

MECHANISM OF WATER DIFFUSION INTO NONCROSSLINKED AND IONICALLY CROSSLINKED CHITOSAN MEMBRANES

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Abstract

Ionicly crosslinked chitosan membranes were prepared and their swelling behaviour was analysed. Low-molecular pentasodium tripolyphosphate (TPP) and/or high-molecular sodium alginate (NaAlg) were used as ionic crosslinkers. Dynamic swelling of noncrosslinked (Ch) as well as singly (Ch/TPP, Ch/NaAlg) and doubly (Ch/NaAlg/TPP) crosslinked chitosan membranes was performed in buffered aqueous solutions of various pH to determine the mechanism of water diffusion into these hydrogels. It was stated out that mechanism of water diffusion into studied chitosan hydrogel membranes depends both on pH of swelling solution as well as on the type of membrane (type of crosslinker). The water transport mechanism was determined to be: i) Fickian or 'Less Fickian' diffusion, ii) non-Fickian diffusion (anomalous diffusion) and iii) Case II or Super Case II diffusion.

Key words: *pH-responsive hydrogels, chitosan, alginate, tripolyphosphate, swelling.*

1. Introduction

Chitosan (Ch), a linear aminopolisaccharide, composed of randomly distributed (1→4)linked D-glucosamine and N-acetyl-D-glucosamine units, has found wide application in a variety of areas, such as medicine, pharmacy, textiles, metal chelation, food additives, antimicrobial agents, packaging material, membrane material for separations, adhesives and so on [1]. To improve resistance of chitosan, especially in contact with acidic media, this polymer should be modified using chemical or physical methods. Ionic crosslinking, basing on the formation of ionic bonds between protonated amino groups of chitosan and low molecular ions of ionic crosslinker or ionic groups of other polymer, is a well known and commonly used method of chitosan modification. Pure and ionically crosslinked chitosan in contact with water or biological fluids swell and form hydrogels – a unique class of macromolecular networks containing a large fraction of aqueous solvent within their structure [2]. We have reported earlier the equilibrium and dynamic swelling behaviour of physically crosslinked chitosan hydrogels prepared by treating chitosan with sulfuric acid, trisodium citrate, pentasodium tripolyphosphate and sodium alginate, respectively [3]. It was observed, that the swelling of those hydrogels was highly dependent on pH of buffer solution. In the present study chitosan membranes ionically crosslinked with low-molecular pentasodium tripolyphosphate (TPP) and/or high-molecular sodium alginate (NaAlg) were prepared and the dynamic swelling of these membranes in buffered aqueous solutions of various pH was investigated. The swelling data for singly (Ch/TPP, Ch/NaAlg) and doubly (Ch/NaAlg/TPP) crosslinked membranes as well as noncrosslinked chitosan (Ch) membrane were then used to determine the mechanism of water diffusion into these hydrogels. The water transport mechanism into the polymer is particularly important for assessing the suitability of these materials as drug delivery systems and membranes in separation processes.

2. Materials and methods

2.1. Materials

Commercially available chitosan from crab shells of medium molecular weight (MMW-Ch, $M_v = 720$ kDa, DDA = 77.0% ± 2.3%) and high molecular weight (HMW-Ch, $M_v = 957$ kDa, DDA = 79.7% ± 2.4%), sodium alginate (NaAlg, $M_v = 102$ kDa) and pentasodium tripolyphosphate (TPP) purchased from Sigma Aldrich (Germany) were used for membrane preparation.

In swelling experiments the different buffer solutions of constant ionic strength $I = 0.145$ M were used. They were as follows: hydrochloric acid solutions (pH 1.0, 1.5, 2.0), acetic buffers (pH 3.5, 4.5, 5.5, 6.0) and TRIS buffers (pH 7.4, 8.5, 9.0). Reagents for buffer solution preparation (acetic acid, sodium acetate, sodium chloride, hydrochloric acid, sodium hydroxide) of analytical grade were purchased from POCh (Poland) or Aldrich (Germany).

2.2. Membrane preparation

One-component chitosan membrane (Ch), two-component chitosan/pentasodium tripolyphosphate (Ch/TPP) and chitosan/sodium alginate (Ch/NaAlg) membranes and

three-component chitosan/sodium alginate/pentasodium tripolyphosphate (Ch/NaAlg/TPP) membranes were prepared according to previously reported method [4]. Chitosan membranes (Ch) and chitosan/sodium alginate (Ch/NaAlg) membranes were prepared by casting solution and solvent evaporation technique. To obtain pure chitosan membranes 1 wt.% solution, prepared by dissolving chitosan powder in 2 wt.% acetic acid (HAc), was cast as film on clean glass plate, evaporated to dryness at 37 °C and further dried under vacuum at 60 °C. To obtain chitosan/sodium alginate membranes 1 wt.% chitosan solution in 2 wt.% HAc and 1 wt.% NaAlg solution were mixed in the 3:1 volume ratio. Ch/NaAlg membranes were formed analogously as chitosan films. Two-component chitosan/pentasodium tripolyphosphate (Ch/TPP) membranes were prepared by immersing of pure chitosan membranes in aqueous 1.3% (w/v) tripolyphosphate solution for 60 min. Applied crosslinking conditions were as follows: $T_{\text{crosslink}} = 4$ °C, $\text{pH}_{\text{TPP}} = 9.0$ or 5.5. Three-component chitosan/sodium alginate/pentasodium tripolyphosphate (Ch/NaAlg/TPP) membranes were prepared by immersing of two-component Ch/NaAlg membranes in 1.3% (w/v) TPP solution for 1 hr ($T = 4$ °C, $\text{pH}_{\text{TPP}} = 5.5$).

All membranes before swelling experiments were thoroughly dried under vacuum at 60 °C.

2.3. Swelling measurements

Swelling behavior of hydrogel membranes was analysed gravimetrically. Completely dry membranes of known weight (M_0) were placed in swelling solution (37 °C). Swollen samples were periodically removed from the water bath, dried with filter paper, accurately weighed (M_t) and placed in the same bath. The measurements were continued until the membrane constant weight was achieved or it was disintegrated. The degree of swelling (S) was calculated using the following equation:

$$S = \frac{M_t - M_0}{M_0} \quad (1)$$

3. Results and discussion

When a solid polymer is brought into contact with a penetrating liquid or vapour, the penetrant diffuses into the polymer, causing it to swell. Diffusion involves migration of water into pre-existing or dynamically formed spaces between hydrogel chains [5]. *Figure 1* presents the dynamic swelling data for noncrosslinked chitosan membrane and ionically crosslinked chitosan membranes in buffered aqueous solutions of constant ionic strength equal 0.145 M at 37 °C and pH 3.5 and 7.4, respectively.

It can be observed that swelling behavior of noncrosslinked and ionically crosslinked two- and three-component chitosan membranes (except Ch/Alg) in all studied buffer solutions is very similar (*Figure 1*). Degree of swelling increases with time until a certain point, when it becomes constant, i.e. the equilibrium state is reached. Swelling degree values depend strongly on pH of the swelling medium. The equilibrium swelling degree decreases with increasing pH.

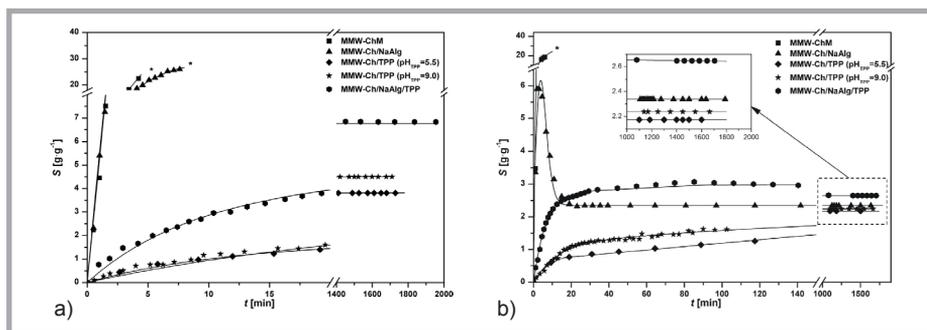


Figure 1. Swelling isotherms of noncrosslinked and ionically crosslinked chitosan membranes in buffered aqueous solution of pH: a) 3.5 & b) 7.4, and ionic strength 0.145 M at 37 °C (* - moment of membrane disintegration).

Moreover, membranes swelling ability is also strongly affected by crosslinking. In general, Ch membrane exhibits the highest swelling degree but the lowest mechanical resistance, while Ch/TPP membrane exhibits the lowest S value but the highest mechanical resistance.

Many mathematical models have been proposed to describe the kinetics of hydrogel swelling. These models are divided into three categories: Fickian diffusion models, Collective diffusion models and Non-Fickian diffusion models [6, 7]. Most dynamic hydrogel swelling models are based in some way on Fick's laws of diffusion. For many gels it should be also considered the mass transport of solvent or analyte molecules via convection mechanism as well. The rate and extent of penetrant sorption into the polymer are determined by both concentration gradient-controlled and/or relaxation-controlled diffusion [8, 9].

To determine the type of diffusion of water into hydrogels the simple and commonly used method, based on the power-law expression (*Equation 2*) was applied [10, 11]:

$$\frac{M_t}{M_\infty} = kt^n \quad (2)$$

where M_t and M_∞ represent the amount of solvent diffused into the gel at time t and at infinite time (equilibrium state), respectively, k is a constant related to the structure of the network and the exponent n is a number that determines the type of diffusion. This equation can be applied only to the initial stages of swelling, i.e. to a 60% increase in the mass of hydrogel ($M_t/M_\infty \leq 0.6$; $\log(M_t/M_\infty) \leq -0.22$).

Calculation of the exponent n and constant k was achieved by plotting the data in log-log plots, according to *Equation 3* and estimating the obtained curves by linear functions.

$$\log\left(\frac{M_t}{M_\infty}\right) = \log k + n \log t \quad (3)$$

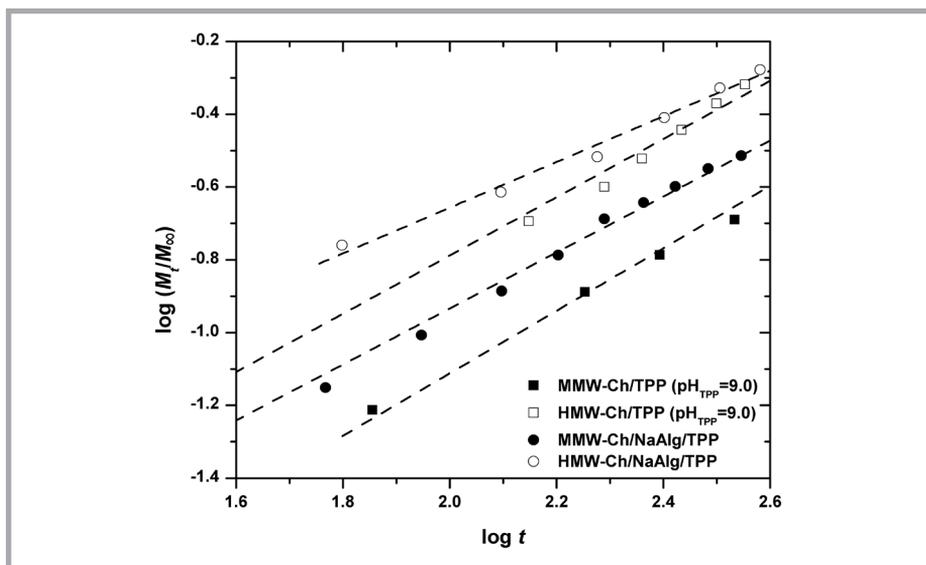


Figure 2. Plots of $\log(M_t/M_\infty)$ against $\log(t)$, for the Ch/TPP and Ch/NaAlg/TPP membranes in acetate buffer of pH 7.4.

Applying of **Equation 3** is possible only if the value of M_∞ is known. Thus, it could be used only to those samples that reached equilibrium swelling and exhibited a ‘regular’ shape of swelling isotherm. In our case it was not possible to calculate n and k values for pure chitosan membrane, because it dissolved in all used swelling solutions (MMW-Ch curves in **Figure 1**) and for chitosan membranes containing NaAlg (**Figure 1.a**: MMW-Ch/NaAlg curve, **Figure 1.b**: MMW-Ch/NaAlg and MMW-Ch/NaAlg/TPP curves) where after reaching of maximum swelling degree a contraction of volume was observed. Similar phenomenon was observed and discussed earlier by us for Ch, Ch/TPP, Ch/NaAlg and Ch/NaAlg/TPP membranes swelled in water [12] and by Cárdenas et al. for Ch/NaAlg membrane [13].

Figure 2 shows the typical log-log curves of swelling kinetics of Ch/TPP ($\text{pH}_{\text{TPP}}=9.0$) and Ch/NaAlg/TPP hydrogel membranes in acetate buffer of pH 7.4. The n values were calculated from the slopes of the lines. Swelling diffusional exponents n are listed in **Table 1**.

According to the relative rates of diffusion (R_{diff}) and polymer relaxation (R_{relax}) three classes of diffusion can be distinguished. For a planar geometry, the value of i) $n = 0.5$ indicates a Fickian diffusion mechanism (Case I) in which the rate of diffusion is much smaller than the rate of relaxation ($R_{\text{diff}} \ll R_{\text{relax}}$, system controlled by diffusion), ii) $n = 1.0$ indicates Case II, where the diffusion process is much faster than the relaxation process ($R_{\text{diff}} \gg R_{\text{relax}}$, system controlled by relaxation), iii) $0.5 < n < 1.0$ indicates non-Fickian (anomalous) diffusion mechanism, which describes those cases where the diffusion and relaxation rates are comparable ($R_{\text{diff}} \approx R_{\text{relax}}$) [5, 14, 15]. Occasionally, values of $n > 1$

Table 1. Swelling diffusional exponents (n) determined by linear regression of $\log(M_t/M_{\infty})$ versus $\log t$; *a)* membrane dissolution, *b)* not analysed samples, *c)* “irregular” shape of swelling curve (swelling-contraction phenomenon).

Hydrogel membrane	Diffusional exponent n values for swelling of membranes in buffer of pH:						
	3.5	4.5	5.5	6.0	7.4	8.5	9.0
MMW-ChNaAlg	-a)	1.051	1.136	1.023	-c)	-c)	-c)
HMW-ChNaAlg	-a)	1.010	1.136	1.106	-c)	-c)	-c)
MMW-Ch/TPP (pH _{TPP} =5.5)	0.805	0.606	0.874	0.353	0.358	-c)	-c)
HMW-Ch/TPP (pH _{TPP} =5.5)	0.756	0.735	0.849	0.455	0.501	-c)	-c)
MMW-Ch/TPP (pH _{TPP} =9.0)	0.704	0.597	0.756	0.788	0.785	0.855	0.855
HMW-Ch/TPP (pH _{TPP} =9.0)	0.763	0.777	0.701	0.701	0.795	0.887	0.830
MMW-ChNaAlg/TPP	0.487	-b)	0.603	-b)	-c)	-b)	-c)
HMW-ChNaAlg/TPP	0.533	-b)	0.644	-b)	-c)	-b)	-c)

Table 2. Water transport mechanisms and diffusional exponents n for hydrogel membranes.

Type of transport	Diffusional exponent (n)	Time dependence
“Less Fickian” diffusion	$n < 0.5$	$t^{1/2}$
Fickian diffusion	$n = 0.5$	
Non-Fickian (anomalous) diffusion	$0.5 < n < 1.0$	t^{n-1}
Case II transport	$n = 1.0$	time independent
Super Case II transport	$n > 1.0$	

have been observed, which are regarded as Super Case II kinetics [16, 17]. When the water penetration rate is much below the polymer chain relaxation rate, it is possible to record the n values below 0.5. This situation, which is classified also as Fickian diffusion, is called as ‘Less Fickian’ behavior [6, 18]. All types of water transport discussed above are presented in **Table 2**.

It can be clearly seen from **Table 1** that values of the diffusional exponent range between 0.353 and 1.136. For Ch/NaAlg membrane diffusional coefficients are higher than 1 or close to 1.0 what indicates that the transport mechanism is Super Case II or Case II (relaxation controlled). Depending on pH of swelling medium two-component Ch/TPP and three-component Ch/NaAlg/TPP membranes exhibit ‘Less Fickian’, Fickian or non-Fickian diffusion. Moreover, for Ch/TPP (pH_{TPP}=9.0) and Ch/NaAlg/TPP membranes values of n increase with increasing pH. Our results stay in good agreement with those presented by Kim et al. [9] for poly(methacrylic acid-*co*-methacryloxyethyl glucoside) and poly(methacrylic acid-*g*-ethylene glycol) hydrogels.

As discussed earlier by Peppas et al. [5, 9], the dynamic swelling behaviour of hydrogels is dependent on the relative contribution of penetrant diffusion and polymer relaxation. In the ionic hydrogels the polymer relaxation is affected by the ionisation of functional groups. An increase in the degree of ionization results in the electrostatic repulsion between ionized functional groups, leading to chain expansion, which in turn affects macromolecular chain relaxation. Thus, the swelling mechanism becomes more relaxation-controlled when the ionization of hydrogel increases. For hydrogels studied by us an increase of pH of swelling solution from 3.5 to 9.0 cause a decrease of protonation

of chitosan amine groups and simultaneously a deprotonation of alginate carboxylic acid groups or increase of degree of ionization of low-molecular TPP. Therefore, the swelling mechanism becomes more relaxation-controlled as ionization of NaAlg and TPP becomes prominent, and n values increases.

For a given buffer solution (buffer solution of pH 3.5, 4.5 and 5.5) values of n depend on type of chitosan membrane and decrease in the following order: Ch/NaAlg > Ch/TPP ($\text{pH}_{\text{TPP}} = 5.5$) \approx Ch/TPP ($\text{pH}_{\text{TPP}} = 9.0$) > Ch/NaAlg/TPP. These membranes differ in the type of ionic crosslinker and/or the crosslinking density that, in turn, can affect the relative contribution of penetrant diffusion and polymer relaxation processes.

Results presented in **Table I** indicate that molecular weight of chitosan only slightly influenced the mechanism of water diffusion, both in the case of chitosan as well as in the case of modified chitosan membranes.

4. Conclusions

The swelling behaviour of chitosan, chitosan/pentasodium tripolyphosphate, chitosan/sodium alginate and chitosan/sodium alginate/pentasodium tripolyphosphate hydrogel membranes was dependent on pH of buffer solution. The mechanism of water diffusion into one-, two-, and three-component chitosan membranes depended both on pH of swelling solution as well as on the type of membrane (type of ionic crosslinker and crosslinking density). The water transport was strongly affected by the ionisation of polymer functional groups. Increasing pH of swelling media resulted in protonation of chitosan amino groups and deprotonation of alginate carboxylic groups or increase of degree of ionization of low-molecular TPP. Depending on solution pH and type of crosslinker water transport mechanism was determined to be:

- i) Fickian or 'Less Fickian' diffusion (for Ch/TPP, Ch/NaAlg/TPP),
- ii) non-Fickian diffusion (anomalous diffusion) (for Ch/TPP, Ch/NaAlg/TPP) and
- iii) Case II or Super Case II diffusion (for Ch/NaAlg).

5. References

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