

Study of Electrospinning of Sodium Alginate, Blended Solutions of Sodium Alginate/Poly(vinyl alcohol) and Sodium Alginate/Poly(ethylene oxide)

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ABSTRACT: Alginate is an interesting natural biopolymer for many of its merits and good biological properties. This paper investigates the electrospinning of sodium alginate (NaAlg), NaAlg/PVA- and NaAlg/PEO- blended systems. It was found in this research that although NaAlg can easily be dissolved in water, the aqueous NaAlg solution could not be electrospun into ultrafine nanofibers. To overcome the poor electrospinnability of NaAlg solution, synthetic polymers such as PEO and PVA solutions were blended with NaAlg solution to improve its spinnability. The SEM images of electrospun nanofibers showed that the alginate (2%, w/v)–PVA (8%, w/v) blended system in the volume ratio of 70 : 30 and the alginate (2%, w/v)–PEO (8% w/v) blended system in the volume ratio of 50 : 50 could be

electrospun into finest and uniform nanofibers with average diameters of 118.3 nm (diameter distribution, 75.8–204 nm) and 99.1 nm (diameter distribution, 71–122 nm), respectively. Rheological studies showed a strong dependence of spinnability and fiber morphology on solution viscosity and thus on the alginate-to-synthetic polymer (PVA or PEO) blend ratios. FTIR studies indicate that there are the hydrogen bonding interactions due to the ether oxygen of PEO (or the hydroxyl groups of PVA) and the hydroxyl groups of NaAlg. © 2007 Wiley Periodicals, Inc. *J Appl Polym Sci* 104: 3245–3255, 2007

Key words: sodium alginate; electrospinning; nanofibers; poly(vinyl alcohol); poly(ethylene oxide); polymer blending

INTRODUCTION

In the past decade, electrospinning technique has attracted great attention as the simplest and least expensive means in producing polymer nanofibers with high surface-to-volume ratio and diameters ranging from microns down to a few nanometers.^{1–3} This technique has been employed to fabricate nanofibers from a variety of synthetic or natural polymers. Natural polymers are generally favored over synthetic polymers due to their biocompatibility and biodegradation in biomedical applications. However, their mechanical properties and their processability are often poor and to fabricate ultrafine fibers from natural polymers is usually more difficult than from synthetic polymers.^{4–8} Therefore, to overcome these problems, solution blends of synthetic and natural polymers have been prepared and spun into nanofibers.^{8–10}

Alginates form a group of polysaccharides that occur in the cell walls of brown seaweed and are comprised of linear chains of (1,4)- β -D-mannuronic acid and (1,3)- α -L-guluronic acid.^{11–15} Sodium alginate (NaAlg), a polyelectrolyte with many merits such as

biological origin, biodegradability, and biocompatibility, has been extensively reevaluated and used recently as an attractive natural resource in biomedical applications such as wound dressing,^{16–20} drug carrier,^{21,22} tissue engineering scaffold,^{23,24} and so forth. The processability and performance of NaAlg may be improved by blending its aqueous solution with appropriate polymers because polymer blends have provided the polymeric materials with desired properties, low basic cost, and improved processability. Generally, the formation of specific intermolecular interactions through hydrogen bonding between two or more polymers leads to the observed resulting behaviors and properties of the blends prepared from aqueous solutions.⁹

Poly(ethylene oxide) (PEO) is a unique class of water-soluble aerobically biodegradable thermoplastic. Because of its excellent biocompatibility and very low toxicity, the potential use of PEO in biomedical applications has attracted a great attention from both the industrial and scientific points of view.^{9,25,26} Studies by Kondo et al.²⁷ have shown that the primary hydroxyl groups on cellulose and methylcellulose can form hydrogen bond to the oxygen of ether groups in PEO. Similarly, hydroxyl groups on NaAlg can also form hydrogen bond to the oxygen of ether groups in PEO.⁹ Therefore, PEO was selected as a suitable candidate to be blended with NaAlg.

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Moreover, poly(vinyl alcohol) (PVA) was also chosen for two reasons¹: PVA could strongly interact with NaAlg through hydrogen bonding on a molecular level²; PVA can conveniently be electrospun from an aqueous medium. PVA, a water-soluble polyhydroxy polymer, has excellent chemical resistance, physical properties, and biodegradability. The chemical stability of PVA at room temperature along with its excellent physical and mechanical properties has led to its broadly practical applications.⁸ PVA and NaAlg are both biodegradable polymers, which exhibit no pollution to environment.^{8,10}

In contrast to the numerous studies carried out on the physical properties and industrial applications of alginate gels,^{11–13,15,23,28} there have been only a few studies dealing with alginate/synthetic polymer blends in the film form.^{9,10} However, no report about electrospinning of nanofiber mats from solution of NaAlg or solution blends of NaAlg/PVA and NaAlg/PEO was found in the literature.

This study was carried out in two parts to fabricate electrospun nonwoven mats of NaAlg. In the first part, pure NaAlg system was studied. Then, in the second part, the blended systems of NaAlg with other polymers, i.e., PVA and PEO were examined.

EXPERIMENTAL

Material

The alginate material used had viscosity of 700–900 cps and was a commercial product of NaAlg, Cecalgun™ S1300 purchased from Degussa Co. (France). PVA with $\overline{M}_w = 5 \times 10^4$ g/mol and degree of hydrolysis of 98% and PEO with $\overline{M}_w = 3 \times 10^5$ g/mol were obtained from Sigma-Aldrich (USA). Distilled water (DW) was used as the solvent.

Solution preparation

First, PVA and NaAlg were dissolved separately. Alginate was dissolved in DW at room temperature.

Transparent solutions of PVA were prepared by dissolving PVA in DW at about 80°C, with continuous stirring for 3–4 h. Different PVA solutions with concentrations of 5–13% (w/v) were prepared to investigate the spinnability of PVA solutions. In regard to the formation of continuous and uniform nanofibers observed by optical microscopy photographs and SEM images, three solutions with concentrations of 7, 8, and 9% (w/v) were found to be spinnable and these three particular concentrations were selected as the spinnable PVA solutions and were each mixed separately with a NaAlg solution of 2% (w/v) to obtain the blends with the volume ratios of NaAlg to PVA ranging 70 : 30, 50 : 50, and 30 : 70. Each blended solution was stirred for 2 h at room temperature.

Moreover, the alginate solution of 2% (w/v) and PEO solution of 8% (w/v) were separately prepared in DW, and then were mixed to obtain the blends with three volume ratios of 70 : 30, 50 : 50, and 30 : 70 NaAlg/PEO. These resultant blends were stirred for 2 h at room temperature.

By blending the above-mentioned solutions, it is possible to study the effects of addition of PEO and PVA solutions to NaAlg solution on the morphology of nanofibers of NaAlg/PVA and NaAlg/PEO blends separately, as well as to investigate the effect of PVA solution concentrations on the morphology of electrospun nanofibers of NaAlg and PVA blends.

The shear viscosities of NaAlg and those of the different solutions ratios of NaAlg/PVA and NaAlg/PEO were measured using a Haake Rotovisco RV12 coaxial viscometer equipped with double concentric cylinder-type NV sensors in a shear rate range of 2–400 s⁻¹.

Electrospinning of nanofibers

The apparatus for the electrospinning was assembled as was in previous studies.¹ A high-voltage power supply was used to generate the electric field of 0–20 kV. The polymer solution was placed into a 1 mL

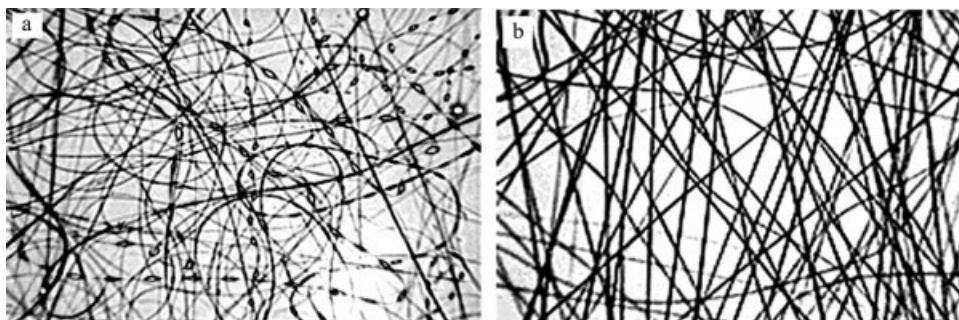


Figure 1 Optical microscopy images of electrospun mats prepared from PVA solutions with concentration of (a) 6% and (b) 7%.

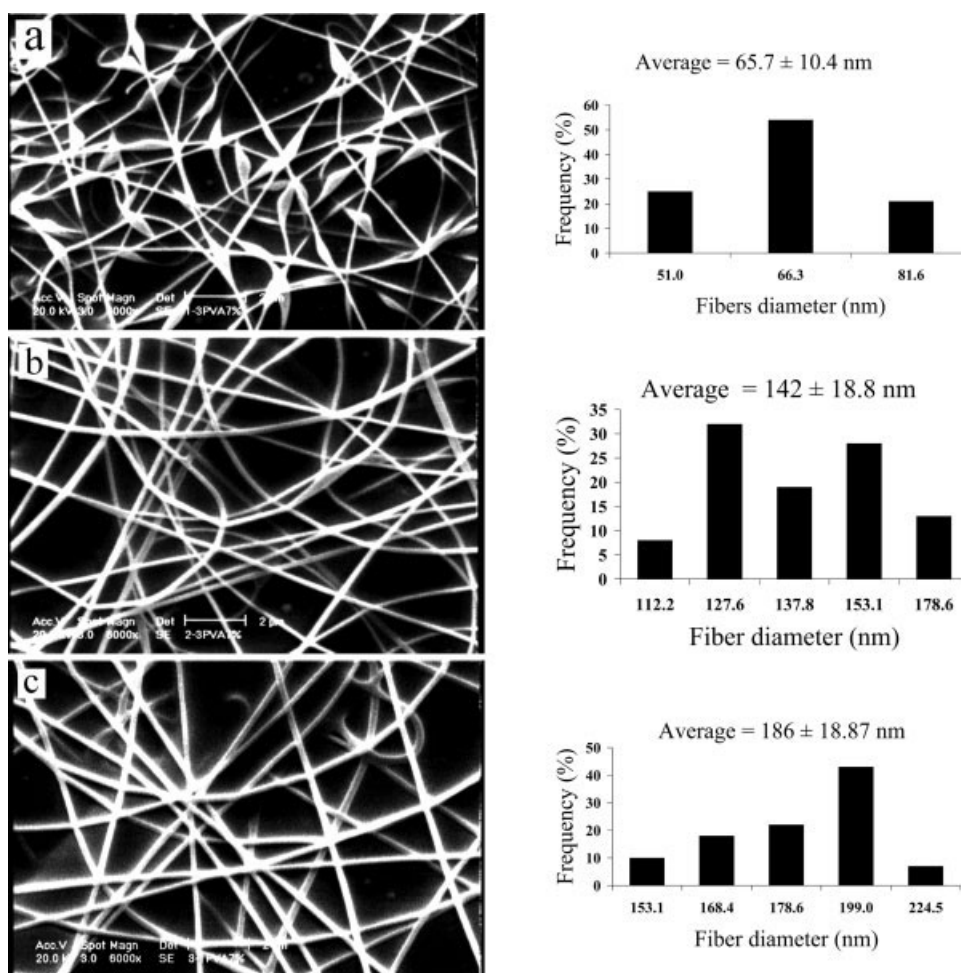


Figure 2 SEM images of electrospun nanofibers prepared from solutions of NaAlg (2%, w/v)–PVA (7%, w/v) at different volume ratios: (a) 50 : 50, (b) 30 : 70, and (c) 0 : 100.

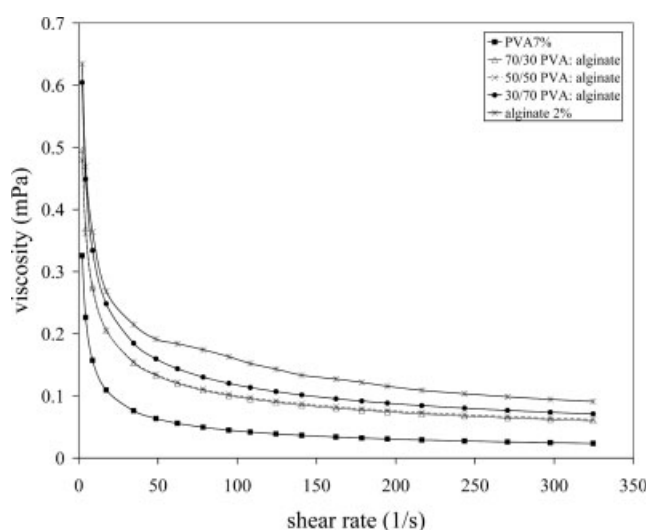


Figure 3 Shear viscosity as a function of shear rate of polymer solutions of NaAlg (2%, w/v)–PVA (7%, w/v) with different volume ratios.

syringe with a capillary tip having an outer diameter of 0.7 mm (gauge 22). The stainless steel needle of syringe was connected to the positive electrode by a copper wire. A flat piece of aluminum foil, which was connected to the negative electrode, was used to collect the nonwoven nanofibers mat. A syringe pump was used to control constant mass flow of the polymer solution during the electrospinning. All the spinning experiments were performed at ambient conditions. The DC voltage was adjusted from 0 to the levels that the corresponding solutions could be electrospun without any visible liquid drops as observed by naked eyes. Since lower electric potentials usually favor finer fiber formation, the lowest possible voltage was chosen to electrospun polymer solution into ultrafine fibers. Therefore, in this study, the applied voltage and the tip-to-collector distance were chosen at fixed values of 12 kV and 100 mm, respectively, for NaAlg/PVA-blended system, and 11 kV and 100 mm for NaAlg/PEO-blended systems.

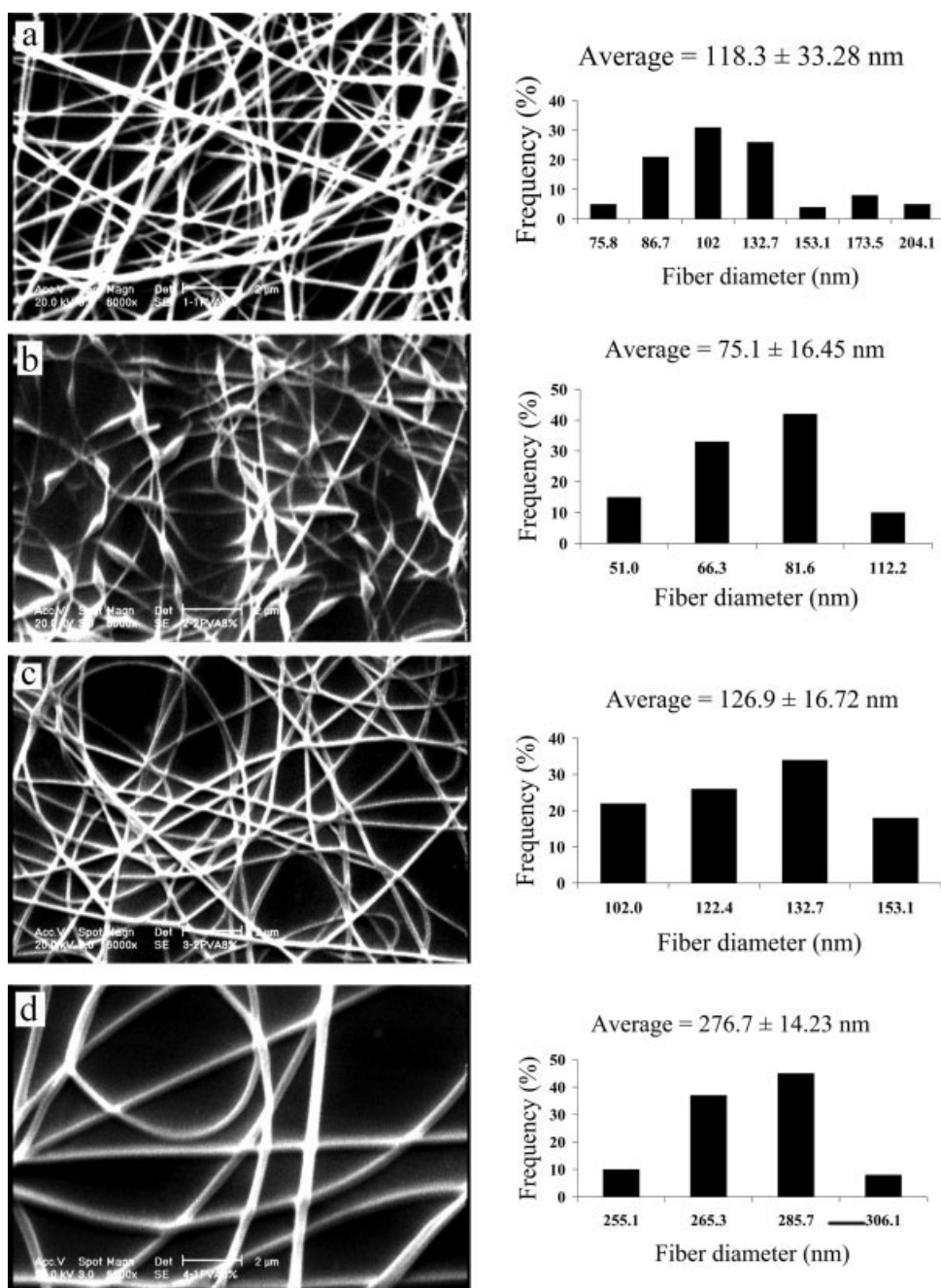


Figure 4 SEM images of electrospun nanofibers prepared from solutions of NaAlg (2%, w/v)–PVA (8%, w/v) at different volume ratios: (a) 70 : 30, (b) 50 : 50, (c) 30 : 70, and (d) 0 : 100.

Characterization

The morphology of electrospun NaAlg/PVA and NaAlg/PEO nanofibers after gold coating was studied using a Philips Scanning Electron Microscope (XL-30). The average fiber diameter of electrospun nanofibers was determined by measuring the diameters of the nanofibers at 100 different points on a SEM image (6000 \times). The diameters were presented as the average \pm standard deviation.

FTIR spectra were obtained from KBr pellets of 1 wt % of materials using BOMEM MB-series 100 FTIR spectrometer in the range of 4000–400 cm^{-1} .

RESULTS AND DISCUSSION

Electrospinning of pure alginate system

For pure alginate system, i.e., NaAlg aqueous solutions with no PVA- or PEO-blended solutions, no jet

was formed upon applying the high voltage even above 20 kV. For pure NaAlg solutions with polymer concentrations equal to or less than 2%, no continuous jets were formed and the solution was sprayed as droplets on the collector. These findings were similar to the electrostatic droplet generation technique that was used for alginate microbead production by Nedovic et al.²⁹ In that technique, alginate droplets were formed by the action of electrostatic and gravitational forces. While the solutions with polymer concentrations above 2% were too viscous to be spinnable, i.e., no continuous flow of the polymer solution through the capillary tip happened. Thus, although different conditions and concentrations of NaAlg solutions were used, no fibers could be electrospun from pure alginate solutions. This could be attributed to its polyelectrolyte characteristic.¹² Huang et al.⁴ reported that gelatin is a polyelectrolyte biopolymer as is NaAlg, and its aqueous solution did not yield into nanofibers by electrospinning. On the other hand, in general, NaAlg is not soluble in organic solvents.^{11–15}

Spinnability of PVA solutions

In this research, the spinnability was mainly depended on the PVA concentration when the electrospinning was performed at room temperature. Continuous fibers were successfully electrospun separately from the PVA solutions of 7, 8, and 9% (w/v). The optical microscopy images shown in Figure 1 clearly demonstrates that whereas beads-on-string formed with the 6% (w/v) concentration, essentially no beads was seen on the fibers electrospun from the PVA solutions with the higher mass concentrations from 7 to 9% (w/v). It has been found in this study that two solutions with the lowest and the highest PVA concentrations were difficult to be electrospun into nanofibers. For the concentrations below the 7% (w/v), fibers with beads were obtained [Fig. 1(a)], but no beads were found with the nanofibers obtained from the solutions of the 7–9% (w/v) concentrations [Fig. 1(b)]. Solutions with polymer concentrations above 9% were too viscous so that noncontinuous flow of the polymer solution through the capillary tip was observed.

Electrospinning of blended solution of 2% (w/v) alginate and 7% (w/v) PVA

Since PVA in an aqueous medium can conveniently be electrospun, it was used to improve the spinnability of the NaAlg solution. Figure 2 shows SEM photographs and nanofiber diameter distribution of the electrospun mats of alginate/PVA blended solutions. At the ratio of 70 : 30 NaAlg : PVA, no jet was formed and only sprayed droplets were obtained. When equal volumes of the alginate and PVA (50 : 50) solutions were blended, spindle-like beads were seen. The

average fiber diameter between the beads was 65.7 ± 10.4 nm [Fig. 2(a); diameter distribution, 51–81.6 nm]. By increasing the ratio of PVA content (NaAlg : PVA, 30 : 70), the morphology was changed from beaded fiber to the uniform fiber structure and the fiber diameter was also increased to 142 ± 18.8 nm [Fig. 2(b); diameter distribution, 112.2–178.6 nm]. On the other hand, nanofibers electrospun from pure PVA solution had a relatively thicker mean diameter of 186 ± 18.9 nm [Fig. 2(c); diameter distribution, 153–224.5 nm].

It was observed that the average diameters of electrospun nanofibers were increased by increasing the PVA content and decreasing the NaAlg content in the blended solutions. It appears that NaAlg as an anionic polyelectrolyte increases the charge density in the ejected jets and this leads to thinner fiber formation as the NaAlg to PVA ratio increases in the solution blend.

To study how the PVA content in the blended solution would affect the viscosity and thus spinnability of NaAlg solution, shear viscosity as a function of shear rate was measured for solutions of different NaAlg : PVA ratios. The results showed that the viscosity of polymer blend solutions decreased with increasing PVA content (Fig. 3). The blended solution with ratio of 70 : 30 NaAlg : PVA had higher viscosity than the two other blended solutions. SEM images showed that the morphology of electrospun nanofibers progressively changed from a beaded-like structure to a uniform structure as the ratio of PVA-to-alginate increased. The decrease in the viscosity of blended solutions with the increase in the PVA content can be attributed to the change in the inter- and intramolecular interactions of alginate chains.^{10–12}

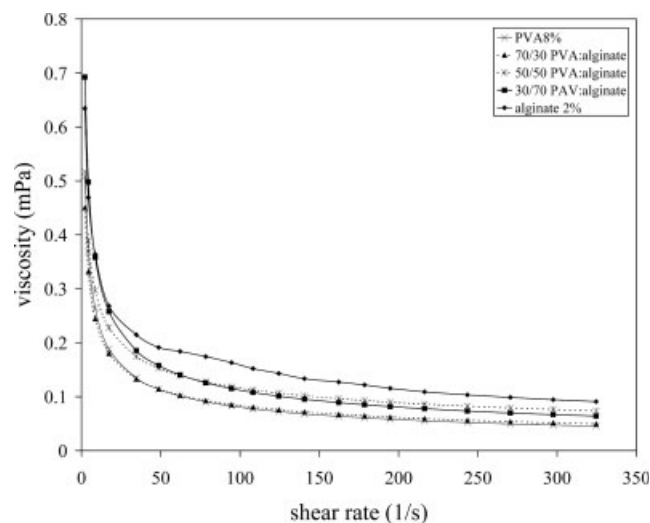


Figure 5 Shear viscosity as a function of shear rate of polymer solutions of NaAlg (2%, w/v)–PVA (8%, w/v) with different volume ratios.

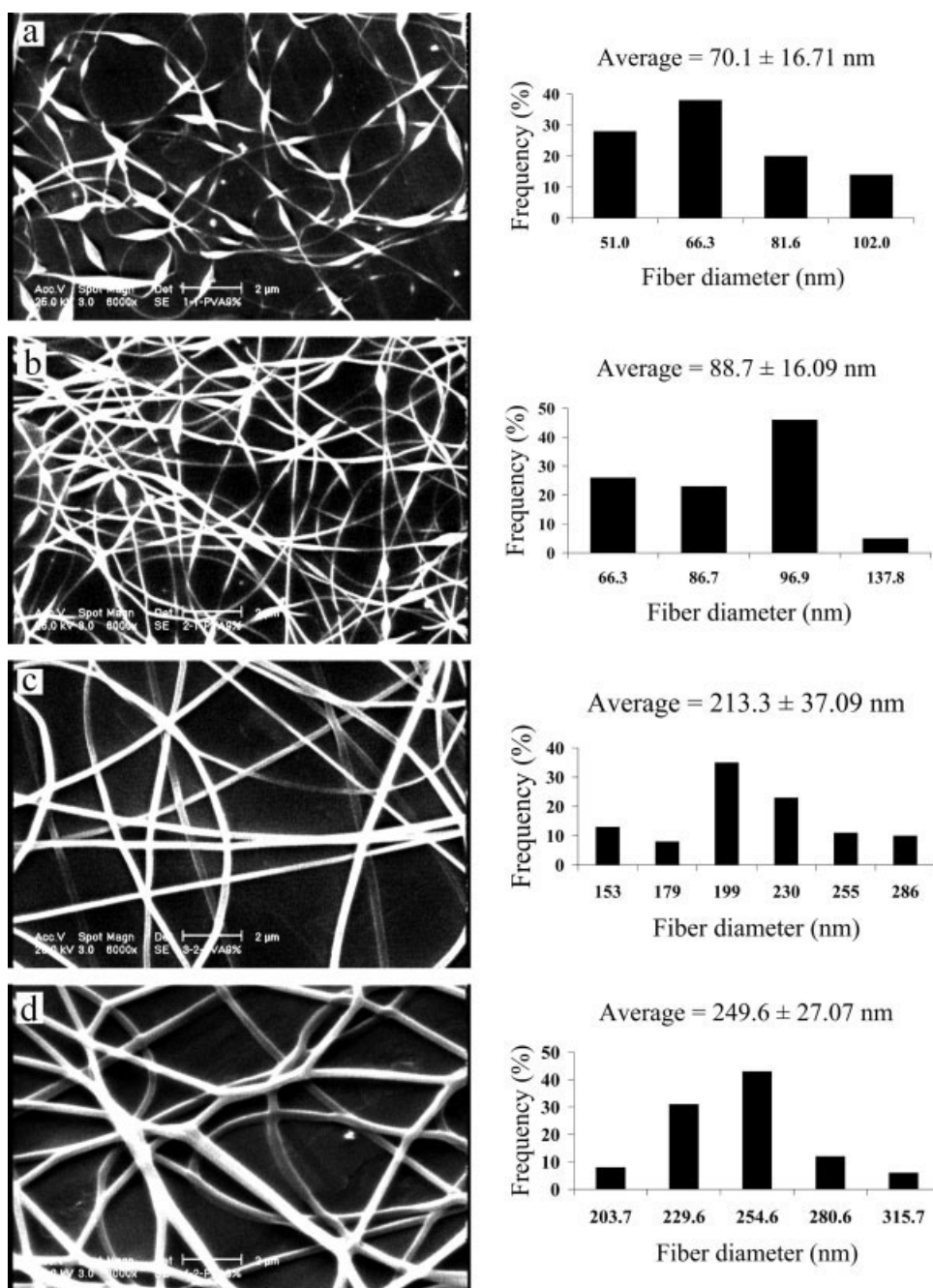


Figure 6 SEM images of electrospun nanofibers prepared from solutions of NaAlg (2%, w/v)–PVA (9%, w/v) at different volume ratios: (a) 70 : 30, (b) 50 : 50, (c) 30 : 70, and (d) 0 : 100.

Electrospinning of blended solution of 2% (w/v) alginate and 8% (w/v) PVA

Electrospun nanofibers were also prepared from blended solutions of 2% (w/v) NaAlg in DW and 8% (w/v) PVA in DW in three different volume ratios of 70 : 30, 50 : 50, and 30 : 70 (Fig. 4). At volume ratio of 70 : 30 NaAlg : PVA, as shown in Figure 4(a), homogenous and uniform nanofibers with an average diameter of 118.3 ± 14.23 nm were spun (diameter distri-

bution, 75.8–204.1 nm). At an equal volume ratio of 50 : 50 NaAlg and PVA solution blend, nanofibers with spindle-like beads were produced [as shown in Fig. 4(b); average diameter between beads, 75.1 ± 16.72 nm; diameter distribution, 51–112.2 nm]. By increasing the content of PVA in blend solution, the morphology was changed from beaded fibers to uniform fiber structure. The diameter of the electrospun nanofiber from NaAlg : PVA ratio of 30 : 70 was 126.9

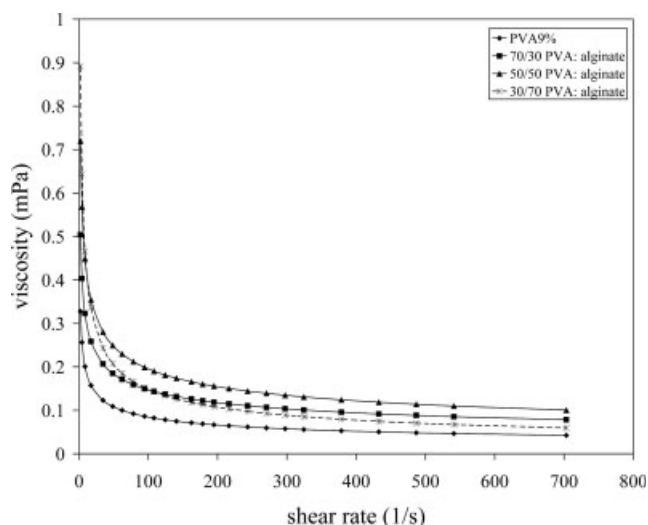


Figure 7 Shear viscosity as a function of shear rate of polymer solutions of NaAlg (2%, w/v)-PVA (9%, w/v) with different volume ratios.

± 16.45 nm [Fig. 4(c); diameter distribution, 102–153.1 nm]. Homogenous nanofibers could be electrospun from pure PVA solution (8%, w/v), which had a mean diameter of 276.7 ± 33.28 nm with diameter distribution of 255.1–306.1 nm.

Similarly, as in Electrospinning of Blended Solution of 2% (w/v) Alginate and 7% (w/v) PVA section, shear viscosity–shear rate was measured (Fig. 5). The results showed that at volume ratio of 50 : 50 NaAlg : PVA, the viscosity of the blended solution was more than the other two blended solutions. It seems that this is the main cause of no uniform structure formation of nanofibers obtained at this blend ratio. The results showed that the morphology of electrospun nanofibers progressively changed from a beaded like structure to a uniform structure as viscosity of blended solutions decreased.

Electrospinning of blended solution of 2% (w/v) alginate and 9% (w/v) PVA

At the ratios of 70 : 30 and 50 : 50 NaAlg : PVA, nanofiber with small beads were produced and the average fiber diameters between the beads were 70.1 ± 16.71 nm [Fig. 6(a); diameter distribution, 51–102 nm] and 88.7 ± 16.09 nm [Fig. 6(b); diameter distribution, 66.3–137.8 nm], respectively. By increasing the volume ratio of PVA content to 70% (NaAlg : PVA, 30 : 70), uniform nanofibers with mean diameter of 213.3 ± 37.09 nm and diameter distribution of 153–286 nm were obtained [Fig. 6(c)]. Nanofibers electrospun from pure PVA (9%, w/v) were uniform with average diameter of 249.6 ± 27.07 nm [Fig. 6(d); diameter distribution, 203.7–315.7 nm]. Figure 7 shows that the

shear viscosity of the blended solution decreased with increasing PVA content. The viscosity of the blended solution is one of the most significant parameters affecting the fiber diameter and structure of nanofibers. It seems that this viscosity difference is the main cause of nonuniform beaded structure formation of nanofibers [Fig. 6(a)] obtained at volume ratio of 70 : 30 NaAlg : PVA (9%, w/v) with higher shear viscosity in comparison with the homogenous and uniform nanofibers [Fig. 4(a)] obtained from blended solution with the same volume ratio of NaAlg : PVA but lower concentration (8%, w/v) and lower shear viscosity. Figure 8 shows shear viscosities of blended solutions with volume ratio of 70 : 30 of NaAlg (2%, w/v) and PVA (with two different concentrations of 8 and 9%).

Electrospinning of blended solution of 2% (w/v) alginate and 8% (w/v) PEO

In this section, nanofibers were electrospun from a blended solutions of alginate (2%, w/v) and PEO (8%, w/v) in the volume ratios of 70 : 30, 50 : 50, and 30 : 70 to make a comparison with the nanofibers obtained from blended solutions of alginate (2%, w/v) and PVA (8%, w/v). As illustrated in Figure 9, at NaAlg : PEO ratio of 70 : 30, nanofibers with small beads were obtained and the average fiber diameter between the beads was 80.9 ± 11.04 nm [Fig. 9(a); diameter distribution, 71.4–102 nm]. At an equal volume ratio of 50 : 50 NaAlg and PEO blend, uniform nanofibers with mean diameter of 99.1 ± 113.21 nm and diameter distribution of 71–112 nm was obtained [Fig. 9(b)]. By increasing the ratio of PEO content

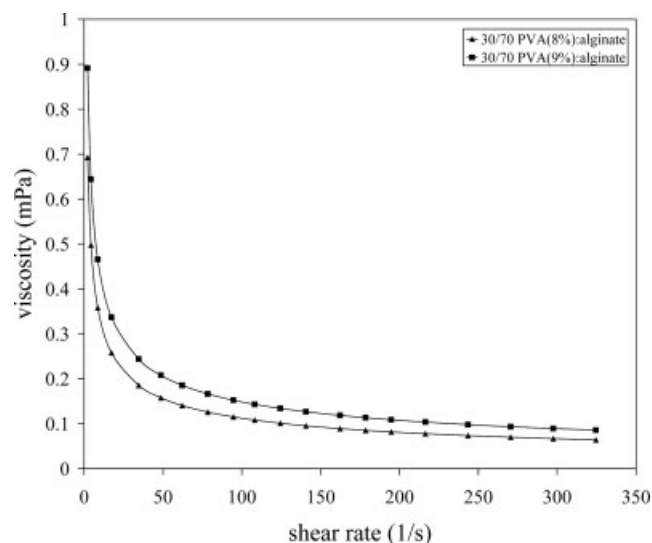


Figure 8 Shear viscosity of blended solutions with volume ratio of 70 : 30 of NaAlg (2%, w/v) and PVA (concentrations of 8 and 9%, w/v).

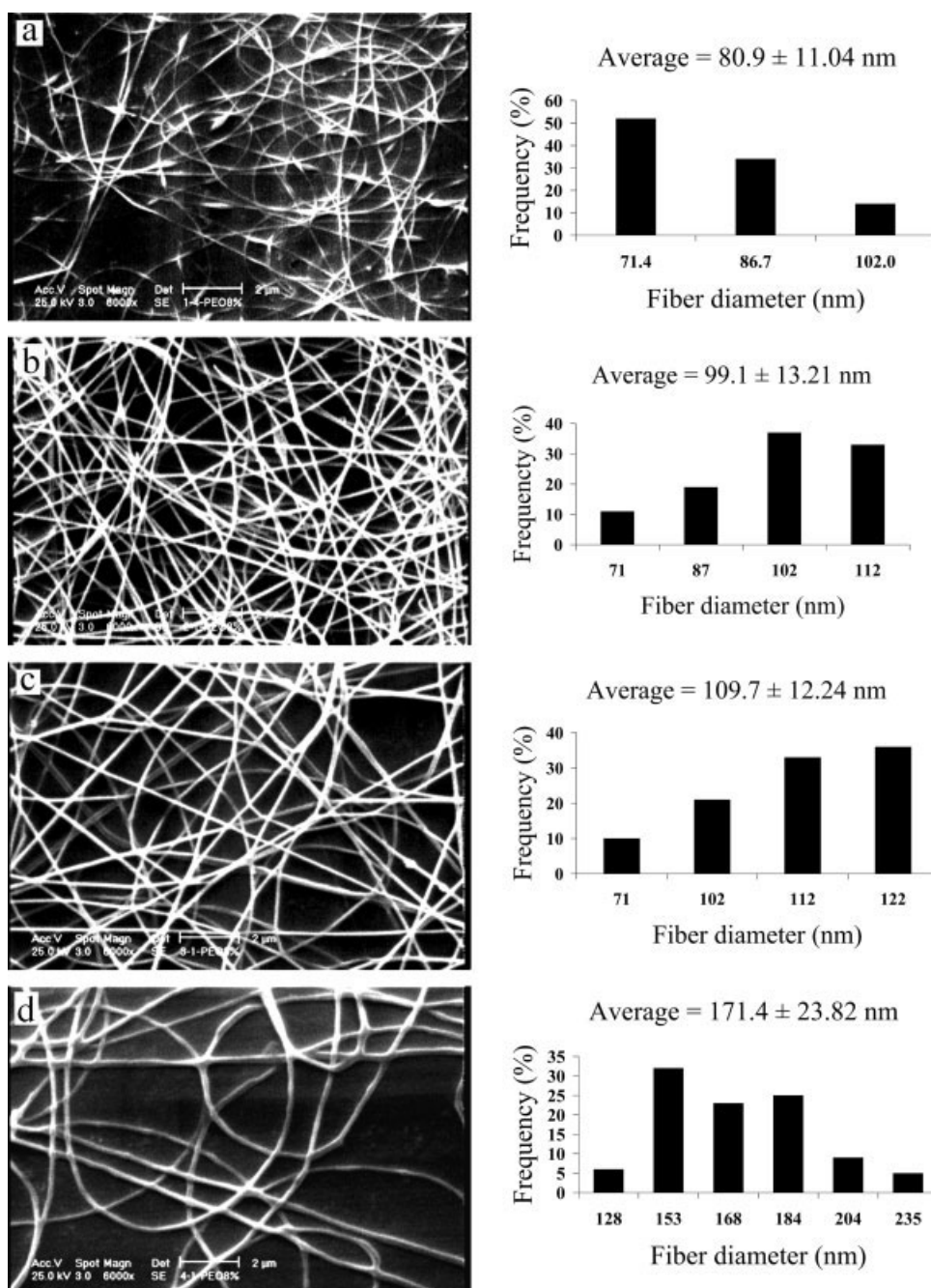


Figure 9 SEM images of electrospun nanofibers prepared from solutions of NaAlg (2%, w/v)–PEO (8%, w/v) at different volume ratios: (a) 70 : 30, (b) 50 : 50, (c) 30 : 70, and (d) 0 : 100.

(NaAlg : PEO, 30 : 70), uniform nanofibers were also produced but the fiber diameter was increased to 109.7 ± 12.24 nm [Fig. 9(c); diameter distribution, 71–122 nm]. The nanofibers electrospun from pure PEO had also uniform structure but with a thicker mean diameter of 171.4 ± 23.82 nm [Fig. 9(d); diameter distribution, 128–235 nm].

To study how the PEO content in the blended solution would affect the viscosity and thus spinnability of NaAlg solution, shear viscosity as a function of

shear rate was measured for solutions with different NaAlg/PEO ratios (Fig. 10). The results showed that the viscosity of the polymer blend solutions decreased with increasing PEO content and correspondingly such a decrease in viscosity is the main cause of further improvement in structural uniformity of nanofibers that were obtained. The decrease in viscosity with the addition of PEO can be attributed to the change in inter- and intramolecular interactions of NaAlg chains.^{9,11,12}

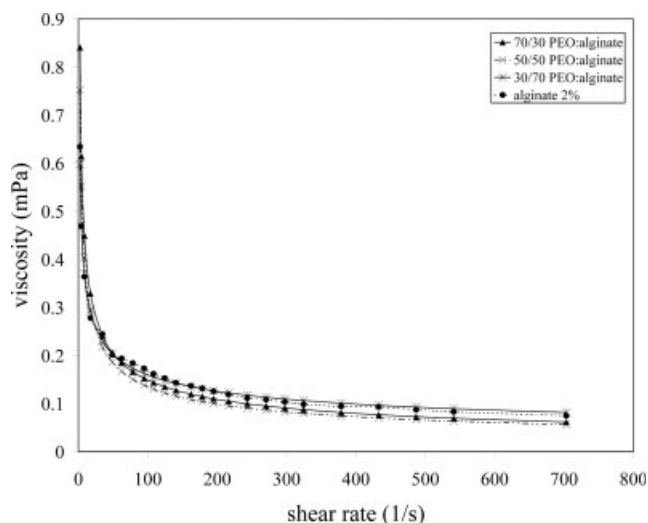


Figure 10 Shear viscosity as a function of shear rate of polymer solutions of NaAlg (2%, w/v)-PEO (8%, w/v) with different volume ratios.

Moreover, it was observed that the average diameters of electrospun nanofibers were increased by increasing the PEO content. It seems that NaAlg as an anionic polyelectrolyte increases the charge density in the ejected jets, and this leads to finer fiber formation as the NaAlg to PEO ratio increases in the solution blend. Similar results have been reported in using PEO to improve the electrospinnability of chitosan solutions by Bhattarai et al.⁷

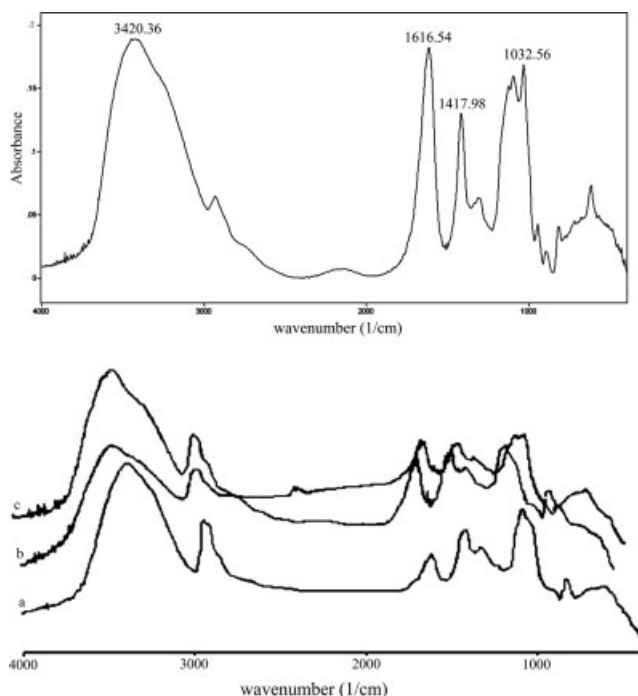


Figure 11 FTIR spectra of the pure alginate film (top) and NaAlg : PVA blend nanofibers (bottom): (a) 30 : 70, (b) 50 : 50, and (c) 70 : 30.

Fourier transform infrared spectra

FTIR spectroscopy of nanofibers electrospun from blended solutions were carried out to detect any peak shift that could be attributed to interactions between the two blended polymers such as hydrogen bonding or any complex structure formation. The FTIR spectra of blended polymers show spectral features similar to those for the individual polymers, but with some bands shifted from their original positions. Hydrogen bonds are formed between the proton-donor and proton-acceptor molecules. The intensity of the hydrogen-bonding band depends on the acidity of the hydrogen in the proton-donor, the alkalinity of the proton-acceptor, and the distance between these groups. Because of hydrogen bond formation, the covalent bonds in the donor and acceptor become weaker, while the energy barrier for angle deformation becomes higher. Hence, for the groups that are involved in the hydrogen bond formation, frequency of the valence vibrations decreases while there is a simultaneous increase in the frequency of the deformation vibrations. Figure 11 shows the FTIR spectra of the pure alginate film and NaAlg : PVA blend nanofibers in the wavelength ranges of 4000–400 cm^{-1} . The characteristic bands for the OH stretching vibration of PVA and PEO were observed at 3408 and 3410 cm^{-1} , respectively (Fig. 12). On the other hand, for the NaAlg the band appeared at 3420 cm^{-1} for the hydroxyl groups. It is worth mentioning that the bands appearing in the region of 3400 cm^{-1} belong

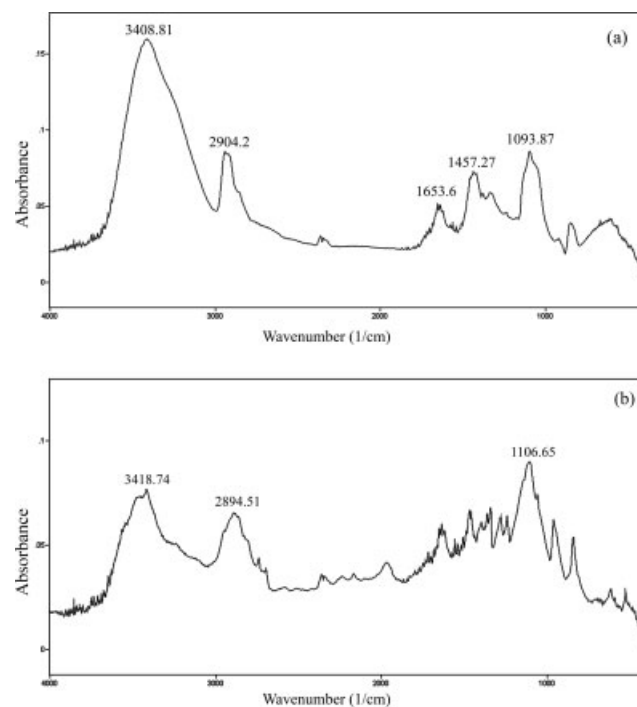


Figure 12 FTIR spectra of (a) PVA and (b) PEO.

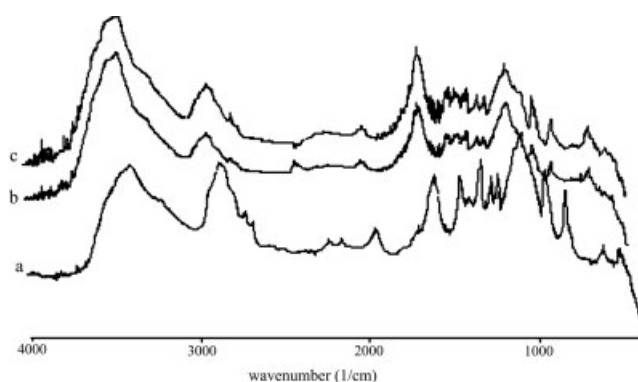


Figure 13 FTIR spectra of NaAlg : PEO blend nanofibers: (a) 30 : 70, (b) 50 : 50, and (c) 70 : 30.

to the all types of hydrogen bonded OH groups. The bands appeared at 1615 and 1417 cm^{-1} belong to the asymmetric and symmetric $-\text{COO}^-$ stretching vibrations, respectively (Fig. 11). However, the bending vibration of water also appears in about 1615 cm^{-1} .

The FTIR spectrum of NaAlg/PVA (Fig. 11) and NaAlg/PEO (Fig. 13) biconstituent nanofibers characterized by the absorption bands was typical of the pure components, with the intensity of each band roughly proportional to the blending ratio of each component. For NaAlg, the characteristic bands appeared at 1615 and 3420 cm^{-1} and these two bands were observed in all spectra of the blends. As for the spectrum of the PVA/NaAlg and PEO/NaAlg blend nanofibers, a significant difference at 1090–1617 and 1100–1600 cm^{-1} was observed (Figs. 11 and 13). The blend nanofibers that have undergone the transition step, in the fingerprint regions, show a broader CH bands compared with the pure components. This broadening of the CH band in the spectrum could be related to the conformational changes occurred. In addition, hydrogen bonding has the strongest influence on the donor (in this case the $-\text{OH}$ of NaAlg) and consequently the absorption maxima of stretching vibration shifts toward lower frequencies in comparison with the pure NaAlg. It is also observed that the bands of hydroxyl stretching became much broader with increase in NaAlg content. This strongly supports the idea that hydrogen bonding could be formed between the oxygen atoms of ether groups of PEO (or the hydroxyl groups of PVA) and the hydroxyl groups of NaAlg, and even between the PVA chains that remained close together in the blended solution.

CONCLUSIONS

The results in this research showed that a pure alginate system as such could not directly be electrospun to yield continuous and uniform nanofibers. In this

case, no jet was formed upon applying high voltage even above 20 kV. Thus, to overcome the poor electrospinnability of NaAlg solution, synthetic polymers such as PEO and PVA solutions were blended with NaAlg solution to improve its spinnability. The viscosity measurements of blended solutions showed that the alginate solution viscosity decreased by increasing the PEO or PVA content. The intermolecular interaction of PEO and PVA with alginate through hydrogen bonding improved substantially the spinnability of each blended solutions and consequently uniform and continuous nanofibers were electrospun.

The SEM images indicated that the NaAlg (2%, w/v)–PVA (8%, w/v) blended system in the volume ratio of 70 : 30 and the alginate (2%, w/v)–PEO (8%, w/v) blended system in the volume ratio of 50 : 50 could be electrospun into finest uniform nanofibers with average diameters of 118.3 nm (diameter distribution, 75.8–204 nm) and 99.1 nm (diameter distribution, 71–122 nm), respectively. FTIR analysis revealed the intermolecular interactions between PVA (or PEO) and NaAlg from the shift and change of intensity of $-\text{OH}$ and $\text{C}-\text{O}-\text{C}$ bands.

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