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Membranes based on poly(vinyl alcohol)/β-cyclodextrin blends

Summary — Membranes based on poly(vinyl alcohol)/β-cyclodextrin (PVA/β-CD) with various compositions have been prepared by using a series of three freezing/thawing cycles. The membranes were studied with scanning electron microscopy (SEM), X-ray diffraction (XRD), differential scanning calorimetry (DSC) and also water swelling tests as well as contact angle measurements have been performed. The swelling kinetics of membranes in water at different temperatures have been also evaluated. It was established that the membrane properties are influenced by the β-cyclodextrin (β-CD) content and the pores diameter. The crystalline fraction in PVA/β-CD membranes increases with the increase of β-CD content.
Key words: β-cyclodextrin, poly(vinyl alcohol), membranes, swelling.

MEMBRANY WYKONANE Z MIESZANEK POLI(ALKOHOLU WINYLOWEGO) Z β-CYKLODEKSTRYNĄ

Streszczenie — Za pomocą trzykrotnie powtarzanego cyklu zamrażanie/rozmrażanie przygotowano membrany z mieszanek poli(alkoholu winylowego) (PVA) z różną zawartością β-cyklodekstryny (β-CD, tabela 1). Membrany badano za pomocą skaningowego mikroskopu elektronowego (SEM, rys. 1, tabela 2), dyfrakcji promieniowania rentgenowskiego (XRD, rys. 2, tabela 3), różnicowej kalorymetrii skaningowej (DSC, rys. 5, tabela 5), a także określano krzywe pęcznienia w wodzie (rys. 3) oraz kąty zwilżania. Kinetykę pęcznienia membran w wodzie badano w temp. 25 i 37 °C i zaobserwowano, że wpływ temperatury na proces pęcznienia jest nieznaczny (tabela 4). Stwierdzono natomiast istotny wpływ zawartości β-CD na wymiary porów i wynikającą z tego zdolność do pęcznienia. Wzrost zawartości β-CD powodował ponadto wzrost stopnia krystaliczności próbek.
Słowa kluczowe: β-cyklodekstryna, poli(alkohol winylowy), membrany, pęcznienie.

Cyclodextrins (CDs) include a family of three major CDs, which are crystalline, homogeneous and nonhygroscopic substances [1]. Chemically, they are cyclic oligosaccharides containing α-D-glucopyranose units linked by α-(1,4) glucosidic bonds. The main differences between the three natural α-, β- and γ-CD are the number of glucose units (6, 7 and 8, respectively), their ring size and solubility [2]. The glucose units form a rigid conical structure, characterized by a hydrophobic central cavity and a hydrophilic outer surface. Due to the hydrophobic cavity, CDs could interact with a large variety of guest molecules of the same polarity and form inclusion complexes [3]. CDs are used as solubilizers, stabilizers for biologically active compounds, enzyme models, as separating agents in chromatography, as catalysts, additives, *etc.* [4].

Poly(vinyl alcohol) (PVA) is a biodegradable, water-soluble, non-toxic, synthetic polymer, with wide applicability due to its low price, easy processability and peculiar chemical properties. PVA can be crosslinked by means of chemical methods (using chemical crosslinkers) or using physical methods (δ-irradiation, ultrasounds and/or microwaves, freezing/thawing cycles, *etc.*), forming chemical or physical hydrogels. These hydrogels have special properties, such as nontoxicity, lack of carcinogenicity, good biocompatibility, bioadhesivity, good mechanical properties, high degree of swelling in water and ease of processing [5]. These properties make PVA an excellent biomaterial which can be used in a variety of applications such as controlled drug delivery [6, 7], artificial tissue and organs [8, 9], wound bandages and dressings [10], separation process [11], *etc.*

Aqueous solutions of PVA exposed to a series of freezing/thawing cycles lead to stable hydrogel membranes that are physically crosslinked by the presence of PVA crystallites. This physical method of crosslinking has advantages against other methods: it is simple, it does not need high temperatures, it is not toxic due to the fact that the presence of a chemical crosslinker is not requested [12]. PVA hydrogels prepared with the freezing/thawing method have improved properties compared to hydro-

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gels prepared with traditional chemical techniques [13]. These properties depend on the PVA molecular weight, solution concentration, freezing time and the number of freezing/thawing cycles [14].

In order to improve the functionality of the hydrogels, PVA is often combined with nanoparticles [15, 16] and with other synthetic and natural polymers, such as polyacrylic acid [17], polyethylene glycol [18], poly(*N*-isopropylacrylamide) [19], poly(vinyl pyrolidone) [20], chitosan [21—23], cyclodextrins [24—27] and gelatin [28].

In our previous study we investigated the phase behavior of PVA/β-CD blends obtained by solution casting method [29]. It has been shown that the two polymers have a good compatibility, but water evaporation requires high energy consumption.

This study presents obtaining and characterization of some hydrogel membranes, prepared from PVA/β-CD blends, using the freezing/thawing technique which is much advantageous, safe and nonpolluting method. Such membranes may be used in different fields, for example in biotechnologies for bioseparation, as biomaterials for delivery of some drugs, for purification of waste water, separation through diffusion membranes, *etc*.

EXPERIMENTAL

Materials

PVA with an average molecular weight of 40 400 and a degree of hydrolysis of 98 % was purchased from S.A. ROMACRIL Rasnov (Romania).

β-CD with a purity higher than 98 %, M = 1135 g/mol and water content between 10 and 15 wt. % was purchased from Merck.

PVA/β-CD membranes preparation

PVA dissolved in distilled water was magnetically stirred for 3 h at 80 °C. The insoluble fraction was removed by centrifugation. Constant amounts of 14.5 wt. % of PVA solution were mixed with various amounts of β-CD and stirred for 30 min at 60 °C. After cooling, the obtained mixtures were poured into Petri dishes. These were subjected to three repeated freeze/thaw cycles (the freezing step at -20 °C for 8 h, followed by the thawing step at room temperature for 8 h). The samples were dried by lyophilization for 20 h, using LABCONCO 117 freezing-dryer. The compositions of the obtained membranes are shown in Table 1.

T a b l e 1. Membranes composition

Sample	Membranes composition, wt. %	
	PVA	β-CD
S1	95.1	4.9
S2	89.3	10.7
S3	78.4	21.6
S4	60.9	39.1

Methods of characterization

The obtained membranes were examined with TESLA BS1 301 scanning electron microscope (SEM). A gold layer was imposed on the surface of the dried membranes. The magnification was 2500X.

The X-ray diffraction (XRD) investigations were performed using Bruker AXS D8 Advance X-ray Diffractometer, with a CuKα radiation source. The data were collected at 2θ between 2—50°.

The samples were also studied using differential scanning calorimetry (DSC) method with Perkin Elmer apparatus, at the heating rate of 10 °C/min in the 20—250 °C temperature range. The sample weight was 9 mg.

The contact angle measurements were done by means of CAM-PLUS Micro apparatus. The solvents used were: water, formamide and α-bromnaphthalene.

In their customary approximation Lifshitz—van der Walls/acid-base (LW/AB), Van Oss, Good and Chaudhury [30—32] consider the non-polar contribution of the surface tension (γ_{sv}^{LW}), being a consequence of London dispersion forces, of the Keesom dipole-dipole interaction, of the Debye induced-dipole, dominated by London forces between two induced-dipoles. The polar part of the surface tension (γ_{sv}^{AB}), corresponding to Lewis polar interactions acid/alkali is formed from electron-donor interactions (γ_{sv}^{-}) and electron-acceptor interactions (γ_{sv}^{+}). These parameters were correlated using equations:

$$\gamma_{sl} = \left(\sqrt{\gamma_{sv}^{LW}} + \sqrt{\gamma_{lv}^{LW}}\right)^2 + 2\left(\sqrt{\gamma_{sv}^{+}\gamma_{lv}^{-}} + \sqrt{\gamma_{lv}^{+}\gamma_{lv}^{-}} - \sqrt{\gamma_{sv}^{+}\gamma_{lv}^{-}} - \sqrt{\gamma_{sv}^{-}\gamma_{lv}^{+}}\right) \quad (1)$$

$$\gamma_{sv}^{AB} = 2 \cdot \sqrt{\gamma_{sv}^{-}\gamma_{sv}^{+}} \quad (2)$$

$$\gamma_{sv}^{LW/AB} = \gamma_{sv}^{LW} + \gamma_{sv}^{AB} \quad (3)$$

where: *superscripts "LW" and "AB" denote the disperse component, respectively the polar one, while superscript "LW/AB" denote the total surface tension;* γ_{sv} *— surface tension of the solid in equilibrium with the liquid saturated vapors,* γ_{lv} *— interfacial liquid-vapor tension.*

From the combination of the Young and Dupree equation with eq. (1)—(3), the following equation was obtained:

$$1 + \cos\theta = \frac{2}{\gamma_{lv}} \cdot \left(\sqrt{\gamma_{sv}^{LW} \cdot \gamma_{lv}^{LW}} + \sqrt{\gamma_{sv}^{+} \cdot \gamma_{lv}^{-}} + \sqrt{\gamma_{sv}^{-} \cdot \gamma_{lv}^{+}}\right) \quad (4)$$

where: θ — *contact angle*.

If contact angles for three liquids are known, a series of equations could be resolved in order to obtain the parameters of the surface tensions, γ_{sv}^{LW}, γ_{sv}^{+}, γ_{sv}^{-}. Knowing

these parameters, the polar component of the surface tension (γ_{sv}^{AB}) and the total surface tension ($\gamma_{sv}^{LW/AB}$) can be calculated using eq. (2) and (3). In the case that one of the test liquids is non-polar, eq. (4) is simplified [33].

The swelling studies were carried out in distilled water at two different temperatures: 25 °C and 37 °C. The dried samples were weighed, immersed in distilled water and maintained at constant temperature (25 °C and 37 °C, respectively). At definite intervals the samples were taken from water and weighed. The equilibrium water absorption (EWA) was determined according to the eq. (5):

$$EWA = \frac{W_s - W_d}{W_d} \quad (5)$$

where: W_s — *weight of the swollen sample at a given saturation,* W_d — *weight of the dried sample*.

RESULTS AND DISCUSSION

The solutions of the PVA/β-CD blends present a slight opalescent aspect and the obtained membranes have a homogenous aspect.

The morphology of the PVA/β-CD membranes was studied using SEM technique. As it can be seen in Fig. 1, the PVA/β-CD membranes have microporous structure. These images show various shapes and dimensions of pores, which can be controlled by modification of the system composition.

As it can be seen in Table 2, the pores diameter grows with the increase of β-CD content in the membrane material. The pores diameter of S2 sample containing 10.7 wt. % of β-CD is almost three times bigger compared to the pores diameter of the pure PVA. It has an average pores size of 8.96 μm, being more uniform compared to pores of the other membranes studied.

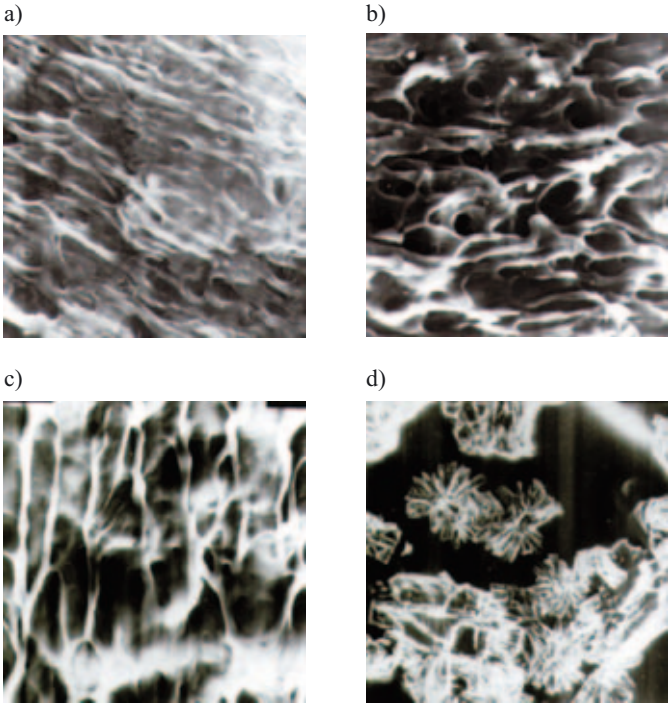

Fig. 1. The SEM images of the PVA and its blends with β*-CD: a) PVA, b) sample S1, c) sample S2, d) sample S4*

T a b l e 2. Pores diameter evaluated from SEM images

Sample	Pore diameter, μm
PVA	3.08
S1	5.65
S2	8.96

Figure 2 presents the XRD diffractograms of the pure β-CD, PVA and PVA/β-CD membranes with various compositions.

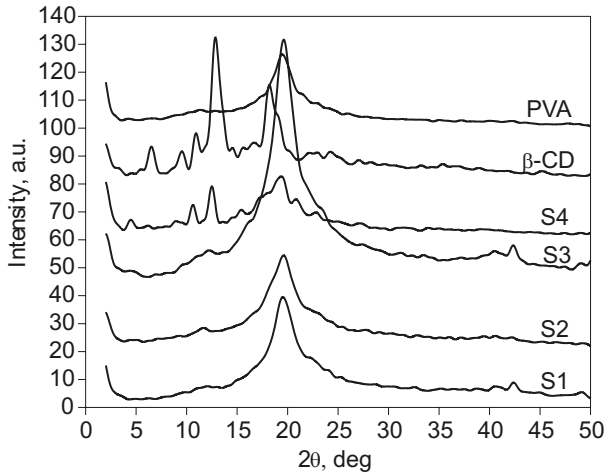

Fig. 2. The XRD diffractograms of the membranes of PVA, β*-CD and their blends (samples S1—S4)*

The XRD pattern of the PVA membrane revealed an intense peak at 2θ = 19.53°, while the pure β-CD has two intense peaks at 2θ = 12.86° and 2θ = 18.19°. The diffractograms of the samples show intense peaks at around 19.37°—19.53°, close to the PVA peak value. The β-CD peak corresponding to 2θ = 12.86° decreases in intensity with the decrease of β-CD content in the membranes.

T a b l e 3. The samples crystallinity degree

Sample	Crystallinity degree (experimental), %	Additive values (calculated), %
CD	60.75	60.75
PVA	37.40	37.40
S1	35.72	38.54
S2	43.30	39.89
S3	36.70	42.44
S4	48.72	46.52

As it is shown in Table 3 an increase of the crystalline fraction with the increase of cyclodextrin content is observed. The crystallinity degree was calculated by dividing the surface of the crystalline peak by the total surface of the peak. The membrane containing 39.1 wt. % of β-CD (sample S4) has the highest crystallinity degree. The additive values of the crystallinity degree were determined assuming absence of interactions between components. The additive values are different compared to the experimental values, indicating changes in blends morphology and interactions between components.

For the swelling experiments, samples were allowed to swell to the equilibrium in water at two temperatures: 25 or 37 °C. These temperatures were selected in order to simulate the environmental conditions and the physiological conditions, respectively.

In order to determine the type of the water diffusion in the membranes studied, the obtained data were kinetically analyzed using the following equation [34]:

$$F = W_t/W_c = kt^n \quad (6)$$

where: F — *the swelling fraction*, W_t, W_e — *the weight of the swollen sample at a given time (t) and at equilibrium, respectively*, k — *the swelling constant*, n — *the swelling exponent*.

The swelling curves are given in Fig. 3. These results show that swelling of the PVA/β-CD membranes is not influenced by temperature.

Eq. (6) is applied to the initial swelling stages, until the sample weight increased by approximately 60 %. For a membrane, $n = 0.5$ indicates a Fickian diffusion, $n > 0.5$ indicates non-Fickian or abnormal transport, and $n = 1$ implies a transport of II degree (controlled by the relaxation) [35].

To determine the coefficients k and n we take natural logarithm of both sides of eq. (6) and we get:

$$\ln F = \ln k + n \ln t \quad (7)$$

This equation is comparable with equation of a straight line. Plotting a graph of ln F against ln t we can calculate the value of slope equal to n, and ln k as the y-axis intercept. The obtained data are given in Table 4 together with *EWA* values.

The values of the swelling exponents revealed a Fickian kinetics of the water diffusion in these membranes.

T a b l e 4. The swelling parameters of the PVA and PVA/β-CD membranes

Sample	Swelling parameters at 25 °C			Swelling parameters at 37 °C		
	EWA	k, min^{-n}	n	*EWA*	k, min^{-n}	n
PVA	3.5	0.24	0.37	4.07	0.41	0.27
S1	4.11	0.40	0.29	3.75	0.28	0.37
S2	3.9	0.30	0.37	3.47	0.27	0.36
S3	3.9	0.38	0.30	3.5	0.48	0.24
S4	3.38	0.19	0.45	3.15	0.41	0.25

As it can be seen in Fig. 4, the water absorption increased with the increase of PVA content in the samples, because PVA is more hydrophilic than β-CD. Another

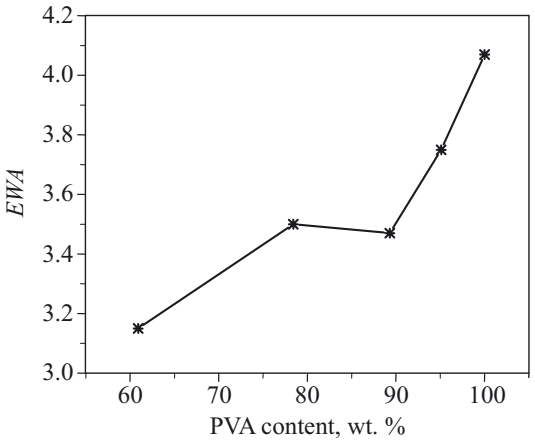

Fig. 4. Equilibrium water absorption (EWA) at 37 °C versus PVA content in PVA/β-CD membranes

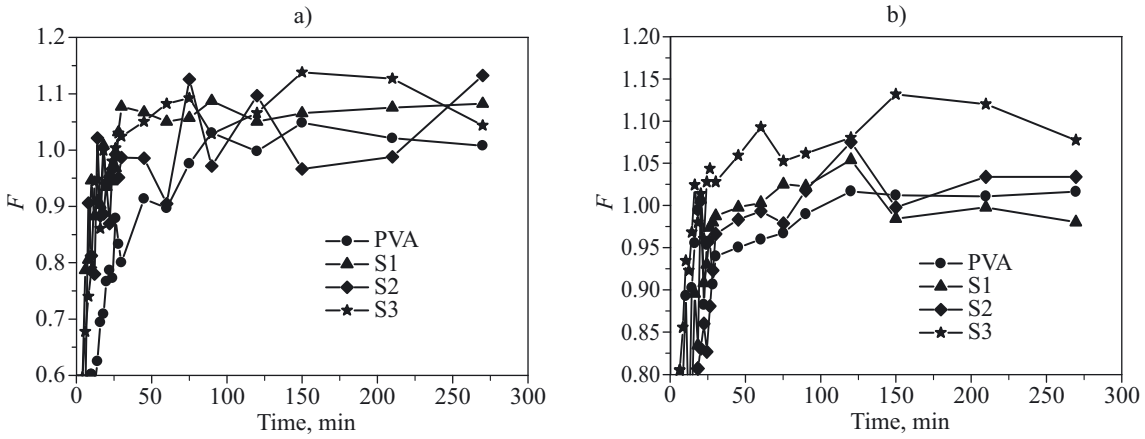

Fig. 3. Swelling fraction (F) curves as a function of time for PVA and PVA/β-CD membranes at the temperature of: a) 25 °C, b) 37 °C

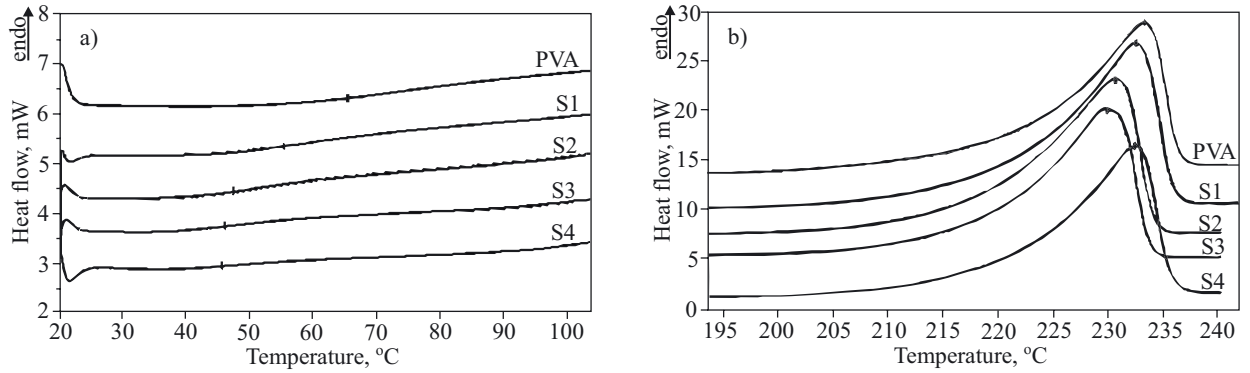

Fig. 5. The DSC thermograms for PVA and PVA/β-CD membranes at temperature ranges: a) 20—100 °C, b) 195—240 °C

explanation of the increased adsorption is the fact that the membranes have smaller pores, and therefore a greater surface available to absorption.

Figure 5 shows the DSC thermograms of PVA and the obtained membranes. The DSC curves of the membranes were recorded below 250 °C, due to the fact that β-cyclodextrin decomposes during melting at temperatures higher than 250 °C.

The recorded curves present two peaks at 45—65 °C and 230—235 °C. The first peak is assigned to the transition temperature, while the second peak corresponds to the PVA melting.

T a b l e 5. The DSC results of the studied samples

Sample	T_{tr}, °C	T_m, °C	ΔH_m, J/g
PVA	63.53	233.26	82.94
S1	56.32	232.52	74.09
S2	47.97	230.71	72.82
S3	47.14	229.86	66.39
S4	46.87	232.50	67.71

The values of the melting enthalpy (ΔH_m), transition (T_{tr}) and melting temperatures (T_m) are presented in Table 5. Pure PVA has T_m of 233.26 °C and ΔH_m of 82.94 J/g. The T_{tr} increased with the decrease of PVA content in the samples indicating some interactions between membranes components. At the same time, it can be noted a decrease of both T_m and ΔH_m with the increase of the β-CD content in membranes. This decrease appears as a consequence of interactions between β-CD molecules and PVA chains. Due to these interactions, the PVA chains cannot associate and crystallize.

Table 6 presents the parameters determined by contact angle measurements. The γ_{sl} represents the interfacial tension between blood and the film surface. Values of γ_{sl} between 3.66—4.56 mN/m showed a relatively good hemocompatibility of samples and, at the same time, an appropriate mechanical stability of the interface. The contact angle method shows that an increase of β-CD content leads to an increase of interfacial tension between blood and biomaterial, but they remain close to those for a good hemocompatibility (~ 3 mN/m).

T a b l e 6. The values of Lifshitz-van der Waals and acid-base parameters, surface tensions and interfacial tension between blood and biomaterial; description of symbols in the text

Sample	γ_{sv}^{LW} mN/m	γ_{sv}^{+} mN/m	γ_{sv}^{-} mN/m	γ_{sv}^{AB} mN/m	γ_{sv} mN/m	γ_{sl} mN/m
PVA	40.55	0.49	36.36	36.85	77.40	3.99
S2	41.41	2.10	38.68	40.78	82.19	3.66
S3	36.76	1.66	29.48	31.14	67.90	4.36
S4	37.41	23.04	7.95	30.99	68.40	4.56

CONCLUSIONS

Membranes based on poly(vinyl alcohol)/β-cyclodextrin were obtained by physical crosslinking, exposing the PVA/β-CD mixtures to a series of freezing/thawing cycles. The morphology and physical properties of the obtained membranes were determined.

The obtained results proved that the properties of PVA/β-CD membranes can be controlled with β-CD content. The membranes displayed microporous structure, with the pores diameter depending on β-CD content. The DSC data revealed interactions between membranes components. The temperature had no influence on the membranes swelling. The values obtained from contact angle measurements proved a good compatibility of the membranes with the blood.

The toxicity issues determined by the presence of chemical crosslinkers are solved by using the physical method for membranes obtaining. Therefore, these membranes can be used in biomedical applications.

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