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New grafted polysaccharides based on *O*-carboxymethyl-*O*-hydroxypropyl guar gum and *N*-isopropylacrylamide: Synthesis and phase transition behavior in aqueous media

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Abstract

Poly(*N*-isopropylacrylamide) (PNIPAAm) was grafted onto *O*-carboxymethyl-*O*-hydroxypropyl guar gum (CMHPG) in aqueous solutions by using potassium persulfate (KPS) and *N*,*N*,*N*,*N*′-tetramethylethylene diamine (TMEDA) as the initiation system, resulting in new stimuli-responsive grafted polysaccharides. The effects of various factors such as the concentrations of KPS and TMEDA, the feed weight ratio of NIPAAm to CMHPG, and polymerization temperature on the graft copolymerization were studied with respect to the grafting percentage (%*G*), grafting efficiency of the reaction (%*E*) and grafting conversion of the monomer (%*C*). It was found that the %*G*, %*E*, and %*C* increased and then decreased with increasing the concentrations of TMEDA and KPS, as well as polymerization temperature. With the increase of NIPAAm amount, the %*G* increased whereas the %*E* and %*C* both decreased. The resulting grafted polysaccharides could exhibit lower critical solution temperatures in aqueous media due to the thermosensitivity of their PNIAAm graft chains, and their temperature-induced phase transitions were influenced by the grafting percentage, the solution concentration of grafted polysaccharide, as well as the kind and concentration of added salts, as confirmed by determining the optical transmittance of the solutions under various conditions.

Keywords: *O*-Carboxymethyl-*O*-hydroxypropyl guar gum; *N*-Isopropylacrylamide; Graft copolymer; Thermo-responsive property

1. Introduction

Over the past years, stimuli-responsive polymers, especially thermo-responsive polymers, have become very attractive due to a variety of applications for the bio-related technologies (Gil & Hudson, 2004; Jeong & Gutowska, 2002). For example, such polymers can self-assemble into intelligent core-shell type nanoparticles in aqueous solutions for drug release applications (Cammas-Marion, Okano, & Kataoka, 1999; Chung et al., 1997; Kim, Jeong, Cho, & Kim, 2000). In addition, they can be also used for separations and enzyme immobilization (Kim & Park, 1999; Lee & Park, 1998). A representative of the thermo-responsive polymers is poly(*N*-isopropylacrylamide) (PNIPAAm) and its copolymers. They exhibit lower critical solution temperatures (LCSTs) in aqueous media where their hydration–dehydration change occurs reversibly and rapidly in response to small temperature changes (Schild, 1992). Such reversible phase transitions have been used in various fields, especially for a temperature-responsive drug release system (Jeong & Gutowska, 2002).

O-Carboxymethyl-*O*-hydroxypropyl guar gum (CMHPG) is a chemically modified guar gum with high water solubility and functionality (Zhang, Zhou, & Hui,

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2005). Due to good biodegradability and biocompatibility, guar gum has been used to design as colon targeted drug delivery systems (Durig & Fassihi, 2002; Soppimath, Kulkarni, & Aminabhavi, 2001). In this work, the grafting of PNIPAAm side chains onto the hydrophilic CMHPC backbone is expected to provide CMHPG with new, thermo-sensitive properties in aqueous solutions. Described here is the synthesis, characterization and phase-separation behavior of this kind of new polysaccharide graft copolymers in aqueous media.

2. Experimental part

2.1. Materials

O-Carboxymethyl-*O*-hydroxypropyl guar gum (CMHPG) is a commercial product and was kindly provided by China Agency Office of Economy Polymers & Chemicals Company of USA. Its intrinsic viscosity was determined at 30 ± 0.02 °C by an Ubbelohde capillary viscometer, and found to be 4502.7 ml/g. For aqueous 1% solution of CMHPG sample, the moisture content and the pH value were determined to be 9.0% and 6.0%, respectively. *N*-Isopropylacrylamide (NIPAAm) was purchased from Aldrich Chemical Co., and used without further purification. Potassium persulfate (KPS; analytical grade) was purified by recrystallization from ethanol. *N*,*N*,*N*′,*N*′-Tetramethylethylene diamine (TMEDA; biochemical grade) was used without further purification. Other chemical compounds were reagent grade and were used as received.

2.2. Graft copolymerization

In a three-necked flask equipped with a reflux condenser and a magnetic stirrer, the weighted amount of CMHPG was dissolved in 50 ml of deionized water. The flask was purged with nitrogen for 30 min, and the temperature was adjusted to desired temperature with a water bath. Then, KPS solution and TMEDA solution were added by order. After stirring for 10 min, NIPAAm was added to the flask. The reaction was continued for 6 h under the nitrogen atmosphere. The resulting product was precipitated by pouring the reaction mixture into acetone, filtered and washed with acetone for several times, then dried under reduced pressure to constant weight. In order to obtain pure graft copolymer, the resulting product was extracted also for three times with ethanol to remove the NIPAAm homopolymer. The grafting parameters such as the grafting percentage of the graft copolymer (%*G*), grafting efficiency of the reaction (%*E*) and grafting conversion of the monomer (%*C*) were determined as follows (Tan, Zhang, & Li, 1998):

$$\%G = (W_2 - W_0) \times 100/W_0$$
$$\%E = (W_2 - W_0) \times 100/(W_1 - W_0)$$
$$\%C = (W_2 - W_0) \times 100/W_3$$

where W_0, W_1, W_2, and W_3 denote the weights of CMHPG, resulting product, pure graft copolymer, and the monomer NIPAAm, respectively. In order to confirm the graft copolymerization, the infrared spectra of the substrate CMHPG and its pure graft copolymer as well as the homopolymer (PNIPAAm) were run on a NICOLET FT-20SX spectrophotometer using KBr pellets in range of 400–4000 cm^{-1}.

2.3. Transmittance measurements

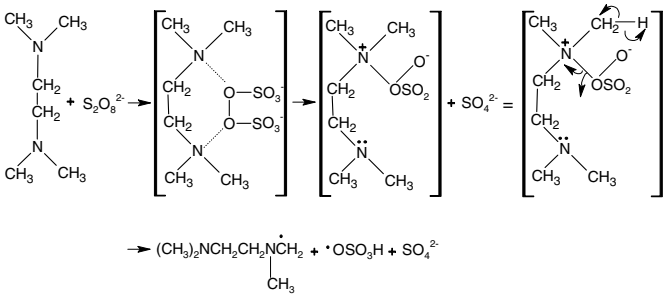
The optical transmittance for each sample solution was monitored under various conditions as a function of the temperature at 500 nm by using a 721 spectrophotometer made in Shanghai Instrument Company of China. The temperature of the sample cell was thermostatically controlled using a circulator system. At each temperature, the sample solution was allowed to equilibrate for about 10 min before the measurement. Pure water was used as a reference. The value of the LCST of the polymer solution was determined as the temperature at which the transmittance is 50% of the value (Chaw et al., 2004; Shtanko, Lequieu, Goethals, & Prez, 2003). The effects of the grafting percentage, the concentration of grafted polysaccharide, as well as the kind and concentration of added salt on the phase transition behavior were investigated.

3. Results and discussion

3.1. Synthesis by graft copolymerization

Among various methods capable of initiating the graft copolymerization onto polysaccharide, potassium persulfate (KPS) initiation has been proven to be effective (Fang, Fowler, & Hill, 2005; Mondal, Alam, & Sayeed, 2004; Najjar, Yunus, Ahmad, & Rahman, 2000). Further investigation (Tan et al., 1998) shows *N*,*N*,*N*′,*N*′-tetramethylethylene diamine (TMEDA) as the reducing agent can obviously improve the initiating efficiency of KPS. Thus, the graft copolymerization of *O*-carboxymethyl-*O*-hydroxypropyl guar gum (CMHPG) with *N*-isopropylacrylamide (NIPAAm) initiated by KPS/TMEDA redox system would be expected to be more effective.

The effect of KPS on the graft copolymerization was studied by varying its concentration from 3.7×10^{-4} to 5.9×10^{-3} mol/L, as shown in Fig. 1. It was observed that the %*G*, %*E*, and %*C* increase with increasing KPS concentration from 3.7×10^{-4} to 4.4×10^{-3} mol/L but beyond the above concentration range the %*G*, %*E*, and %*C* decreased. It is known that KPS and TMEDA could better form 1:1 complexes of charge transfer and then produce easier more free radicals, leading to high efficiency of initiation, as illustrated in the following scheme (Tan et al., 1998):



The enhancement of grafting within the cited range may be attributed to progressive reduction, producing $(CH_3)_2NCH_2CH_2N\,(CH_3)CH_2\cdot$ and $\cdot OSO_3H$ free radicals, which attack the CMHPG molecule and produce more free radical sites to which monomer addition takes place. At higher concentration, however, KPS may decompose to HSO_4^- and O_2, according to the following modes:

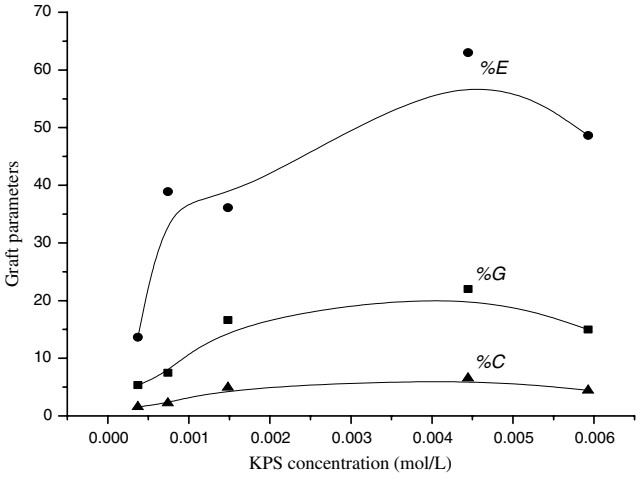


Fig. 1. The effect of KPS concentration on the grafting. Reaction conditions: CMHPG, 0.5 g; NIPAAm, 1 g; H_2O, 50 ml; TEMAD, 4.4×10^{-3} mol/L; 60 °C; 6 h.

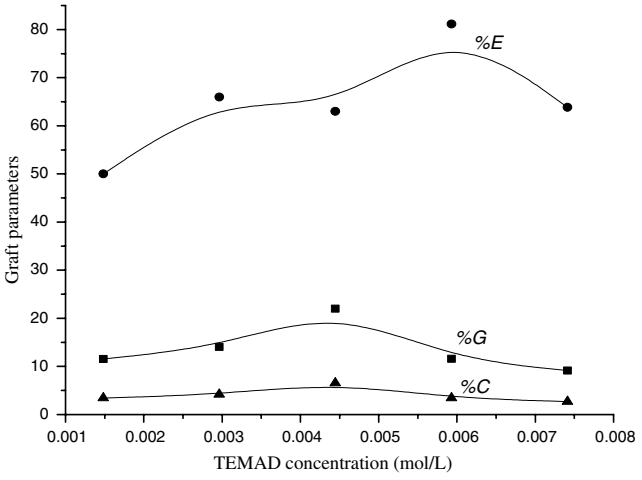


Fig. 2. The effect of TEMAD concentration on the grafting. Reaction conditions: CMHPG, 0.5 g; NIPAAm, 1 g; H_2O, 50 ml; KPS, 4.4×10^{-3} mol/L; 60 °C; 6 h.

$$S_2O_8^{2-} \rightarrow 2SO_4^{-\cdot} \quad (1)$$

$$SO_4^{-\cdot} + H_2O \rightarrow HSO_4^- + HO^{\cdot} \quad (2)$$

$$2HO^{\cdot} \rightarrow HOOH \quad (3)$$

$$HO^{\cdot} + HOOH \rightarrow H_2O + HO_2^{\cdot} \quad (4)$$

$$S_2O_8^{2-} + HO_2^{\cdot} \rightarrow HSO_4^- + SO_4^{-\cdot} + O_2 \quad (5)$$

In this case, the G%, E%, and C% decreased due to the fact that O_2 acts as a scavenger for free radicals (Qudsieh et al., 2004).

Fig. 2 gives the effect of TMEDA concentration on the graft copolymerization. The %G and the %C both increase with the increase of TMEDA concentration from 3.7×10^{-3} to 4.5×10^{-3} mol/L but decreased with further increasing the concentration. The maximum %E was observed when the concentration of TMEDA was 5.9×10^{-3} mol/L. The increase in the %G and the %C may result from the increase in the number of free radicals. The decrease in the %G and the %C at higher concentration may be due to the fact that excess TMEDA further reacts with primary free radicals. The maximum of %G and %C were observed when TMEDA and KPS were at same concentration of 4.5×10^{-3} mol/L. This shows that the best molar ratio of KPS to TMEDA was 1:1 for the grafting, as mentioned above.

Fig. 3 shows the grafting parameters changed with the feed weight ratio of NIPAAm to CMHPG. In every trail, the weight of CMHPG was kept to be constant. The %G increases with the increase of feed weight ratio from 1 to 10, whereas the %E and %C both decrease as the feed ratio increased. The increase of %G might be attributed to the greater availability of the monomer molecules at the chain-propagating site. The decrease of %E and %C may be attributed to the possible increase in the homopolymer (PNIPAAm) formation – as a reaction competitive with the grafting process – which consequently increased the viscosity of the medium and impeded the diffusion of the monomer

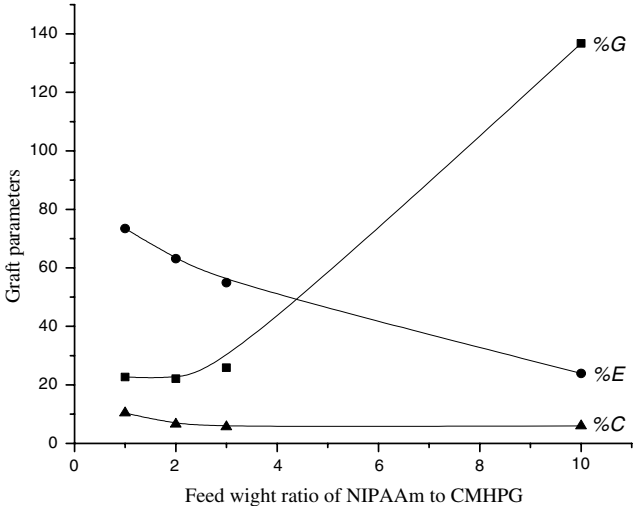


Fig. 3. The effect of feed weight ratio of NIPAAm to CMHPG on the grafting. Reaction conditions: CMHPG, 0.5 g; KPS, 4.4×10^{-3} mol/L; H_2O, 50 ml; TEMAD, 4.4×10^{-3} mol/L; 60 °C; 6 h.

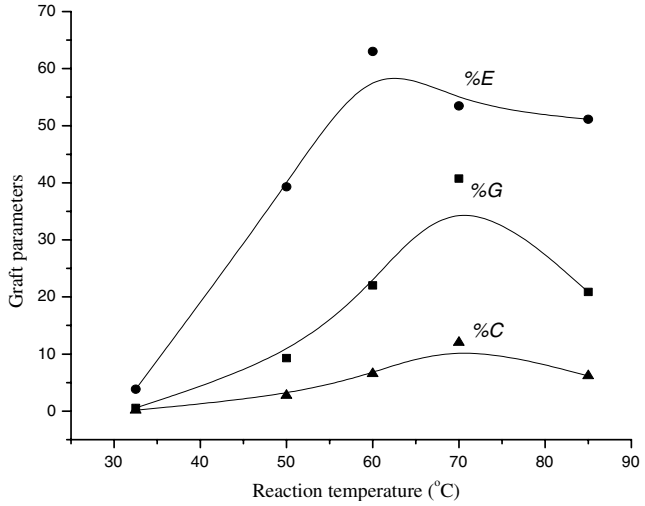


Fig. 4. The effect of reaction temperature on the grafting. Reaction conditions: CMHPG, 0.5 g; NIPAAm, 1 g; H_2O, 50 ml; $K_2S_2O_8$, 4.4×10^{-3} mol/L; TEMAD, 4.4×10^{-3} mol/L; 60 °C; 6 h.

towards the chitin matrix (Mostafa, Naguib, Sabaa, & Mokhtar, 2005; Zhang, Tan, Huang, Chen, & Li, 2000).

Fig. 4 shows the effect of temperature on the grafting. A maximum in the dependence of grafting parameters (%*G*, %*E*, and %*C*) on the temperature has been observed. The appropriate increase in the temperature favors the activation of backbone radicals and monomer radicals, leading to an increase in %*G*, %*E*, and %*C*. Beyond the optimum temperature, an increase in the temperature may favor the homopolymerization rather than the graft copolymerization, resulting in a decrease in %*G*, %*E*, and %*C*. Similar results were also obtained by Qudsieh et al. (2004) when they grafted poly(methyl methacrylate) onto sago starch using potassium persulfate as the redox initiator.

Evidence of grafting has been obtained by the increase in weight of the treated CMHPG when compared with the original matrix, and also evidenced by observing the difference among the infrared spectra of the substrate CMHPG, the homopolymer (PNIPAAm) and the graft copolymer CMHPG-*g*-PNIPAAm. As shown in Fig. 5, the spectrum of the graft copolymer shows not only the characteristic bands of CMHPG substrate at 3400 and 1023 cm^{-1}, which correspond to the characteristic stretching vibrations of hydroxyl group, but also the additional bands at 1652 and 1541 cm^{-1}, which are attributed to the acyl group of PNIPAAm. This result indicates that the graft copolymerization has occurred between CMHPG and *N*-isopropylacrylamide Fig. 5.

3.2. Phase transition behavior in aqueous solutions

Fig. 6 demonstrates the optical transmittances of aqueous solutions of CMHPG and its graft copolymers with various grafting percentages as a function of temperature. As expected, aqueous CMHPG solution is transparent in the whole temperature range studied due to its high hydrophilicity. For the graft copolymers, however, they could show an obvious thermo-responsive behavior in aqueous solution except the graft copolymer with lower graft percentage of 13.6%. With the increase of %*G*, the phase transition temperature range of the grafted polysaccharides becomes narrower. For three grafted polysaccharides with respective %*G* of 29.8%, 59.9%, and 136.7%, corresponding LCST values for their 10.0 g/L aqueous solutions were determined to be 32.6, 32.4, and 31.4 °C, separately. It is known that the PNIPAAm homopolymer exhibits a LCST around 32 °C. Below the LCST, the polymer chains hydrate to form expanded structures in water, while above the LCST they become compact structures due to dehydra-

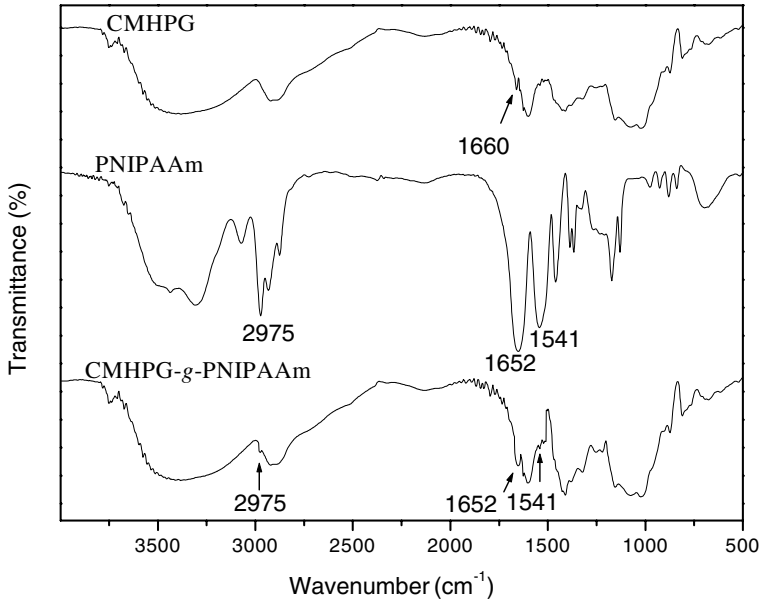


Fig. 5. FTIR spectra of CMHPG, PNIPAAm, and CMHPG-*g*-PNIPAAm.

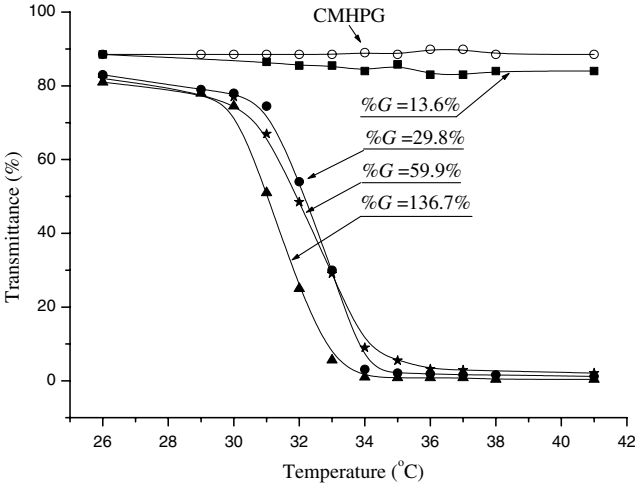


Fig. 6. The optical transmittances of aqueous solutions of CMHPG and its graft copolymers with various grafting percentages as a function of temperature (solution concentration, 10.0 g/L).

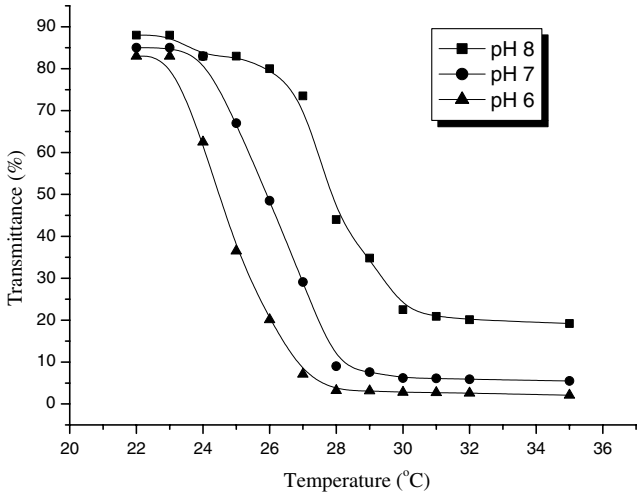


Fig. 8. The optical transmittance change with the temperature under various pH values for aqueous solutions of the grafted polysaccharide (%G = 59.9%) (solution concentration, 2.5 g/L).

tion. It seems that the combination of CMHPG as the main chain with PNIPAAm as the graft chains changed the LCST of PNIPAAm.

Fig. 7 shows the effect of solution concentration on the optical transmittance under various temperatures for aqueous solutions of the grafted polysaccharide with the %G of 59.9%. As seen, the phase transition point of the grafted polysaccharide in aqueous solution moves to higher temperature when the solution concentration decreases, and an increasing concentration leads to a lower value of the LCST. This is in correspondence to the general accepted LCST principle for dilute solutions: a higher water content leads to more polymer/water interactions, thus more thermal energy is needed to break the water structure and consequently to let the hydrophobic polymer/polymer interactions rule out the polymer/water interactions. Similar results were also observed by Verbrugghe, Bernaerts, and Prez (2003) when they investigated the thermo-responsive properties of poly(*N*-vinylcaprolactam) based graft copolymers.

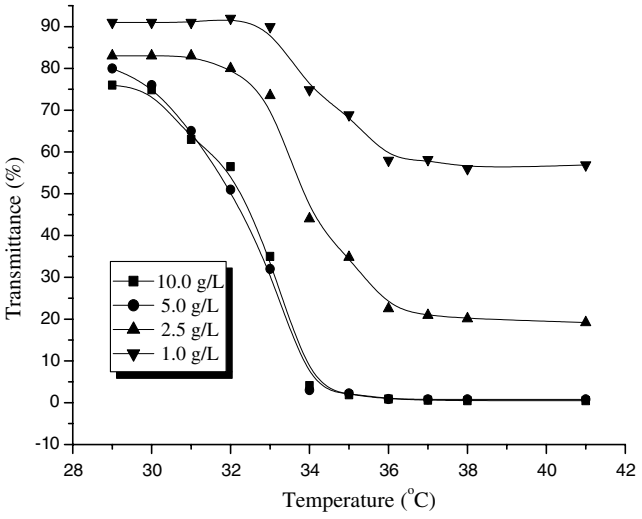


Fig. 7. Effect of solution concentration on the optical transmittance under various temperatures for aqueous solution of the graft copolymers (%G = 59.9%).

The effect of the pH on the temperature-dependent transmittance change for aqueous solutions of the grafted polysaccharide with the %G of 59.9% is shown in Fig. 8. The phase-separation behavior of the grafted polysaccharide was observed at higher temperatures with the increase of pH values. The higher pH values of the solution prompted more ionic dissociation of the carboxylic acid groups from the CMHPG main chains of the grafted polysaccharide, causing an increase of the electrostactic repulsion among the macromolecular chains. Therefore, the grafted polysaccharide formed the hydrophobic aggregates until higher temperature to overcome the electrostactic repulsion. These results are in good agreement with the previous study (Shibanuma et al., 2000).

Table 1
Effect of added salt on the LCST value of aqueous solution of the grafted polysaccharide with the grafting percentage of 60.5%

Salt kind	Salt concentration (mol/L)	LCST (°C)
Without salt	0	32.5
KCl	0.005	32.3
	0.010	32.2
	0.050	31.9
	0.100	31.1
	0.500	25.2
	1.000	19.1
KBr	0.005	32.5
	0.010	32.5
	0.050	32.1
	0.100	32.0
	0.500	29.0
	1.000	23.4
KI	0.005	32.5
	0.010	33.0
	0.050	33.1
	0.100	32.9
	0.500	32.5
	1.000	28.0

Simple salts were also found to influence the temperature-induced phase transition of the grafted polysaccharide. As shown in Table 1, the concentration and kind of added salts have a great effect on the phase transition temperature. With the exception of low concentrations of KI, all salts investigated were observed to lower the LCST value, and the LCST value had a continuous decrease when the salt concentration increased. Among three salts investigated, the effect intensity was found to vary with the following order: KCl > KBr > KI. A possible explanation for the salt effects relies on a competition for the water molecules available for solvation, which affected the phase transition temperature of the grafted polysaccharide.

4. Conclusion

New grafted polysaccharides were prepared in aqueous solutions by grafting *N*-isopropylacrylamide onto *O*-carboxymethyl-*O*-hydroxypropyl guar gum using KPS/TMEDA as the initiating system. It is possible to control the extent of grafting by varying the reaction conditions. The %*G*, %*E*, and %*C* increase and then decrease with increasing concentrations of TMEDA and KPS, as well as polymerization temperature. With the increase of NIPAAm amount, the %*G* increases whereas the %*E* and %*C* both decrease. For the resulting grafted polysaccharides with higher graft percentages, they could show an obvious thermo-responsive behavior in aqueous solutions, and their LCST values could be modulated by the change of the grafting percentage, the concentration of grafted polysaccharide or the pH of aqueous media. In addition, simple salts were found to influence the temperature-induced phase transition of the grafted polysaccharide in aqueous media.

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