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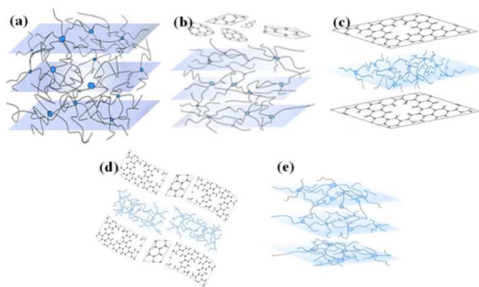
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Highlight: The PVA hydrogel with high-transparence has been prepared, the 1DMSO/2H₂O network structure and the transparent mechanism were also explored.

Colour graphics:



Schematic diagrams of spatial structure for PVA hydrogels prepared with different concentration of DMSO aqueous solutions: deionized water (a), 40wt% DMSO aqueous solution (b), 68.5wt% DMSO aqueous solution (c), 80wt% DMSO aqueous solution (d) and pure DMSO (e)

Preparation of PVA hydrogel with high-transparence and investigations on its transparent mechanism

Yi Hou[†],^a Chen Chen[†],^a Kemin Liu,^a Ying Tu,^a Li Zhang^{*},^a Yubao Li^{*a}

Abstract: Polyvinyl alcohol (PVA) hydrogels with high-transparence were prepared by dissolving PVA powders into the dimethyl sulfoxide (DMSO) aqueous solutions with different concentration to obtain 16.7wt% PVA hydrogels followed by several freeze-thaw cycles. The transparence, crystallinity, mechanical strength and compositions of PVA hydrogels were tested and analyzed by using spectrophotometer, universal testing machine and Infrared spectroscopy (IR), indicating that when the concentration of DMSO was 80wt%, the transparence of PVA hydrogel displayed a maximum value (99.8±0.2%), close to that of natural human cornea (99.7-99.9%), which is closely related to the interaction between DMSO and H₂O molecules as well as the crystallinity of PVA hydrogel. Based on this, the interaction between DMSO and H₂O molecules and the transparent mechanism were also explored. It has been found that the viscosity of DMSO aqueous solution reaches the maximum value when its concentration is 68.5% and is prone to be affected by temperature, while the 80wt% DMSO aqueous solution endows PVA hydrogel with the highest transparence. Based on IR and DSC analysis, the spatial structures of PVA hydrogels prepared with different DMSO aqueous solutions were schemed, and it was thought that the formation of 1DMSO/2H₂O network structure contributes the most to the crystallinity and the transparence of PVA hydrogel. Such a PVA hydrogel with high transparence could have a great potential to be used as the optical core of artificial cornea.

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Introduction

Corneal blindness is now the second leading cause of blindness globally^[1]. It is estimated that about 2 million new cases of corneal blindness occur every year caused from trachoma trauma and corneal ulcerations^[2]. Up to now, the only widely accepted treatment of diseased or damaged human corneas is corneal transplantation using human donor corneal tissue. But the donor corneas are in short supply. So, it is very urgent and necessary to create an artificial substitute able to simulate the physical characteristics of the natural cornea and to perform some of its essential functions.

From literatures we can know that, the materials and the structure design had played important roles in the development history of Keratoprosthesis (KPro)^[3-5]. Especially, since Slazer^[6] proposed "core-and-skirt" concept in the structure design of artificial corneas, study of artificial cornea materials

have entered a stage of rapid development^[7-11]. An ideal KPro should have a biocompatible porous skirt able to interlock or heal with the host cornea and, an optical core with high transparence and a suitable refractive index. Also, the KPro should be flexible and should have sufficient tensile strength to allow surgical manipulation and fixation. So far, developing a KPro has been attempted by many groups^[12-17], among which, the most promising artificial cornea is the PHEMA KPro explored by Chirila group^[18-24]. The PHEMA KPro had been assessed by replacing the damaged regions of the cornea of different animals, and found that the KPro could be retained longer than 3 years in some animals. And the pilot clinical trial in human patients had also been operated, but found the long-term survival was not satisfactory. Analysis demonstrated that most of the postoperative complications were caused by the low tensile strength and the bio-inert property of the porous PHEMA skirt. To solve the problem, our research group had developed an improved KPro, in which a hydrophilic polymer, poly(vinyl alcohol) (PVA) hydrogel, was used for both porous skirt (opaque sponge containing hydroxyapatite or graphite powder) and the transparent optical core, and the attachment of

^a Analytical & Testing Center, Research Center for Nano-biomaterials, Sichuan University, Chengdu, 610064, P. R. China.

[†] These authors contribute equally to this work.

the skirt to the core was achieved through an interpenetrating polymer network, at the same time, the porous skirt permitted the ingrowth of the host cornea tissue and formed a reliable biofixation^[25-28]. The *in vivo* tests showed encouraging results, the porous PVA composite porous skirt allowed the ingrowth of cells from the host cornea tissue and their proliferation, and formed a tight fixation with the surrounding host tissue^[29,30]. But it was a pity that the transparency of the optical core made of PVA hydrogel was not so high and also became more and more blurred with the adsorption of proteins, finally could not fulfill its functions.

How to improve the transparency of PVA hydrogel used as the optical core is what we should firstly consider here. PVA hydrogel has been studied extensively and considered as one of the most suitable hydrogels for biomedical applications due to its biocompatibility and nontoxicity^[31]. In recent years, it has also been reported that PVA hydrogel has many excellent properties, such as sufficient mechanical strength, light transparency and nutrition permeability. Besides, PVA hydrogel prepared under appropriate conditions has been proved able to autonomously self-heal, exhibiting good self-healing capability. Therefore, PVA hydrogel is always being and will still be the research hotspot in the field of artificial corneas and contact lens. PVA is a representative water soluble polymer and its aqueous solution can form both chemical and physical gels depending on the preparation conditions, and the low-temperature crystallized PVA hydrogel has light transparency and nutrition permeability. In addition, PVA hydrogels with high transparency and low protein adsorption have been reported to be obtained by doping with different solvents^[32-36].

So, in the present study, we prepared PVA hydrogels with different transparency by adjusting the concentration of DMSO aqueous solutions and investigated the effects of DMSO concentration on the properties of PVA hydrogels, and ultimately optimized the concentration of DMSO aqueous solution to obtain the PVA hydrogel with the highest transparency to be used as the optical core of artificial cornea. Based on these results, the transparent mechanism of PVA hydrogels was also analyzed and explored in order to provide not only some reference data for the optical core of artificial cornea made of PVA hydrogels with high transparency and excellent mechanical strength but also important theoretical guidance for the further development of biomaterials used for artificial cornea and contact lens.

Experimental section

Preparation of PVA hydrogels

PVA powder (mean degree of polymerization 1700 ± 50 , hydrolysis degree 99%, residual content of acetate groups 0.13%, content of PVA more than 90.5 wt.%) was from Chongqing Beipei Chemical Co. Ltd., China, and analytical grade DMSO was purchased from Chengdu Kelong Chemical Co. Ltd., China. Both the two chemicals were used here without further purification. Firstly, PVA powders were dissolved in mixed solvents composed of DMSO and deionized water, in which the DMSO concentration was 0, 20, 40, 60, 68.5, 75, 80,

90 and 100 respectively, with continuous stirring for 3h at 90°C to obtain a 16.7wt% PVA solution. Then, the PVA solution was poured into a mold and frozen at -18°C for 7h, subsequently taken out and thawed at room temperature for 3h. After such a freeze-thaw cycle was repeated 7 times, PVA hydrogels could be obtained. After that, the products were rinsed thoroughly with deionized water at 37.5°C to remove DMSO as clean as possible, and the PVA hydrogel samples were achieved to be used for characterization. The process can be schemed in Fig.1 in order to be understood more easily.

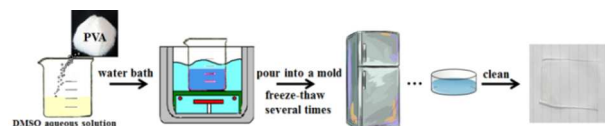


Fig. 1 The schematic diagram for the preparation process of PVA hydrogels

Characterization

Transparency. Light transmittance is an important indicator of the transparency. Transmittance (T) of PVA hydrogels fully swollen by deionized water was measured by using a UV-visible spectrophotometer (754UV-visible spectrophotometer, Shanghai Spectrum Instruments). We selected the wavelengths of 425nm, 450nm, 485nm, 550nm, 590nm, 600nm and 700nm in the visible region as the incident light to measure the transmittance. According to literature^[37], the thickness of artificial cornea or corneal contact lens is about 0.5mm, so here the transmittance (Ta) of PVA hydrogel films with 0.5mm thickness was calculated by the following formula based on the transmittance of the PVA hydrogel films (T) and its actual thickness (d).

$$T_a = 100 - (100 - T) \times 0.5/d$$

Crystallinity. PVA hydrogels were dried until the weight remained constant in a thermostatic oven at 55°C. Then, the crystal melting enthalpy of the dry gels (ΔH) was determined by differential scanning calorimetry (DSC)^[38]. Compared with the complete crystallization of endothermic enthalpy (ΔH^*) for pure PVA powder, the relative degree of crystallinity (Xc) was calculated by the following equation: $X_c = \Delta H / \Delta H^*$. (Here, ΔH^* was measured by using pure PVA powder, and the value of ΔH^* was determined as 55.19/g.)

IR and DSC analysis. Pure PVA powder and PVA hydrogels prepared with different concentration of DMSO aqueous solutions were characterized by IR in order to analyze the composition changes in the molecule chains. The FTIR spectra were obtained over a wavenumber range of 500–4000 cm^{-1} using an infrared spectrometer (SENSOR27, BRUKER Co. Germany). Also, differential scanning calorimetry (DSC, NETZSCH DSC 204 F1, Germany) was used to analyze the thermal property of 68.5wt% DMSO aqueous solution as well as PVA hydrogels prepared with different DMSO aqueous solutions.

Mechanical strength. The standard samples of PVA hydrogels were prepared according to the requirement of tensile strength for plastics based on the national standard GB/T 1040-1992.

Then, the tensile strength and the elongation at break of these samples were tested using a universal testing machine (AG-10TA universal testing machine, Shimadzu, Japan).

Viscosity. The mixture solutions composed of DMSO and H₂O with different ratios were prepared at 30°C, and the densities (ρ) of these solutions were calculated by the convention formula. Based on this, the flow time (t) of these solutions were measured using an Ubbelohde viscometer. Thus, the viscosity of these solutions could be calculated according to the following formula: $\eta = A \rho t$ (Where A is the instrument constant).

Results and discussion

Properties of PVA hydrogels

Transparence of PVA hydrogels. The transmittance of PVA hydrogels were determined using different wavelengths of incident lights in the visible region. Table 1 showed that the longer the wavelength of the incident light, the higher the transmittance of PVA hydrogels. The formation mechanism of PVA hydrogel is generally considered that, freeze-thaw cycles at low temperature make crystallization of PVA occur in the action of hydrogen bonds, resulting in the formation of PVA crystallites that act as physical cross-links to hold the network structure in the PVA hydrogel. These crystallites, that is crystallized regions in PVA hydrogel, influence the direction and the intensity of the light and generate some physical phenomena, such as light scattering, refraction and reflection, and then affect the transparence of PVA hydrogels. From Table 1, it is obvious that the transparence of PVA hydrogels increases with the DMSO concentration at first, then reaches a maximum value gradually, subsequently decreases. We can find that the PVA hydrogel prepared by 80wt% DMSO aqueous solution demonstrates the highest average transmittance, about $99.8 \pm 0.2\%$, which is higher than that reported in patent^[39], and is also close to that of natural human corneas ($99.7-99.9\%$)^[40].

Table 1 Transparence of PVA hydrogels prepared with DMSO aqueous solutions with different concentration

DMSO content (wt%)	Wavelength (nm)							average value
	420	450	485	550	590	600	700	
0	77.0±0.1	77.0±0.1	77.0±0.1	77.0±0.1	77.0±0.1	77.0±0.2	77.0±0.1	77.0±0.1
20	86.9±0.1	86.9±0.2	86.9±0.1	86.9±0.1	87.0±0.1	87.0±0.1	87.0±0.2	87.0±0.1
40	88.4±0.2	88.4±0.1	88.4±0.2	88.4±0.1	88.4±0.1	88.4±0.1	88.4±0.2	88.4±0.1
60	93.4±0.1	94.6±0.2	95.6±0.1	97.1±0.2	97.7±0.2	97.8±0.2	98.6±0.2	96.4±0.2
68.5	96.0±0.2	96.9±0.1	97.6±0.2	98.7±0.2	98.9±0.3	98.8±0.2	99.4±0.3	98.0±0.2
75	98.9±0.2	99.3±0.2	99.4±0.2	99.8±0.2	99.8±0.3	99.9±0.3	99.9±0.3	99.6±0.2
80	99.3±0.2	99.6±0.2	99.8±0.2	99.9±0.3	99.9±0.2	99.9±0.3	99.9±0.2	99.8±0.2
90	97.6±0.1	98.1±0.2	98.4±0.3	98.7±0.2	98.8±0.2	98.8±0.2	99.0±0.3	98.5±0.2
100	87.0±0.1	87.8±0.1	88.6±0.1	90.2±0.2	91.1±0.2	91.3±0.2	93.2±0.2	89.9±0.2

Crystallinity. Crystallinity is an important physical quantity to reflect the crosslinking degree of PVA hydrogel. The value of crystallinity corresponds to the total amount of crystallites, including the number of crystallites and crystallite volumes. Fig.2 (Fig. S1 and Table S1) showed that the crystallinity of PVA hydrogels increased at 20wt% of DMSO solution firstly, and kept a slight fluctuation. Then, the curve decreased

dramatically when the concentration of DMSO was 68.5wt%, after that continue to increase.

Combined with the above results in Table 1, we find that the relationship between the transparence and the crystallinity of PVA hydrogels is inversely proportional, that is to say, the weaker the crystallinity, the higher the transparence of PVA hydrogels. This is consistent with the fact that when the crystallinity gets to a higher value, it would increase the scattering of visible light, thus results in a decreased transparency.

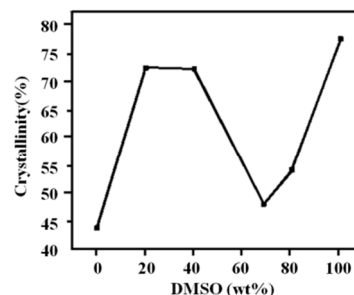


Fig. 2 Crystallinity of PVA hydrogels as a function of DMSO concentration

IR analysis. Compared curve *a* with curve *b* in Fig. 3, it could be found that the adsorption peaks attributed to the adsorption peaks of $-\text{CH}_2$ and/or $-\text{CH}$ at 2946cm^{-1} and/or 849cm^{-1} have not displaced obviously, indicating that the chemical environment of these groups has not changed significantly in PVA hydrogels. In addition, the absorption peak at 1144cm^{-1} assigning to PVA crystal band has not shifted but the relative intensity increased, indicating that the type of the formed PVA crystallites has not transformed and just the number of these crystallites and the crystallite volumes might have changed. Fig.3 also demonstrated that most of DMSO molecules in PVA hydrogel had been cleaned up because the absorption peak of DMSO at 2996cm^{-1} disappeared in curve *b* compared with curve *c*.

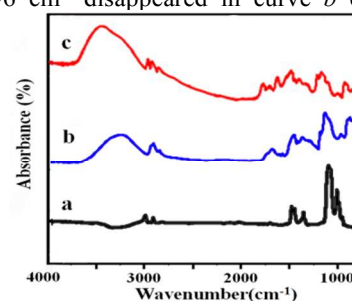


Fig. 3 IR spectra for pure PVA powder (a), PVA hydrogel prepared with 80wt% DMSO aqueous solution (b) and pure DMSO (c)

Mechanical strength. The tensile strength and the elongation at break of PVA hydrogels were tested after being fully swollen in deionized water at 37.5°C . Fig.4a showed that the tensile strength of PVA hydrogel prepared with 80wt% DMSO aqueous solution was $3.36 \pm 0.14\text{MPa}$, higher than that of PVA hydrogels prepared with other concentrations of DMSO aqueous solution, and similar to the average tensile strength of natural cornea (3.81Mpa)^[41], could endure the normal

intraocular pressure of human (about 1.95KPa)[42]. Elongation at break of PVA hydrogel prepared with 80wt% DMSO aqueous solution was over 600%, as shown in Fig.4b, demonstrating that such a PVA hydrogel with high transparence could still keep excellent mechanical strengths which could endure the normal intraocular pressure of human.

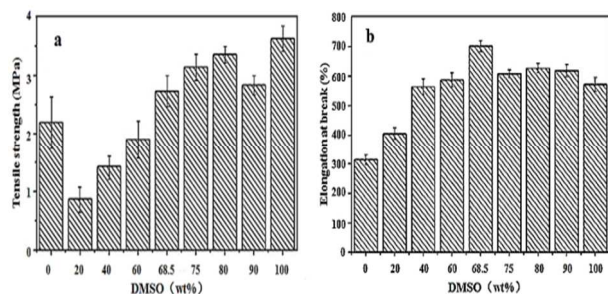


Fig. 4 Tensile strength (a) and elongation at break (b) of PVA hydrogels

Characterization of DMSO aqueous solutions

Viscosity. Viscosity of DMSO aqueous solutions with different concentrations were measured at different temperatures. Fig.5 showed that the viscosity curves at different temperatures displayed a similar changing trend, going up firstly and then falling down with the increase of DMSO concentrations. And the maximum value of viscosity showed up when the DMSO concentration was about 70wt%, corresponding to the molar ratio of around 1:2 for DMSO/H₂O (the theoretical value is about 68.5wt%). It suggests that DMSO aqueous solution might have the strongest intermolecular action when the molar ratio of DMSO/H₂O is 1:2. Also it implies that the intermolecular force between DMSO and H₂O molecules is much stronger than that in single molecules such as pure H₂O or pure DMSO. In addition, it is obvious that the viscosity for all the samples shows a declined tendency along with the increase of temperature, hinting that the interaction between DMSO and H₂O molecules is inversely proportional to the temperature.

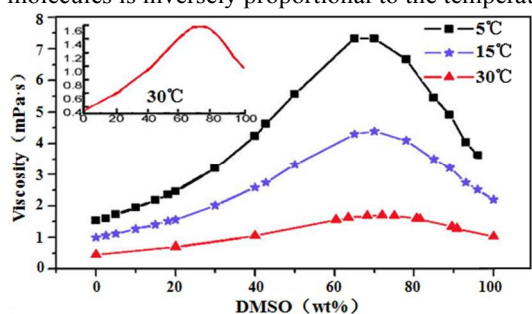


Fig. 5 Viscosity of the DMSO aqueous solutions at different temperatures

DSC. It can be seen from Fig.6 that the freezing point of 68.5wt% DMSO aqueous solution (1DMSO/2H₂O) is -139.1°C, far below that of pure water (0°C) and pure DMSO (18.4°C), indicating that the 1DMSO/2H₂O system becomes more difficult to solidify because of the strong interaction between molecules. The thermodynamics of 68.5wt% DMSO aqueous solution kept stable in the range of -100°C~100°C without significant endothermic peak presence. Besides, it can also be

observed that two endothermic peaks appeared at 140.0°C and 199.0°C respectively, higher than that of pure water (100°C) and pure DMSO (189°C), implying that two or more types of strong intermolecular actions have occurred between DMSO and H₂O. It is further testified the fact that the intermolecular actions in 1DMSO/2H₂O solution is limited by temperature.

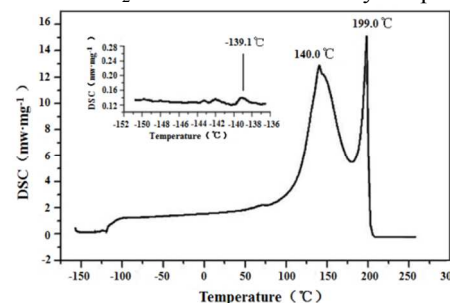


Fig.6 DSC curves for the 68.5wt% DMSO aqueous solution

Interaction between DMSO and H₂O molecules in 1DMSO/2H₂O network structure. The above results confirmed that strong interaction between DMSO and H₂O molecules had occurred compared to that in pure H₂O or pure DMSO molecules, so it can be concluded that a new structure of 1DMSO/2H₂O network might be formed in DMSO aqueous solution. As we know, the two lone pair electrons of oxygen atom in DMSO molecule do not participate in any bonding in pure DMSO, but they are entirely possible to bond with hydrogen atom of H₂O through hydrogen bonds. The molecule clusters of H₂O and DMSO existed in DMSO aqueous solution had been proved using mass spectrometer by Dong, et al^[43]. While Cabral, et al^[44] had proved that the hydrogen atom on methyl group (-CH₃) did not participate in the formation of hydrogen bonds. Therefore, a network structure as schemed in Fig.7 might be very likely formed between DMSO and H₂O molecules.

There are two major types of the six membered rings in Fig.7(c), one is composed of two DMSO and four H₂O molecules connected by hydrogen bonds, as shown in Fig.7(a), and the other is composed of six H₂O molecules connected by hydrogen bonds shown in Fig.7(b). The network structure we described could be well coincident with the relationship between 1DMSO and 2H₂O, in which H₂O molecules still remain their tetrahedral structure and the hydrogen bonds generate from the interaction between the hydrogen atom and the lone pair electrons of O atom. While, -CH₃ groups in DMSO are gathered in clusters, reducing the repulsion between H₂O molecule and the polar group of S=O.

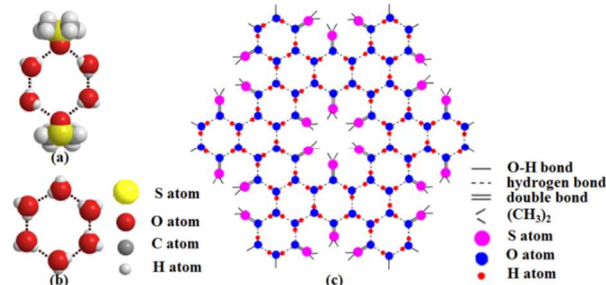


Fig. 7 Configurations for the 1DMSO/2H₂O cluster

Transparent mechanism of PVA hydrogel

IR. The IR spectra in Fig.8 showed that the well-defined characteristic bands assigned to PVA were present at 3442, 2903, 2903, 2835 and 849cm⁻¹ for all samples, and the changes in peak intensity and location might be caused by hydrogen bonding between PVA chains which was influenced by the solvents containing different DMSO content. In Fig.8a, 8b, 8d and 8e, the intensity of absorption peaks at 2835cm⁻¹ belonging to O-H stretching vibration (intramolecular H-bond) has changed, indicating that PVA chains might interact with H₂O or DMSO molecules through hydrogen bonds in different circumstances with the change of DMSO concentration. The adsorption peak assigning to C=C stretching vibration appeared at 1652cm⁻¹ obviously in Fig.8a-d compared with that of PVA powder in Fig.3(a), suggesting that the existence of DMSO and H₂O molecules could affect the interaction between PVA molecular chains.

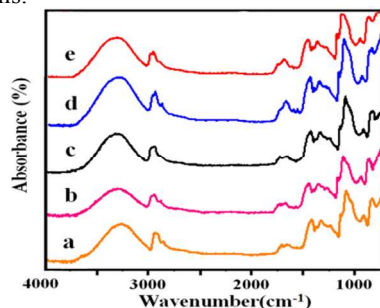


Fig. 8 IR spectra of PVA hydrogels prepared with different concentration of DMSO aqueous solutions: 0wt% (a), 40wt% (b), 68.5wt% (c), 80wt% (d) and 100wt% (e) DMSO aqueous solutions.

DSC. The DSC curve of PVA hydrogel prepared with pure water (0wt% DMSO) was shown in Fig.9a, it could be seen that there were two endothermic peaks, the one appeared at 102.6°C, close to the boiling point of pure water (100°C), contributing to the fact that a large number of H₂O molecules in the form of free water existed in PVA hydrogel; and the other appeared at 123.4°C, much higher than 100°C, implying that large amount of hydrogen bonds formed between H₂O molecules and PVA chains. In Fig.9c, it can be found that endothermic peak appeared at 114.7°C, between the boiling points of pure water and pure DMSO (189°C), meaning that 1DMSO/2H₂O network structure was formed in 68.5wt% DMSO aqueous solution, which is exactly agreed with the proposed configuration in Fig.7. Therefore, the two endothermic peaks at 107.8°C and 119.3°C in Fig.9b confirmed the fact that part of H₂O molecules bonded with PVA chains through hydrogen bonding, while the rest combined with DMSO molecules, forming 1DMSO/2H₂O network structure. In Fig.9e, two endothermic peaks appeared at 123.6°C and 182.5°C, close to the boiling point of pure DMSO, indicating that large amount of DMSO molecules might combine with PVA chains through hydrogen bonding, and the rest of DMSO molecules existed freely in PVA hydrogel. Based on the above analysis, it can be easily explained that the endothermic peaks at 105.8°C and 160.7°C in

Fig.9d might be caused by DMSO molecules hydrogen-bonded with H₂O molecules (or PVA molecule chains) and the freely existed DMSO molecules respectively.

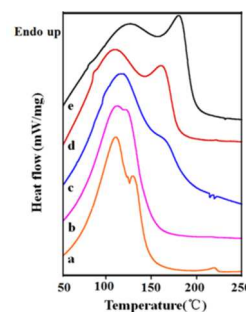


Fig. 9 DSC curves for PVA hydrogels prepared with different concentration of DMSO aqueous solutions: 0wt% (a), 40wt% (b), 68.5wt% (c), 80wt% (d) and 100wt% (e) DMSO aqueous solutions.

Transparent mechanism. It was considered that the physical cross-linked points including microcrystalline zones and hydrogen bonds in molecular chains contributed to the formation of three-dimensional structures during the freezing process. Compared with hydrogen bonds, microcrystalline zones are relatively stable in cross-linked structures due to their tightly arranged molecular chains and strong interaction. Therefore, hydrogen bonds play a more important role in the crystallization of PVA hydrogel, which in turn influences the transparency of PVA hydrogel.

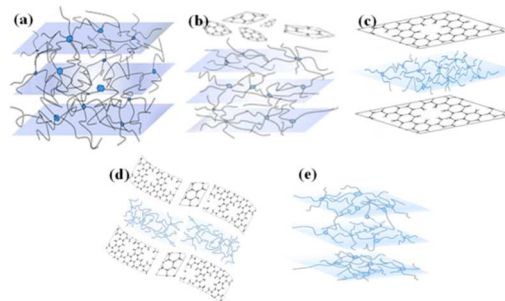


Fig. 10 Schematic diagrams of spatial structure for PVA hydrogels prepared with different concentration of DMSO aqueous solutions: deionized water (a), 40wt% DMSO aqueous solution (b), 68.5wt% DMSO aqueous solution (c), 80wt% DMSO aqueous solution (d) and pure DMSO (e)

When the solvent to prepare PVA hydrogel was just composed of pure water, hydrogen bonds formed between PVA molecular chains. What's more, plenty of H₂O molecules could provide H atoms to combine with polar groups of -OH in PVA molecular chains by hydrogen bonds^[45,46], which in turn promoted the cross-linking degree of PVA and made the cross-linked structure grow tightly along three-dimensional directions. Consequently, the volume of crystalline regions became larger. But these larger crystalline regions are prone to blocking the penetration of the light, thus leading to the lower transmittance, schemed in Fig.10(a).

With the DMSO concentration in the solvent increasing to 40wt%, O atoms in DMSO preferentially combined with the active H atoms in H₂O, showing a tendency to form

1DMSO/2H₂O network structure. Hydrogen bonds in PVA hydrogel could be formed not only between PVA molecular chains but also between PVA molecular chains and H₂O. However, since part of active H atoms of H₂O had combined with O atoms in DMSO yet^[47], the number of hydrogen bonds between PVA and H₂O would be reduced. Thus, the density and the strength of cross-linked structure in three-dimensional direction would correspondingly decrease. Meanwhile, the presence of the 1DMSO/2H₂O network structure might affect the growth of PVA crystals in spite of its incompleteness and fragmental shapes. Under such a growth circumstance, the volume of PVA crystalline regions would decrease and show a growth trend along two-dimensional direction gradually. Consequently, the transparency of PVA hydrogel became higher and higher. This process was schemed in Fig.10(b).

According to the intermolecular action between DMSO and H₂O molecules, a schematic diagram shown in Fig.7 was made. When the concentration of DMSO in aqueous solution was 68.5%, a precise 1DMSO/2H₂O network structure would be formed^[48]. The crystallization of PVA hydrogel was restricted by such a structure, and presented a growth trend along the two-dimensional direction. Finally, a flat-shaped crystal structure of PVA could be obtained, as shown in Fig.10(c). Despite the PVA crystalline region was long and thin, its volume was still large, so the light couldn't pass through smoothly all the same. That is why we has not got PVA hydrogel with the highest transmittance when the concentration of DMSO is 68.5wt%. In addition, the plane of PVA crystallites were parallel each other, resulting in the relative shift happened easily, therefore, a maximum value of elongation at break have been obtained at such circumstances. However, we have not got the maximum value of tensile strength due to the weaker interaction between PVA molecular chains in the two-dimensional direction compared with that in the three-dimensional direction.

When the concentration of DMSO increased to 80wt%, we got a PVA hydrogel with a maximum value of transmittance. Under this condition, excessive DMSO molecules outside of 1DMSO/2H₂O network structure might affect or even destroy this complete structure into fragments. Thus, a three-dimensional crosslinking structure of PVA hydrogel appeared, as shown in Fig.10(d). Besides, hydrogen bonds formed between excessive DMSO molecules and -OH on PVA chains limited the crystallization of PVA hydrogel and also hindered the growth of crystalline regions along the two-dimensional direction, resulting in the smallest volume of PVA crystallites. Also, the tensile strength was improved with the increase in number of PVA crystallites formed in two-dimensional or three-dimensional space.

Finally, 1DMSO/2H₂O network structure disappeared when the concentration of DMSO aqueous solutions was up to 100wt%. Crystallization of PVA hydrogel grew along three-dimensional direction because most of DMSO molecules bonded with PVA chains by hydrogen bonds. The volume of crystalline region in PVA hydrogel prepared by pure DMSO became smaller compared with that prepared by pure water due to the weaker crosslinking within molecules, as schemed in

Fig.10(e). Therefore, the transparency for such a PVA hydrogel could keep higher, but was still slight lower than that of the PVA hydrogel prepared with 80wt% DMSO solution.

Conclusion

We have prepared highly transparent PVA hydrogels with different concentrations of DMSO aqueous solution in the experiment. And the optimum concentration of DMSO was also determined by a series of tests. The results showed that the average transmittance of PVA hydrogel prepared with 80wt% DMSO aqueous solution reached a maximum value ($99.8 \pm 0.2\%$). According to investigations on the properties of DMSO aqueous solution with different concentrations, the network structure of 1DMSO/2H₂O existed in the mixed solution was put forward at the DMSO concentration of 68.5wt%. And the influencing mechanism of such a network structure on the transparency and mechanical strength of PVA hydrogels was analyzed thoroughly. Based on this, why the highest transparency of PVA hydrogel was obtained at the 80wt% DMSO was explained clearly. The PVA hydrogel with highly transparency prepared in this study might have a great potential to be applied in the fields of artificial corneas and contact lens.

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References

- [1]M. A. Princz, H. Sheardown, M. Griffith. 5-Corneal tissue engineering versus synthetic artificial corneas. *Biomaterials and regenerative medicine in ophthalmology*, 2010, 134-149.
- [2]M. A. Rafat, J. M. Hackett, P. Fagerholm, et al. Artificial cornea. *Encyclopedia of the Eye*, 2010, 128-134.
- [3]H. Cardona. Keratoprosthesis: acrylic optical cylinder with supporting intralamellar plate. *American journal of ophthalmology*. 1962, 54: 284-294.
- [4]H. Cardona. Plastic keratoprosthesis—A description of plastic material and comparative, histologic study of recipient cornea. *American journal of ophthalmology*. 1964, 58: 247-252.
- [5]J. C. Barber. Keratoprosthesis: past and present. *International ophthalmology clinics*. 1988, 28(2): 103-109.
- [6]T. V. Chirila, C. R. Hicks, P. D. Dalton, et al. Artificial cornea. *Progress in Polymer Science*, 1998, 23(3): 447-473.
- [7]T. V. Chirila. An overview of the development of artificial corneas with porous skirts and the use of PHEMA for such an application. *Biomaterials*, 2001, 22(24): 3311-3317.
- [8]H. Cardona. The cardona keratoprosthesis: 40 years experience. *Refractive and corneal surgery*, 1991, 7(6): 486-471.
- [9]J. M. Legeais, G. Renard, J. M. Parel, et al. Expanded fluorocarbon for keratoprosthesis cellular ingrowth and transparency. *Experimental eye research*. 1994, 58(1): 41-51.

- [10]C. Hicks, G. Crawford, T. V. Chirila, et al. Development and clinical assessment of an artificial cornea. *Progress in Retinal and Eye Research*, 2000, 19(2):149-170.
- [11]D. R. Caldwell. The soft keratoprosthesis. *Transactions of the American Ophthalmological Society*, 1997, 95:751-802.
- [12]D. I. Ham and J. H. Lee. A tectonic keratoprosthesis using expanded polytetrafluoroethylene as a supporting skirt in humans. *Korean Journal of Ophthalmology*. 1991, 5(2): 83-87.
- [13]G. H. Hsiue, S. D. Lee and P. C. Chang. Surface modification of silicone rubber membrane by plasma induced graft copolymerization as artificial cornea. *Artificial Organs*, 1996, 20(11):1196-1207.
- [14]R. J. Linnola, R. P. Happonen, O. H. Andersson, et al. Titanium and bioactive glass-ceramic coated titanium as materials for keratoprosthesis. *Experimental Eye Research*, 1996, 63(4):471-478.
- [15]C. R. Leon, J. J. Barraquer, J. S. Barraquer. Coralline hydroxyapatite keratoprosthesis in rabbits. *Journal of Refractive Surgery*. 1997, 13(1):74-77.
- [16]H. Miyashita, S. Shimmura, H. Kobayashi, et al. Collagen-immobilized poly(vinyl alcohol) as an artificial cornea scaffold that supports a stratified corneal epithelium. *Journal of Biomedical Materials Research, Part B: Applied Biomaterials*, 2006, 76B:56-63.
- [17]Y. Uchino, S. Shimmura, H. Miyashita, et al. Amniotic membrane immobilized poly(vinyl alcohol) hybrid polymers as an artificial scaffold the supports a stratified and differentiated corneal epithelium. *Journal of Biomedical Materials Research, Part B: Applied Biomaterials*, 2007, 81B:201-206.
- [18]Traian V. Chirila. An overview of the development of artificial corneas with porous skirts and the use of PHEMA for such an application. *Biomaterials*, 2001, 22(24): 3311-3317.
- [19]Traian V. Chirila, David A. Morrison, Celia R. Hicks, et al. In Vitro Drug-Induced Spoliation of a Keratoprosthetic Hydrogel. *Lippincott Williams and Wilkins*, 2004, 23(6): 620-629.
- [20]Zainuddin, T. V. Chirila, D.J.T. Hill, et al. Study of the calcification of PHEMA hydrogels using a two compartment permeation cell. *Journal of Molecular Structure*, 2005, 739(1-3): 199-206.
- [21]Traian V. Chirila, Anita J. Hill and David T. Richens. Effect of Redundant Chain Packing on the Uptake of Calcium Phosphate in Poly(2-Hydroxyethyl Methacrylate) Hydrogels. *Journal of Materials Science: Materials in Medicine*, 2006, 17(12): 1245-1254.
- [22]Ylenia S. Casadio, David H. Brown, Traian V. Chirila, et al. Biodegradation of Poly (2-hydroxyethyl methacrylate) (PHEMA) and Poly{(2-hydroxyethyl methacrylate)-co-[poly(ethyleneglycol) methyl ether methacrylate]} Hydrogels Containing Peptide-Based Cross-Linking Agents. *Biomacromolecules*, 2010, 11(11): 2949–2959.
- [23]Zainuddin, Traian V. Chirila, ZekeBarnard, et al. F2 excimer laser(157nm) radiation modification and surface ablation of PHEMA hydrogels and the effects on bioactivity: Surface attachment and proliferation of human corneal epithelial cells. *Radiation Physics and Chemistry* , 2011, 80(2): 219 – 229.
- [24]Traian V. Chirila, Karina A. George, Wael A. Abdul Ghafor, et al. Homo-Interpenetrating Polymer Networks of Poly(2-hydroxyethyl methacrylate): Synthesis, Characterization, and Calcium Uptake. *Journal of Applied Polymer Science*, 2012, 126: E455–E466.
- [25]Fenglan Xu, Yubao Li, Jimei Han, et al. Biodegradable porous nano-hydroxyapatite/alginate scaffold. *Materials Science Forum*, 2005, 486-487: 189-92.
- [26]Yuanhua Mu, Yubao Li, Mingbo Wang, et al. Novel method to fabricate porous n-HA/PVA hydrogel scaffolds. *Materials Science Forum*, 2006, 510-511: 878-881.
- [27]Mingbo Wang, Yubao Li, Fenglan Xu, et al. Synthesis and characterization of n-HA/PVA/gel composite. *Key Engineering Materials*, 2007, 330-332: 471-474.
- [28]Kemin Liu, Yubao Li, Fenglan Xu, et al. Graphite/poly(vinyl alcohol) hydrogel composite as porous ringy skirt for artificial cornea. *Materials Science and Engineering: C(Materials for Biological Applications)*, 2009, 29(1): 261 – 266.
- [29]Fenglan Xu, Yubao Li, Xiaoming Yao, et al. Preparation and in vivo investigation of artificial cornea made of nano-hydroxyapatite/poly (vinyl alcohol) hydrogel composite. *Journal of materials science: Materials in medicine*, 2007, 18(4): 635-640.
- [30]Fenglan Xu, Yubao Li, Yingpin Deng, et al. Porous nano-hydroxyapatite/poly(vinyl alcohol) composite hydrogel as artificial cornea fringe: characterization and evaluation in vitro. *Journal of Biomaterials Science-Polymer Edition*, 2008, 19(4): 431-439.
- [31]H Zhang, H Xia, Y Zhao. Poly(vinyl alcohol) hydrogel can autonomously self-heal. *ACS Macro Letters*, 2012, 1(11):1233-1236.
- [32]S. Kim Il, S. J. Kim, G. M. Shin, et al. Biocompatible IPN hydrogel comprising PVA and PDADMAC useful as contact lens. Korean patent, C08L029-04, KR 2004106881. 2003-06-12.
- [33]Sasahara Shuichi, Fujita Takahiko, Yoshikawa Kazuhiro. High-strength hydrous gel and manufacture of the gel. Japanese patent, C08L101-00, JP 2004292592. 2004-10-21.
- [34]Marmo, J. Christopher. Hydrogel contact lenses and package systems and production methods for same. American patent, C08K003-00, US 2004214914. 2004-10-28.
- [35]C. Dispenza, M. Leone, C. L. Presti, et al. Smart hydrogels for novel optical functions. *Times of Polymers and Composites*, 2007, 247:303-310.
- [36]N. Mintoura, T. Koyano, N. Koshizaki, et al. Preparation, properties, and cell attachment/growth behavior of PVA/chitosan-blended hydrogels. *Materials Science and Engineering C*, 1998, 6:275-280.
- [37]S. Josef, F. Viviana, L. Peggy, et al. Biocompatibility of a nonpenetrating synthetic cornea in vascularized rabbit corneas. *The Journal of Cornea and External Disease*. 2005, 24(4): 467~473

ARTICLE

- [38]C. M. Hassan and N. A. Peppas. Structure and morphology of freeze/thawed PVA hydrogels. *Macromolecules*, 2000, 33:2472-2479.
- [39]J. Gen, Y. Ikada. Manufacture of porous and transparent poly (vinyl alc.) hydrogel. Japanese patent, C08L029-04, JP 1985-94091. 1985-05-01
- [40]D. M. Maurice. The structure and transparency of the cornea. *Journal of physiology*. 1957, 136:263-286.
- [41]Y. Zeng, J. Yang, K. Huang, et al. A comparison of biomechanical properties between human and porcine cornea. *Journal of Biomechanics*, 2001, 34:533-537.
- [42]L. Xu, H. Wang, Y. X. Wang, et al. Intraocular pressure correlated with arterial blood pressure: the Beijing eye study. *American journal of ophthalmology Am.* 2007, 144: 461-462.
- [43]Dong Nam Shin, Jan W. Wijnen, Jan B. F. N. Engberts, et al. On the origin of microheterogeneity: mass spectrometric study of dimethyl sulfoxide-water binary mixtures. *Journal of Physical Chemistry B.* 2001, 105: 6759~6762.
- [44]Cabral J. T, Luzar A, Teixeira J, et al. Single-particle dynamics in dimethyl-sulfoxide/water eutectic mixture by neutron scattering. *Journal of chemical physics*, 2000, 113(19): 8736-8745.
- [45]Masuda K, Horii F. CP/MAS¹³CNMR analyses of the chain conformation and hydrogen bonding for frozen poly(vinyl alcohol) solution. *Macromolecules*, 1998, 31(17): 5810-5817.
- [46]Ricciardi R, Gaillet R, Ducouret G, et al. Investigation of the relationships between the chain organization and rheological properties of atactic poly(vinyl alcohol) hydrogels. *Polymer*, 2003, 44(11): 3375-3380.
- [47]Ning Zhang; Weizhong Li; Cong Chen, et al. Molecular dynamics simulation of aggregation in dimethyl sulfoxide-water binary mixture. *Computational and Theoretical Chemistry*, 2013, 1017: 126-35.
- [48]Roy S, Bagchi B. Solvation dynamics of tryptophan in water-dimethyl sulfoxide binary mixture: In search of molecular origin of composition dependent multiple anomalies. *Journal of chemical physics*, 2013, 139(3): 1-10.