Qinghua Wei, Yingfeng Zhang, Yanen Wang*, Weihong Chai, Mingming Yang, Wenxiao Zeng* and Meng Wang

Study of the effects of water content and temperature on polyacrylamide/polyvinyl alcohol interpenetrating network hydrogel performance by a molecular dynamics method

DOI 10.1515/epoly-2015-0087
Received April 8, 2015; accepted July 12, 2015; previously published online August 13, 2015

Abstract: An investigation of the molecular interaction within a hydrogel system was conducted using molecular dynamics simulation, and the interaction mechanism of a polyacrylamide/polyvinyl alcohol (PAM/PVA) hydrogel system was examined specifically at the molecular level. Several characteristics of the PAM/PVA composite hydrogel system that are largely dependent on water content and temperature were studied in this paper, such as cohesive energy density, binding energy, mechanical properties and pair correlation function. The cohesive energy density and binding energy of the hydrogel system increased with higher water content. Results also showed that increased temperatures led to a decrease in the cohesive energy density of the system, while binding energy remained unchanged. The mechanical properties of the system were evaluated by analyzing the static mechanic performance. Results showed that elastic coefficients, engineering modulus and ductility decreased with increasing water content and temperature. In addition, analysis of the pair correlation function revealed mainly hydrogen bonding interactions between H₂O molecules and surrounding atoms or functional groups. Results also indicated that the strength of these hydrogen bonds was \( O_{\text{water}} > O_{\text{PVA}} > O_{\text{PAM}} > N_{\text{PAM}} \) confirming both the potential and the difficulty of hydrogen bond formation. The aforementioned findings help in understanding the interaction mechanisms between the components of a hydrogel system and in demonstrating the effects of water content and temperature on the PAM/PVA hydrogel system, which provides useful information on the possible operating windows of a biomedical hydrogel-making process.

Keywords: cohesive energy density; mechanical properties; molecular dynamics; pair correlation function; polyacrylamide; polyvinyl alcohol.

1 Introduction

Since the concept of tissue engineering has been proposed, the repair and reconstruction of articular cartilage have become the focus and difficulty in this area of research. After more than 20 years of development, cartilage tissue engineering has made significant progress in basic research and clinical applications. When choosing cartilage substitute materials, highly elastic materials whose biomechanical properties are similar to those of cartilage are more preferred, such as silicone rubber, polyurethane, water gel, etc. Because water gel can provide a microenvironment for the extracellular matrix that is closer to natural cartilage, it is considered to be an ideal material for cartilage tissue repair.

Polyacrylamide (PAM) is a type of biomaterial that is used for preparing biomedical hydrogel. It is characterized typically by its three-dimensional network structure, non-toxic side effects and stable performance. However, the lower mechanical strength of PAM limits its application, especially for clinical uses such as artificial muscles and cartilage. To compensate for this defect, a new kind of material for preparing an interpenetrating network (IPN)
hydrogel has been introduced. It is considered to be the most effective material for this purpose.

An IPN hydrogel is a kind of polymer blend with unique properties, which is composed of two or more polymers. The components of the IPN hydrogel maintain their basic properties, providing a unique synergy in terms of performance and function (1, 2) that leverages the advantages of both materials. In addition, this improves the mechanical properties of the blending system (3, 4).

Although considerable research studies have been conducted on the IPN hydrogel, these studies focused on experimental and preparation technology (5–7), while theoretical studies on the IPN hydrogel are rare. Molecular dynamics (MD) simulation is currently the most important theoretical method for studying material microstructure and properties at the molecular scale. This method has been applied in various fields, yielding interesting conclusions not possible with traditional testing methods (8–10). In this study, we employed MD simulation to investigate an IPN hydrogel composed of PAM and polyvinyl alcohol (PVA). Specifically, we examined the effect of water content and temperature on the basic performance of the PAM/PVA IPN hydrogel at the molecular level. This allowed us to build a much-needed theoretical basis for the preparation of an IPN hydrogel.

2 Experimental

2.1 Force field

The MD simulation was conducted using the Materials Studio software package v. 5.5 (Accelrys, San Diego, CA, USA), with the COMPASS (Condensed-phase, Optimized Molecular Potential for Atomistic Simulation Studies) force-field module. The COMPASS (11) force field is a general, all-atom force field used for atomistic simulation and was developed using state-of-the-art ab initio and empirical parameterization techniques. It is useful for both organic and inorganic materials, and its applicability for polymer systems has been verified in many research studies (12–14).

2.2 Model building and details of the MD simulation

In accordance with the molecular structures of PAM and PVA, we built polymer chains using the Visualizer module of Materials Studio. This yielded a PAM chain with 25 monomers and a PVA chain with 40 monomers. The carbon atoms of the end group were hydrogenated to reach saturation and optimized using the Smart Minimizer procedure of the Discover module in Materials Studio to obtain a stable configuration. Next, we built amorphous molecular models of the PAM/PVA IPN hydrogel based on different water contents using the Amorphous Cell module of Materials Studio. To reduce the size effect and avoid excessive computations, there were only four polymer chains in each amorphous cell. We also examined the influence of water content on hydrogel properties. To this end, we constructed amorphous unit cells with different water contents. The mass percentages of water content were 0%, 20%, 40%, 60% and 80%. Table 1 shows the detailed parameters for the constructed models.

After the initial model energy minimization, we conducted MD simulations on these PAM/PVA models under the NVT (number of particles, volume and temperature) ensemble with a time step of 1 fs for 50 ps until the system reached equilibrium. Then an additional 30-ps MD calculations were conducted for analysis. For every 500 steps, the trajectory of the system was recorded. For the simulation process, we used an Andersen thermostat (15) with the velocity Verlet integration method to solve the Newton equation of motion. The initial velocity was determined using the Boltzmann random distribution method. Van der Waals and Coulomb forces were respectively calculated using an atom-based method (16) and the Ewald (17) method, with a cut-off distance of 9.5×10^{-10} m. We set the simulation temperature to 298 K in order to calculate the influence of water content on

<table>
<thead>
<tr>
<th>Water content (g/m^3)</th>
<th>0%</th>
<th>20%</th>
<th>40%</th>
<th>60%</th>
<th>80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial density (g/m^3)</td>
<td>1.12</td>
<td>1.08</td>
<td>1.04</td>
<td>1.03</td>
<td>1.02</td>
</tr>
<tr>
<td>Unit cell size (Å)</td>
<td>23.10±0.04</td>
<td>23.78±0.06</td>
<td>26.45±0.06</td>
<td>31.06±0.07</td>
<td>38.62±0.08</td>
</tr>
<tr>
<td>Number of water molecules</td>
<td>0</td>
<td>99</td>
<td>262</td>
<td>590</td>
<td>1575</td>
</tr>
<tr>
<td>Total number of atoms</td>
<td>1068</td>
<td>1365</td>
<td>1854</td>
<td>2838</td>
<td>4725</td>
</tr>
</tbody>
</table>
the properties of the hydrogel. Simulation temperatures were set to 248, 298, 348 and 398 K, respectively, to calculate the effects of temperature.

2.3 Evaluation of system balance and equilibrium structures

To determine whether the MD simulation was balanced, two standards were used. One standard was used when the temperature fluctuation was tiny, while the other was used when the energy fluctuation was small. This requires that both of them be constant or that they fluctuated slightly up and down along a constant value. In general, temperature and energy fluctuations between 5% and 10% indicate that the system has reached equilibrium. Figures 1 and 2 show that both the temperature and the energy change for the PAM/PVA mixed system were small, indicating that it had reached equilibrium after the MD simulation.

After carrying out the MD simulation, we obtained the equilibrium structures of the PAM/PVA hydrogel system with different water contents at 298 K. For example, we obtained the equilibrium structures for 40% water content at different temperatures. Figure 3 shows the three-dimensional equilibrium structures of the PAM/PVA hydrogel system with different water contents obtained from the MD calculations.

3 Results and discussion

3.1 Cohesive energy density

Cohesive energy density (CED) refers to the energy 1 mol condensed matter into gas that is needed to overcome the interaction force between molecules. CED is the cohesive energy per unit volume, which is a measure of the molecular interaction force between molecules. The material and physical properties related to material interactions are intrinsically linked to cohesive energy. These properties include solubility, compatibility and heat of vaporization. CED is defined in equation 1:

\[ \text{CED} = \frac{E_{\text{coh}}}{v} \]  

where \( E_{\text{coh}} \) refers to the cohesive energy and \( v \) is the mixed volume of materials.

To explore the effects of water content and temperature on the CED for the hydrogel system, we calculated...
The results shown in Table 2 and Figure 4 indicate that the CED of the hydrogel system increased with the increase in water content at 298 K. This was mainly because, as water content increases, the number of molecules contained per unit volume also increases. As water molecules interact, more hydrogen bonds form and more electrostatic interactions occur. This results in an increase in CED. In addition, the amount of CED reflects the stability of materials. Therefore, the stability of a PAM/PVA IPN hydrogel system is strengthened with increasing water content. Table 3 and Figure 5 show that, as the temperature increased, CED, van der Waals forces and electrostatic forces decreased. This indicates that less energy is required as the system changes from liquid to gas. The higher the temperature is, the smaller the interaction force between the molecules in the system is, and the more unstable the system becomes. This explains the effects of temperature on system stability from the perspective of CED.

### 3.2 Binding energy

The adhesion between PAM and PVA can be evaluated by examining the binding energy between their molecules. In this study, we considered PAM and water as a whole and, therefore, calculated the binding energy through the following equation:

\[
E_{\text{inter}} = E_{\text{total}} - (E_{\text{PVA}} + E_{\text{PAM-H}_2\text{O}})
\]

where \(E_{\text{PVA}}\) is the energy of PVA, \(E_{\text{PAM-H}_2\text{O}}\) is the energy of PAM and water molecules, and \(E_{\text{total}}\) is the energy of the PAM/PVA IPN hydrogel system. Binding energy is defined as the negative of the interaction energy, \(E_{\text{bind}} = -E_{\text{inter}}\). Binding energy can reflect the strength of the molecular interaction between the components. The greater the binding energy, the stronger the force generated by molecular interactions.

Binding energy is composed of non-bond energy and lattice-limit energy. The non-bond energy is the predominant part of it. Table 4 shows that the binding energy of the system increased with increasing water content, and primarily because of the latter, the binding energy may produce greater intermolecular interactions within the system.

It makes sense that the binding energy and CED vary with changing water content, which also demonstrates the accuracy of this method. Table 5 and Figure 6 show that, as the temperature increased, the energy of the system and each composition also increased. However,
where \( m_i \) and \( V_i \) represent the quality and speed of the atoms, respectively, and \( V_0 \) is the volume without distortion.

The elastic coefficient matrix was obtained by solving the first derivative of the corresponding stress and strain. The least squares fitting for the tensile modulus (\( E \)) and Poisson’s ratio allowed us to obtain the effective isotropic mechanical properties such as the shear modulus (\( G \)), bulk modulus (\( K \)) and Cauchy pressure (\( C_{12}-C_{44} \)). The modulus for isotropic materials can be expressed using the Lamé coefficients as follows (19):

\[
E = \mu \left( \frac{3\lambda + 2\mu}{\lambda + 2\mu} \right), \quad K = \lambda + \frac{2}{3\mu}, \quad G = \mu, \quad \gamma = \frac{\lambda}{2(\lambda + \mu)}
\]  

[4]

The tensile or Young’s modulus, shear modulus and bulk modulus indicate the strength of a rigid material under different stress conditions, including the ability to resist elastic deformation. The Cauchy pressure is often used to measure the ductility of a system. A negative Cauchy stress indicates a brittle material, while a positive one indicates a tough material. The higher the value, the better the system ductility (20, 21).

According to the principle of static mechanics, we analyzed the trajectory of the structures of the equilibrium system. The mechanical properties of PAM/PVA with different water contents at different temperatures were obtained, as shown in Tables 6 and 7.

Table 6 shows that increasing water content reduced the elasticity coefficient and various engineering moduli, and the fluctuation of the binding energy between components was nearly unchanged. It is evident that the molecular interactions between polymer chains were less affected by the temperature.

### 3.3 Mechanical properties

Mechanical properties can be determined by analyzing the static model at the atomic level. The Virial equation was used to calculate the internal stress tensor (\( \sigma \)) (18) in the static model:

\[
\sigma = \frac{1}{V_0} \left[ \sum_{i=1}^{N} m_i \mathbf{V}_i \mathbf{V}_i^T \right]
\]  

[3]
of the PAM/PVA hydrogel system. This indicates isotropic growth and rigid decline. Data in the $C_{11}$, $C_{22}$ and $C_{33}$ group; the $C_{12}$, $C_{13}$ and $C_{23}$ group; as well as the $C_{44}$, $C_{55}$ and $C_{66}$ group were closer to each other within a group. This demonstrates that increasing the water content of the hydrogel system could make the material closer to the isotropic elastic body. In addition, the value of the Cauchy pressure decreased with an increase in water content. This indicates that the system ductility degrades with an increase in water content.

Together, the data from Table 7 and Figure 7 show that the various engineering moduli of the PAM/PVA hydrogel system decreased significantly as the temperature increased. This means that the rigidity of the hydrogel system gradually declined. It occurred mainly because the kinetic energy of the molecules increased with the temperature. Thus, the polymer hydrogel system became more adaptable and the flexibility increased, thereby relaxing the rigidity of the hydrogel system. In addition, the Cauchy pressure value of the system also decreased significantly with an increase in temperature. System ductility also decreased as the temperature increased.

### 3.4 Analysis of the pair correlation function

To a certain extent, binding energy can reflect the strength of the interaction between components. However, there is a lack of research on the distribution of $H_2O$ and on the mode of molecular interaction between the other components in a hydrogel system. This study fills a gap in the literature by analyzing the pair correlation function (PCF) of the equilibrium structures. Thus, this work reveals the interfacial interaction mechanism and the relationship between $H_2O$ molecules and other molecules in a hydrogel system. The PCF $g(r)$ reflects the physical characteristics of the material microstructure. This indicates a probability density to another molecule at a distance $r$ around a location where the ratio of the molecules is randomly distributed in terms of probability density. Its expression is

$$g_{A,B}(r) = \frac{n_B}{4\pi r^2 \, dr} \left(\frac{N_B}{v}\right)$$

where $n_B$ is the number of B atoms around the A atom at a distance $r$, $N_B$ is the total number of B atoms and $v$ represents the volume of the entire hydrogel system.

Since $H_2O$ molecules form interaction mainly through hydrogen bonding with the PAM/PVA polymer, only the PCF of atoms that may share strong interactions requires analysis. Taking the $H_2O$ molecule as a whole, we need only to mark the oxygen atom representing the $H_2O$ molecule. PAM molecular chains may interact with $H_2O$ molecules through the oxygen atoms of the carbonyl groups ($-$C=O), as well as through the nitrogen atoms attached to the carbonyl groups. PVA molecular chains interact with $H_2O$ molecules mainly through the oxygen atoms of the hydroxyl groups ($-$OH). In addition, $H_2O$ molecules can interact with other $H_2O$ molecules in the system. The aforementioned atoms were marked as $O_{\text{water}}$, $O_{\text{PAM}}$, $N_{\text{PAM}}$ and $O_{\text{PVA}}$, as shown in Figure 8. (The graph displays the

![Figure 7: Mechanical properties of the PAM/PVA hydrogel system with 40% water content vs. temperature.](image)

![Figure 8: PCF schematic of marked atoms.](image)
Figure 10 compares the PCFs with different water contents in the hydrogel system. Our analysis found that, in terms of the water content of the hydrogel system, the peak value increased with increasing water content. This is mainly because, with increasing water content, more water molecules would be around the polymer, forming more sufficient contact. Also, as shown in Figure 10C, the highest peak of the PCF between H$_2$O molecules and other H$_2$O molecules in the system was close to $r=2.76$ Å. This structure of the H$_2$O molecules and polymer monomers).

The PCF of atoms can show the interaction pattern and the principle between non-bonded atoms. In general, a peak value lower than 3.5 Å is mainly composed of chemical bonds and hydrogen bonds. The van der Waals force is dominant between 3.5 and 5 Å. As shown in Figure 9, the peak values of the PCF between H$_2$O and O$_{PAM}$, N$_{PAM}$, O$_{PVA}$ lie within $r=3.5$ Å. This shows that the atoms and the aforementioned functional groups formed hydrogen bonds to interact with each other. The distribution of the PCF peak may reflect the strength relationship of the hydrogen bond. The strength relationship of the hydrogen bond that formed between the H$_2$O molecules and the atoms in the aforementioned functional groups was O$_{PVA}>$O$_{PAM}>$N$_{PAM}$. In addition, the peak value of PCF can also reflect the possibility (and difficulty) of forming a hydrogen bond between the H$_2$O molecules and the atoms in the functional groups surrounding the H$_2$O molecules. Figure 9 shows the possible relationship of the hydrogen bonds between the H$_2$O molecules and the surrounding atoms, which was O$_{water}>$O$_{PVA}>$O$_{PAM}>$N$_{PAM}$. This is consistent with the previously noted strength relationship.

To explore the effects of water content and temperature on the distribution of H$_2$O molecules in the PAM/PVA IPN hydrogel system, we selected strongly interacting atoms for analysis. Thus we obtained the PCFs between H$_2$O molecules and the oxygen atoms of the hydroxyl groups (-OH) in PVA, the oxygen atoms of the carbonyl groups (-C=O) in PAM, as well as other H$_2$O molecules around. The PCFs are shown in Figures 10 and 11.

Figure 10 compares the PCFs with different water contents in the hydrogel system. Our analysis found that, in terms of the water content of the hydrogel system, the peak value increased with increasing water content. This is mainly because, with increasing water content, more water molecules would be around the polymer, forming more sufficient contact. Also, as shown in Figure 10C, the highest peak of the PCF between H$_2$O molecules and other H$_2$O molecules in the system was close to $r=2.76$ Å.
is consistent with the conclusion obtained by Seung et al. (22), and Jang et al. (23, 24).

Figure 11 shows the PCF of the PAM/PVA hydrogel system with 40% water content at different temperatures. The figure shows that the peak of PCF decreased as the temperature increased. The higher the temperature, the smaller the peak value. With an increase in temperature, the Brownian movement of the H$_2$O molecules in the system becomes more intense, breaking some hydrogen bonds. In turn, this leads to volume expansion and a decrease in H$_2$O molecule density. Ultimately, all of these are reflected by the peak value of a decreased PCF. Figure 11 shows that the highest peak value of the H$_2$O molecule was obtained at 248 K while the water was solid and crystalline in the system. This result accords with the finding that the H$_2$O molecule coordination number achieves its maximum value in the ice structure.

4 Conclusion

This study used a simulation method to demonstrate how temperature and water content affect the cohesive energy density, binding energy, mechanical properties and pair correlation function of atoms in the PAM/PVA IPN hydrogel system. Cohesive energy density and binding energy were found to increase with increasing water content in the hydrogel system. However, with the increase in temperature, the cohesive energy density followed a decreasing trend, while binding energy remained nearly unchanged. Meanwhile, the elastic coefficient, engineering modulus and ductility of the system decreased with increasing water content and temperature. In addition, the H$_2$O molecules interacted with the surrounding atoms and functional groups mainly through hydrogen bonding. The strength relationship of the hydrogen bond was $O_{\text{water}} > O_{\text{PVA}} > O_{\text{PAM}} > N_{\text{PAM}}$, which indicates the possibility (and difficulty) of hydrogen bond formation.

Acknowledgments: This project is sponsored by the National Natural Science Foundation of China (grant no. 51175432), the Doctor Special Science and Technological Funding of the China Ministry of Education (grant no. 20116102110046), the Fundamental Research Funds for the Central Universities (grant no. 31020141CS05007), the Key Industrial Science and Technology Projects of Shaanxi (no. 2015GY047) and the Science and Technology Project of the Xinjiang Uygur Autonomous Region (grant no. 201130112).

References