A Study of the Interaction between Chitosan and Poly(Ethylene Glycol) by Viscosity Method

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Abstract: The viscometric coefficient, k_{AB}, characterizing the interaction of chemically dissimilar polymer segments was estimated from changes of the intrinsic viscosity of chitosan in "pseudosolvents," i.e., dilute solutions of poly(ethylene glycol) (PEG) in a solution of 0.1 M acetic acid/0.2 M sodium acetate (1:1). The blends were studied at 25°, 35°, and 45°C. The miscibility between chitosan and PEG was found to increase with the temperature of the measured systems and to decrease with increasing molar mass of PEG. In the cases where favorable compatibility was exhibited between chitosan and PEG, H-bonding interaction between the two polymers should be strong enough to overcome the intra- and intermolecular H-bonding among chitosan chains.

INTRODUCTION

Chitosan is a polysaccharide primarily obtained as a result of deacetylation of chitin. Chitin is present in the extra-skelletal material of crustaceans.[1] There is an increasing interest in the application of chitosan and chitin in a wide range of technologies, taking advantage of their special properties such as biocompatibility, biodegradability, reactivity,

nontoxicity, and adsorption properties.[2] Chitosan can also be applied as a (often very effective) chelating agent for removing heavy toxic metals from sewage,[3] and because of its good film-forming properties, for covering drugs in biomedicine,[4–8] for protecting seeds in agriculture,[9] and in the food industry.[10] Nevertheless, the applications of chitosan are limited by its poor solubility. Furthermore, the amine groups of chitosan are protonated in acid solutions and the chitosan would be expected to exhibit behavior typical of a polyelectrolyte.[11] Studying polyelectrolytes in aqueous solutions requires an addition of a salt to minimize the electrostatic contributions and to screen ionic sites along the chains. From the technological point of view, it is extremely important that chitosan is water soluble and positively charged. These properties enable chitosan to interact with negatively charged macromolecules and even with certain polyanions in aqueous solutions.

Poly(ethylene glycol) (PEG) is a biodegradable, hydrophilic polymer that has found uses in cosmetic, ceramic, and pharmaceutical industries[12] for its water solubility, low toxicity, thermoplasticity, and flocculation ability. It is also inherently biocompatible for applications in transplantation, drug delivery, and as a component in medical devices. Selecting an uncharged polymer like PEG as a second polymer might avoid a strong interaction between the components. At the same time, PEG is a flexible polymer and it would significantly change mechanical properties of the blends.[13]

It is well known that the majority of polymer pairs are incompatible. This incompatibility leads to a separation that affects the properties of the polymer blends. Since both chitosan and PEG have many common properties, knowledge of miscibility of these polymers may be useful for cosmetic, pharmaceutical, and biological formulations in solution or in solid state.

In recent years, chitosan viscosity behavior has been investigated by several authors.[14–16] However, very few investigations of the viscosity behavior of mixed dilute solution and of the interaction between two kinds of macromolecules were carried out. In these studies, authors have used many criteria of polymer-polymer miscibility determined by the viscosity method, i.e., the interaction parameter μ proposed by Chee,[17] the thermodynamic parameter α,[18] and the miscibility parameter Δb[19] and Δk.[20] As most of these methods are rather time consuming, a simple viscometric method has been proposed.[21–23] It is referred to as the method of "polymeric solvents" or "pseudosolvents." The intrinsic viscosity, $[\eta_A]_B$, of polymer A is measured in mixed solvents consisting of a low-molar mass solvent and polymer B of various concentrations, c_B. The interaction is characterized by the coefficient k_{AB} evaluated from the dependence of $[\eta_A]_B$ versus $[\eta_B]c_B$ or, more precisely, as $k_{AB} = \text{slope}/2$ from the slope of the plot of $p^*(\eta_r)_B$ versus $[\eta]_B c_B$, where $p^* = [\eta_A]_B/[\eta_A]$.

The symbol $(\eta_r)_B$ stands for the relative viscosity of the "pseudosolvent," $[\eta_A]_B$ is the intrinsic viscosity of polymer A in the "pseudosolvent," and $[\eta_A]$ and $[\eta_B]$ are the intrinsic viscosities of polymer A and polymer B, respectively, in the low-molar mass solvent. A necessary condition for good estimation of the coefficient k_{AB} is the linearity of the plot mentioned above.

The coefficient k_{AB} is an analogy to the Huggins coefficient, k_H, which is well known from studies of binary systems. Whereas the latter coefficient reflects the interaction of two molecules of the same polymer, the former is characteristic of the interaction of two molecules of polymers A and B.

The Huggins coefficient contains the contributions from the hydrodynamic and thermodynamic interactions. Since under Θ-conditions, the thermodynamic contribution vanishes, the value of $k_H = 0.5$ may be associated with the hydrodynamic interaction. Under Θ-conditions, polymer molecules can overlap without restriction. As the thermodynamic quality of the solvent is improved, overlapping is reduced due to the prevalence of the "repulsive" interactions, which are manifested in a decrease of k_H to values lower than 0.5. Below the Θ-temperature, the attractive interactions prevail and the Huggins coefficient becomes higher than 0.5.

In analogy with the Huggins coefficient, the k_{AB} parameter will probably be dependent on the solvent. There is no theory for this parameter, so the same picture is adopted for polymer molecules.[23]

The method of "pseudosolvents" has been applied to a variety of systems.[21–23] Most of these have consisted of nonpolar or weakly polar polymers. No systematic study, however, has been devoted to amphiphilic polymer-containing hydrophobic and hydrophilic groups, where complicated interactions can be expected at various concentrations.

The aim of this work is to study the compatibility of the pair chitosan and PEG in dilute solution by viscometry. This method is the most suitable technique since it is a convenient, effective, easy, fast, and inexpensive procedure and it provides information on the interactions at the molecular level. The purpose of the study was to estimate the k_{AB} coefficient and its dependence on the temperature and molar mass of PEG.

The following rules have been deduced from the published literature: [21–23]

(1) If $k_{AB} < 0.5$, the intrinsic viscosity of polymer A in "pseudosolvent" is a decreasing function of $[\eta_B]c_B$. If $k_{AB} > 0.5$, the dependence exhibits a maximum.

(2) Incompatibility (repulsive interaction) of chemically dissimilar polymer segments is indicated by $k_{AB} < 0.5$. If $0.5 < k_{AB} < 0.6$, the segments are compatible. The values of $k_{AB} \gg 0.6$ indicate stable polymer complexes.

EXPERIMENTAL SECTION

Materials

The chitosan (polymer A) was CEROSAN, type 5000, of food quality, produced by C.E. Roeper GmbH (Hamburg, Germany), degree of deacetylation 90%, and the poly(ethylene glycol) (PEG) (polymer B) was SLOVAPEG, number-average molar masses M_n 300, 1000, and 6000 g/mol provided by Chemické závody (Nováky, Slovak Republic). A solution of 0.1 M CH_3COOH/0.2 M CH_3COONa (1:1, pH 4.9) was used as the solvent. Both the acid and the salt were the products of Lachema Brno (Czech Republic) and used without further purification.

Preparation of Solutions

Solutions used in the viscosity measurements were prepared in the following way. Polymer B (PEG), whose solutions were used as the "polymer solvents," were dissolved to give a series of solutions having different concentrations (Table I).

Stock solutions of PEG were prepared by heating samples with 0.1 M CH_3COOH/0.2 M CH_3COONa for 1 h at $60^{\circ}C$ in volumetric flasks. After dissolution and filtration through a glass filter (S2), the second polymer, A (chitosan, concentration 0.25 g/dL), was dissolved in this "polymer solvent" by shaking for 1 h. Then the mixture was left standing for 24 h at room temperature. Concentrations of "polymer solvents" were chosen so that the solutions were perfectly dissolved; viscometry flow times were at intervals above 90 s and under 250 s.

Viscometry

The viscosities of the solutions were measured at 25°, 35°, $45^{\circ} \pm 0.05^{\circ}C$ in a Ubbelohde capillary viscometer adapted for subsequent dilutions. The intrinsic viscosities, $[\eta]$, were calculated by a linear regression of the

Table I. Concentration of "polymer solvent"

Polymer	Temperature [$^{\circ}$C]	Concentration [g/dL]
PEG 6000	25, 35	1, 2, 3, 4, 5
PEG 6000	45	1.5, 2.5, 3.5, 5, 7.5
PEG 1000	25, 35, 45	2.5, 5, 7.5, 10, 12
PEG 300	25, 35, 45	5, 7.5, 10, 12.5, 15

PEG in 0.1 M CH_3COOH/0.2 M CH_3COONa.

reduced viscosity over concentration versus concentration. The intrinsic viscosity, $[\eta_A]_B$, was calculated from viscosities measured for given systems polymer A – polymer B – solvent, each at five polymer B concentrations. The Heller method was used to estimate the intrinsic viscosities.[21–23] Plots of the reduced viscosity over concentration values against concentration were linear for all samples, with correlation coefficients of 0.99.

RESULTS AND DISCUSSION

Poly(ethylene glycol) is a flexible uncharged polymer that obeys the Hugggins equation. Dilute solutions of organic acids are good solvents for chitosan, owing to the protonation of the free amino groups on the polysaccharide backbone. For this reason, chitosan exhibits characteristic polyelectrolyte solution properties and the polycation forms a rigid-rod conformation that deviates from the classic Huggins equation. To overcome this difficulty, an acetic acid/sodium acetate solution was chosen as the solvent. In this solution, the chitosan has a random-coil conformation due to the screening effect of the ions on the cationic centers of the polymer backbone.[24] Roberts and Domszy[25] have found that the cationic effect of the positively charged amine groups on the chitosan backbone plays a major role in coil expansion in comparison with the acetyl groups. The coil expansion is caused by the electrostatic repulsions, which closely depend on the degree of deacetylation of the samples. However, such a trend has been observed with the use of an acetic acid/sodium chloride solvent system. Consequently, it was supposed[26,27] that the acetic acid/sodium acetate solvent system could minimize the difference in electrolytic effects of amine and acetyl groups. The specific interactions such as dipole-dipole or H-bonding should be responsible for the miscibility observed between chitosan and poly(ethylene glycol) in solution. Consequently, favorable interactions may occur between amide or amine nitrogen on the chitosan backbone and hydroxyl and etheric oxygen of PEG. Whenever the miscibility between PEG and chitosan occurs, the H-bonding interaction between the two polymers should be strong enough to overcome the intra- and intermolecular H-bonding among chitosan chains themselves.

Intrinsic viscosities for the solutions of chitosan and PEG are provided in Table II. The dependences of the reduced viscosity over concentration values for chitosan and PEG samples at 25°, 35°, and 45°C as a function of concentration were plotted. All such plots were linear, which might be interpreted as caused by the presence of an appropriate quantity of sodium acetate in the acetic acid solution. As can be seen in Table II, the intrinsic viscosities of chitosan are remarkably higher than those of all types of PEG because of strong internal hydrogen bond among chitosan

Table II. Values of intrinsic viscosities for chitosan and PEG, at 25°, 35°, and 45°C

Polymers A, B	[η] (dl/g)		
	t = 25°C	t = 35°C	t = 45°C
Chitosan	3,542	2,632	2,230
PEG 300	0,037	0,033	0,032
PEG 1000	0,056	0,054	0,052
PEG 6000	0,143	0,136	0,125

molecules. The hydroxyl groups in PEG molecules could form hydrogen bonds. However, molar mass of PEG is much lower and its molecular chain is more flexible than that of chitosan. Consequently, the intrinsic viscosities of the blends chitosan-PEG at 25°C are lower than the intrinsic viscosity of chitosan in 0.1 M CH_3COOH/0.2 M CH_3COONa solution at the same temperature; see Figures 1–3. The values of [η] for blends decrease at 25°C, and, according to theory, the interaction constants k_{AB} are lower than 0.5, thus indicating the immiscibility of these units. On the other hand, the presence of PEG caused an increase in [η] of chitosan at higher temperatures, 35° and 45°C. As can be seen Figures 1–3, the plots of $[\eta_A]_B$ versus $[\eta_B]c_B$ exhibit the maxima, which is an indication of $k_{AB} > 0.5$, i.e., the compatibility of units of chitosan and PEG. Jiang and Han[14] studied the blends of chitosan and PEG of higher molar masses (6000, 10 000, and 20 000 g/mol) at 45°C. They investigated the systems by the viscosity method according to the rule of Sun et al.[18]. All the values of α were positive, meaning that, according to the theory, two kinds of macromolecules are attractive and this mixture system is
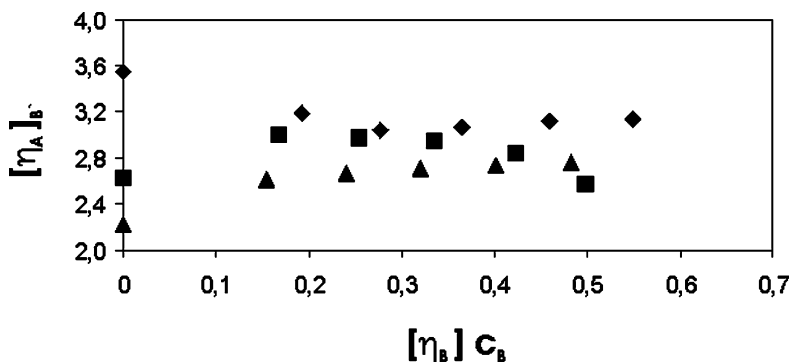
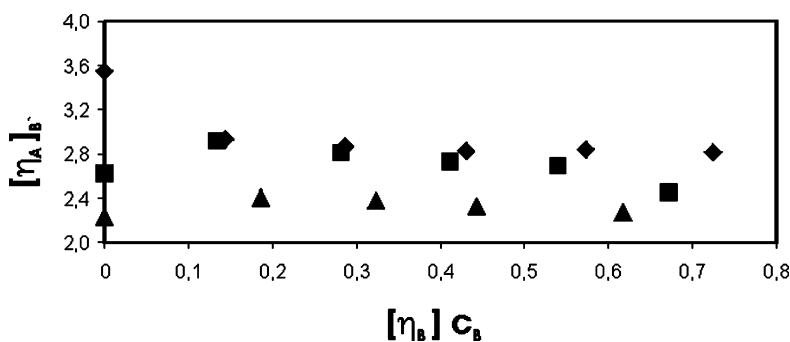**Figure 1.** Variation of intrinsic viscosity $[\eta_A]_B$ of chitosan with composition of "pseudosolvents" PEG 300-0.1 M CH_3COOH/0.2 M CH_3COONa at temperatures 25°C ◆, 35°C ■, 45°C ▲.
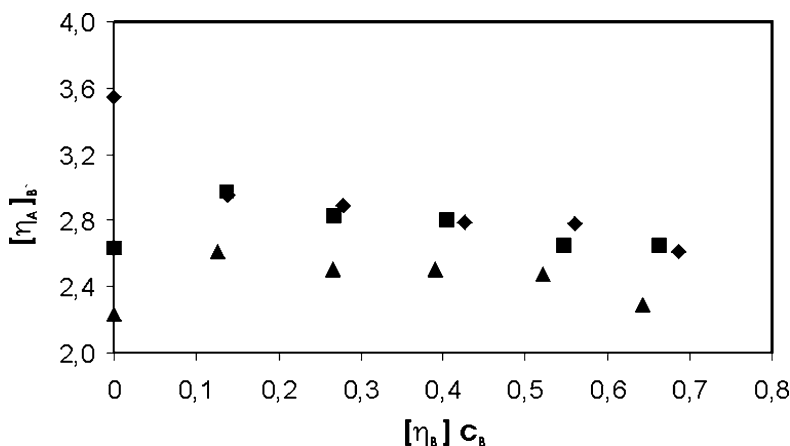
Figure 2. Variation of intrinsic viscosity $[\eta_A]_B$ of chitosan with composition of "pseudosolvents" PEG 1000-0.1 M CH_3COOH/0.2 M CH_3COONa at temperatures 25°C ◆, 35°C ■, 45°C ▲.

fully compatible. It has also been found that the presence of PEG causes an increase in the intrinsic viscosity of chitosan, which corresponds to our results, and the critical point of the intrinsic viscosity appears in low concentration.

The coefficients k_{AB} for chitosan in solutions of PEG (300, 1000, 6000 g/mol) are listed in Table III. These values were calculated from the slope of the plot of $p^*(\eta_r)_B$ versus $[\eta]_B c_B$ (Figures 4–6). The maximum error in coefficient k_{AB}, resulting from the viscometry, is of the order of $\pm 5\%$. The straight line corresponds to $k_{AB} = 0.5$. At 25°C, all dependences are moderately curved, namely, at the lowest concentrations


Figure 3. Variation of intrinsic viscosity $[\eta_A]_B$ of chitosan with composition of "pseudosolvents" PEG 6000-0.1 M CH_3COOH/0.2 M CH_3COONa at temperatures 25°C ◆, 35°C ■, 45°C ▲.

Table III. Coefficients of interaction k_{AB} of chitosan in solutions of PEG

Temperature [°C]	Polymer A, B		
	Chitosan PEG 300 k_{AB}	Chitosan PEG 1000 k_{AB}	Chitosan PEG 6000 k_{AB}
25	0,42	0,32	0,32
35	0,79	0,72	0,64
45	1,07	0,80	0,70

of polymer B (PEG). The values of $p^*(\eta_r)_B$ are positioned under the straight line, which, according to Staszewska et al.,[21] Staszewska and Bohdanecký,[22] and Moskowicz and Rosen,[23] indicates the limit of compatibility. Contrary to this, the plot at 45°C is linear in all cases. The interaction coefficients of k_{AB} are the lowest at 25°C, and the values of k_{AB} decrease with increasing molar mass of PEG. According to the theory of parameter miscibility, the molecules of chitosan and PEG (300, 1000, and 6000 g/mol) exhibit repulsive character at 25°C. While the results of k_{AB} at 35°C give evidence of favorable interaction of the segments of A and B, all types of PEG, and chitosan and at 45°C exhibit values much higher than 0.6. It indicates very strong interactions between the polymers. Yilmaz et al.[15] studied mixtures of chitosan and PEG at temperatures of 25°, 30°, and 35°C. They characterized the miscibility or immiscibility according to the Δb parameter, proposed by Rudin et al.[19] For the studied system, the miscibility of chitosan and PEG
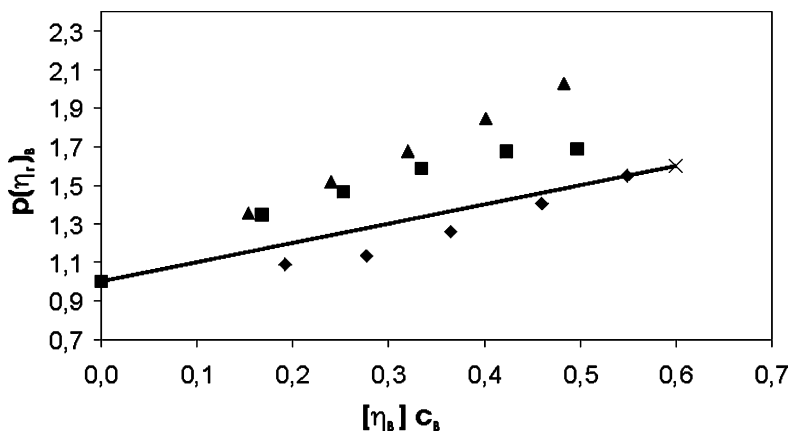
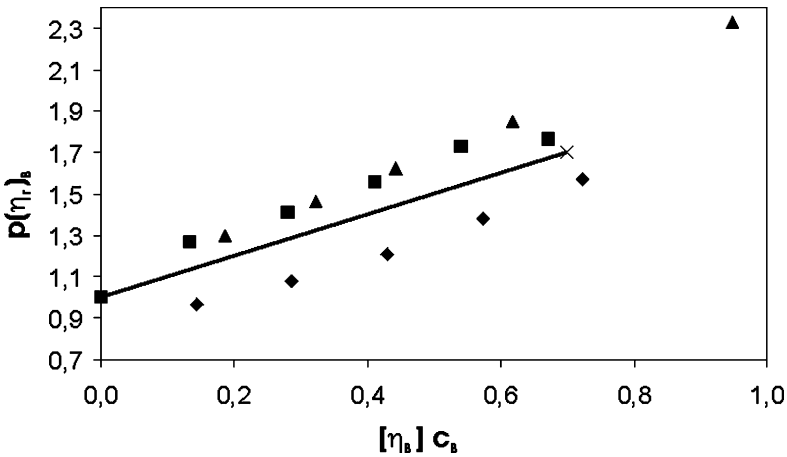

Figure 4. Estimation of interaction coefficient k_{AB} for chitosan and PEG 300 from the results presented in Figure 1 at temperatures 25°C ♦, 35°C ■, 45°C ▲. The straight line corresponds to $k_{AB} = 0.5\times$.
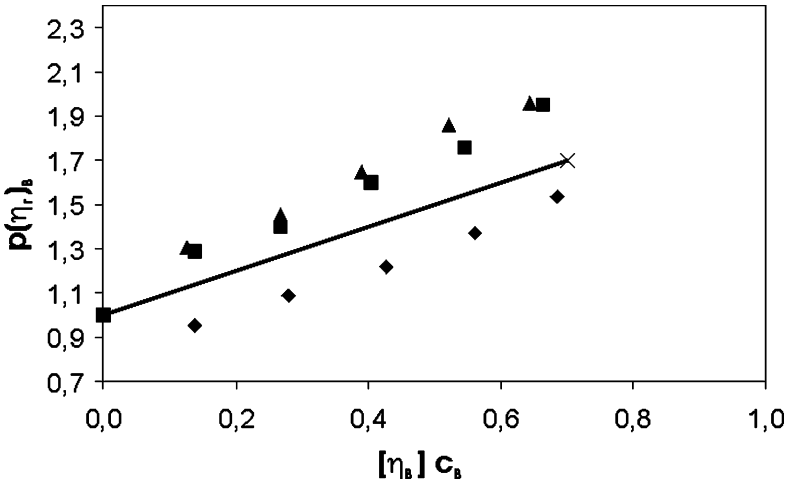
Figure 5. Estimation of interaction coefficient k_{AB} for chitosan and PEG 1000 from the results presented in Figure 2 at temperatures 25°C ◆, 35°C ■, 45°C ▲. The straight line corresponds to $k_{AB} = 0.5 \times$.

increases with the weight fraction of PEG in the blends, at all investigated temperatures. On the other hand, the miscibility between chitosan and PEG appears to be independent of temperature within a narrow temperature range (25°–35°C), although a slight increase in the miscibility parameter values is observed at 35°C.

Figure 6. Estimation of interaction coefficient k_{AB} for chitosan and PEG 6000 from the results presented in Figure 3 at temperatures 25°C ◆, 35°C ■, 45°C ▲. The straight line corresponds to $k_{AB} = 0.5 \times$.

Jiang and Han[16] revised the criterion of polymer-polymer miscibility determined by viscometry as a function of the following variables: (1) the intrinsic viscosity for polymeric components, (2) the weight fraction of polymeric components, and (3) the difference of the cross Huggins coefficient for blend and the geometric average of the Huggins coefficient for the constituent polymers. They studied the literature data of dilute solution viscosity for binary blend, and the above-mentioned law was also tested by measurement of chitosan and PEG (6000, 10 000, 20 000 g/mol) polyblend at 35°C. They found the sign of parameters β (Jiang & Han[14]) and Δk (Cragg & Bigelow[20]) positive, as well as that of α (Sun et al.[18]). As a result, whenever the concerned parameter is positive, the blend is compatible.

CONCLUSIONS

The results of this article demonstrate that chitosan and PEG in dilute solutions in 0.1 M CH_3COOH/0.2 M CH_3COONa exhibit compatibility at 35° and 45°C. The values of the interaction coefficient at 25°C are lower than 0.5, and the molecules of chitosan and PEG are immiscible. The interaction is the most favorable between molecules of chitosan and PEG 300 at 45°C ($k_{AB} = 1.07$). The values of the interaction coefficient k_{AB} are dependent on the molar mass of PEG and temperature.

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