PREPARATION AND CHARACTERIZATION OF A TEMPERATURE-SENSITIVE LIGNIN-BASED HYDROGEL

Qinghua Feng, Fangeng Chen,* and Huiran Wu

A novel class of hydrogel was prepared by graft copolymerization of acetic acid lignin (AAL) and N-isopropylacrylamide (NIPAAm) in the presence of N,N'-Methylenebisacrylamide (MBAAm) as the crosslinker and H_2O_2 as the initiator. The impact of AAL content on the hydrogel properties were investigated in terms of their swelling behavior, thermal behavior, and interior morphology. The data showed that these newly synthesized hydrogels were temperature-sensitive. Differential scanning calorimetry (DSC) curves demonstrated that the lower critical solution temperature (LCST) of the lignin-based hydrogels was approximately 31°C. The thermogravimetric analysis (TGA) data revealed that the temperature of rapid decomposition of all the hydrogel samples was within a narrow range of 400 to 410°C. Furthermore, the scanning electron microscopy (SEM) images showed that the pore size of the hydrogel increased with increasing the AAL content.

Keywords: Hydrogels; Acetic acid lignin; N-isopropylacrylamide; Temperature sensitive

*Contact information: State Key Laboratory of Pulp and Paper Engineering, South China University of Technology, Guangzhou, 510640, China. * Corresponding author: fgchen@scut.edu.cn*

INTRODUCTION

Stimuli-responsive hydrogels, also known as smart hydrogels, are crosslinked polymeric materials that show drastic changes in their swelling ratio with the changes of the external environment, e.g. pH (Torres-Lugo and Peppas 1999) and temperature (Hoffman 1987). These smart hydrogels have been developed for various applications, such as tissue engineering (Rosso et al. 2005), immobilization of enzyme (Liu et al. 1993), and drug delivery (Ramkissoon-Ganorkar et al. 1999).

Poly(N-isopropylacrylamide) (PNIPAAm) hydrogels are the most investigated temperature-sensitive hydrogels due to the sharp transition and a transition temperature that is close to body temperature (Schild 1992; Temtem et al, 2007). Normally, the properties of PNIPAAm hydrogels can be improved via copolymerization of hydrophobic or hydrophilic monomers with N-isopropylacrylamide (NIPAAm). However, PNIPAAm hydrogels with these hydrophobic or hydrophilic monomers exhibit poor biocompatibility, which may limit their biomedical applications. The biocompatiblility of PNIPAAm hydrogels can be improved by the introduction of natural polymers, e. g., cellulose (Chauhan et al. 2004), hemicellulose (Yang et al. 2011), chitosan (Zhang et al. 2009), and dextran (Zhang et al. 2004). In comparison with poly(N-isopropylacrylamide) (PNIPAAm) gel, the incorporation of a hydrophobic component into the PNIPAAm gel had much more advantages, e.g., controlled release of hydrophilic drug and improved mechanical properties (Lee and Yeh 2005). However, the natural polymers listed above

are rather hydrophilic, and the effect of relatively hydrophobic natural polymer on the properties of PNIPAAm hydrogels has seldom been reported.

Lignin is a hydrophobic network of phenyl propanoid units that binds cellulose and hemicellulose chains together (Peri et al. 2011). Lignin often appears as a low-valued by-product of pulping with its utilization limited as a fuel. Until now, less than 2% of technical lignin is isolated from pulping liquors and used as surfactants, adsorption agents, stabilizer for plastics, etc. (Argyropoulos and Menachem 1998). Recently, novel materials prepared from lignin have attracted considerable interest. Yamamoto et al. (2000) prepared biodegradable lignin-based gels from lignin-phenol-resorcinol resin in the presence of glutaraldehyde as crosslinker. Uraki et al. (2004) prepared temperature-sensitive hydrogels based on hydroxypropylcellulose containing 6.63% of lignin that exhibited a LCST that was 5 °C lower than those of lignin-free hydrogels. Kim and Kadla (2010) prepared several lignin-based temperature-sensitive graft copolymers from lignin and NIPAAm via atom transfer radical polymerization (ATRP). The materials, which presented the degrees of polymerization of PNIPAM graft side chains from 8 to 43, exhibited constant LCST at 32 °C, *i.e.* the same temperature as PNIPAAm. These studies indicate that hydrophobic lignin can be used for the preparation of hydrogels by the introduction of hydrophilic groups. However, temperature-sensitive hydrogel prepared from lignin has rarely been reported. The effect of the lignin on the properties, especially LCST behavior, of PNIPAAm also needs further study.

Acetic acid lignin (AAL) is a kind of organosolv lignin precipitated from waste liquor of acetic acid pulping. AAL presents a narrower molecular weight distribution and higher hydroxyl content and seems to be more reactive than lignosulfonates and alkali lignins. In this paper, a new type of hydrogels was synthesized from AAL and NIPAAm via graft copolymerization in the presence of N,N'-methylenebisacrylamide (MBAAm) as the crosslinker and H_2O_2 as the initiator. The effect of AAL on swelling behavior, thermal behavior and interior morphology of the hydrogels was investigated.

EXPERIMENTAL

Materials

AAL was prepared from cooking of eucalyptus in acetic acid according to Uraki et al. (1991). AAL was dissolved in 1 M NaOH aqueous solution and subjected to deacetylation at 70 °C for 3 h. The number-average molecular weight, weight-average molecular weight, and polydispersity of AAL were 5327, 12060 and 2.264, respectively. The hydroxyl content of AAL was measured to be 3.76 mmol/g by the method of Granata and Argyropoulos (1995). N-isopropylacrylamide (NIPAAm, 98%) and N,N'-methylene-bisacrylamide (MBAAm) were the products of Aladdin Reagent Co. Ltd, Shanghai, China. The other chemicals were all of reagent grade and used as received.

Hydrogel Formation

The hydrogel was synthesized in reference to the method of Meister and Chen (1991). 0.2 g of calcium chloride and various amounts of AAL were dissolved in 2 mL of DMSO, successively. Then, H_2O_2 (5 wt% to AAL), the initiator, was added into the

solution. Subsequently, 1.2 g of NIPAAm and 0.017g of MBAAm were added into the solution. After being bubbled with N_2 for 10 min, the solution was placed in a 70°C bath. The reaction was allowed to proceed for 12 h. After that, the gel was soaked in DMSO for 5 days and then was allowed to swell in deionized water, where it was equilibrated for 5 days at ambient temperature. DMSO and deionized water were replaced every 12h to remove unreacted AAL, NIPAAm, and other impurities. Then, the hydrogel was carefully cut into small pieces for further characterization. In this paper, the hydrogels prepared with 0.05, 0.1, and 0.15 g of AAL were named as LGN1, LGN2, and LGN3, respectively. The conversion of feedstock to the hydrogel was defined as follows,

$$Conversion\ (\%) = (W_d / (W_m + W_{AAL})) \times 100 \quad (1)$$

where W_d, W_m, and W_{AAL} represent the weight of dry hydrogel, monomer, and AAL, respectively.

The PNIPAAm hydrogel was synthesized for comparison. 1.2 g of NIPAAm and 0.017g of MBAAm were dissolved in 2 mL of DMSO, successively. Then, 0.008 g of 2,2-azobisisobutyronitrile (AIBN), the initiator, was added into the solution. After being bubbled with N_2 for 10 min, the solution was placed in a 70 °C bath for 12h. The hydrogel was purified according to the method above.

Characterization of AAL, PNIPAAm and the LGN hydrogels

The LCST of the LGN hydrogels was determined by differential scanning calorimetry (DSC) with a TA Instruments Q200 apparatus. The hydrogel sample was allowed to swell in deionized water at room temperature until swelling equilibrium. The sample surface was wiped with moistened filter paper to remove free water. Then 5 mg of the swollen sample was placed in an aluminum pan. The DSC measurement was performed on swollen samples from 10 °C to 40 °C at a rate 10 °C/min, referenced against an empty pan.

Thermogravimetric analysis (TGA) of AAL, the LGN hydrogels, and PNIPAAm was performed on a TA Instruments Q500 using approximately 5 to 10 mg of sample under nitrogen at a heating rate of 20°C min^{-1} over the temperature range from room temperature to 700°C. All the samples were vacuum-dried at -50°C for 24 h and then dried in a vacuum oven at 40°C for 12h prior to FT-IR and TGA measurements. The lignin content of the hydrogel was defined as follows,

$$Lignin\ content\ (\%) = ((P_{LGN} - P_{PNIPAAm}) / (P_{AAL} - P_{PNIPAAm})) \times 100 \quad (2)$$

where P_{LGN}, $P_{PNIPAAm}$, and P_{AAL} represent the char residue of LGN, PNIPAAm, and AAL, respectively.

The swollen hydrogels, after reaching their maximum swelling ratios in deionized water at 5 °C, were frozen at -60 °C and then vacuum-dried at -50 °C for 24 h. The freeze-dried hydrogels were fractured carefully in liquid nitrogen. After being sputter-coated with gold, the hydrogels were characterized with scanning electron microcopy (SEM) on a FEI Quanta 200 apparatus with an accelerating voltage of 10 to 20 kV.

The equilibrium swelling ratio of the hydrogels was measured in the temperature range 22 to 38 °C with an interval of 2 °C. After being immersed in deionized water for 24 h at each temperature, the hydrogel was taken out from water and blotted with wet filter paper to remove excess water on the hydrogel surface. The weight of wet hydrogel was recorded. The swelling ratio was calculated as follows,

$$Swelling\ ratio = W_s/W_d \quad (3)$$

where W_s and W_d represent the weight of swollen and dry hydrogel, respectively.

The swollen hydrogel sample was immersed in deionized water at 40 °C for 2 h to lose bulk of their water. The shrunken hydrogel was then dried in a vacuum oven at 40 °C overnight until a constant weight was reached. The dried sample was immersed in deionized water at 22 ºC and removed from water at pre-determined time intervals. Then they were removed from water and blotted with wet filter paper for the removal of excess water on the hydrogel surface (Zhang et al. 2004). The weight of wet hydrogel was recorded. The water uptake (*WU*) was defined as follows,

$$WU = ((W_t - W_d)/W_s) \times 100 \quad (4)$$

where W_t is the weight of the wet hydrogel at time *t* and the other symbols are the same as defined above.

The deswelling kinetics were studied by investigating the volume variations of the hydrogel during the deswelling procedure. The hydrogel was first immersed at 22 °C to 40 °C deionized water bath and then was removed from water and blotted with wet filter paper for the removal of excess water on the hydrogel surface at pre-desired time intervals. The weight of wet hydrogel was recorded. The water retention (*WR*) was defined as follows,

$$WR = ((W_t - W_d)/W_s) \times 100 \quad (5)$$

where W_t is the weight of the wet hydrogel at time *t* and the other symbols are the same as defined above.

RESULTS AND DISCUSSION

Synthesis of the LGN Hydrogels

During the formation of the hydrogels, hydroperoxide reacted with chloride anion to form a chlorine atom. Chlorine then abstracted hydrogen from lignin to form the free-radical site on the lignin. Subsequently, the lignin initiated polymerization. The LGN hydrogels were easily formed in the presence of crosslinker, but the conversion efficiency of the hydrogels was different and depended on the composition ratio of AAL to NIPAAm. The conversion efficiency (%) for the hybrid hydrogels was reduced with an increase in the AAL content. Specifically, LGN1, LGN2, and LGN3 exhibited conversion efficiencies of 87.9%, 85.9%, and 81.3%, respectively. This decrease in

conversion efficiency is attributed to the increased AAL ratio during the polymerization. As mentioned above, AAL containing free-radical sites initiated the polymerization, i.e., LGN3 had more initiators than LGN1. This means LGN3 contained AAL with shorter grafted polyNIPAAm side chains during the polymerization. On the other hand, AAL with short grafted polyNIPAAm side chains might be difficult to be crosslinked in the presence of a crosslinker. As a result, the conversion efficiency decreased.

LCST of PNIPAAm and the LGN Hydrogels

Figure 1 plots the DSC curves of PNIPAAm and the LGN hydrogels. LGN1, LGN2, and LGN3 represent the hydrogel prepared with 0.05, 0.1, and 0.15 g of AAL, respectively. The experimental results indicated that the LCST of PNIPAAm and the LGN hydrogels containing different contents of AAL remained constant at 31 °C. This is consistent with results reported by Kim and Kadla (2010), in which lignin-*g*-polyNIPAAm copolymers prepared via atom transfer radical polymerization (ATRP) presented a constant LCST at approximately 32 °C. The slight difference between the LCSTs of LGN hydrogels and lignin-*g*-polyNIPAAm copolymers may be derived from different solvent system. Contrasting results, however, were also reported by Uraki et al. (2004), who reported that hydroxyprolylated pulps bearing lignin showed a 5 °C lower LCST than hydroxypropyl cellulose (HPC) of similar molecular weight. It is well known that there exists a hydrophilic/hydrophobic balance in the temperature-sensitive PNIPAAm. At temperatures below the LCST, the hydrophilic groups bond to water molecules through hydrogen bonds, leading to a water-uptake of PNIPAAm. When the temperature is above LCST, the chain is dehydrated and becomes hydrophobic (Takei et al. 1993). The results indicated that the hydrophobic interactions between the hydrophobic AAL and PNIPAAm are not strong enough to disrupt hydrophilic/ hydrophobic balance, and so have little effect on the LCST.

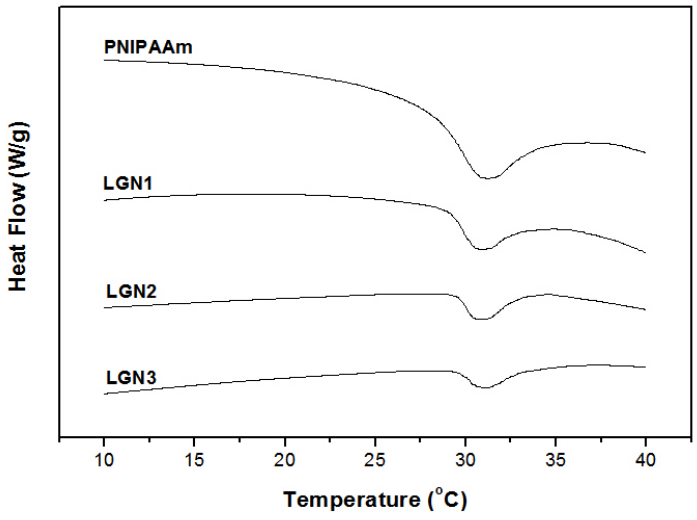

Fig. 1. LCST of PNIPAAm and the LGN hydrogels

Thermogravimetric Analysis of Lignin, PNIPAAm, and the LGN Hydrogels

Thermal stability is very important for polymer materials. For some thermally unstable biomaterials, thermal treatment during the process of manufacturing and long-term usage at 37 °C can lead to degradation of their mechanical properties and alteration of their cytotoxicity and biocompatibility (Xu et al. 2011). Thus, the thermal properties of LGN hydrogels were also studied.

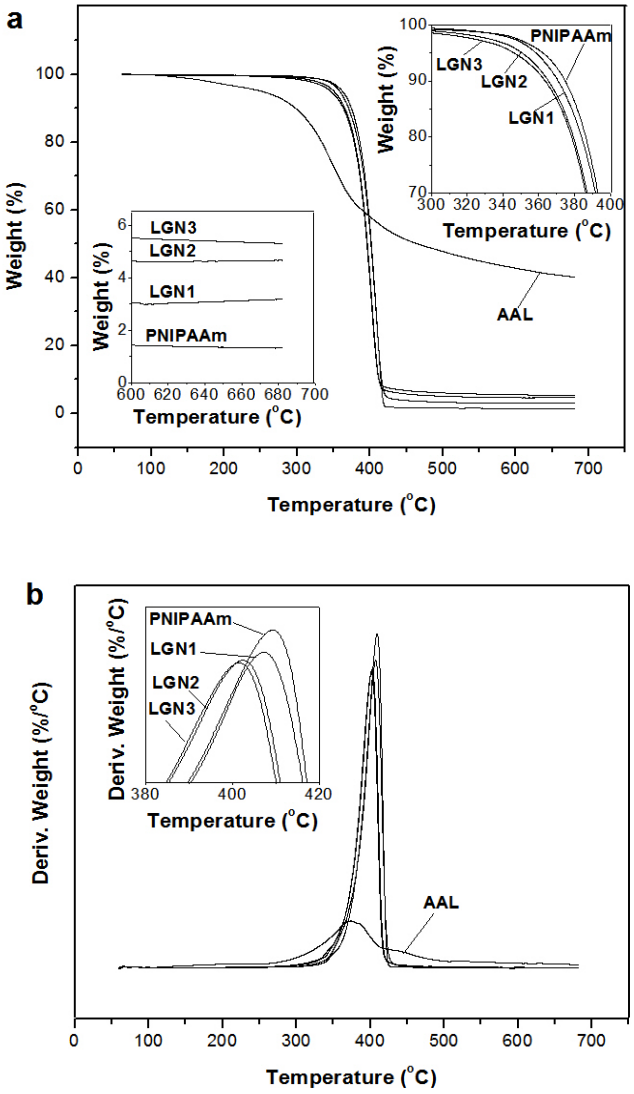

Fig. 2. TG (a) and DTG (b) curves of the LGN hydrogels, AAL and PNIPAAm

Table 1. Thermal Properties of LGN Hydrogels, AAL, and PNIPAAm

Sample	Temperature at 5% weight loss (°C)	DTG maxima (°C)	Char residue (wt %)	Lignin content (wt %)
AAL	250.1	374.4, 417.5	40.1	100
LGN1	358.3	407.3	3.2	4.9
LGN2	350.5	402.5	4.6	8.5
LGN3	346.1	401.5	5.3	10.3
PNIPAAm	362.2	409.3	1.3	0

TGA and DTG curves of LGN hydrogels, AAL, and PNIPAAm are shown in Fig. 2. It is apparent that LGN hydrogels and PNIPAAm gave similar TGA and DTG curves. Temperature at 5% weight loss and DTG maxima decreased slightly when the hydrogels incorporated AAL into PNIPAAm. The results mean that the introduction of AAL had no significant impact on the thermal stability of PNIPAAm. Fig. 2 also plots the impact of the ratio of AAL/NIPAAm on the char residue percentage of these hydrogels obtained by TGA. All the hydrogels had been converted into char residue when the temperature reached 700°C. The char residue and lignin content of LGN hydrogels rose with the increased ratio of AAL/NIPAAm. The TGA and DTG data are summarized in Table 1.

Interior Morphology of the LGN Hydrogels

The interior morphology of the LGN hydrogels, obtained by freeze fracturing, is shown in Fig. 3. PNIPAAm hydrogel could not be used as a control because gas bubbles formed from the decomposition of AIBN during the polymerization of NIPAAm had changed the interior morphology of the PNIPAAm hydrogel. The images clearly illustrate the dependence of hydrogel morphology on the AAL/NIPAAm ratio. As shown in Fig. 3, the pore size of these porous, honeycomb-like structures increased with an increase in AAL content in the hydrogel composition; i.e., LGN1 had the smallest pore size, while the LGN3 had the largest. The increased pore size was attributed to a decrease in conversion efficiency. The decreased conversion efficiency from LGN1 to LGN3 would decrease crosslinking density of the hydrogel. As a result, the pore size of the LGN hydrogels increased.

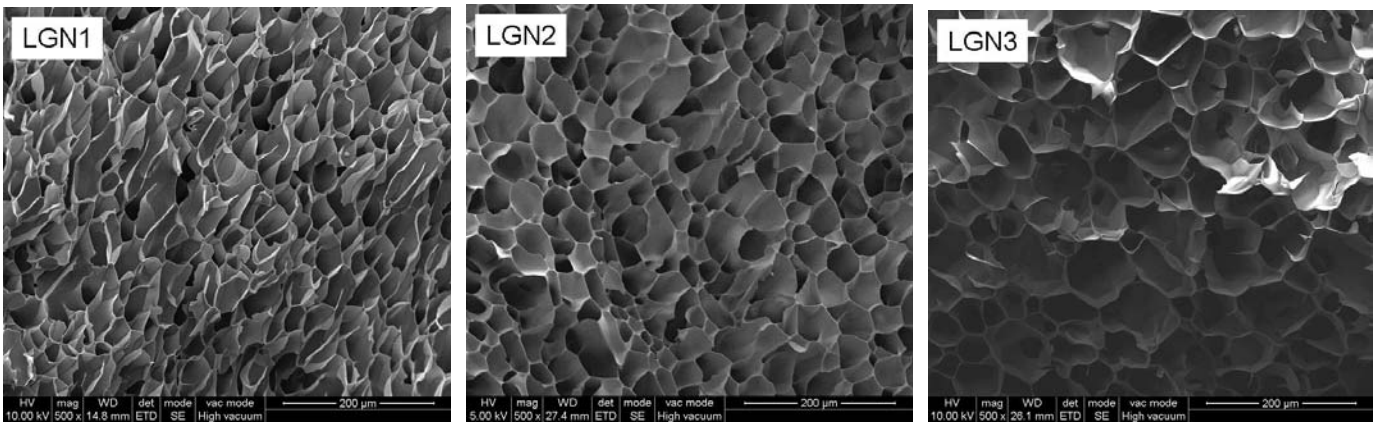

Fig. 3. SEM micrographs of the LGN hydrogels

Equilibrium Swelling Ratio

Equilibrium swelling ratios of LGN hydrogels at different temperature are shown in Fig. 4. The results indicated that the swelling ratio increased with decreasing temperature and increasing AAL/NIPAAm ratio. LGN3 exhibited the highest swelling ratio (20.3) at 22 °C, while LGN1 showed the smallest (11.2). In case of LGN1, the swelling ratio was 3.1 at 30 °C, and it changed to 0.2 at 32 °C. Hence, the variation was changed depending both on temperature and AAL/NIPAAm ratio.

The hydrogel usually becomes less hydrophilic when a hydrophobic moiety like AAL is incorporated into it. As a result, the swelling rate of the hydrogel is expected to decrease. In this study, however, the swelling ratio increased with the increase in AAL content. As mentioned above, an increasing AAL content in LGN hydrogels decreases its conversion efficiency. This decreased conversion efficiency from LGN1 to LGN3 would decrease crosslinking density of the hydrogel. As a result, the swollen capacity of the LGN hydrogels increased greatly. The SEM micrographs (Fig. 3) previously described also support this hypothesis.

The swelling ratio of hydrogel decreases dramatically at the temperature of LCST. Figure 4 illustrates the fact that the LGN hydrogels were responsive to the change of external temperature as well as PNIPAAm. The data stated that the LCST of the hydrogels varied in the range between 30 and 32 °C, which was consistent with the results determined by DSC.

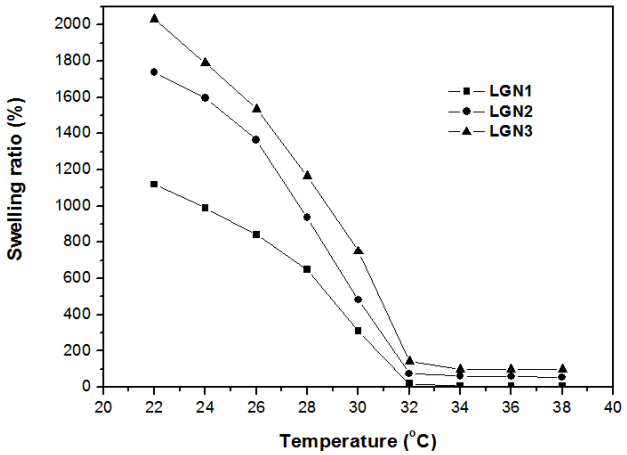

Fig. 4. Swelling ratios of the LGN hydrogels in the temperature range from 22 to 38 °C

Swelling and Deswelling Kinetics

Figure 5 plots the water uptake as a function of time of LGN hydrogels in deionized water at 22 °C. The curves showed that the water uptake of the hydrogels increased as the content of hydrophobic component (AAL) decreased. This means that water diffused into LGN hydrogels network more slowly, if the hydrogels had higher AAL content. Specifically, LGN1 exhibited a relatively fast swelling rate, reaching water uptake around 42% within 2h, while the water uptake of LGN3 was less than 26%. This tendency may be attributed to the hydrophobic AAL that had been incorporated. Before the swelling, there existed strong intermolecular and/or polymer-polymer interactions, such as hydrogen bonds and hydrophobic interactions, in the dried hydrogel samples. This suggests that the hydrophobic AAL in the LGN hydrogels may lead to strong such interactions. As a result, the hydrogels with high AAL content would lead to a significant reduction in the rate of water uptake.

Figure 6 shows the deswelling kinetics curves of LGN hydrogels. The data illustrated that LGN1 exhibited relatively fast response rates. Specifically, the water retention of LGN1 decreased from 100% to 21.5% within 10 min, while that of LGN3

decreased from 100% to 28.7% within 10 min. This tendency was attributed to three possible reasons. Firstly, the temperature sensitive property of PNIPAAm was "diluted" by incorporation of non-temperature-sensitive species such as AAL. The level of dilution depended on the amount of the non-temperature-sensitive species incorporated. Secondly, the introduction of hydrophobic AAL in PNIPAAm hydrogel increased the hydrophobicity of the LGN hydrogels, which led to a denser skin layer of the gel surface. Thirdly, a porous matrix might prevent the generation of a dense skin layer during the deswelling process. The decreasingly porous structure from LGN1 to LGN3 exhibited an increasingly dense skin layer (Zhang et al. 2003). Hence, the skin layer of the hydrogels became thicker when the content of the hydrophobic monomer was increased (Kaneko et al. 1995). The thick skin layer made the water inside the gels more difficult to release.

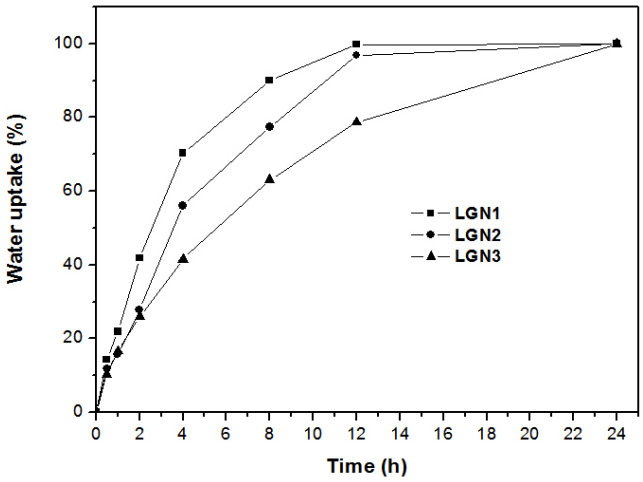

Fig. 5. Swelling kinetics of the LGN hydrogels at 22 °C

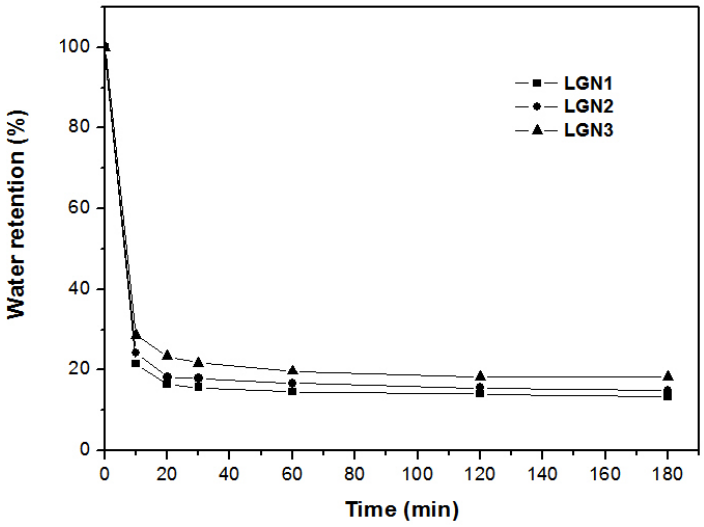

Fig. 6. Deswelling kinetics of the LGN hydrogels at 40 °C

CONCLUSIONS

1. Temperature-sensitive hydrogels containing AAL and NIPAAm were prepared via graft polymerization with MBAAm as the crosslinker and H_2O_2 as the initiator.
2. The hydrogels exhibited constant transition temperature regardless of AAL content. Thermal stability of the hydrogels was slightly influenced by the introduction of AAL.
3. The interior network of the hydrogels was porous. The pore size increased with an increase in AAL ratio.

ACKNOWLEDGMENTS

The authors appreciate the National Basic Research Program of China (Grant No. 2010cb732206) for financial support.

REFERENCES CITED

Argyropoulos, D. S., and Menachem. S. B. (1998). "Lignin," in: B*iopolymers from Renewable Resources*, Kaplan D. L. (ed.), Springer Verlag, pp. 292-322.

Chauhan, G. S., Lal, H., and Mahajan, S. (2004). "Synthesis, characterization, and swelling responses of poly(N-Isopropylacrylamide)- and hydroxypropyl cellulose-based environmentally sensitive biphasic hydrogels," *J. Appl. Polym. Sci.* 91(1), 479-488.

Granata, A., and Argyropoulos, D. S. (1995). "2-Chloro-4,4,5,5-tetramethyl-1,3,2-dioxaphospholaan reagent for the accurate determination of the uncondensed and condensed phenolic moieties in lignins," *J. Agric. Food Chem.* 43(6), 1538-1544.

Hoffman, A. S. (1987). "Application of thermally reversible polymers and hydrogels in therapeutics and diagnostics," *J. Control. Release* 6(1), 297-305.

Kanekoa Y., Yoshidab R., Sakaia K., Sakuraib Y., and Okano T. (1995). "Temperature-responsive shrinking kinetics of poly (N-isopropylacrylamide) copolymer gels with hydrophilic and hydrophobic comonomers," *J. Membrane Sci.* 101(1-2), 13-22

Kim, Y. S., and Kadla, J. F. (2010). "Preparation of a thermoresponsive lignin-based biomaterial through atom transfer radical polymerization," *Biomacromolecules*. 11(4), 981-988.

Lee, W. F., and Yeh, Y. C. (2005). "Studies on preparation and properties of NIPAAm/hydrophobic monomer copolymeric hydrogels," *Eur. Polym. J.* 41(10), 2488-2495.

Liu, F., Tao, G. L., and Zhuo, R. X. (1993). "Synthesis of thermal phase-separating reactive polymers and their applications in immobilized enzymes," *Polym. J*. 25(6), 561-567.

Meister, J. J., and Chen, M. J. (1991). "Graft 1-phenylethylene copolymers of lignin. 1. Synthesis and proof of copolymerization," *Macromolecules*. 24(26), 6843-6848.

Nishida, M., Uraki, Y., and Sano, Y. (2003). "Lignin gel with unique swelling property," *Bioresource Technol*. 88(1), 81-83.

Peri, S., Karim, M. N., Khare R. (2011). "Potential of mean force for separation of the repeating units in cellulose and hemicellulose", *Carbohydr. Res.* 346(6), 867-871

Ramkissoon-Ganorkar, C., Liu, F., Baudyš, M., and Kim, S. W. (1999). "Modulating insulin-release profile from pH thermosensitive polymeric beads through polymer molecular weight," *J. Control. Release* 59(3), 287-298.

Rosso, F., Marino, G., Giordano, A., Barbarisi, M., Parmeggiani, D., and Barbarisi, A. (2005). "Smart materials as scaffolds for tissue engineering," *J. Cell. Physiol.* 203(3), 465-470.

Schild, H. G. (1992). "Poly(N-Isopropylacrylamide): Experiment, theory and application," *Prog. Polym. Sci*. 17(2), 163-249

Takei, Y. G., Aoki, T., Sanui, K., Ogata, N., Okano, T., and Sakurai, Y. (1993). "Temperature-responsive bioconjugates. 2. Molecular design for temperature-modulated bioseparations," *Bioconjugate Chem.* 4(5), 341-346.

Temtem, M., Casimiro, T., Mano, J. F., and Aguiar-Ricardo, A. (2007). "Green synthesis of a temperature sensitive hydrogel," *Green Chem*. 9(1), 75-79

Torres-Lugo, M., and Peppas, N. A. (1999). "Molecular design and in vitro studies of novel pH-sensitive hydrogels for the oral delivery of calcitonin," *Macromolecules*. 32(20), 6646-6651.

Uraki, Y., Imura, T., Kishimoto, T., and Ubukata, M. (2004). "Body temperature-responsive gels derived from hydroxypropylcellulose bearing lignin," *Carbohyd. Polym*. 58(2), 123-130.

Uraki, Y., Sano, Y., and Sasaya, T. (1991). "Cooking of hardwoods with organosolv pulping in aqueous acetic acid containing sulfuric acid at atmospheric pressure," *Jpn. Tappi J*. 45, 1018-1024.

Xu, L. Q., Yao, F., Fu, G. D., and Kang, E. T. (2011). "Interpenetrating network hydrogels via simultaneous "click chemistry" and atom transfer radical polymerization," *Biomacromolecules*. 11(7), 1810-1817.

Yamamoto, H., Amaike, M., Saitoh, H., and Sano, Y. (2000). "Gel formation of lignin and biodegradation of the lignin gels by microorganisms," *Mater. Sci. Eng. C*. 7(2), 143-147.

Yang, J. Y., Zhou, X. S., and Fang, J. (2011). "Synthesis and characterization of temperature sensitive hemicellulose-based hydrogels," *Carbohyd. Polym*. 86(3), 1113-1117.

Zhang, H., Zhong, H., Zhang, L., Chen, S., Zhao, Y., and Zhu, Y. (2009). "Synthesis and characterization of thermosensitive graft copolymer of N-isopropylacrylamide with biodegradable carboxymethylchitosan," *Carbohyd. Polym.* 77(4), 785-790.

Zhang, X. Z., Wu, D. Q., and Chu, C. C. (2003). "Effect of crosslinking level on the properties of temperature-sensitive poly(N-isopropylacylamide) hydrogels," *J. Polym. Sci. Part B: Polym. Phys.* 41(6), 582-593.

Zhang, X. Z., Wu, D. Q., and Chu, C. C. (2004). "Synthesis and characterization of partially biodegradable, temperature and pH sensitive Dex-MA/PNIPAAm hydrogels," *Biomaterials*. 25(19), 4719-4730.

Article submitted: July 18, 2011; Peer review completed: September 24, 2011; Revised version received and accepted: October 15, 2011; Published: October 18, 2011.