

# Preparation and properties of carbon nanotube-reinforced vinyl ester/nanocomposite bipolar plates for polymer electrolyte membrane fuel cells

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## Abstract

Novel multiwalled carbon nanotubes (MWNTs) were prepared using poly(oxypropylene)-backboned diamines of molecular weights  $M_w$  400 and 2000 to disperse acid-treated MWNTs, improving the performance of composite bipolar plates in polymer electrolyte membrane fuel cells. A lightweight polymer composite bipolar plate that contained vinyl ester resin, graphite powder and MWNTs was fabricated using a bulk molding compound (BMC) process. Results demonstrate that the qualitative dispersion of MWNTs crucially determined the resultant bulk electrical conductivity, the mechanical properties and the physical properties of bipolar plates. The flexural strength of the composite bipolar plate with 1 phr of MWNTs was approximately 48% higher than that of the original composite bipolar plate. The coefficient of thermal expansion of the composite bipolar plate was reduced from 37.00 to 20.40  $\mu\text{m m}^{-1} \text{ }^\circ\text{C}^{-1}$  by adding 1 phr of MWNTs, suggesting that the composite bipolar plate has excellent thermal stability. The porosity of the composite bipolar plate was also evaluated. Additionally, the bulk electrical conductivity of the composite bipolar plate with different MWNTs types and contents exceeds 100  $\text{S cm}^{-1}$ . The results of the polarization curves confirm that the addition of MWNTs leads to a significant improvement on the single cell performance.

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**Keywords:** Fuel cell; Bipolar plate; Nanocomposite; Carbon nanotube; Bulk molding compound (BMC); Dispersion

## 1. Introduction

Polymer electrolyte membrane fuel cells (PEMFCs) have been regarded as attractive power sources for stationary, mobile and portable applications. The main components of PEMFCs are the perfluorosulphonated electrolyte membrane, the Pt catalyst and the bipolar plates. Bipolar plates electrically connect successive cells in a fuel cell stack, and also provide the gas flow field. Accordingly, bipolar plates must have high electrical conductivity, satisfactory mechanical properties, excellent corrosion resistance, lightweight, and other favorable properties [1–4].

Conventional materials for producing bipolar plates are graphite or metal. Graphite plates have been used because

they exhibit high electrical conductivity, high corrosion resistance, and a lower density than that of metals [5]. However, the technology required to manufacture graphite plates is relatively complicated, especially because of their brittleness and the high cost associated with machining channels into their surfaces. These considerations have motivated research to develop an alternative material [6].

Graphite-based polymer composite bipolar plates have the potential to replace graphite plates. They offer the advantages of lower cost, higher flexibility, lighter weight and greater ease of manufacturing than graphite plates; the gas flow channels can be molded directly into the plate, eliminating the need for a costly machining step [4–7]. However, polymer composites are associated with problems of electrical conductivity that remain to be solved. Therefore, excessive carbon or graphite fillers have to be incorporated into the composite to meet the minimum requirement on electrical conductivities. High carbon loading in polymer composites substantially reduces the strength and

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ductility of polymer composites, and this issue must be considered. Improving the high electrical conductivity and mechanical properties of polymer composite bipolar plates has become an important research topic.

Iijima, in 1991, was the first to identify carbon nanotubes [8]. Since then, carbon nanotubes have been investigated in various fields, because of their excellent mechanical and electrical properties which can develop unique applications [9–13]. Their intrinsic high-aspect ratio and lightweight enables carbon nanotubes to reinforce polymer composites [10]. However, carbon nanotubes are strongly affected by van der Waals forces because of their small size and large surface area. Thus, carbon nanotubes commonly aggregate into bundles, restricting their usefulness in polymer composites [14,15]. One challenge in the fabrication of carbon nanotube-reinforced composites is the homogeneous dispersion of the carbon nanotubes in the polymer matrix and its relation to the uniformity of properties. Numerous methods of the non-covalent modification of carbon nanotubes have been studied. They include polymer wrapping [16,17], adsorption and surfactant mixing [18–20].

In this investigation, acid-treated carbon nanotubes were dispersed by POP-diamines and then used to fabricate composite bipolar plates. The effects of the surfactant-dispersed MWNTs on the electrical, physical, mechanical and thermal properties of composite bipolar plates were examined. The performance of the single cells with these composite bipolar plates was evaluated.

## 2. Experimental

### 2.1. Materials

The multiwalled carbon nanotubes (MWNTs, trade name: C<sub>tube</sub>100) with the purity (95%), and 150–250 m<sup>2</sup> g<sup>-1</sup> of surface area were obtained from the CNT Co. Ltd., Korea. The diameters of MWNTs are 10–50 nm and the lengths are 1–25 μm. Poly(oxyalkylene)amines were purchased from the Huntsman Chemical Co., Philadelphia, PA, USA, include poly(oxypropylene) (POP)-backboned diamines with the molecular weight,  $M_w$ , 400 and 2000 g mol<sup>-1</sup> used as the dispersion agents and denoted as POP400 and POP2000, respectively. Phenolic-novolac, epoxy-based vinyl ester resin was used, which was provided by the Swancor Co., Taiwan. Graphite powder was obtained from the Great Carbon Co. Ltd., Taiwan. The density of the graphite powder is 1.88 g cm<sup>-3</sup> and the particle size is less than 1000 μm.

### 2.2. Acid treatment of MWNTs [18]

The acid-treated MWNTs were first achieved according to a nitric acid washing procedure; 8 g of raw MWNTs were boiled in 400 ml of concentrated nitric acid for 40 min to obtain acid-functionalized MWNTs. Then, the MWNTs were filtered, washed with 600 ml distilled water for several times to remove acid, and dried at 105 °C in an oven. After acid treatment, most of the impurities were removed. Furthermore, the acid treatment may induce defects and several types of func-

tional groups, including hydroxyl groups (3416 cm<sup>-1</sup>), carboxyl groups (1720 cm<sup>-1</sup>) and carbonyl groups (1583 cm<sup>-1</sup>) as shown at 3416, 1720 and 1583 cm<sup>-1</sup> in Fourier transfer infrared (FT-IR) spectra, respectively.

### 2.3. Preparation of acid-treated MWNTs with POP-diamines

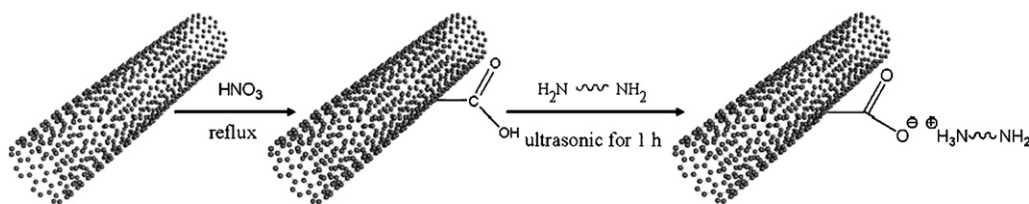
A mixture of acid-treated MWNTs (1000 mg) and poly(oxyalkylene)amines (POP400 and/or POP2000, 0.82 × 10<sup>-3</sup> mol) was under sonication at room temperature for 1 h. The MWNTs solution was separated by filtration through polytetrafluoroethylene (PTFE) membrane and thoroughly washed with excess anhydrous tetrahydrofuran (THF). The resulting MWNTs slurry was dried overnight in a vacuum oven at 60 °C to obtain MWNTs/POP-diamines (MWNTs/POP400 and MWNTs/POP2000). Scheme 1 depicts the procedure of preparing the acid-treated MWNTs and dispersing with POP-diamines. Furthermore, various MWNTs – pristine MWNTs, acid-treated MWNTs, MWNTs/POP400 and MWNTs/POP2000 – were used to prepare various MWNTs/vinyl ester resin solutions by ultrasonication for 1 h.

### 2.4. Preparation of composite bipolar plates

The bulk molding compound (BMC) was prepared by mixing various MWNTs/vinyl ester resin solutions, low profile agent (PS/SM series), styrene monomer, thickening agent (MgO), release agent (ZnSt), graphite and MWNTs in a kneader for 30 min. The BMC formulation is summarized in Table 1. The BMC was thickened for 36 h before the hot-pressing process. The processing temperature was 140 °C and the processing time was 5 min.

### 2.5. Characterization and instruments

Raman spectra were recorded with LabRam I confocal Raman spectrometer (Dilor, France). The excitation wavelength was 632.8 nm from He to Ne laser with a laser power of ca. 15 mW at the sample surface. A holographic notch filter reflected the exciting line into Olympus BX40 microscope, Tokyo, Japan. Thermogravimetric analysis (TGA) was conducted utilizing a DuPont-TGA951 with a heating rate of 10 °C min<sup>-1</sup> under N<sub>2</sub> atmosphere. The interaction between amine (–NH<sub>2</sub>) and carboxyl (–COOH) groups were analyzed by X-ray photoelectron spectra (XPS) acquired with a VG Scientific ESCALAB 220 iXL spectrometer equipped with a hemispherical electron analyzer and an Mg Kα ( $h\nu = 1253.6$  eV) X-ray source. The porosity of each composite bipolar plate was determined following the ASTM C20 test procedure. The flexural strength tests were performed based on the procedure of ASTM D-790 by an Instron Model 4468 universal tester and the specimen dimensions were 60.0 mm × 13.0 mm × 3.0 mm ( $L \times W \times T$ ). The coefficient of thermal expansion (CTE) was determined by TMA (TMA2940, DuPont, USA) at a temperature range from 30 to 145 °C in both the X and Y directions according to ASTM D-696 [21]. The

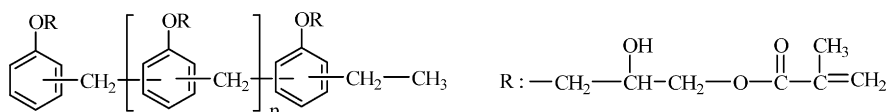


Scheme 1. Preparation of acid-treated MWNTs with POP-diamines.

Table 1  
Formulation of BMC process

Components	Composition	
	Resin composition	BMC composition (wt%)
Vinyl ester <sup>a</sup> (wt%)	75	30
Low profile agent (wt%)	8	
Styrene monomer (wt%)	17	
TBPB (phr)	1.8	
Zinc stearate (phr)	3.5	
Magnesium oxide (phr)	1.8	
MWNTs (phr)	0–2	
Graphite powder (wt%)		70
Total		100

<sup>a</sup> Chemical structure of phenolic-novolac, epoxy-based, vinyl ester is as follows:



bulk electrical conductivity of the composite bipolar plate was examined with a four-point probe detector (C4S-54/5S, Cascade Microtech, Beaverton, OR, USA).

### 2.6. Single fuel cell stack integration and performance tests

A single stack PEMFC was developed at our laboratory as reported in our previous paper [7]. The catalyst ink for the electrodes was prepared by mixing the catalyst powders (20 wt% Pt/C, E-TEK), Nafion<sup>®</sup> solution, and *iso*-propyl alcohol. Then the prepared catalyst ink was sprayed on to the wet-proofed carbon paper with a platinum loading of 0.4 mg cm<sup>-2</sup> for the anode and cathode. The membrane–electrode assembly (MEA) was fabricated by placing the electrodes at both sides of pre-treated Nafion<sup>®</sup> 115 membrane, followed by hot-pressing at 140 °C and 200 kg cm<sup>-2</sup> for 90 s. The active electrode area was 4 cm<sup>2</sup>.

A single fuel cell was constructed from the prepared MEA, Teflon gasket, and the prepared composite bipolar plate on both sides of the MEA. The thickness of the composite bipolar plates was 1.2 mm. The operating temperature and pressure of the single fuel cell were 70 °C and 1 atm, respectively. Hydrogen and oxygen gases were fed to the anode and cathode, respectively, after passing through a bubble humidifier, and the flow rate ratio of the fuel and the oxidant was 1/1 (l min<sup>-1</sup>). The performance of the single fuel cell was evaluated by measuring the *I*–*V* characteristics using an electronic load (Agilent, N3301A).

## 3. Results and discussion

### 3.1. Analysis of acid-treated MWNTs

Fig. 1 presents the Raman spectra of MWNTs before and after acid treatment, which increased the area ratio (D-band (~1322 cm<sup>-1</sup>) to G-band (~1570 cm<sup>-1</sup>)) of acid-treated MWNTs to pristine MWNTs from 0.961 to 1.107. The area ratio was clearly higher after the sidewalls were covalently function-

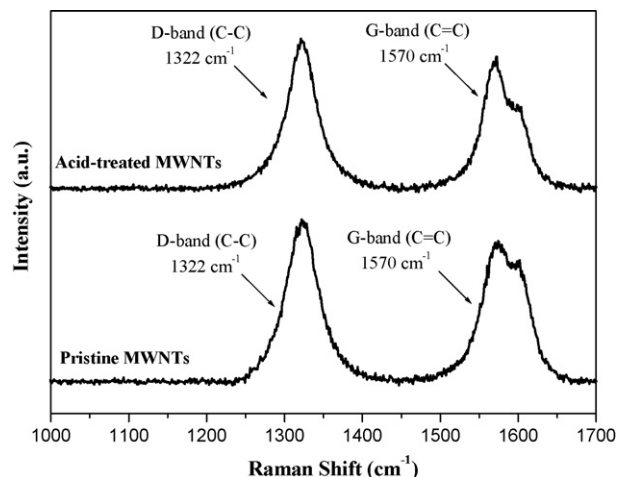


Fig. 1. The Raman spectra of pristine and acid-treated MWNTs.

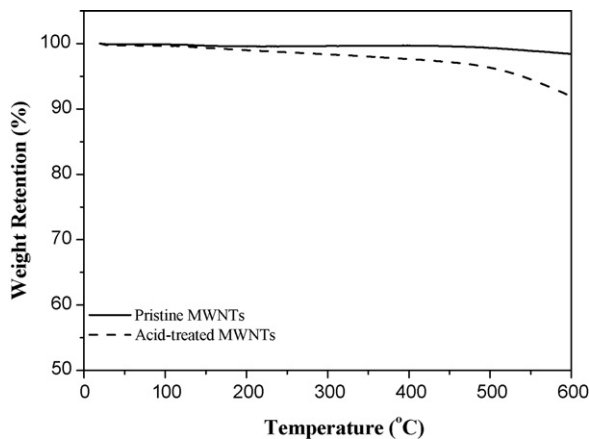


Fig. 2. TGA curve of the pristine and acid-treated MWNTs.

alized. The results may be attributed to the extent of destruction of MWNTs by slight oxidation. They also reveal that the C=C bond may be broken to form the C–C bond, generating defects in the MWNTs.

The quantitative analysis of the organic weight fraction of acid-treated MWNTs was characterized by TGA. Fig. 2 plots the results. The organic part of functionalized MWNTs could be removed in the temperature range from 250 to 500 °C [22–24]. The weight-loss region below 500 °C may be attributed to the decomposition of the surface-grafted carboxyl groups. Therefore, the content of acid functionalities in MWNTs can be calculated by comparing the weight-loss of pristine MWNTs upon treatment with acid at 500 °C. The results indicate that the pristine MWNTs exhibited almost no weight-loss, and that the relative organic weight fraction of acid-treated MWNTs was 3.05% based on the weight of pristine MWNTs.

### 3.2. Analysis of MWNTs/POP400 and MWNTs/POP2000 by XPS

XPS analysis was conducted to elucidate the surface state of MWNTs/POP400 and MWNTs/POP2000. The presence amine is further confirmed by the N 1s high-resolution spectrum (see Fig. 3), in which the binding energy peak at 399.6 and 400.1 eV is attributed to the presence of amine groups from MWNTs/POP400 and MWNTs/POP2000. [N 1s binding energies for amines are expected to be between 399.5 and 400.5 eV.] [25,26] Since the POP-diamines were introduced into acid-treated MWNTs, a portion of the –NH<sub>2</sub> groups can be compensated by –COOH groups to form a zwitterion. Indeed, a lower binding energy is observed in the presence of the POP-diamines. The lower binding energies suggest interactions between the –COOH and –NH<sub>2</sub> groups. A similar observation was made of the acid-treated MWNTs and those functionalized with imidazolium-based ionic liquids [27]. Although adding the same amounts of various POP-diamines were added to the MWNTs, the observed binding energies vary in the order of MWNTs/POP400 > MWNTs/POP2000, revealing that MWNTs/POP2000 possesses a strong interaction between the –COOH and –NH<sub>2</sub> groups.

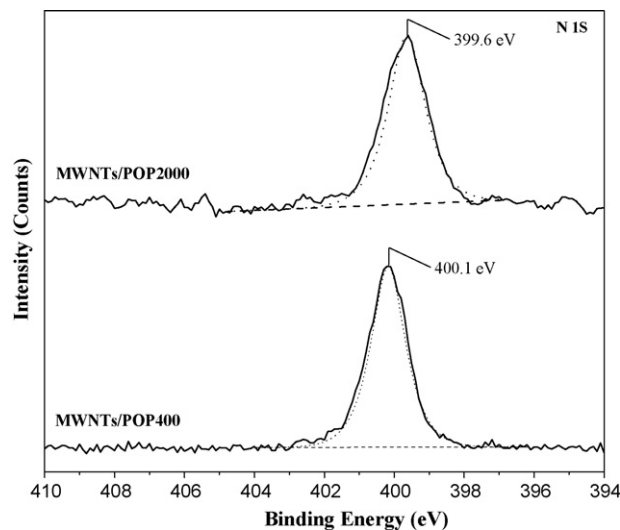


Fig. 3. High-resolution XPS spectra of the surface of MWNTs/POP400 and MWNTs/POP2000.

### 3.3. Solubility of MWNTs derivatives in organic solvent

Table 2 summarizes the qualitative dispersion solubility of the MWNTs in a variety of solvents. The pristine MWNTs could not be stably dispersed and easily aggregated, because of their high surface energy. After oxidation with nitric acid, acid-treated MWNTs become dispersible in water. Furthermore, the introduction of hydrophobic POP-diamines promoted the solubility of acid-treated MWNTs in THF. The MWNTs/POP-diamines became highly hydrophobic as the molecular weight of POP-diamines was increased from 400 to 2000. Accordingly, as shown in Table 2, MWNTs/POP2000 dispersed much more than MWNTs/POP400 in a non-polar solvent, such as styrene monomers. Next, various species of MWNTs were compared to determine their relative effectiveness in enhancing the physical properties of composite bipolar plates by correlating the results with the content and dispersion of MWNTs in the BMC materials.

### 3.4. Bulk electrical conductivity of the composite bipolar plates

A high bulk electrical conductivity is required for PEMFC bipolar plates. If the material is tough enough, a thinner plate and higher stack compaction pressure can be used to reduce the

Table 2  
Qualitative solvophilicity of the MWNTs in a variety of solvents

MWNTs	Solvophilicity <sup>a</sup>		
	SM <sup>b</sup>	THF	Water
Pristine MWNTs	–	–	–
Acid-treated MWNTs	–	–	+
MWNTs/POP400	–	+	–
MWNTs/POP2000	+	+	–

<sup>a</sup> +: dispersible; –: aggregate (1 mg sample in 1 ml solvent).

<sup>b</sup> Styrene monomer.



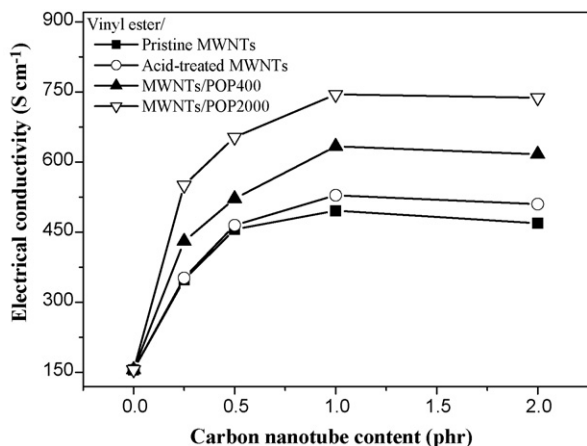


Fig. 4. The electrical conductivity of composite bipolar plates with various MWNTs.

bulk electrical resistance and the interfacial resistance of bipolar plates within the stack. Consequently, the performance of the PEMFC can be improved [28]. In this work, a thin composite bipolar plate with MWNTs possesses high bulk electrical conductivity, as shown in Fig. 4. The bulk electrical conductivity exceeds the industry's requirements or DOE target for composite bipolar plates [29]. A percolating conducting path is necessary to achieve high electrical conductivity [30]. A thin layer of insulating polymer matrix with high electrical resistance along a conducting path will increase the total resistance of the path. Therefore, graphites can contribute only to the limited conductivity of the composite bipolar plate.

Fig. 4 plots variations in the bulk electrical conductivity of the nanocomposite bipolar plate with MWNT content. Bulk electrical conductivity increased and then leveled as MWNTs loading increased. For a 1 phr (phr: parts per hundred parts of resin, based on amount of vinyl ester, low profile agent and styrene monomer) MWNT content, the bulk electrical conductivities of MWNTs/POP2000, MWNTs/POP400, acid-treated MWNTs, and pristine MWNTs composites were measured at 496, 529, 633, 744 S cm<sup>-1</sup>, respectively. Additionally, as revealed by

Fig. 4, the bulk electrical conductivity increased significantly in the order of MWNTs/POP2000 > MWNTs/POP400 > acid-treated MWNTs > pristine MWNTs composite bipolar plates, for a given MWNT content. The incorporation of conductive fillers into immiscible polymer blends to improve the electrical conductivity at much lower filler contents has recently attracted increasing attention. Friedrich [31] proposed that this effect was related to the reduced number of filler–filler hops that are required to traverse a given distance. Moreover, the solubility of MWNTs has a pronounced effect on the bulk electrical conductivity. For pristine MWNTs, acid-treated MWNTs, and MWNTs/POP400, the formation of local nanotube clusters was associated with the lack of chemical compatibility between the polymer and MWNTs. Such clusters were already present as entangled MWNTs before the BMC process. This fact is consistent with the expectation that MWNTs clusters may be incorporated only into a local conductive network in the composite bipolar plate. However, since MWNTs/POP2000 possesses homogeneous dispersion in styrene monomers, it implicates that MWNTs/POP2000 can lead to the formation of a much more efficient electrical network in the composite bipolar plate.

Fig. 5 depicts a suggested model of the conductivity paths in a composite bipolar plate that consists of MWNTs. The model was based on the presented experimental results. Insulating polymers are filled with electrically conductive graphites and carbon nanotubes. At the boundaries the graphites are zones of conductive MWNTs. When voltage is applied, more continuous paths become available for the flow of electrical current due to the homogeneity of MWNTs/POP2000. In contrast, aggregated MWNTs provide only a few conductive paths.

### 3.5. Mechanical properties of the composite bipolar plates

In addition to high electrical conductivity, high-performance bipolar plates should provide the required mechanical strength for PEMFC applications. However, polymer composites with high graphite powder loadings cannot easily be formed with high conductivity and favorable mechanical properties.

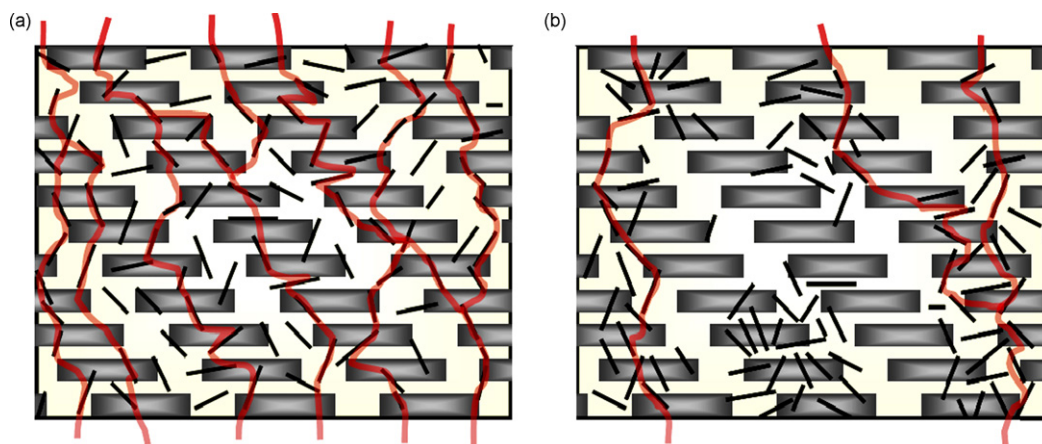


Fig. 5. Models of conductive paths in composite bipolar plates with (a) homogeneous MWNTs/POP2000 and (b) MWNTs aggregation. Graphite (gray flakes) and carbon nanotubes (black rods) forming conductive paths (curves).

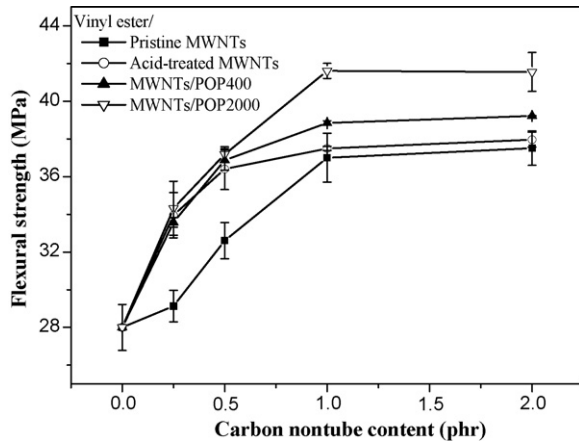


Fig. 6. The flexural strengths of composite bipolar plates with various MWNTs.

Carbon nanotubes have distinctly superior mechanical strength, and so improve the stiffness of composite materials. The flexural properties of MWNT composite bipolar plates are investigated. As shown in Fig. 6, when the MWNT content reached 2 phr, the flexural strengths of composite bipolar plates consisting of pristine MWNTs, acid-treated MWNTs, MWNTs/POP400 and MWNTs/POP2000 were increased from 28 to 37.51, 37.96, 39.22 and 41.55 MPa, respectively. First, the increase in flexural strength is associated mainly with the rigidity and high-aspect ratio of MWNTs, which are critical in determining the mechanical properties of the resulting composite. Moreover, the improvement of the flexural strengths of MWNTs composite bipolar plates was increased in the order of MWNTs/POP2000 > MWNTs/POP400 > acid-treated MWNTs > pristine MWNTs, at a given loading level. This fact clearly demonstrates that adding MWNTs/POP2000 more significantly increased the flexural strength than adding other MWNTs.

The poor dispersion of MWNTs is widely recognized as impeding the development of MWNT-reinforced composites. These MWNTs typically appear as clusters in the polymer matrix because of a lack of chemical compatibility [32]. Our approach used herein to increase the solubility of MWNTs involves the interaction of long-chain POP-diamines with acid-treated MWNTs. MWNTs/POP2000 are more soluble in non-polar solvents, such as styrene monomers, than other MWNTs. Therefore, the dispersion of MWNTs/POP2000 in the polymer matrix is homogeneous. In this case, the homogeneous dispersion of MWNTs/POP2000 promotes the formation of a filler–polymer network structure, and enables the composite bipolar plate more efficiently to handle the load transfer from the host polymer matrix to MWNTs [33,34].

Finally, surfactant-assisted processing of MWNTs [35–37], especially, MWNTs/POP2000, is a useful method for producing composite bipolar plates. The MWNTs-reinforced composites offer considerable scope for improving the flexural strengths of the bipolar plates by improving the dispersion of carbon nanotubes or by modulating the interface with the polymer matrix [38].

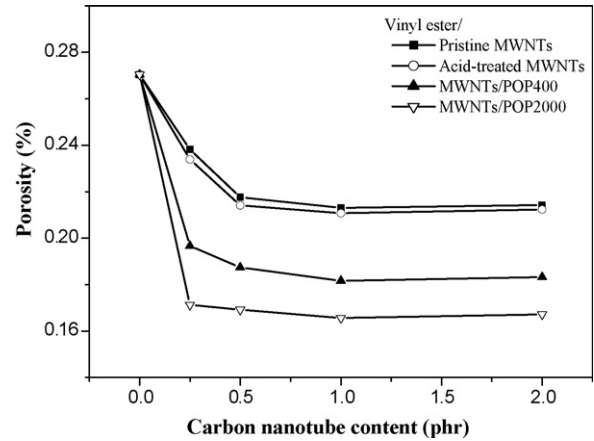


Fig. 7. The porosity of composite bipolar plates with various MWNTs.

### 3.6. Porosity analysis of composite bipolar plates

The porosity may arise because of the phase separation of styrene monomers and BMC materials [39]. The high free energy may result from the large specific surface area of MWNTs, causing aggregation of MWNTs fillers. Therefore, carbon nanotubes may not be completely wetted by vinyl ester resin. Consequently, an insufficiency of vinyl ester resin may induce voids in the composite bipolar plates, suggesting that the well-dispersed filler in the polymer matrix may effectively reduce the porosity of composite bipolar plates.

Fig. 7 plots the effect of MWNTs on the porosity of composite bipolar plates. The porosity in the composite materials was reduced more by adding surfactant-dispersed MWNTs than by adding either acid-treated MWNTs or pristine MWNTs. The porosity decreased from 1.8% (0 phr) to 0.214–0.167% (2 phr) as the MWNT content increased, implying that MWNTs interrupt the phase separation that is caused by the diffusion of styrene. This result was attributed to the degree of organophilicity and the extent of dispersion of MWNTs in composite bipolar plates. Accordingly, the drop in porosity that is caused by adding MWNTs/POP2000 may be related to the higher organophilicity of the MWNTs, which can act as a compatibilizer. Therefore, since MWNTs/POP2000 much more easily disperse in the polymer matrix than other MWNTs, they may more effectively block the diffusion of styrene molecules, constraining phase separation in the composite materials.

### 3.7. The thermal expansion behavior of composite bipolar plates

Thermal mechanical analysis was conducted to investigate the thermal stability of composite bipolar plates. The coefficient of thermal expansion (CTE) decreased dramatically as the MWNTs content increased in the range 0.25–1 phr loading, as shown in Fig. 8. The CTE of composite bipolar plates with 1 phr of pristine MWNTs, acid-treated MWNTs, MWNTs/POP400 and MWNTs/POP2000 are 25.05, 23.08, 21.37 and 20.40  $\mu\text{m m}^{-1} \text{ } ^\circ\text{C}^{-1}$ , respectively. However, these values were expected to be low, because the thermal expansion

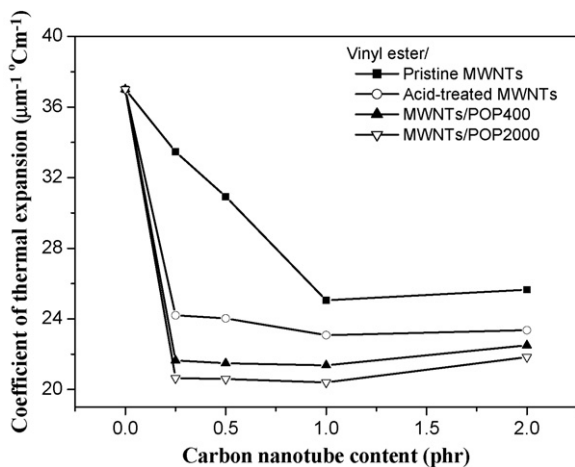


Fig. 8. The coefficient of thermal expansion of composite bipolar plates with various MWNTs.

coefficient of the MWNTs was low. The decrease in CTE that was caused by adding MWNTs/POP2000 may be related to the better dispersion of the MWNTs in polymer matrix, which is attributable to a strong interaction with the polymer. Polymer chains cannot move or extend effectively at elevated temperature, reducing the free volume of the composite bipolar plate. Therefore, the composite bipolar plate with MWNTs/POP2000 has a much lower CTE than MWNTs/POP400, acid-treated MWNTs and pristine MWNTs.

When the MWNT loading exceeded 1 phr, the CTEs of composite bipolar plates with various MWNTs were similar. Notably, the CTEs slightly increased for two reasons: (1) local concentrations of MWNTs act as inhomogeneities; (2) the temperature effect causes the surfactant chains of MWNTs/POP400 and MWNTs/POP2000 to have a high free volume; the POP-diamine chains were long, flexible and more easily extended, and thus resulted in a higher CTE than those of acid-treated MWNTs and pristine MWNTs. In fact, the CTE of the composite bipolar plate prepared herein was still substantially lower than the pure vinyl ester resin ( $50.8 \mu\text{m m}^{-1} \text{ } ^\circ\text{C}^{-1}$ ), revealing that the thermal stability of the composite bipolar plates was high enough for PEMFC applications.

### 3.8. Single cell performance test

Fig. 9 presents the performance of the single cells that were assembled with composite bipolar plates. Open circuit voltage (OCV) of the single cells was almost the same at 1.0 V. At low current densities, the single cell that incorporated various MWNT composite bipolar plates performed comparably with the original composite bipolar plates. All MWNTs composite bipolar plates slightly outperformed the pristine composite plates. The results indicate the performance of the PEMFC was improved by introducing MWNTs. The current density of the single cells increased in the order of using original composite bipolar plates < pristine MWNTs < acid-treated MWNTs < MWNTs/POP400 < MWNTs/POP2000 composite bipolar plates; at a cell voltage of 0.5 V, the current densities were 0.74, 0.86, 0.90, 0.95 and 1.04  $\text{A cm}^{-2}$ , respectively. The

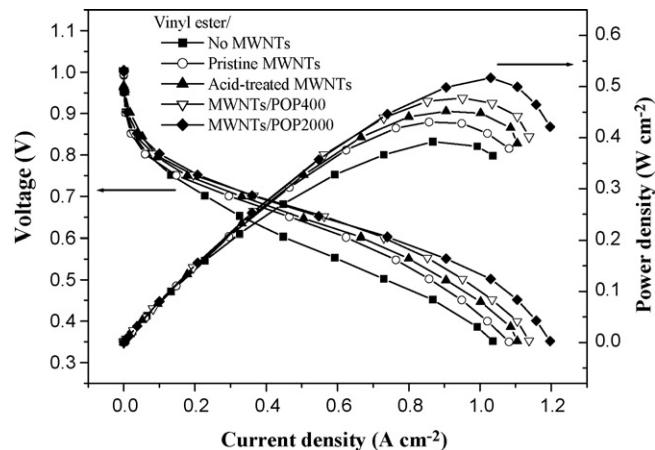


Fig. 9.  $I$ - $V$  and  $I$ - $P$  curves of single cell using composite bipolar plate with 70 wt% graphite and with various MWNTs (1 phr).

composite bipolar plate with 1 phr of MWNTs/POP2000 had the highest power density,  $0.517 \text{ W cm}^{-2}$ . The presented system of bipolar plates-MWNTs/POP2000 gave promising results for two reasons: (1) the compatibility of MWNTs/POP2000 was better than the compatibility associated with other MWNTs; (2) more continuous conducting paths promoted the transfer of electrons in PEMFC.

## 4. Conclusions

Organic species bearing  $-\text{NH}_2$  groups were attracted by  $-\text{COOH}$  groups on the surface of acid-treated MWNTs using POP-backed diamines of molecular weights  $M_w$  400 and 2000, as surfactants for forming MWNTs/POP-diamines. The dispersion and the degree of organophilicity of various MWNTs in BMC materials are correlated with the properties composite bipolar plates. All MWNTs/POP-diamines, especially MWNTs/POP2000, effectively improved bulk electrical conductivity, flexural strength, porosity and thermal expansion properties. The composite bipolar plates meet the electrical and physical development targets of PEMFC bipolar plates. In single cell performance test, the power density was measured at  $0.517 \text{ W cm}^{-2}$  using a composite bipolar plate that contained 1 phr MWNTs/POP2000. This value was approximately 32% higher than that of the original composite bipolar plate, because more continuous conducting paths resulted in better electron transfer in PEMFC. All of those results show that the composite bipolar plates with MWNTs/POP2000 developed in this work perform excellently as PEMFC bipolar plates.

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