

# Proton conducting gel polyelectrolytes based on 2-acrylamido-2-methyl-1-propanesulfonic acid (AMPSA) copolymers with polyfunctional monomers

## Part I. Anhydrous systems

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### Abstract

The synthesis of crosslinked gel polyelectrolytes in polar aprotic solvents such as dimethylformamide (DMF) and a DMF and propylene carbonate (PC) mixture has been carried out in the copolymerization of 2-acrylamido-2-methyl-1-propanesulfonic acid (AMPSA) and polyfunctional monomers. *N,N'*-Methylene-bis-acrylamide, trioxethylene dimethacrylate ( $M_n \sim 330$ ) and trimethylolpropane ethoxylate (14/3 EO/OH) triacrylate were used as crosslinking monomers. The reactions were initiated thermally or by UV irradiation in the presence of Irgacure 184 or methyl benzoin ether. The crosslinking monomer was used in an amount of 0.5–13 wt.%. The effect of the type and concentration of the polyfunctional comonomer and type of solvent on the optical (color, transparency) and mechanical properties as well as the ability to conduct electrical charges have been studied. The application of a DMF and PC mixture enables to obtain transparent systems of good mechanical properties and high ambient temperature ionic conductivity of the order of  $10^{-3}$  to  $10^{-4}$  S cm $^{-1}$ , slightly lowered as compared with that of gels comprising DMF alone. The conducting properties of crosslinked gels have been compared with that of the AMPSA homopolymer solutions in analogous solvents. © 2006 Elsevier B.V. All rights reserved.

**Keywords:** 2-Acrylamido-2-methyl-1-propanesulfonic acid (AMPSA); AMPSA copolymers; Gel polyelectrolytes; Electrochromic devices

### 1. Introduction

Progress in the field of modern electrochemical systems, such as fuel cells, lithium batteries, chemical sensors, as well as applications taking advantage of the electrochromic effect imposes high requirements on the properties of the electrolyte fulfilling the role of a charge carrier and electrode separator. From among the high-conducting materials offered as electrolytes for application in fuel cells or electrochromic devices, polymeric sulfonic acids find great interest. These can include various types of perfluorosulfonic ionomers, polyaryketones or organically modified silicates [1]. The high price is a basic drawback of a majority of these polymers, which considerably limits the possibility of their practical application. In seeking cheaper substitutes, attempts to develop proton conducting polyelectrolytes

from the cheap and easily available 2-acrylamido-2-methyl-1-propanesulfonic acid (AMPSA) have been undertaken. Examples of using polymers of this acid in the synthesis of both proton and lithium conducting polyelectrolytes are known in the literature [2–6]. They may constitute conductors in moisture sensors [7], packing of chromatographic columns [8], membranes in lithium batteries [5,9] or fuel cells [10–12].

Crosslinked copolymers, which in the presence of suitable solvents form gels, are of special interest. In aqueous medium, the AMPSA sulfonic group undergoes complete dissociation over the whole pH range, due to which the hydrogels formed show ability to swelling irrespective of the medium pH. Hydrogels based on AMPSA copolymers with *N-tert*-butylacrylamide [10,11] or 2-hydroxyethyl methacrylate [12] were studied as potential membranes for fuel cells.

In the case of some applications, e.g. in electrooptic devices utilizing the electrochromic effect, the presence of water is unfavorable due to the quick corrosion of electrodes. Polar aprotic systems are introduced in such systems, which should assure

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high ionic conductivity and appropriate mechanical properties [13]. Examples of high-conducting gels containing organic solutions of low molecular weight phosphoric acids as materials suitable for application in electrochromic devices can be found in the literature.

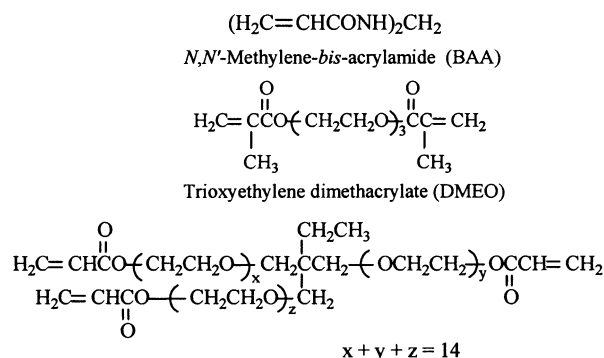
Gel polyelectrolytes achieve mechanical stability due to crosslinking, which can proceed by chemical reaction with a polyfunctional comonomer or is a physical process, in which the polymer crystallites constitute the network nodes. Both in the case of hydrogels and anhydrous systems, their ability to swelling depends on the polymer network formed.

In this work, we present the results of studies of crosslinked AMPSA copolymers with polyfunctional monomers in an organic medium. From studies carried out for polyAMPSA in the form of solutions in dimethylformamide (DMF) [14–21], it is known that such systems show high ionic conductivity values and very good optical properties. The relatively high volatility, and connected with this problems with surface drying of the electrolytes, is a disadvantage resulting from using this solvent. Propylene carbonate (PC), a typical component of gel electrolytes in lithium batteries exhibits much better properties. The small solubility of AMPSA is a limitation in the application of this solvent. In this work, we used PC and DMF mixtures of various weight ratio in order to obtain homogeneous gel electrolytes. The synthesis of organic gels was carried out by various techniques, taking advantage of radical polymerization initiated thermally or by means of UV radiation. Acrylic monomers were applied as crosslinking monomers in the synthesis of gels, with which AMPSA easily undergoes copolymerization.

## 2. Experimental

### 2.1. Materials

2-Acrylamido-2-methyl-1-propanesulfonic acid (AMPSA) (Aldrich, 99% purity), *N,N'*-methylene-bis-acrylamide (BAA) (Merck–Schuchardt), trioxyethylene dimethacrylate (DMEO) ( $M_n \sim 330$ , Aldrich, 95% purity) and trimethylolpropane ethoxylate (14/3 EO/OH) triacrylate (TAEO) (Aldrich) were used without further purification, dimethylformamide (DMF), propylene carbonate (PC) and methanol were distilled and stored in a nitrogen atmosphere.



Trimethylolpropane ethoxylate (14/3 EO/OH) triacrylate (TAEO)

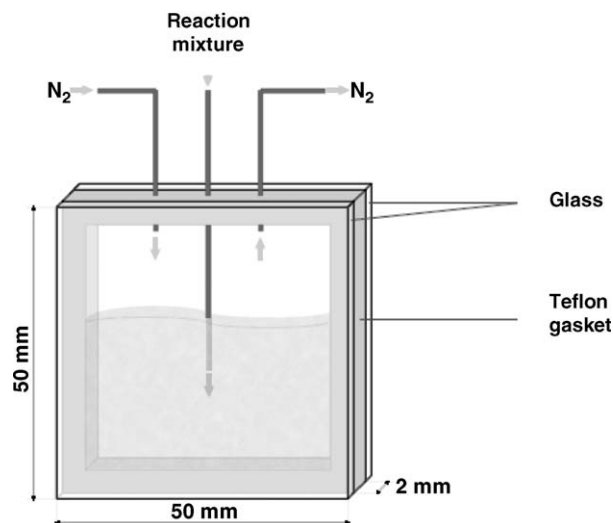


Fig. 1. Model of a window for obtaining gel electrolytes.

### 2.2. Preparation of gel electrolytes

The synthesis of gel electrolytes was carried out by two methods applying thermal initiation or by means of UV irradiation. The reactions initiated thermally were carried out in the atmosphere of pure and dry nitrogen in glass ampoules or in a thin layer between two glass plates (Fig. 1). The polymerization was carried out at 70 °C in the presence of benzoyl peroxide (1 wt.%) as the radical initiator. After introduction of the AMPSA solution, crosslinking monomer and initiator in an organic solvent to a previously nitrogen flushed window model, the whole was placed in a thermostated chamber. The reaction system was heated for 5–30 min depending on the crosslinking monomer used. Homopolymers in the form of viscous solutions were obtained in pressure glass ampoules in a nitrogen atmosphere.

The photoinitiator Irgacure 184 or benzoin methyl ether (BME) were used in reactions initiated by UV irradiation. A thin layer of the monomer solution was placed on the glass surface with a Teflon® spacer in a nitrogen filled chamber and then irradiated perpendicularly from a distance of 20 cm by means of a UV lamp of 4 × 15 W or 300 W power (Fig. 2). The irradiation time was from 2 to 20 min, depending on the power of the lamp used and kind of photoinitiator. In the case

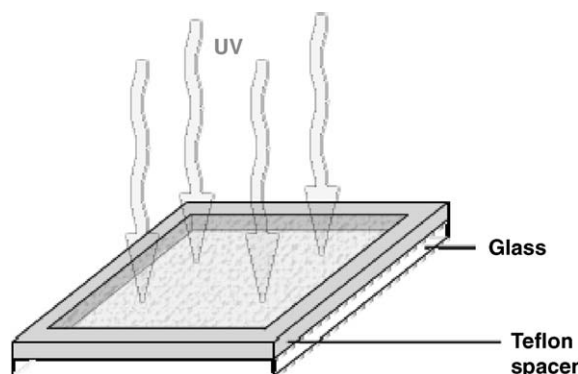


Fig. 2. Model of a window for obtaining gel electrolytes by the polymerization initiated by UV irradiation.

of reactions carried out in the atmosphere of air, the time of obtaining a gel was from 10 to 60 min.

### 2.3. Techniques of studying the electrolytes

#### 2.3.1. Impedance spectroscopy

Ionic conductivity was determined using the complex impedance method in the temperature range from  $-60$  to  $70$  °C. The samples were sandwiched between stainless steel blocking electrodes and placed in a temperature-controlled oven. The impedance measurements were carried out on a computer-interfaced Solartron–Schlumberger 1255 impedance analyzer over the 1 Hz to 1 MHz frequency range. The reproducibility of impedance spectroscopy results was checked by multiple experiments performed at room temperature. The results for samples of the same composition do not differ by more than  $\pm 5\%$ .

#### 2.3.2. Viscosity measurements

Viscosity measurements were carried out by means of a Mettler-Toledo RM180 rotational viscometer at  $25$  °C. Viscosity as function of shear strength was measured.

#### 2.3.3. Solvent take-up of membranes

The freshly prepared gel electrolytes were weighed and immersed in water or methanol at room temperature. After a certain time, the wetted membranes were blotted dry with absorbent

paper before weighing again. The amount of embedded solvent was calculated based on the difference in the gel mass before and after keeping in a solvent for a given period.

## 3. Results and discussion

### 3.1. Synthesis of gel polyelectrolytes

The synthesis of crosslinked gel polyelectrolytes under anhydrous conditions in the copolymerization of AMPSA with polyfunctional monomers was carried out. BAA, DMEO and TAE0 were used as crosslinking monomers.

The reactions were carried out by various methods in order to study the effect of the copolymerization initiation mode and mode of gel formation on the properties of the systems prepared, and their ability to water and methanol embedding. The reactions were carried out in polar aprotic solvents such as DMF and a DMF and PC mixture at a polymer matrix (AMPSA + crosslinking comonomer) content of 20 wt.%. The crosslinking comonomer was used in a 0.5–13 wt.% content. Two methods of initiation were applied: thermal in the presence of benzoyl peroxide and by UV irradiation in the presence of Irgacure 184 or BME. The mechanical and optical properties (color, transparency) of the gels obtained were evaluated in relation to their application in electrochromic devices. The synthesis conditions and results obtained are presented in Table 1.

Table 1

Conditions of obtaining gel polyelectrolytes based on 2-acrylamido-2-methyl-1-propanesulfonic acid (AMPSA) copolymers with monomers bearing a various number of functional groups ( $f$ ) in organic solvents

Crosslinking monomer	Share of crosslinking monomer in polymer matrix		Time of crosslinking <sup>a</sup> min				Electrolyte appearance
	wt.%	mol% $\times f$	Method A <sup>b</sup>	Method B <sup>c</sup>	Method C <sup>d</sup>	Method D <sup>e</sup>	
BAA <sup>f</sup> $f=2$	0.5	1.3	5–15	10–15 (20–30)	15–20 (30–60)	2–5 (10–15)	Transparent, flexible
	1	2.6					Transparent, flexible
	2	5.2					Transparent, flexible
	5	13.0					Transparent, less flexible
	5 <sup>g</sup>	13.0					Transparent, flexible
	5 <sup>h</sup>	13.0					Transparent, flexible
	6	15.6					Milky-white, brittle
	6 <sup>g</sup>	15.6					Milky-white, brittle
	7.5 <sup>g</sup>	19.5					Milky-white, brittle
	10	26.0					Milky-white, brittle
TAE0 <sup>h</sup> $f=3$	2	1.3	15–30				Transparent, flexible
	3	2.0					Transparent, flexible
	5	3.3					Transparent, flexible
	6	3.9					Opalescent, less flexible
	10	6.6					Milky-white, brittle
DME0 <sup>h</sup> $f=2$	2–5	2.6–6.6	10–20				Transparent, flexible
	5–13	6.6–17.2					Milky-white, brittle

Polymer matrix content (AMPSA + crosslinking monomer) 20 wt.%.

<sup>a</sup> Times of crosslinking presented are the average ones for a given method and crosslinking monomer; values without parentheses concern reactions carried out under argon, and those in parenthesis—under air.

<sup>b</sup> Process initiated thermally (initiator: benzoyl peroxide), reaction temperature  $70$  °C.

<sup>c</sup> Process initiated by UV irradiation (initiator: Irgacure 184), irradiation source: four Philips CLEO, 60 W lamps.

<sup>d</sup> Process initiated by UV irradiation (initiator: benzoin methyl ether), irradiation source: four Philips CLEO, 60 W lamps.

<sup>e</sup> Process initiated by UV irradiation (initiator: Irgacure 184), irradiation source: Polar 300 W lamp.

<sup>f</sup> Solvent: DMF and PC mixture of 1:1 (w/w).

<sup>g</sup> Solvent: DMF and PC mixture of 1:3 (w/w).

<sup>h</sup> Solvent: DMF.

Polymers of a gel structure have been obtained from the copolymerization of AMPSA with the studied crosslinking monomers in the presence of aprotic organic solvents. The properties of the gels obtained are affected by the polyfunctional comonomer concentration, and hence the crosslinking density of the polymer matrix. In the case of BAA, fully transparent and flexible electrolytes are obtained at this comonomer content of 0.5–2 wt.%, which corresponds to the molar content multiplied by the number of unsaturated bonds ( $f=2$ ) 1.3–5.2 mol%. With a further increase in the BAA concentration, a decrease in the gel flexibility is noticeable. Systems containing over 5 wt.% (mol%  $\times f=13$ ) of the crosslinking agent are brittle and loose transparency, take on a milky-white coloring, more and more intense with an increase in the amount of BAA. At the same time, the adhesion of the gels to the glass surface decreases.

The effect of the type of crosslinking monomer on the gel properties is also noticeable; the larger the distances between the nodes, the better are the properties shown by the gel at a smaller content of the crosslinking monomer. In the case of copolymerization with TAE0 ( $f=3$ ), the best mechanical and optical properties shown by the gel were at a molar content multiplied by the monomer functionality not exceeding 3 mol%, i.e. at a nearly four times lower concentration of functional groups than that in the case of BAA. A decrease in flexibility and worsening of the gel transparency also occurs with an increase in the content of this monomer, similarly as that in the case of systems with BAA (Table 1). At 10 wt.% of TAE0 (mol%  $\times f=6.6$ ), a milky-white, brittle gel was formed. Similar results are observed in the case of DME0, for which the distances between the functional groups are several times greater than that for BAA.

Some differences in the properties of the gels obtained can also be noticed with a change of the solvent. DMF and a PC and DMF mixture were applied in the studies. Partial replacement of DMF by PC (AMPSA does not dissolve in PC) is of purpose from the point of view of practical applications (propylene carbonate is a solvent of wider window potential, less hygroscopic and less volatile). The application of DMF in a mixture with PC in the synthesis of gels permits to achieve transparent systems of good mechanical properties at a lower content of the crosslinking agent; in the case of BAA, this is 0.5 and 1 wt.%, which are maintained to the BAA content up to 5 wt.%.

The crosslinking times in the case of reactions initiated thermally, in the atmosphere of an inert gas, are equal to 5–15 min for BAA, 10–20 min for DME0 and 15–30 min for TAE0, depending on the amount of the crosslinking monomer (Table 1). In the case of initiating the polymerization by means of UV irradiation, the time of gel formation is affected by the type of the photoinitiator used and power of the source of irradiation applied. The initiator Irgacure 184 appeared to be more effective in the obtaining of gels. Moreover, it was observed that all the crosslinked systems resulting from the reaction initiated thermally (at 70 °C, with benzoyl peroxide as initiator) do not change their optical properties in time. In the case of gels obtained in the UV initiated polymerization, their appearance depends on the type of photoinitiator used. The use of BME causes after several hours of reaction completion, a change in the gel coloring to slightly

yellow, probably as a result of side reactions of the initiator decomposition products.

The synthesis of gels has been performed directly in the window model, carrying out the crosslinking on a glass surface or between two layers of glass with deposited electrode layers (Figs. 1 and 2). In the case of applying DMF or a DMF and PC mixture as a solvent, the maximum monomer concentration is limited by their solubility. The maximal AMPSA and BAA (20:1) concentration at room temperature was found to be 41 wt.%. At a 20 wt.% monomer concentration, an ambient temperature homogeneous solution is obtained at a maximal weight excess of PC in relation to DMF equal to 1.4. In the studies presented, gels are obtained containing 20 wt.% of the polymer matrix at an equiweight ratio of both solvents, for the composition of which the ambient temperature monomer solubility is maintained. The crosslinking was carried out by thermal initiation or by means of UV irradiation. If the process was carried out under inert gas conditions, then the times of gel formation in a thin layer were comparable with those of reactions in bulk. However, when the copolymerizations were carried out in the atmosphere of air, an oxygen inhibition effect was observed, which caused elongation of the crosslinking time, even a several-fold one (Table 1).

Moreover, gels obtained involving a crosslinking comonomer in an up to 5 wt.% amount with respect to AMPSA are characterized by relatively good adhesion to the glass surfaces applied. After polymerization completion, the gel obtained acts as an electrolyte and glue binding both electrodes. This is important from the viewpoint of applying the described gel electrolytes in electrochromic devices, such as, e.g. windows of controlled light transmission.

### 3.2. Embedding of AMPSA gel polyelectrolytes

In some applications of gel polyelectrolytes in the form of crosslinked systems, such as, e.g. moisture sensors, the ability to water embedding is an essential parameter. Gels comprising 5 wt.% of the crosslinking comonomer (with respect to AMPSA) obtained in DMF have been applied for studies on the behavior, towards water, of gels formed in the organic solvent medium. For comparison, analogous studies on the gel structure towards another proton solvent—methanol, have been carried out (Figs. 3 and 4).

In the case of water, greater embedding was shown by electrolytes crosslinked with TAE0; after 168 h, the mass increase was about 16,000% (2.5 g of the gel embedded 400 g of water) with retaining the gel structure. This same polyelectrolyte in methanol, during 48 h increased its mass by about 2400% (2.5 g of the gel embedded 60 g of methanol), and after 72 h, it underwent complete digestion. Systems crosslinked with BAA showed lesser ability towards water embedding. After 168 h, the mass increase in both solvents is similar and is about 2400% (2.5 g of the gel embeds about 60 g of water and methanol). AMPSA copolymers with TAE0, after 48 h of immersion in water, reach a nearly linear mass increase equal to about 40–50 g per day, which is shown in Fig. 4. A lack of a swelling border of these gels in H<sub>2</sub>O and relatively rapid loss of structure in

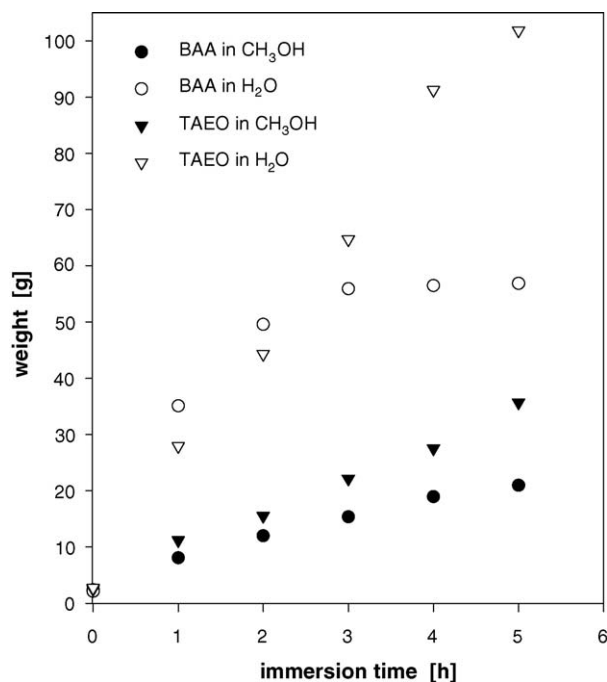


Fig. 3. Embedding of gel polyelectrolytes of AMPSA crosslinked with 5 wt.% of BAA or TAEO in water or methanol in the first 5 h.

methanol disqualify these systems for practical applications. However, the AMPSA and BAA copolymers, both in water and methanol, after 24 h reach practically a maximum of water embedding, and during subsequent days only slightly increase their mass and shape. The different crosslinking density and distances between the network nodes is the reason for the differences in behavior of both systems in water and methanol. The application of BAA in an amount of 5 wt.% (with respect to AMPSA) corresponds to 6.5 mol%, whereas in the case of TAEO, at the same weight percentage share, it is 1.1 mol%. When considering that BAA is a difunctional monomer and

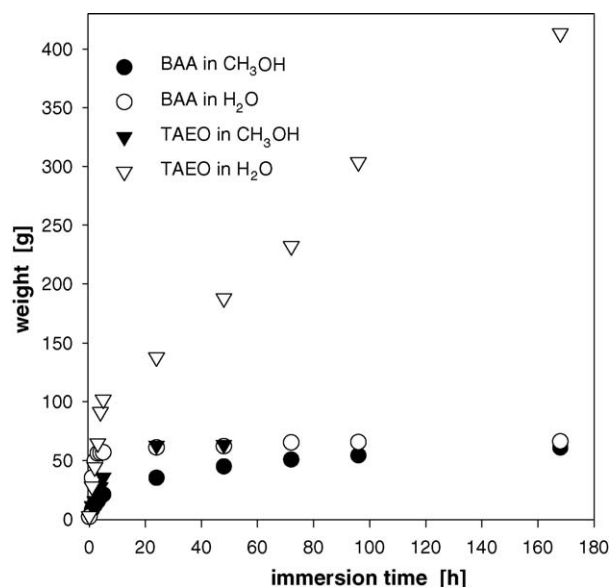
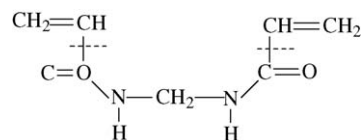


Fig. 4. Embedding of gel polyelectrolytes of AMPSA crosslinked with 5 wt.% of BAA or TAEO in water or methanol.



Scheme 1. Repeating unit between the network nodes in the AMPSA/BAA system.

TAEO a trifunctional one, then still the mole concentration of unsaturated bonds is several times lower. In the case of BAA, there are five atoms between the nodes of the network (a repeating unit between the network nodes in the AMPSA/BAA system is presented in Scheme 1), whereas in the case of TEAO there are at least eight oxyethylene units between the nodes. These differences in the structure cause that less solvent can be placed in the more dense structure of the gel involving BAA than that in the case of TAEO.

### 3.3. Conductivity of AMPSA gel polyelectrolytes

The proton conductivity of gels obtained in DMF and DMF/PC mixtures was studied. In the case of AMPSA copolymerized with BAA, the systems studied contained from 0.5 to 2 wt.% of the crosslinking agent with respect to AMPSA and an equiweight PC and DMF mixture. The results obtained are presented in Fig. 5.

The system comprising 0.5 wt.% of BAA shows ambient temperature conductivity of  $1.4 \times 10^{-3} \text{ S cm}^{-1}$ . An increase in the crosslinking density causes only slight changes in conductivity, at 2 wt.% of BAA, it is  $9.4 \times 10^{-4} \text{ S cm}^{-1}$ . At such small structural changes of the gel, no effect of the amount of crosslinking agent on proton transport in the gel is observed. Similarly, for gels crosslinked with TAEO and containing DMF, within the applied amounts of the trifunctional comonomer of 2–5 wt.%, no clear effect of its content on the electrolyte conductivity is observed (Fig. 6).

The type of solvent used is of much greater importance for the charge transport. In order to establish its effect on conductivity,

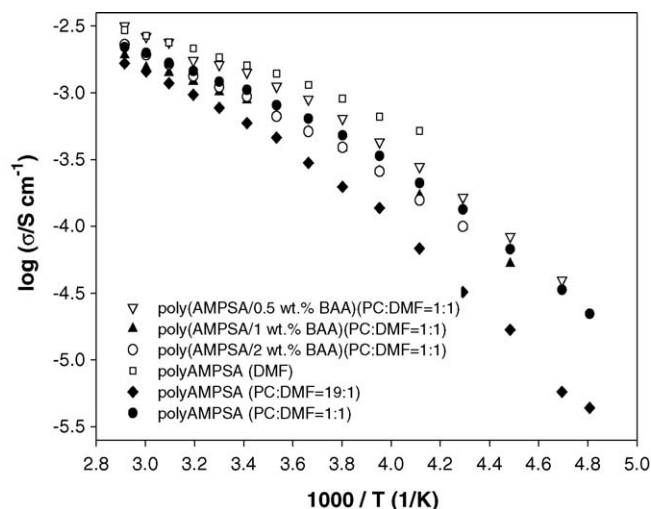


Fig. 5. Conductivity of polyAMPSA and gel electrolytes crosslinked with BAA in organic solvents at a 20 wt.% content of the polymer matrix.

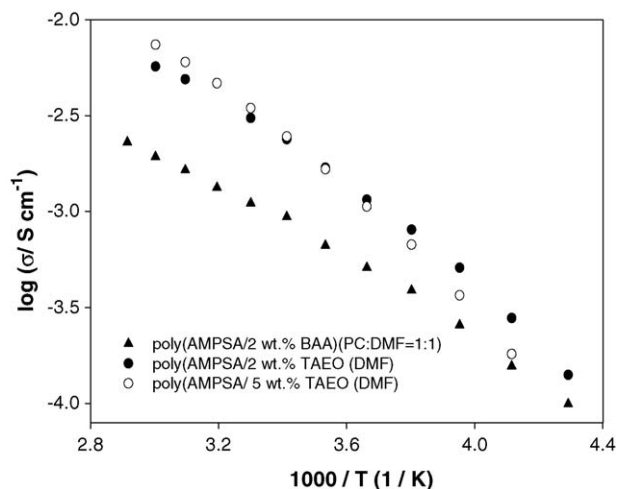


Fig. 6. Conductivity of gel polyelectrolytes of AMPSA crosslinked with BAA or TAE0, containing 20 wt.% of the polymer matrix.

non-crosslinked electrolytes were studied in the form of viscous solutions containing 20 wt.% of the polyAMPSA polymer matrix. Thus, a clear effect of the solvent can be observed, which is not affected by the polymer network structure. Fig. 5 shows the conductivity of electrolytes involving DMF and a PC/DMF mixture at a weight ratio of 1:1 and 19:1. As can be noticed, the conductivity of the solution in DMF is considerably higher over the whole temperature range studied. The addition of PC causes a decrease in conductivity, which is much evident the more PC is present in the mixture. A similar effect is observed for electrolytes in the form of crosslinked gels. Fig. 6 shows the conductivity of systems crosslinked with 2 wt.% of TAE0 and containing DMF or an equiweight PC and DMF mixture. The presence of PC causes a nearly double decrease in the ambient temperature conductivity.

The polymer gel structure should be taken into account when investigating the differences in conducting properties of the electrolytes described. The nodes of the network formed by the AMPSA copolymer with a polyfunctional monomer are not regularly distributed over the gel volume, but result from the reactivity of comonomers. The kinetic model describing the copolymerization in such a system is complicated and until now no reactivity ratios for the AMPSA copolymerization with polyfunctional monomers have been determined. Based on the data for the AMPSA and acrylamide (AA) copolymerization ( $r_{AA} = 1.05$  and  $r_{AMPSA} = 0.42$ ) [2], it can be assumed that the crosslinking monomer is consumed in the initial reaction stage. Thus, the system consists of copolymer nets, which provide

mechanical properties, and of AMPSA homopolymer chains, in the form of a solution captured in network nodes. Such a structure of the gel is indicated by the result of fractionation of the crosslinked form with water by means of a Soxhlet apparatus. Data for hydrogels are presented elsewhere [22]. At 5 wt.% of BAA, ca. 50 wt.% of AMPSA homopolymer is washed out. Therefore, it should be expected that local viscosity of the liquid phase might affect the differences in ionic conductivity of the gels studied. At constant temperature and pressure, the viscosity of polymer solutions is a function of the solution concentration and polymer molecular weight and in an essential way depends on the solvent's properties and strength of its interaction with the polymer chains. The properties of polyAMPSA solutions in various solvents as a function of the polymer matrix concentration have been described by us earlier [14]. From these studies, it results that the introduction of PC to the solutions of polyAMPSA of the same relative molecular weight and the same polymer concentration considerably changes the properties of the solution, causing a rapid increase in viscosity, among others. At the PC content of 75 wt.%, the viscosity of the solution is higher by about two orders of magnitude with respect to that of the DMF solution. The viscosity is still higher at a 95 wt.% content of PC. Thus, the decrease in conductivity resulting from the introduction of PC to the gel can be explained by a decrease in mobility of protons due to an increase in the local viscosity of the solution closed within the polymer network mesh.

The temperature dependence of conductivity for polyAMPSA solutions in various solvents is described by the Arrhenius equation [14]. The conductivity in DMF solutions, which is a good proton acceptor, is characterized by relatively low activation energy, ca.  $12 \text{ kJ mol}^{-1}$ . Charge transport in such an electrolyte proceeds according to the Grotthuss mechanism consisting in proton hopping between the solvent molecules. The presence of PC in the electrolyte causes an increase in the  $E_a$  value to  $17 \text{ kJ mol}^{-1}$  at its 3-fold excess with respect to DMF and  $27 \text{ kJ mol}^{-1}$  at a 19-fold excess. In this latter case, only 0.5 DMF molecules fall per one acid group and it can be assumed that charge transport proceeds rather as diffusion of protonated DMF molecules, than proton exchange between the solvent molecules (vehicle mechanism). At room temperature these systems show a 1000 times higher viscosity than systems with DMF alone, despite that their conductivity is only 2.5 times smaller. This indicates that diffusion barriers and proton transport mechanism do not play a decisive role for the conductivity value of these systems. The possibility of formation of charge carriers by the solvent seems to be of greater importance.

Table 2  
Test conditions of AMPSA gel polyelectrolyte in a model electrochromic window

Electrolyte	Cathode	Anode	Coloration time	Discoloration time
Matrix (20 wt.%): AMPSA/BAA (2 wt.%) copolymer Solvent (80 wt.%): PC:DMF (1:1) Thermal initiation (benzoyl peroxide, 1 wt.%), 70 °C Layer thickness: 300 $\mu\text{m}$ Potential: 1.5 V	WO <sub>3</sub>	NiO <sub>2</sub>	5 s	10 s (complete after 2 min)

The selected gel electrolyte, comprising 2 wt.% of BAA, obtained by the thermal method, was studied in an electrochromic window model (Table 2). This model consisted of glass surfaces doped with layers of conducting glass ITO and electrode material  $\text{WO}_3$  (cathode) and  $\text{NiO}_2$  (anode). A Teflon® spacer of 300  $\mu\text{m}$  in thickness was placed between the layers. A voltage of 1.5 V was applied to the platinum electrical outlets. A change in coloring (coloration time) was achieved after 5 s. Return to a completely colorless form takes place after 2 min.

#### 4. Conclusions

AMPSA readily undergoes copolymerization with polyfunctional monomers, in a medium of organic aprotic polar solvents, such as DMF or a DMF and PC mixture, forming gel polyelectrolytes of properties dependent on the crosslinking density and type of crosslinking monomer and solvent. These electrolytes are characterized by high ionic conductivity, of the order of  $10^{-4}$  to  $10^{-3} \text{ S cm}^{-1}$  at 20 wt.% content of the polymer matrix, only slightly lower with respect to that of AMPSA homopolymer solutions. The gradual replacement of DMF by PC causes a gradual decrease in conductivity resulting probably by an increase in viscosity of the gel's liquid phase. PC undergoes protonation with great difficulty [17], and therefore, at its high share in the mixture of solvents the conduction mechanism consists in the mobility of protonated DMF molecules in the PC solution (vehicle mechanism).

By appropriate selection of the polymerization method and crosslinking comonomer it is possible to obtain in a short time gels in the form of flexible membranes or thin layers deposited on a glass surface or directly between the layers of glass surfaces. At appropriate crosslinking density these gels are transparent and colorless and show high adhesion to glass. Due to these features, they are an attractive material for application in electrochromic devices or other electrochemical devices. The application of a PC and DMF mixture as an aprotic solvent leads to limitation in the evaporation of the solvent from the gel, due to the low volatility of PC. Moreover, PC is characterized by lower hygroscopicity, toxicity and wider potential window in comparison with DMF or DMA.

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