMBV membrane conductivity, which is in good agreement with the previously reported results by Yanagi and Fukuta [32] and Filpi et al. [33]. Therefore, it suggested that the anion conductivities presented in Fig. 7 and Table 3 may be the overall conductivities of OH⁻, HCO₃⁻ and CO₃²⁻ anions.

Combining the results of mechanical properties and conductivity, it is clear that higher VBC composition resulted in higher OH⁻ conductivity, however, also impairing the mechanical properties of the membrane in the humidified working condition. The key is the mechanical property functional groups in the copolymer, MMA and BA, can provide physical strength to enable the QPMBV membranes to work in the fuel cell.

3.4. Fuel cell performance test

The performance of three OH⁻ exchanged QPMBV electrolyte membranes in AFC was measured using the Arbin fuel cell test station. AFC polarization curves were obtained by potential scan at the rate of 5 mV s⁻¹ from OPC (1.00 V) down to 0.1 V. Fig. 8 shows

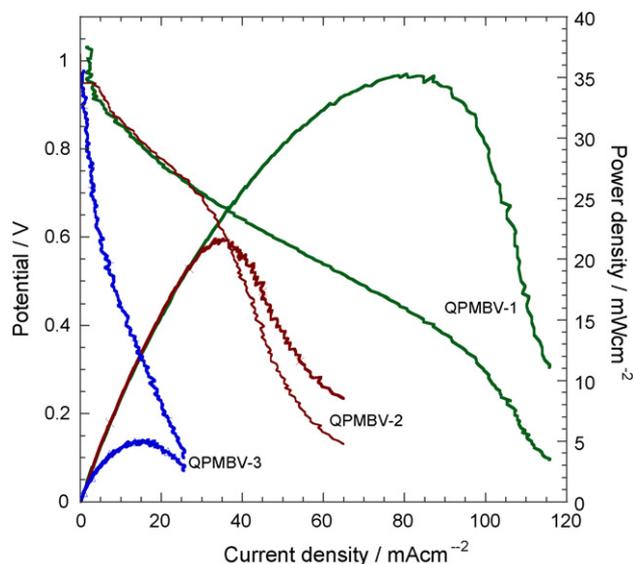


Fig. 8. Polarization curves and power density curves of QPMBV membranes at 60 °C in RH of 60%.

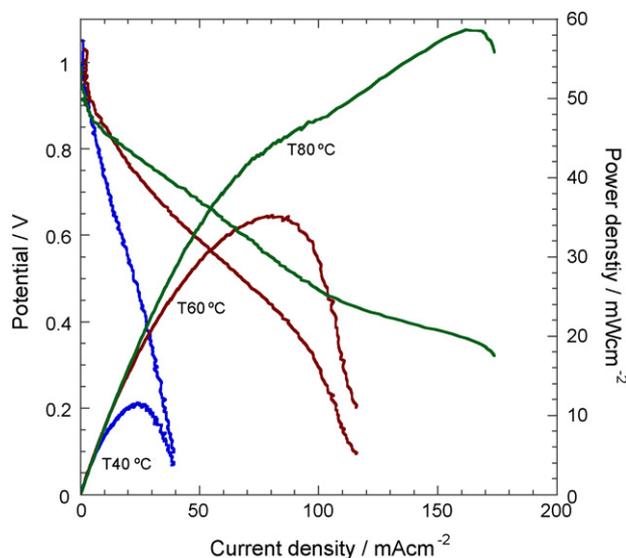


Fig. 9. Polarization curves and power density curves of QPMBV membrane at different temperatures in RH of 60%.

the polarization curves of the three OH⁻ exchanged QPMBV membranes at 60 °C in RH of 60%. As shown in Fig. 8, the performance of the membranes improved as the VBC composition increased in the copolymers. The enhanced performance is attributed to both the low ohmic resistance and high efficiency of catalyst due to the increased quaternized VBC composition. All three membranes have the same thickness (Table 3) so that the thickness effect on resistance can be eliminated. The peak power density of membrane QPMBV-1 was 35 mW cm⁻² when current density was 80 mA cm⁻² and voltage was 0.44 V. These results are consistent with the conductivity results as described previously. QPMBV-1 membrane had the highest VBC incorporation (26 mol.%) so that it had the highest OH⁻ conductivity, thus resulting in the best AFC performance among these three membranes.

The temperature dependence of OH⁻ exchanged QPMBV electrolyte membrane fuel cells was also determined by changing the cell temperature from 40 to 80 °C. Fig. 9 shows the AFC performances of OH⁻ exchanged QPMBV-1 membrane at different temperatures with the same RH of 60%. As expected, performances improved as temperature increased. At 80 °C, the maximum current density was 180 mA cm⁻² while peak power density reached 59 mW cm⁻².

Recently, Yanagi and Fukuta [32] reported a series of anion-exchange membranes with extraordinary properties at ambient temperature such as 1.7 mmol g⁻¹ ion-exchange capacity and 40 mS cm⁻¹ OH⁻ conductivity with only 25% water uptake. Although the conductivity and fuel cell performance of QPMBV are still lower than that of the anion-exchange membranes developed by Yanagi and Fukuta [32], it demonstrated a new route to synthesizing a novel anion-exchange membrane. The QPMBV membrane fuel cell reported here, although it is a prototype, represents an important advancement in the development of fuel cell membranes. The fuel cell performance reported here can be largely improved if DMF-dissolved ionomer solution is mixed into the catalyst layer during preparation of the anode and cathode.

4. Conclusion

Successful synthesis of proof-of-concept AFC polyelectrolytes based on a ternary copolymer, namely poly(methyl methacrylate-co-butyl acrylate-co-vinylbenzyl chloride), was reported. The purpose of this study was to demonstrate the feasibility of obtain-

ing desired AFC electrolytes through specific monomer selections and a designed synthesis procedure. All three monomers used in the study were selected based on their unique functionalities, and the synthesis was intentionally designed to reflect the effects of different recipes on membrane mechanical and electrochemical properties. As-prepared membranes demonstrated very promising AFC performance. Although the membrane properties are not as good as the best-reported anion-exchange membranes, the results of this study clearly demonstrated that the trend of membrane properties was well controlled by the researchers' intentions. Therefore, this study brought a new concept to produce AFC polyelectrolytes by well-designed polymerization of specifically selected monomers. Guided by this concept, AFC polyelectrolytes based on novel comb-like structured copolymers are currently under investigation by the authors.

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