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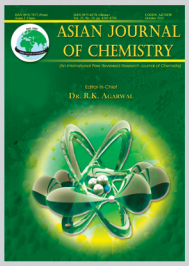

Synthesis of Thermoresponsive Core-Shell Microgels Cross-Linked with Acryloyloxyethylaminopolysuccinimide

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Utilizing a biodegradable cross-linker, acryloyloxyethylaminopolysuccinimide (AEA-PSI), poly(*N*-isopropylacrylamide) (PNIPAAm) microgels and core-shell structure microgels were prepared *via* free-radical precipitation polymerization and their phase transition behaviour, phase transition temperature (PTT), hydrodynamic diameters and size distributions (polydispersity indexes, PDI) were investigated. To prepare small-sized and lower PDI PNIPAAm microgels, the optimum parameters should be selected as the concentrations of AEA-PSI, *N*-isopropylacrylamide (NIPAAm), ammonium peroxodisulfate (APS) and sodium dodecyl sulfate (SDS) were 1.34, 7.56, 0.152 and 0.18 g/L and the hydrodynamic diameter of the microgels was 353.8 nm (PDI, 0.24). All the microgels dispersions exhibited thermoresponsive phase transition at 30.0-32.5 ºC. Using microgels as seeds, the core-shell PNIPAAm microgels were prepared. With increasing the weight ratio of the NIPAAm/AEA-PSI from 1.3:1 to 3:1 and 5:1 in the shell materials, the hydrodynamic diameter of the core-shell microgels increases from 376.4 to 432.5 and 472.3 nm at 25 ºC, respectively. The morphologies of the microgels particles were also investigated by the atomic force microscopy (AFM). The AFM images illuminated that the core-shell microgels particles had symmetrical sizes and non-aggregation, indicating better stability. Compared with the core microgels, the shell-core microgels appear a smoother and denser surface.

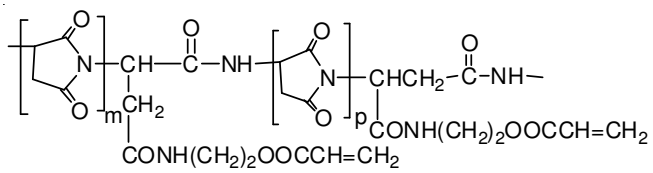
Key Words: *N*-isopropylacrylamide, Acryloyloxyethylaminopolysuccinimide, Thermoresponsive core-shell microgels, Synthesis.

INTRODUCTION

In view of the growing interest in stimuli-responsive polymers[1] for applications in diverse areas such drug delivery[2-4], biosensing[5], soft actuators/valves[6] and catalysis[7], the need to fine-tune the chemical, mechanical and structural characteristics of such materials has also increased. Particularly intriguing subclasses of responsive polymers are hydrogel latex particles or microgels, composed of polymers such as poly(*N*-alkylacrylamides)[8]. These spherical particles display a strong thermo-responsiveness, where below a characteristic lower critical solution temperature (LCST) they are highly swollen in water, but increasing the temperature above the lower critical solution temperature they rapidly deswell to a collapsed polymer globule. For example, in the case of lightly cross-linked poly(*N*-isopropylacrylamide) particles, as the temperature increases above a volume phase transition temperature (PTT, ~32 ºC), which corresponds to the lower critical solution temperature of the linear polymer in water[9], the polymer gels undergo a reversible deswelling event, a coil-to-globule transition, due to dissociation of water molecules from the polymer chains and concomitant polymer self-association. Besides, physico-chemical and structural properties such as size, surface charge, morphology and the composition of the polymer matrix play a key role on their fate and can be easily optimized also to achieve proper drug release kinetics, biological activity and compatibility[10]. There exist numerous reports on the preparation and properties of PNIPAAm hydrogels, microgels, core-shell microgels and nanogels, which have been the topic of several recent reviews [8,11-13]. Be differ from the rods, blocks, or fibers of macrogel, the microgel particles have smaller sizes, thereby the entire response of hydrogel to stimuli is evaluated readily, which is advantageous to elucidate the relationship of structure and response and microgel particles have a high surface-to-volume ratio that is several orders of magnitude larger than that of a comparable macrogel and display colloidal behaviour. Colloidal systems of microgel particles composed of environmentally responsive polymers such as PNIPAAm particles possess a combination of unique properties, the thermo-responsiveness and fast-responsiveness, which make them attractive. The response mechanism of microgel particles is dictated primarily by their chemical composition, surface charge, morphology and size. In numerous instances, submicron microgel particles, are preferred because smaller particles tend to respond faster[14], which is due to their much higher interfacial area per unit mass. They have greater exchange rates[15] and as

a rule, are more preferment drug delivery agents, compared to micron-sized particles[16].

However, an important limitation of PNIPAAm hydrogel or microgel for biomedical application is their lack of bioactivity and biodegradability. By incorporating degradable linkages into hydrogel, the material can accomplish a number of interesting biomedical applications such as temporary implants[17]. Such degradable hydrogel comprises of cross-linking molecules with degradable segments. As degradation occurs, degradable linkages in each arm of the cross-linking molecules are cleaved systematically, lowering the average number of cross-links per kinetic chain with time and causing eventual mass loss[18]. In previous studies[19, 20], we have synthesized the biodegradable cross-linker, acryloyloxyethyl-aminopolysuccinimide (AEA-PSI), which has a mass of biodegradable groups, including amido group and ester group (**Scheme-I**) and prepared a series of looser cross-linked P(NIPAAm-co-AAc) hydrogels using AEA-PSI as cross-linker. Their phase transition behaviour, lower critical solution temperature, was investigated. By alternating the NIPAAm/AAc molar ratio, hydrogels were synthesized to have lower critical solution temperature in the vicinity of 37 ºC. The lower critical solution temperature of the hydrogels was significantly influenced by monomer ratio of the NIPAAm/AAc, but not by the cross-linking density within the polymer network.



Scheme-I Constitutional formula of AEA-PSI

In this work, the PNIPAAm microgels were synthesized using AEA-PSI as cross-linker and used the dispersion of microgels as seeds, a series of core-shell structure thermoresponsive microgels were also synthesized. By incorporating degradable linkages, microgels can accomplish a number of interesting biomedical applications as temporary implants[15,17] and enhance the bioactivity and biodegradability. The particles size and the size distribution of the microgels were investigated by dynamic light scattering method. To prepare small-sized and lower polydispersities PNIPAAm microgels, the optimum synthesis conditions were obtained. To evaluate the thermoresponsive property, the phase transition temperature (PTT) of microgels was characterized by measuring their transmittances and hydrodynamic diameters as a function of temperature. The morphologies were also investigated with atomic force microscopy (AFM).

EXPERIMENTAL

The AEA-PSI cross-linker was synthesized according to the reported method[19]. *N*-isopropylacrylamide (NIPAAm) was purchased from Tokyo Kaset Kogyo Co. Ltd and used as received. All other agents were of analytical grade and were used as received from Shanghai Fine Chemical Co. Ltd, China. Water used in the preparation of the complexes was purified in a Mili Q water purification system.

Preparation of PNIPAAm microgels and core-shell microgels: The PNIPAAm microgels were prepared by precipitation polymerization. In brief, 1.34 g/L NIPAAm monomer, 7.56 g/L AEA-PSI as cross-linker, 0.18 g/L sodium dodecyl sulfate (SDS) as surfactant (The sodium dodecyl sulfate dosages were lower than the CMC of SDS solution, approximately 2.6 g/L) and 150 mL distilled water were mixed in a 250 mL three-neck round-bottom flask. The reaction mixture was heated up to 70 ºC under nitrogen bubbling for about 2 h. 23 mg of ammonium peroxodisulfate (APS) in 1 mL water was added to initiate the reaction. The reaction was carried out at 70 ºC for 6 h under a stream of nitrogen. After cooling to room temperature, the mixture was exhaustively dialyzed in a dialysis tube against ultrapure water (UPW, 18 MΩ cm) for 48 h with periodic bath changes (every 8 h) to eliminate unreacted compounds. A series of microgels dispersions were prepared as specified in Table-1.

TABLE-1
DESCRIPTION OF SYNTHESIS OF THE MICROGELS DISPERSIONS

Samples	AEA-PSI (g/L)	NIPAAm (g/L)	APS (g/L)
1	0.67	7.56	0.152
2	1.34	7.56	0.152
3	2.02	7.56	0.152
4	2.68	7.56	0.152
5	1.34	4.01	0.152
6	1.34	5.33	0.152
7	1.34	8.67	0.152
8	1.34	13.3	0.152
9	1.34	7.56	0.067
10	1.34	7.56	0.200
11	1.34	7.56	0.267
12	1.34	7.56	0.400

The core microgels processed under the optimum parameters were used as seeds for the preparation of core-shell microgels. Cross-linked PNIPAAm shells were fabricated onto the seeds. Briefly, 30 mL core microgels dispersion as the seeds, 45 mL aqueous solution containing defined amount of NIPAAm and AEA-PSI was added in a 250 mL three-neck round-bottom flask. The weight percentage ratio of the shell material to the core material was always 150 %. The mixture was heated to 70 ºC under nitrogen bubbling for about 1 h. 23 mg of APS in 1 mL water was added to initiate the reaction. The reaction was stirred at 70 ºC for 6 h under a stream of nitrogen and cooled down to ambient temperature. A series of core-shell microgels dispersions were prepared as specified in Table-2.

TABLE-2
EFFECT OF SHELL MATERIALS ON THE HYDRODYNAMIC DIAMETER OF CORE-SHELL MICROGELS PARTICLE

Samples	M(NIPAAm) / M(AEA-PSI)	AEA-PSI(g)	NIPAAm (g)	Hydrodynamiciameter (nm)	PDI
1	1.3:1	0.2044	0.2652	376.4	0.084
2	3.0:1	0.1179	0.3526	432.5	0.125
3	5.0:1	0.0788	0.3915	472.3	0.157

Hydrodynamic diameter measurements: Microgel particle sizes and polydispersities indexes (PDI) were determined

via dynamic light scattering (DLS, Zetasizer 3000, Malvern Instruments, Herrenberg, Germany). Dialysis dispersions were diluted and the samples were allowed to equilibrate at each temperature point for 5 min before data collection. Each data presented in this paper represents the average value of five measurements.

Phase transition temperature measurements: The phase transition temperature of the PNIPAAm microgels dispersions was determined as the abscissa of the inflection point of the transmittance *versus* temperature curves. The changes in transmittance of the PNIPAAm microgels dispersions with temperature were captured using an UV-VIS spectrophotometer (569 nm, path length = 3 cm, Spectrum 723p, Shanghai Spectrum Instruments Co. Ltd., China). Temperature was controlled by a high-constant temperature bath (CH-1015, Shanghai Precision Scientific Instrument Co. Ltd., China). The thermal analyses were performed from 25 to 40 ºC at rates of 0.5 ºC /min step by step.

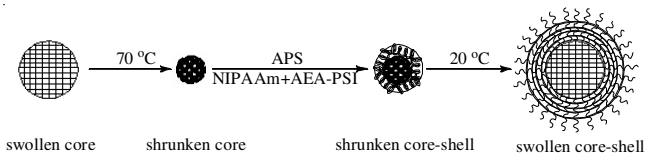
The PTT of the core-shell microgels dispersions was determined as the abscissa of the inflection point of the hydrodynamic diameter *versus* temperature curves. The hydrodynamic diameter was determined *via* dynamic light scattering. The analyses were performed from 20 to 40 °C.

Atomic force microscopy: Morphologies of the microgel particles were observed *via* atomic force microscopy (AFM), which was detected by a nano-scope IIIa multifunctional scanning probe microscope (Digital Instruments Corporation, US). Atomic force microscopy images were recorded with a scan speed of 1.5 Hz. The samples were freshly cleaved silicon substrates depositing a film of the dispersion of microgels on the surface and drying at the room temperature. The measurement was completed at the normal atmospheric temperature and pressure.

RESULTS AND DISCUSSION

Poly(*N*-isopropylacrylamide) microgels dispersions were prepared *via* free-radical precipitation polymerization at 70 ºC, above the phase transition temperature. Firstly, the reaction mixture was maintained at 70 ºC with nitrogen bubbling for 2 h to eliminate dissolved oxygen. At this stage the reaction solution was transparent and with a salmon pink which belonged to the colour of AEA-PSI solution. The polymerization was then carried out at 70 ºC for 6 h under a stream of nitrogen. The transparent solution turned to be milky and white dispersion at this time. While cooled down, the microgels dispersions became clear. This process was considered to be a dehydration/hydration of the microgels around the phase transition temperature. At the end of polymerization, the light-blue colour (owing to the Tyndall effect) was observed in the suspension.

Using microgels processed under the optimum parameters as seeds, the core-shell PNIPAAm microgels were prepared. Cross-linked PNIPAAm shells were fabricated onto the seeds (**Scheme-II**). The PNIPAAm shell was polymerized onto the shrunken core microgel under a stream of nitrogen at 70 ºC, above the phase transition temperature of the polymer. The solution still remained milky even though the solution was kept at room temperature after 6 h of polymerization/crosslinking, indicating the formation of core-shell microgels. This milky appearance is due to a change of light scattering caused by a change in the dimension of the microgel.



Scheme-II Synthesis sketch of core-shell microgels

Hydrodynamic diameters characterization of core microgels and core-shell microgels: In this work, the influences of cross-linker (AEA-PSI), NIPAAm and initiator ammonium peroxodisulfate (APS) concentration on the hydrodynamic diameters of microgels and their size distributions (polydispersities indexes, PDI) were investigated, respectively. Other factors were fixed except the investigated factor during a series of experiments. The chemical compositions of the microgels were listed in Table-1.

Fig. 1 shows the effects of the AEA-PSI dosages on the size distributions of the microgels. As shown in Fig. 1., different AEA-PSI dosages resulted in different sizes and distributions of microgels. The hydrodynamic diameters of microgels with AEA-PSI dosages 1.34 and 2.02 g/L were 353.8 and 548.1 nm, the PDI were 0.24 and 0.55, respectively. The particle size distributions were narrower. Increasing the dosages of AEA-PSI from 2.02 to 2.68 g/L, or decreasing the dosages of AEA-PSI from 1.34 to 0.67 g/L resulted more polydisperse, the PDI were 0.65 and 0.67, respectively. The microgels were prepared by free-radical precipitation polymerization using AEA-PSI as cross-linker. The concentration of cross-linker is closely related to formation of the microgel particles. When the cross-linkers were not enough (*e.g.*, less than 0.67 g/L) to cross link the NIPAAm monomer, some NIPAAm monomer could be polymerized to linear homopolymers with different molecular weights. As a result, the particle sizes of the resulting products decreased and the polydispersity increased. However, by increasing dosages of cross-linkers even more (*e.g.*, larger than 2.68 g/L), some cross-linkers could be polymerized to homopolymers and the polydispersity increased.

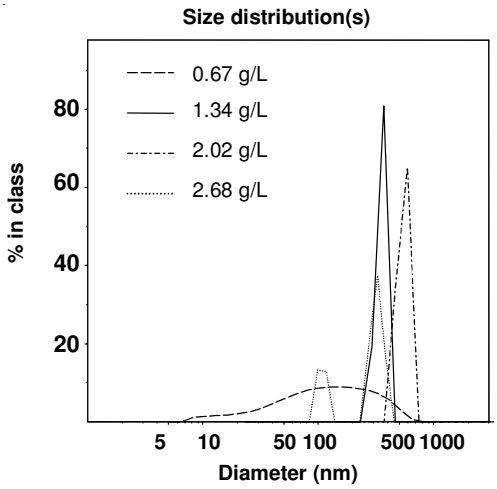


Fig. 1. Size distributions of microgels dispersions with different AEA-PSI dosages (g/L).

Fig. 2. shows the effects of the NIPAAm dosages on the size distributions of the microgels. As shown in Fig. 2, the hydrodynamic diameters of microgels with amounts of

NIPAAm 4.01, 7.56, 8.67 and 13.30 g/L were 35.2, 353.8, 842.0 and 693.3 nm, the PDI were 1.00, 0.24, 1.00 and 1.00, respectively. As the concentration of NIPAAm increased, the hydrodynamic diameters of the microgels increased. The NIPAAm were the monomer materials to synthesize the microgels, the hydrodynamic diameters of microgels became larger simply with increasing the NIPAAm dosages. On the other hand, the free radical density of smaller particles was larger relatively, which was helpful for the smaller particles to absorb more monomers or polymers with low molecular weight onto their surfaces to form larger particles[21]. However, when the concentration of NIPAAm increased further from 8.67 to 13.30 g/L, some NIPAAm could be polymerized to linear homopolymers with different molecular weights, the hydrodynamic diameters microgels decreased and the particles became more polydisperse.

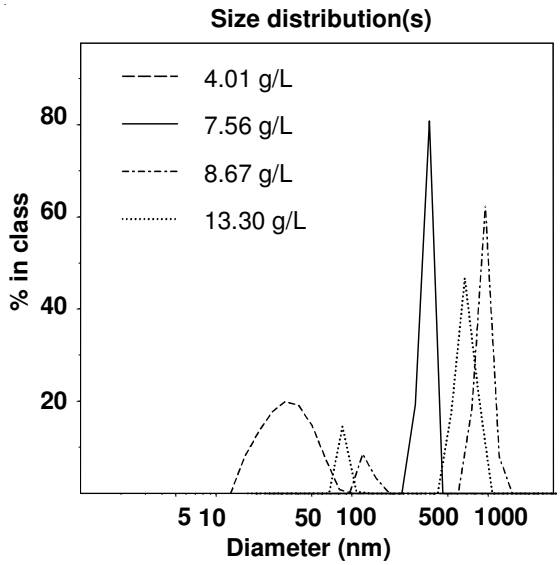


Fig. 2. Size distributions of microgels dispersions with different NIPAAm dosages (g/L).

Fig. 3 shows the effects of the ammonium peroxodisulfate dosages on the size distributions of the microgels. As shown in Fig. 3, the hydrodynamic diameters of microgels with amounts of ammonium peroxodisulfate 0.067, 0.152, 0.267 and 0.400 g/L were 315.0, 353.8, 354.0 and 82.2 nm, the PDI were 0.82, 0.24, 0.70 and 0.60, respectively. Ammonium peroxodisulfate was used as an initiator in the polymerization reaction. Different initiator concentrations resulted in different sizes and distributions of particles. With increasing the APS concentration from 0.067 to 0.267 g/L, the hydrodynamic diameters were increased slightly. However, when the initiator concentration increased further from 0.267 to 0.400 g/L, the hydrodynamic diameters of the particles decreased drastically and the particles became more polydisperse. The initiator produced free radicals by thermal decomposition and the free radicals initiated the polymerization reaction. The reaction was followed by chain propagation and when the chains reached a critical length, the growing chains formed precursor particles by interwinding with each other. Finally, the precursor particles grew into product particles. Termination of chain propagation occurred when two free radicals met or when a free radical contacted oxygen. When the initiator dosage was not very large (*e.g.*, less than 0.267 g/L) the number of resulting free radicals was not very large and the chance of free radicals meeting was limited. This was helpful for growth of particles. Consequently, microgels with good size distribution resulted. However, by increasing the initiator concentration even more (*e.g.*, larger than 0.400 g/L), the number of resulting free radicals increased further and the chance of free radicals meeting increased too much. As a result, the particles could not grow normally, the particle sizes of the resulting products decreased. From the above results, to prepare small-sized and lower PDI PNIPAAm microgels, the optimum parameters should be selected as the concentration of AEA-PSI, NIPAAm and APS were 1.34, 7.56 and 0.152 g/L (Sample 2 in Table-1) and hydrodynamic diameter of microgels was 353.8 nm (PDI, 0.24). The following discussion is based on the core-shell microgels whose cores were prepared with above optimum parameters.

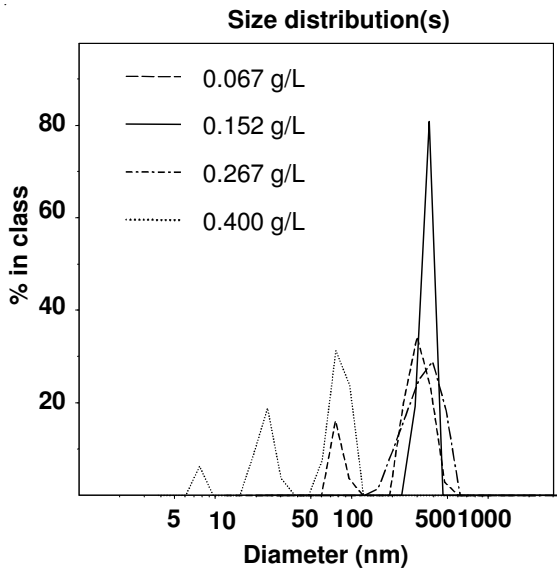


Fig. 3. Size distributions of microgels dispersions with different APS dosages (g/L).

The hydrodynamic diameters of core-shell microgels obtained by dynamic light scattering were listed in Table-2. When no shell material was added, hydrodynamic diameters of the core microgels was 353.8 nm, PDI was 0.24. The addition of shell material resulted in an obvious increase in the particle size (Table-2). The weight percentage ratio of the shell material to the core material was always 150 %. With increasing the weight ratio of the NIPAAm/AEA-PSI from 1.3:1 to 3:1 and 5:1, the hydrodynamic diameter increases from 376.4 to 432.5 and 472.3 nm at 25 ºC, respectively. The PDI of shell-core microgels was lower than that of the core microgels, suggesting that the formation of new PNIPAAm microgels was avoided during the seeded polymerization. Considering the hydrodynamic diameter of the microgels core at 25 ºC, which is 353.8 nm by dynamic light scattering, the thickness of the PNIPAAm shell are about 11.3, 39.4 and 59.3 nm, respectively.

Phase transition temperature characterization of core microgels and shell-core microgels: The thermoresponsive phase transition temperature measurements were taken under equilibrium conditions after holding the sample for 10 min at

each temperature (prolonged equilibration times do not lead to differences in the observed behaviour). We investigated the effects of AEA-PSI, NIPAAm and APS concentrations on the transmittance of microgels dispersions, respectively (Figs. 4-6). The phase transition temperature of the PNIPAAm microgels dispersions was determined as the abscissa of the inflection point of the transmittance *versus* temperature curves. Others factors were fixed except the investigated factor during a series of experiments. The chemical compositions of the microgels were listed in Table-1.

Fig. 4 shows the effect of AEA-PSI concentration on the transmittance of microgels. As seen in Fig. 4, the microgel with cross-linker dosages 0.67 g/L appeared a sharp phase transition at 30.6 ºC (PTT), while the microgels with more cross-linkers exhibited decreased in phase transition temperature slightly and a much broader phase transition. The extremely sharp phase transition of PNIPAAm microgels had been attributed to the hydrophobic/hydrophilic balance of the side groups in polymers, which led to rapid dehydration of the polymer as the temperature increased above phase transition temperature. The AEA-PSI cross-linker was more hydrophilic than the NIPAAm monomer. Thus, incorporation of these chains as cross-linking units should influence the hydrophilic/hydrophilic balance.

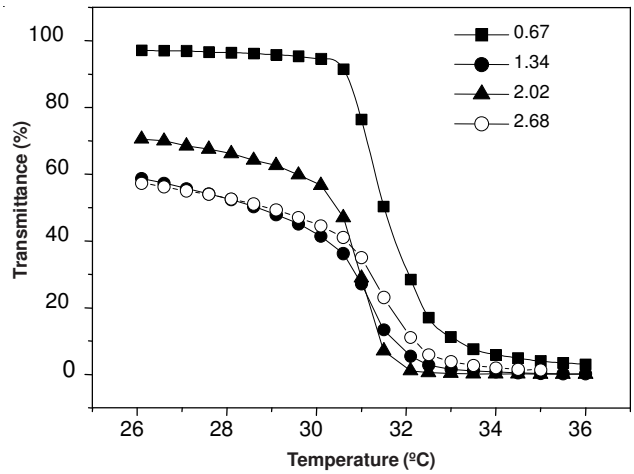


Fig. 4. Transmittance as a function of temperature for microgels dispersions with different AEA-PSI concentration (g/L).

Fig. 5 shows the effect of NIPAAm concentration on the transmittance of microgels. As the NIPAAm concentration in the microgels was increased from 4.0 to 13.3 g/L, the phase transition of the microgels became sharper gradually, while the phase transition temperature of the microgels was not influenced by changing the NIPAAm concentration and remained at -31 ºC. An increase in the amount of NIPAAm monomer provided more material for particle growth. Obviously, the phase transition of the microgels became sharper with increase in the NIPAAm concentration.

Fig. 6 shows the effect of initiator concentration on the transmittance of microgels. As shown in the Fig. 6, when the initiator concentration was increased from 0.067 to 0.267 g/L, the phase transition temperature decreased from 31.5 to 30.5 ºC. The PNIPAAm microgels were prepared *via* free radical polymerization and initiated by ammonium peroxodisulfate. At the beginning of the synthesis, the monomers are soluble. Following the addition of APS, the solution becomes turbid as the growing oligomers reach their critical aggregation length, upon, which phase separation into collapsed chains occurs. This method of precipitation polymerization produces submicron-sized spherical network microgels[10,14-16]. However, by increasing the initiator concentration even more (*e.g.*, larger than 0.400 g/L), the phase transition temperature and transmittance of the microgels no more decreased but increased, the phase transition temperature was 32.0 ºC. As described above, by increasing the initiator concentration even more, the particle sizes of the resulting products decreased, the phase transition temperature and transmittance of the microgels increased simultaneously.

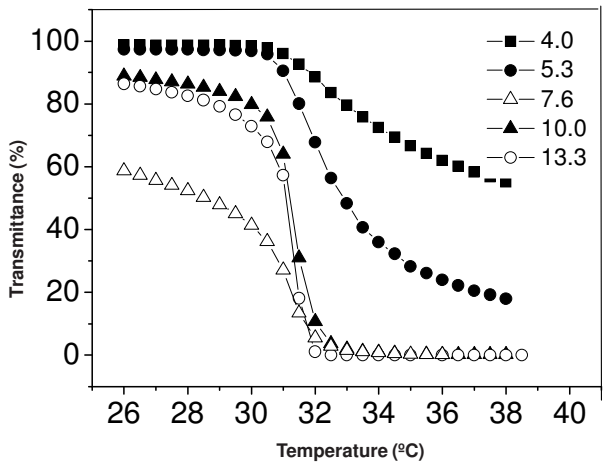


Fig. 5. Transmittance as a function of temperature for microgels dispersions with different NIPAAm concentration (g/L).

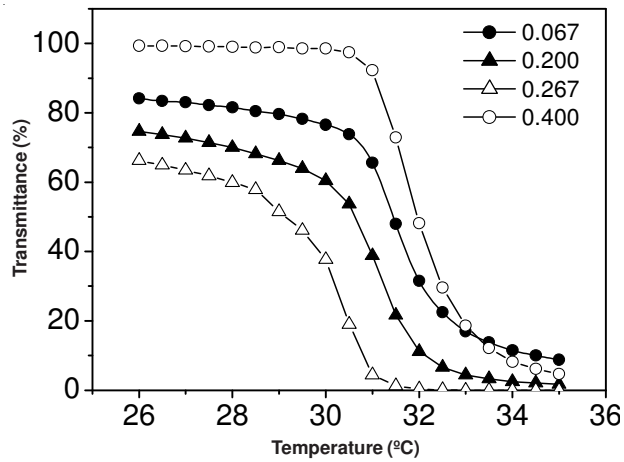


Fig. 6. Transmittance as a function of temperature for microgels dispersions with different ammonium peroxodisulfate concentration (g/L)

By considering the above three factors comprehensively, the thermoresponsive phase transition temperature of the microgels dispersions was influenced by amounts of the AEA-PSI and ammonium peroxodisulfate in the range of consideration, not by amounts of the NIPAAm. The changes of phase transition temperature were smaller than 2.5 ºC. All the microgels dispersions exhibited thermoresponsive phase transition at 30.0-32.5 ºC.

The hydrodynamic diameter shell-core microgels as a function of temperature was measured by dynamic light scattering and the results are displayed in Fig. 7. The measurements were carried out under equilibrium conditions after maintaining the sample for 5 min at each temperature point. At 20 ºC, three microgels are in a swollen state and have average hydrodynamic diameters of 406.7, 453.0 and 506.4 nm respectively as measured by dynamic light scattering. At 40 ºC, the diameters decrease to 140.2, 115.5 and 90.4 nm. The transition temperature of the microgels, where the diameter decreases sharply, is about 31 ºC, which is corresponded with the conventional PNIPAAm microgel crosslinked by MBAAm[22,23]. When cooling the temperature from 40 to 20 ºC, the diameter exhibited similar temperature dependence and the diameters during both heating and cooling processes almost overlapped (the result was not displayed), indicating the temperature sensitivity of the microgels is reversible. With increasing the weight ratio of the NIPAAm/AEA-PSI from 1.3:1 to 3:1 and 5:1, the swelling ratio defined as $(D20\ ºC/D40\ ºC)^3$ increases from 24.4 to 60.2 and 175.6.

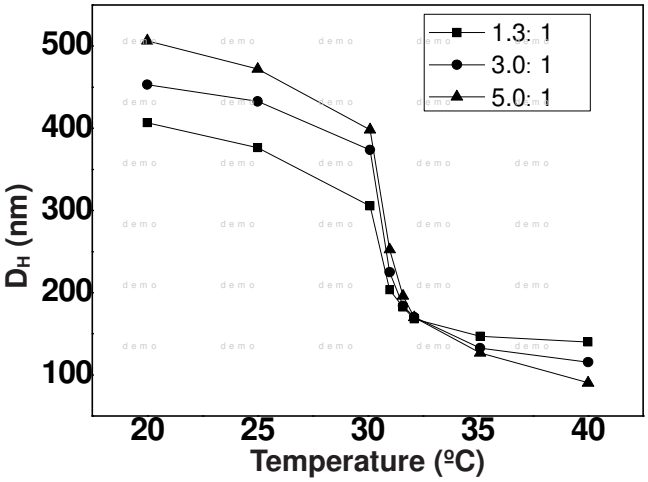


Fig. 7. Hydrodynamic diameter as a function of temperature for the core-shell microgel particles with different weight ratio of the NIPAAm/AEA-PSI

Morphology of the microgels and shell-core microgels: To investigate the morphologies of the core microgels and shell-core microgels, the atomic force microscopy was used to observe their surface morphologies and sizes distribution. The core microgel sample was the sample 2 in Table-1, which hydrodynamic diameter was 353.8 nm (PDI 0.24) by dynamic light scattering (Fig. 8A) and the core-shell microgel sample was the sample 2 in Table-2, which hydrodynamic diameter was 432.5 nm (PDI 0.125) by dynamic light scattering (Fig. 8B). It is obvious that two kinds of microgel particles have spherical structures and the particle size distribution is quite narrow. The diameters of the dry microgels were about 30 and 60 nm, which were much smaller than that measured by dynamic light scattering. Because the mean diameters obtained by dynamic light scattering were the diameters in the distilled water solution in which the microgels were in swelling state, while the mean diameters obtained by AFM were the diameters in dry state in which the microgels were deswelling. These results illuminated that the AEA-PSI cross-linked PNIPAAm microgels were excellent swell-deswell. When the microgels deswell, the PNIPAAm segments collapse to a dense, solid-like globule, decreasing their size and mobility. Compared with the core microgels, the core-shell microgels appear a smoother and denser surface. More experimental and detailed characterization will be reported in the near future.

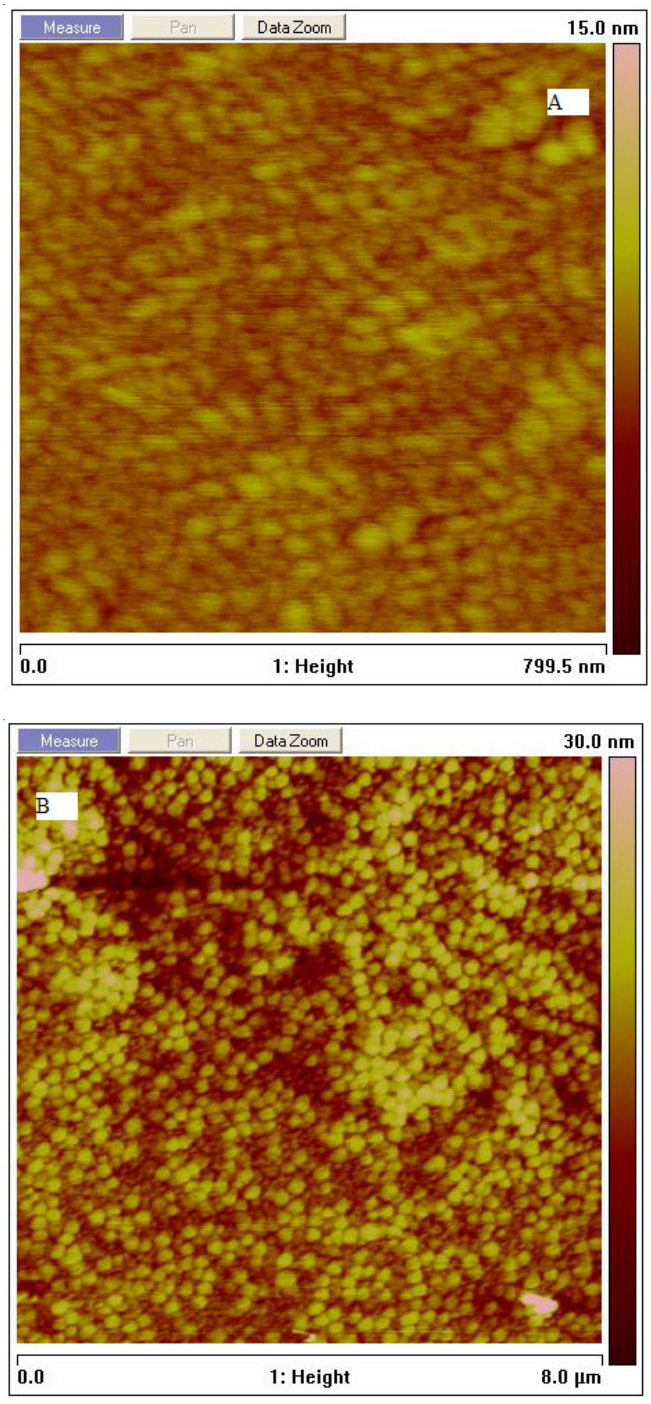


Fig. 8. Atomic force microscopy micrograph of the core microgels (A) and core-shell microgels (B)

Conclusions

Utilizing a biodegradable cross-linker, AEA-PSI, PNIPAAm microgels and core-shell microgels were prepared by free-radical precipitation polymerization. To prepare small-sized and lower PDI microgels, the optimum parameters should

be selected as the concentrations of AEA-PSI, NIPAAm and APS were 1.34, 7.56 and 0.152 g/L and the hydrodynamic diameter of the microgels was 353.8 nm (PDI, 0.24). All the microgels dispersions exhibited thermoresponsive phase transition at 30.0-32.5 ºC. With increasing the weight ratio of the NIPAAm/AEA-PSI from 1.3:1 to 3:1 and 5:1 in the shell materials, the hydrodynamic diameter of the core-shell microgels increases from 376.4 to 432.5 and 472.3 nm at 25 ºC, respectively. The AFM morphologies images illuminated that the core-shell microgels particles had symmetrical sizes and non-aggregation, indicating better stability. Compared with the core microgels, the core-shell microgels appear a smoother and denser surface.

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