Structure and Drug Release of Superabsorbent Sponge Prepared by Polyelectrolyte Complexation and Freezing-Induced Phase Separation

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ABSTRACT: Superabsorbent sponge with uniform porous structure was prepared by polyelectrolyte complex (PEC) of polyacrylic acid (PAA) with inorganic polymers, high polymer state polyaluminum chloride (HPSPAC), in combination with freezing-induced phase separation (FIPS). The above superabsorbent sponge was prepared under mild conditions, without strong heat, oxidation, or corrosion, which is an ideal superabsorbent material for drug embedding. Structure analysis and swelling kinetics of the superabsorbent sponge as well as kinetics of the release of the model drug, 4-acetaminophen (AMP), from the sponge were investigated. In addition, effects of the crosslinker HPSPAC, the pH of the solution, and the concentration of NaCl solution on the structure and the swelling property of the sponge and sustained-release kinetics were explored. Further, the relationship between the structure of the superabsorbent sponge and its swelling property as well as sustained drug-release characteristics was investigated. © 2012 Wiley Periodicals, Inc. J Appl Polym Sci 000: 000–000, 2012

Key words: polyelectrolyte complex; freezing-induced phase separation; superabsorbent sponge; release; kinetics

INTRODUCTION

Superabsorbent polymer (SAR) is novel functional polymeric material with wide applications in physical health supplies, agriculture, drug delivery, and medical devices, because of its unique chemical composition, physical structure, and water absorption property.[1,2] The application of SARs in sustained-release delivery of small molecule compounds as well as the improvement of their water absorption and water retention functions will lead to a wider range of their applications.[3-5]

In the traditional preparation process of superabsorbent with controlled-release functions, the functional molecule is loaded onto the polymer network structure by hydrogen bonds or Van der Waals interactions. In a previous study performed by Rodriguez et al.,[6] cationic cellulose hydrogels were added into the aqueous solution of 0.5 wt % anionic amphiphilic drug, diclofenac sodium, for 3 days at room temperature. The drug was absorbed into the hydrogels by electrostatic attraction and the release properties were investigated in that study. In addition, in another study by Tong et al.,[7] urea-loaded SARs were prepared by the addition of poly (sodium acrylate) SARs into highly concentrated urea solution.

Moreover, there are also some literatures regarding the preparation of functional molecule-loaded SARs by mixing functional molecules with vinyl monomers and loading them onto the network after polymerization. Wu and Liu[8] prepared fertilizer-loaded SARs with the core/shell structure. First, the core was prepared using fertilizer containing nitrogen, phosphorus, and potassium and coating materials, such as chitosan, ethylcellulose, etc. Second, the shell with good swelling property was formed by copolymerization of vinyl monomers. Last, fertilizer was loaded onto the networks. In another study, Lin et al.[9] loaded fly ash onto polyacrylic acid (PAA)-acrylamide SARs, which exhibited controlled release of kalium.

In recent years, to obtain functional SARs with high-water absorption rate, which could be used as exterior hemostatic materials, our research group has been dedicated to developing SARs with porous structures using solvent precipitation,[10] freezing-

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induced phase separation (FIPS),[11,12] and hole foaming method.[13] The water absorption rate of the polymer has been significantly improved. Recently, our group has developed a novel method for the preparation of porous SAR. In this method, the hydrogel network was formed by electrostatic interactions between anionic polyelectrolyte PAA and cationic compounds of polyaluminum, followed by drying and the formation of the pore networks using the method of FIPS, resulting in porous superabsorbent sponge. This technology introduced functional molecules and embedded them mildly during the process of crosslinking, which could ensure the molecular structure and stability of embedded molecules, resulting in efficient embedding and releasing effects of functional molecules. This is a novel preparation approach for functional SARs with promising applications.

Chen et al.[14] prepared porous superabsorbent sponges by crosslinking of PAA solution with oligomeric states of hydrolysis products obtained from $AlCl_3$ under alkaline conditions, in combination with FIPS. In addition, the model drug 4-acetaminophen (AMP) was embedded in during this process, and release properties were investigated. The results indicated that the application of polyelectrolyte complex-FIPS (PEC-FIPS) combination route is an effective method for the preparation of drug-embedded porous absorbent sponge. However, because the direct hydrolysis products of $AlCl_3$ exhibited low degree of polymerization and relatively less complex sites, they did not have strong crosslinking interactions. Thus, this electrostatic crosslinking system was susceptible to damage, resulting in the instability of sponge structures.

In this study, high-polymer state polyaluminum chloride (HPSPAC) with high polymerization degree was directly used as the crosslinker to react with PAA via PEC, and then subjected to FIPS process, resulting in the porous superabsorbent sponge. The addition of multiple HPSPAC cations could significantly improve crosslinking sites with PAA and increase crosslinking effects as well as the stability of the network structure. In addition, this relatively strong electrostatic effect between polyanions and polycations had good tolerance to salt solution, which could improve the absorbency and release effects of the sponge in salt solution. Here, the embedding and control release of AMP, which was used as the model drug, by PAA-HPSPAC superabsorbent sponge were preliminary investigated. In addition, the embedding and sustained release of the drug by the superabsorbent sponge were compared with the porous superabsorbent sponge prepared via Al^{3+}-PAA complexation and FIPS. This study would gain insights into the application of these sponges.

EXPERIMENTAL SECTION

Materials

PAA with average molecular weight of 1.05×10^6 was supplied by Beijing Chemical Reagents Company (China). High polymer state polyaluminum chloride with Al13 content of 87.1% was purchased from Gongyi Deyuan Water Purification Plant (China). Acetaminophen (AMP) was used as the model drug and supplied by Sinopharm Chemical Reagent Co., (China). HCl, NaOH, and NaCl were analytical grade all and used as received.

Preparation of AMP-loaded superabsorbent sponge via PEC-FIPS process

Seventy milliliters of deionzed water and 0.71 g PAA were added into a triple-necked flask, which was equipped with a stirring apparatus and a reflux condenser. Then the polymer was dissolved by quickly stirring and heated in a water bath of 70°C for 30 min. 0.10 g model drug AMP was added into the flask and stirred for 20 min. Then certain amount of HPSPAC solution (20 mL) was dripped into the flask via a constant pressure funnel within 30 min. Moderate amount of deionzed water was supplied and the total volume of the water in the system was kept for 90 mL. After reaction for 4 h, the mixture was poured into a petridish of Φ 90 $\times$ 10 mm and then frozen in the freezer at -20° for 12 h. The frozen sample was freeze-dried on FD-1E lyophilizer (Beijing Detianyou Technology Development Co., China) under the temperature of -60° and pressure of 5 Pa.

Analysis and characterization

It was found in reference Chen et al. (2010) that the solution of AMP has a strong UV absorption at 243 nm. The relationship between the concentration of AMP and UV absorbance, in the range of 5×10^{-4} mg/mL to 1.5×10^{-2} mg/mL was deduced as:

$$A = 0.00891 + 62.03721c, R = 0.9998 \quad (1)$$

in which A is UV absorbance of AMP; c is the sample concentration, mg/mL.

As PAA-HPSPAC SAR was swollen, the solution showed no UV absorption around the wavelength of 243 nm. Thus, the release amount of AMP could be quantitatively determined by UV absorption at 243 nm. The UV absorption curve was obtained using Pgeneral TU-1810 UV-vis spectrophotometer (Beijing Purkinje General Instrument Co., China). The accumulative release percent of AMP from the prepared superabsorbent sponge was calculated according to the method described by Chen et al.[14]

Swelling kinetics of superabsorbent sponge

Swelling kinetics of the PAA-HPSPAC superabsorbent sponge was simulated using the Voigt model according to the reference of Omidian et al.[15]. The model is as follows:

$$\begin{aligned}\varepsilon(t) &= \sigma_0/E\{1-\exp[(t_0-t)]/\tau_0\} \\ &= \varepsilon(\infty)\{1-\exp[(t_0-t)]/\tau_0\}\end{aligned} \quad (2)$$

in which, t_0, the relaxation time (delayed time), imply the resistance of polymer to water penetration. Theoretically, the smaller value of t_0 indicates easier water penetrating through the network and the faster water absorption rate. The value t_0 could be obtained as the reciprocal of the slope of $\ln[1 - \varepsilon_t/\varepsilon_8]$ vs. t curve (ε_t is the absorption ratio of the polymer at time t, ε_8 is the equilibrium water absorbency for the polymer). E is Young's modulus, which indicates the ability of the material to resist deformation. For SAR, E reflects the resistance of the crosslinked network and hydrogen bonding of the polymer structure against the infinite expansion of the molecular chains of the network. $\sigma_0/E = \varepsilon(8)$ is the equilibrium deformation when $t\rightarrow\infty$, which is the equilibrium swelling ratio for SAR. Through the simulation of the swelling process for SARs, the values of σ_0/E and t_0 in the process of polymer swelling could be obtained. Further theoretical curves of polymer swelling process could be obtained. Based on the theoretical curve, the slope of the line from time 0 to the time reaching 70% equilibrium swelling ratio (k_i) and the time when the curve deviates from the equilibrium swelling value (t_c) could be calculated. These two parameters could be used to characterize the rate of polymer swelling. The greater k_i value and the shorter t_c indicate the faster swelling rate.

Pore structure analysis of the porous superabsorbent sponge

According to the reference Chen et al.,[16] pore structures of the prepared porous superabsorbent sponge were studied. First, SEM photographs of the porous superabsorbent sponge were transferred into 256 levels of grayscale images (8-bit photo) and processed by noise reduction through median filtering. Then the images were subjected to segmentation using histogram-based threshold method. Meaningful characteristics of the image or necessary parts were extracted and 256 levels of gray images were converted into black and white binary images. Pore structure parameters of porous superabsorbent sponge were measured using Image J software based on the black pixels gathering area in each image (i.e., each pore) as the unit of measurement after the calibration of the real size of the images. Pore structure parameters were analyzed for SEM photographs taken at three different locations for the same sponge. The average values were calculated and average pore structure parameters of the porous superabsorbent sponges prepared under different conditions were obtained.

Calculation of the release kinetics

Mathematical predictions will allow for good estimates of the required composition, geometry, dimensions and preparation procedure of the respective dosage forms and help to realize the aim to control of drug release.[17] Different mathematical models may be applied for describing the kinetics of the drug release process from the matrix. The kinetics of AMP release from PAA-HPSPAC porous superabsorbent sponge was determined by finding the best fit of the dissolution data (drug-released fraction vs. time) to distinct models: zero-order (3), first-order (4), and Higuchi (5)

Zero-order kinetics

$$Q_t = Q_0 - k_0 t \quad (3)$$

where Q_t is the amount of drug released at time t, Q_0 is the amount of drug in the solution at $t = 0$, (usually, $Q_0 = 0$), and k_0 is the zero-order release constant.[18]

First-order kinetics

$$\ln Q_t = \ln Q_0 - k_1 t \quad (4)$$

where Q_t is the amount of drug released at time t, Q_0 is the amount of drug in the solution at $t = 0$, and k_1 is the first-order release constant.[19]

Higuchi's model

$$Q_t = k_H t^{1/2} \quad (5)$$

where Q_t is the amount of drug released at time t, and k_H is the Higuchi's release rate constant.[20]

RESULTS AND DISCUSSION

Preparation of PAA-HPSPAC complex superabsorbent sponges

The aluminum cation at the aggregation state of HPSPAC molecule is easy to combine with $-COO^-$ of PAA via PEC interaction, forming SAR with crosslinked network structure. To confirm the formation of PEC interaction between PAA and HPSPAC, HPSPAC at the concentrations of 0, 6, and 12 wt % was added into PAA solution (0.11 mol/L), respectively. After mixing for 4 h, the mixture was transferred to a beaker to cool down to room temperature

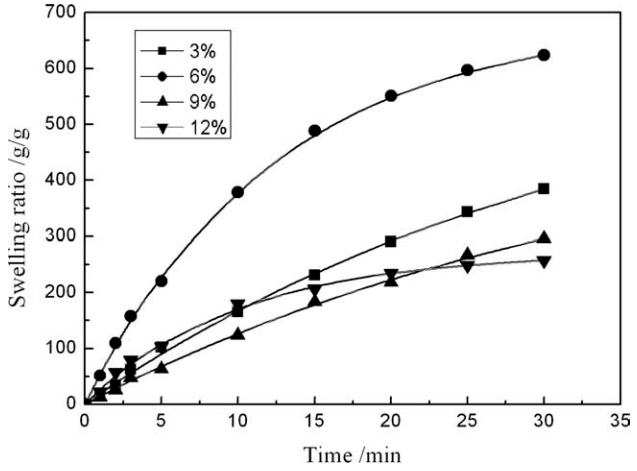

Figure 1 The swelling rates of porous superabsorbent sponge prepared from different amounts of HPSPAC.

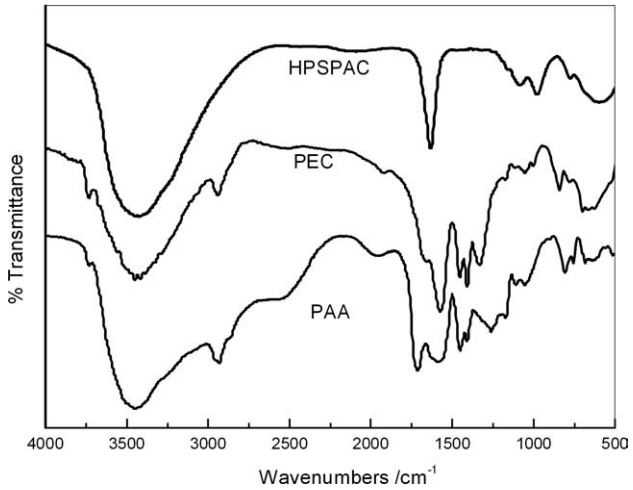

Figure 2 The FTIR spectra of PAA, HPSPAC, and PAA-HPSPAC complex superabsorbent sponges.

and the viscosity was measured using the NDJ-1 rotary viscometer. The viscosity of the solution containing 0% crosslinker, 6% HPSPAC, and 12% HPSPAC was 2600 mPa·s, 2800 mPa·s, and 4300 mPa·s, respectively. The results showed that the viscosity of the PAA solution was increased because of the electrostatic complexation between HPSPAC and PAA.

The swelling properties of porous SARs prepared by PEC-FIPS process with the addition of different crosslinkers were also investigated (Fig. 1 and Table I). When the amount of the crosslinker was relatively low (3%), the water absorption capacity of the polymer was also low. When the crosslinker was around 6%, the swelling rate reached its maximum value. With increased amount of HPSPAC further, the swelling rate of the sponge was gradually reduced. The above rules were consistent with the traditional effect of crosslinker on the swelling ratios of the network structure and confirmed the formation of PEC interaction between PAA and HPSPAC.

Further studies were performed to investigate the interaction between HPSPAC and PAA using FTIR microspectroscopy (Fig. 2). The FTIR microspectroscopy of PEC formed between HPSPAC vs. PAA, and PAA vs. HPSPAC demonstrated that in the complex of PAA and HPSPAC, the absorbance peak attributed to C═O of PAA was shifted from 1733 to 1666 cm^{-1} and the bending vibration peak of Al—O—Al in HPSPAC spectrum was shifted from 972 to 999 cm^{-1}. In addition, the characteristic absorbance peak at 1631 cm^{-1} for HPSPAC and the characteristic absorbance peak at 1566 cm^{-1} for PAA were attributed to the superposition of asymmetric stretching vibration of —COO^- of carboxylic acid salt, which formed a wide peak at 1594 cm^{-1}. The results demonstrated that electrostatic complexation occurred between HPSPAC and PAA, resulting in the formation of network-like sponge. During the preparation of sponge, the model drug AMP was embedded in the network, and porous superabsorbent sponge with embedded drugs were obtained by FIPS process. The effects of aluminum ions at various forms in HPSPAC on PAA complexation will be discussed in another article. This article was focused on effects of polymer structures and solution absorption properties on the release of the model drug AMP from superabsorbent sponge formed by PAA-HPSPAC complex.

Effects of different superabsorbent preparation methods on AMP structures

The structures of AMP released from the superabsorbents prepared through PEC process and free

TABLE I
Effect of HPSPAC Amount on the Swelling Kinetics and Structural Parameters of the Prepared Superabsorbent Sponge

m_{HPSPAC}/m_{PAA} (%)	σ_0/E (g g^{-1})	τ_0 (min)	k_i (g min^{-1})	t_c (min)	Porosity (%)	$\overline{D}$ (μm)
3	384.39	32.82	15.02	21.44	52.87	25.59
6	624.16	11.95	34.79	16.08	52.92	18.20
9	296.06	34.92	11.43	21.65	49.13	20.71
12	257.34	9.56	16.79	14.08	35.30	10.98

$\overline{D}$ means the average diameter of the pores.

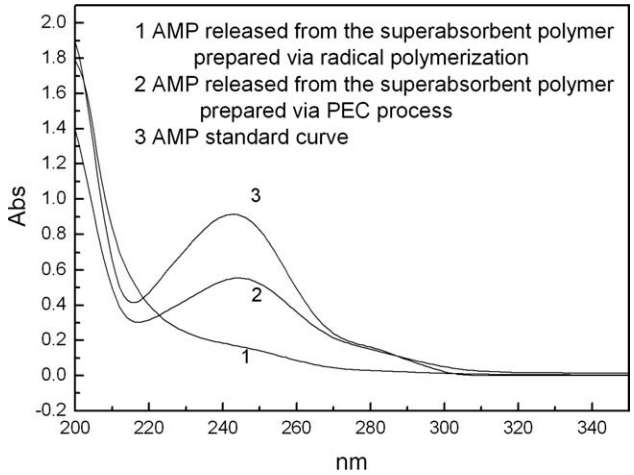

Figure 3 Comparison of the UV absorbance curves of the aqueous solutions in which AMP was released via the superabsorbent prepared through PEC-FIPS method or radical polymerization method.

radical polymerization were studied and compared. Briefly, drug-loaded superabsorbents were immersed into distilled water for 5 hours, and the UV absorbance curves of AMP released into the solutions were recorded. Particularly, as shown in Figure 3, a strong absorption band at 243 nm was observed in the aqueous solution of the drug-loaded superabsorbent prepared via PEC-FIPS method. The UV absorbance curve was consistent with that of AMP standard solutions. However, this absorption band was not observed in the release aqueous solution of the superabsorbent prepared via radical polymerization of acrylic acids. This indicated that the structure of AMP loaded by the latter method might be destroyed, which has been analyzed before.[14] Thus, the latter process might not be suitable for AMP loading. Because the reaction process of PEC was mild, the exothermicity was weak, and there was no corrosion of the acrylate ion and no oxidation of the loaded molecule, the structure of the loaded drugs could be protected and they could be released from the network properly. Thus, this is an ideal process for drug loading.

Effect of HPSPAC amount on the structure of the prepared sponge

Drug release was affected by the crosslinking degree and the porous structure of the superabsorbent sponge, which interacted with each other. In this article, the effect of HPSPAC amount used for sponge preparation on pore structures and swelling properties of the resulting superabsorbent sponge was investigated. Porous superabsorbent sponge with uniform pore structure could be obtained by PEC-FIPS method. The network structure of the SAR was filled with water and subjected to freezing to separate water phase and polymer chains. The network structure was further treated with low temperature and freeze-drying under low vacuum to sublimate moisture in the sponge network, resulting in superabsorbent materials with porous structures. However, once the SAR was dissolved in water, water was unevenly distributed in the polymer network. Thus it is difficult to obtain uniform sponge by the FIPS process. Uncrosslinked polymer was tried to dissolve in water before crosslinking to form sponge, which might improve dispersion uniformity of water in the gel. Then, FIPS process may result in stable and uniform pore structures. However, chemical crosslinking reagents (such as epichlorohydrin and *N*,*N*′-methylenediacrylamide) had low activity for PAA and crosslinked network was not easy to form. However, the network with good crosslinking effect could be formed by crosslinking of PEC between HPSPAC and PAA, which resulted in uniformity of water swelling in the network and superabsorbent sponge with uniform pore structures. Thus, the method of PEC-FIPS in this study is an ideal method for the preparation of porous super absorbent sponge.

As for porous polymer, its pore structure has a significant impact on the swelling ratio, swelling rate, and the release properties of encapsulated drugs.[21] Analysis of the relationship between the structure of porous superabsorbent sponge and its properties has important reference value for the regulation of the property.

The swelling rates of the prepared porous superabsorbent sponge using different amounts of HPSPAC were investigated. The results are shown in Figure 1. In addition, the swelling kinetics was modeled using the Voigt model. As shown in Figure 1, the simulated curve was fitted well with test points, suggesting that the Voigt model could quantitatively simulate the swelling process of the polymer. The swelling kinetics parameters are listed in Table I. Table I also lists the porosity, pore size, and other structural parameters obtained by the Image J software.

On the basis of Figures 1 and 3 and Table I, the association between the pore structure and the swelling properties of the porous superabsorbent sponge was analyzed. When the amount of HPSPAC was less, its increased amount resulted in increased swelling rate and absorption rate at 30 min, which reached maximum when the amount of the crosslinker was 6%. The observation of the pore structure of the superabsorbent sponge indicated that when the amount of the crosslinker was low, high porosity and pore size were obtained by FIPS process due to low crosslinking degree of the network; however, water-carrying capacity of the gel network was weak and the absorbent water was difficult to keep in the network, thus affecting water absorption rate and

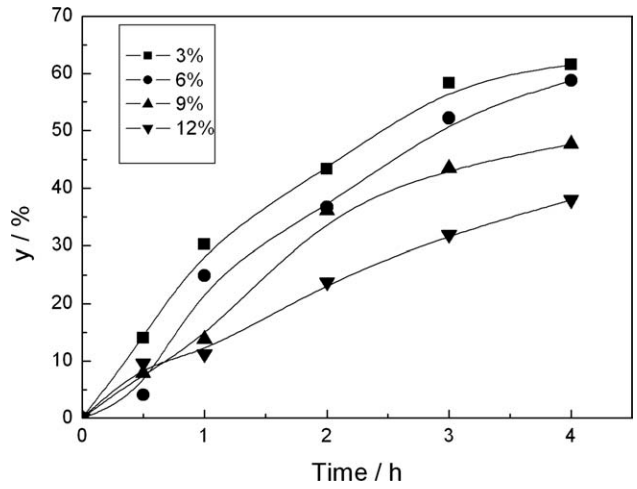

Figure 4 Sustained release of embedded AMP by the sponges prepared with different amounts of HPSPAC.

degree. With increased amount of the crosslinker, the crosslinking degree of the sponge was increased and the sponge exhibited high porosity and reduced pore diameter. The capillary effect of the porosity was increased and the capacity to keep the water in the network was improved, resulting in improved water absorption rate and capacity. When the amount of HPSPAC was higher than 6%, the increase in the amount of crosslinker led to increased crosslinking points in the network and shortened distance between crosslinking points. Thus, during the FIPS process, with continuous evaporation of the crystals, the sponge skeleton was easy to contract and consolidate,[22] resulting in reduced porosity and pore size in the network with increased amount of the crosslinker. Then the entering of water from the sponge surface into its interior became relatively more difficult, and water absorbency and water absorption rate were reduced.

Effect of HPSPAC amount on the release of AMP from the sponge

The effect of HPSPAC amount used in the preparation of porous superabsorbent sponge on the release of the model drug AMP embedded in the sponge was studied (Fig. 4). The curves for the release of AMP from the porous superabsorbent sponge prepared using different amounts of HPSPAC were simulated using zero-order, first-order kinetic formulas, and the Higuchi model, respectively. The results are shown in Table II. When the amount of the crosslinker was less, the release of drugs was better fitted with the Higuchi model. At this time because the network density of the crosslinked porous sponge network was larger and the network diameter was bigger, the mass transfer resistance of the drug in the network was smaller and easy to spread out from the network. Then the drug on the surface of the superabsorbent sponge was dissolved in the liquid and drugs within the sponge were gradually diffused to the surface of SAR through the pores of the network and eventually spread into the liquid because of the concentration gradient. With the gradual increase of the crosslinker, when the amount of HPSPAC was higher than 6%, the resistance for the release of the drug from the network was increased, and the release model was deviated from the Higuchi model, which was better fitted by the zero-order and first-order kinetics. Then, with increased amount of the crosslinker, the network density was decreased and the mesh diameter was decreased too. As a result, the resistance of the drug from the SAR was increased and its release was controlled by surface diffusion and dissolution mechanisms. In addition, Table II indicates that using the same equation to perform the simulation, the slope of the curve obtained was decreased with increase

TABLE II
Simulation of the Release Rate Curves of Embedded AMP by the Sponges Prepared with Different Conditions Using Different Models

		Zero order		One order		Higuchi	
Different conditions	Formulation	K_0 (% h^{-1})	R_0	K_1 (h^{-1})	R_1	K_H (% $h^{-1/2}$)	R_H
Different HPSPAC amounts	m_{HPSPAC}/m_{PAA} = 3%	0.1534	0.9636	0.2468	0.9855	0.3317	0.9885
	m_{HPSPAC}/m_{PAA} = 6%	0.1540	0.9756	0.2328	0.9910	0.3214	0.9654
	m_{HPSPAC}/m_{PAA} = 9%	0.1266	0.9710	0.1741	0.9806	0.2654	0.9655
	m_{HPSPAC}/m_{PAA} = 12%	0.0933	0.9946	0.1185	0.9946	0.1949	0.9791
Different pH values	3	0.1603	0.9408	0.2905	0.9791	0.3567	0.9934
	5	0.1352	0.9856	0.1979	0.9960	0.2847	0.9849
	7	0.0925	0.9829	0.1176	0.9920	0.1959	0.9874
	9	0.1234	0.9782	0.1806	0.9806	0.2606	0.9802
	11	0.1795	0.9587	0.3376	0.9909	0.3916	0.9920
Different NaCl concentrations	Distilled water	0.0925	0.9829	0.1176	0.9920	0.1959	0.9874
	C_{NaCl} = 0.01%	0.1626	0.9573	0.2799	0.9886	0.3546	0.9902
	C_{NaCl} = 0.05%	0.1629	0.9288	0.2983	0.9714	0.3670	0.9927
	C_{NaCl} = 0.10%	0.1626	0.9639	0.2769	0.9920	0.3518	0.9893
	C_{NaCl} = 0.15%	0.1554	0.9826	0.2408	0.9967	0.3263	0.9786

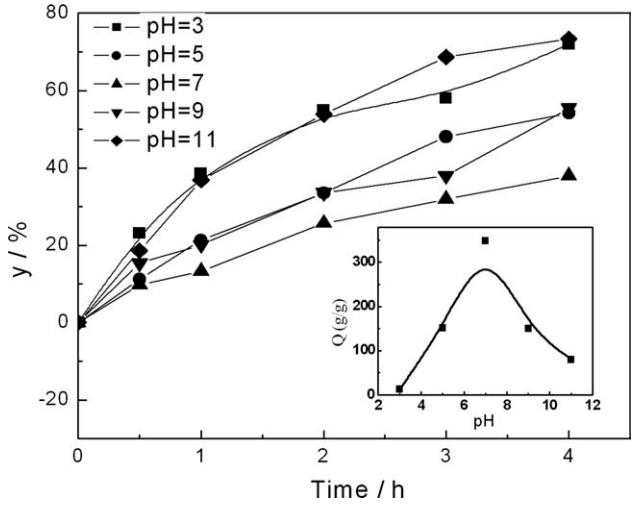

Figure 5 The sustained release of embedded AMP by the sponge in aqueous solutions with different pH values.

amounts of the crosslinker. This demonstrated that the increase of the crosslinking degree may result in decreased release rate of AMP from the network. However, in practice, if too much crosslinker was used, crosslink points would increase in the polymer network. Thus, the diastolic movement of the network would be limited and it might be difficult for water to enter the polymer, which resulted in decreased water absorption ratio. In practical applications, a balance needs to be obtained between water absorption ratio and drug release.

In the previous study,[14] superabsorbent sponge was prepared using Al^{3+} hydrolysis as the crosslinker to form complex with PAA. The release of AMP was still fitted well using the Higuchi model with the addition of 15% $AlCl_3$; with increased amount of the crosslinker, the release of AMP was gradually fitted well using zero- and first-order kinetics. The findings further indicated that because HPSPAC has more cationic groups to form electrostatic complex with PAA, it had higher crosslinking effect and better control for the embedding and release of drugs. The use of lower amount of crosslinker HPSPAC could make the drug release fit better by zero-order and first-order kinetics.

Sustained release of embedded AMP by superabsorbent sponge under different pH values

The release of AMP by the sponge under different pH values was studied (Fig. 5). As shown in the Figure, the sustained release of AMP was affected by pH. At pH = 3, the release of AMP was high. With decreased acidity of the solution, the release of AMP was reduced and reached the minimum when pH = 7; whereas in alkaline solution, with increased alkalinity, the release rate of AMP was increased.

The sponge complex of PAA and HPSPAC formed crosslinked structure by PAC action between $-COO^-$ and cationic HPSPAC. When the acidity of the solution was strong, a large amount of HCl broke this electrostatic interaction and $-COO^-$ was transferred to $-COOH$.[23] In addition, the aggregated HPSPAC cation was combined with Cl^- and the crosslinking density of the sponge was significantly decreased. As shown in Figure 5, the swelling property of the sponge was significantly reduced compared with that in neutral conditions. In such liquid condition, the resistance for drug to release from the sponge was low and the release rate of the drug was high. In alkaline solution, the existence of a large amount of NaOH also damaged the crosslinked structure of the sponge. Under this situation, $-COO^-$ was surrounded by extensive Na^+ and the cationic HPSPAC was surrounded by excess OH^-, which resulted in significant decrease in the crosslinking degree of the sponge and reduced swelling capacity. Thus, the resistance for drug spread was decreased. Under neural conditions, because of the strong electrostatic action between $-COO^-$ and Al^{3+}, the sponge had appropriate crosslinking degree and higher swelling properties. However, because of the resistance of the crosslinking network, the resistance for the release of the model drug AMP from the network was higher, resulting in minimum release rate.

The kinetics for the release of AMP from porous superabsorbent sponge at different pH values was simulated (Table II). Under strong acid (pH = 3) or alkali (pH = 11) conditions, the drug release from the sponge network was fitted well with the Higuchi model. This might be due to the damage of the crosslinking network of the sponge, resulting in reduced crosslinking degree of the sponge. Then the release of the drug from the sponge network was mainly controlled by the spread rate of the drug. Under such conditions, the slopes of the lines obtained using the three models were greater, suggesting that under this condition, the release rate for the drug was high. When the pH was 5-9, the crosslinking degree of the sponge was high. Then the release of drug from the sponge was limited by expansion of the sponge network structure and the release of drug was fitted well with the zero-order or first-order kinetics. The slopes of the simulated lines at pH = 5 and pH = 9 were lower compared with those under strong acidic and alkaline conditions, suggesting that the release rate of the drug was low; and the slope of the curve was lowest around pH = 7, accompanied with lowest drug release rate.

Sustained release in salt solutions at different concentrations

The saturated swelling properties of porous superabsorbent sponges prepared by PAA-HPSPAC in NaCl

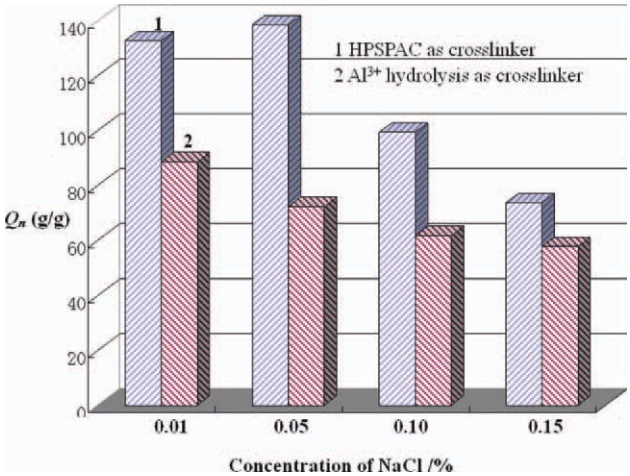

Figure 6 The equilibrium swelling ratios of the superabsorbent sponges in NaCl solutions of different concentrations. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

solutions at different concentrations were studied. As shown in Figure 6, when the concentration of NaCl was low, with increased NaCl concentration, the swelling properties of these superabsorbent sponges were increased, reflecting special properties of the polyampholyte complex hydrogel. This was mainly due to the fact that the addition of NaCl had certain shielding effect on the electrostatic action between $-COO^-$ and HPSPAC cations, resulting in decreased crosslinking of the sponge.[24] As an inorganic polymer, there were more sites for HPSPAC to react with PAA. Appropriate decrease in the crosslinking degree could increase the spread channel of the sponge and improve the swelling property rather than decrease the swelling property of the sponge. However, with further increased concentrations of the salt solution, the crosslinking structure of the sponge was significantly damaged; the osmotic pressure difference between inside and outside of the sponge network was also decreased and the swelling ratio of the sponge in the NaCl solution was reduced.

Compared with the above superabsorbent sponge, for the superabsorbent sponge prepared with the initial polymeric aluminum obtained by Al^{3+} hydrolysis as the crosslinker, the porous superabsorbent sponge formed by complexation with PAA exhibited lower swelling rate in the NaCl solution compared with the PAA-HPSPAC superabsorbent sponge. In addition, with increased salt solution concentration, the swelling rate exhibited a decreased trend. Because the initial polymeric aluminum had less crosslinking sites with PAA, the sponge exhibited weak water carrying capacity. With the addition of NaCl, the electrostatic effect of the sponge was shielded, resulting in the damage of the crosslinking network structure of the sponge and reduced swelling property of the sponge.

The sustained release of embedded AMP by the sponge in NaCl solutions at different concentrations was studied (Fig. 7). The kinetics for drug release in different media was simulated (Table II). As shown in Figure 7 and Table II, in pure water, because the crosslinking density of the network was high and there was greater resistance for drug release, the rate for the sustained release of AMP from porous superabsorbent sponge was lower. At this time, the release of AMP from the sponge network was fitted well with the first-order kinetics, and the expansion of the crosslinked structure and dissolution of the sponge played a major role in sustained drug release. With increased concentration of salt solution, the rate of sustained release was increased and reached maximum when the NaCl concentration was 0.05%. When NaCl concentration was below 0.05%, the release of AMP was fitted well by the Higuchi model. When the concentration of NaCl was increased to above 0.05%, the release rate of the drug was decreased and fitted well with the first-order kinetics. However, the release of the drug was higher in solutions with higher NaCl concentration than in pure water. With increased NaCl concentration in the outside solution, the changes in the release rate of the drug was due to the decreased crosslinking degree of sponge and reduced osmotic pressure difference between inside and outside of the network. The former effect made drug diffusion from the hydrogel network become easier, and the latter one caused the network contract and the resistance for the release of drug was increased. The experimental results on the release properties and effect of salt concentration on the swelling properties of the sponge indicated that when the NaCl

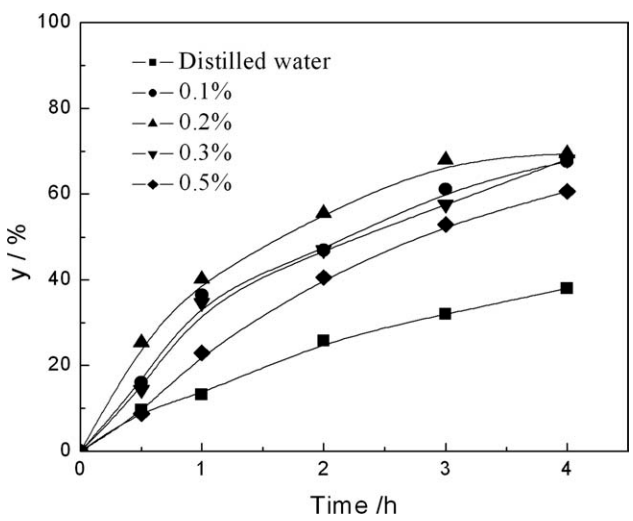

Figure 7 The sustained release of embedded AMP by the sponge in NaCl solutions with different concentrations.

concentration was lower, its effect to reduce the osmotic pressure difference between inside and outside of the network was not significant, and the former effect had greater effect on improving the swelling property of the sponge and drug release; and with further increased NaCl concentration, the latter effect played a major role in the contraction of the sponge network and drug release resistance.

CONCLUSIONS

Superabsorbent sponges with uniform porous structure were prepared by PEC of PAA with HPSPAC, in combination with FIPS process. Based on the analysis of the pores in the superabsorbent sponges and swelling kinetics of the sponge, as well as kinetics for the release of the model drug from the sponge, the encapsulation and the release of the model drug were investigated. In addition, the association between the structure of the superabsorbent sponges and the properties of swelling and drug release were investigated. The results indicated that when HPSPAC amount was less than 6%, the increase in the amount of the crosslinkers was helpful to improve the swelling ratio and swelling rate of the sponges and to obtain porous superabsorbent sponges with uniform pore sizes. With increased amount of crosslinkers, the swelling ratio and swelling rate of the sponges were decreased and pore structures became heterogeneous. When the amount of HPSPAC was increased, the control for the release of drug from the sponge was changed from the Higuchi model to zero and first-order dynamic models. The resistance for the release of the drug from the sponge was increased and the release rate was gradually reduced. In addition, the effect of the pH value on the swelling behavior and drug release properties of the sponge were studied. Under strong acid and alkaline conditions, as the crosslinked network structure of the sponge was destroyed, the swelling ratio of the sponge was decreased, the drug release rate was increased, and the drug release was controlled by the Higuchi model. Although under neutral pH conditions, the swelling properties of sponge were improved. However, the resistance for the release of the drug from the sponge network was increased, which was controlled by first-order and zero-order kinetics. The effects of the external ionic concentration on the swelling behavior of sponge and drug release properties were also investigated. It was found that low NaCl concentration in the solution was helpful to improve the swelling properties of the sponge and to improve the release rate of the drugs, which was controlled by the Higuchi model; with increased NaCl concentration, the effect of sponge contraction on sponge properties became significant and the swelling properties of sponge was reduced, resulting in decreased release rate of the drug, which was controlled by first-order and zero-order kinetics.

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