Synthesis and Characterization of Secondary-Amine-Functional Microparticles

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ABSTRACT: Secondary-amine-functional microparticles were prepared in the range of 50–250 μm through the suspension polymerization of styrene, divinylbenzene (DVB), and 2-(*tert*-butylamino)ethyl methacrylate (tBAEMA). This study focused on the effects of the DVB, tBAEMA, initiator, and stabilizer concentrations and shaking rate on the experimental amine content, swelling ratio, average particle size, and particle size distribution. The suspension polymerization experiments were carried out in two different systems. In the first system, an organic phase, including the monomers and initiator, was dispersed in an aqueous medium in the presence of $Al_2(SO_4)_3$. $Al_2(SO_4)_3$, in the presence of an amine monomer (pH $\sim$ 10), formed colloidal $Al(OH)_3$, which built a nonsticky layer on the surface of the polymerizing droplets that prevented them from coalescing and aggregating. Individual and spherical particles within the range of 50–200 μm were obtained by this polymerization method. The second method was similar to the first polymerization protocol, except that a certain amount of sodium dodecyl sulfate was added as a costabilizer in the presence of $Al_2(SO_4)_3$. In these experiments, individual and spherical particles were obtained within the range of 130–250 μm. © 2004 Wiley Periodicals, Inc. J Polym Sci Part A: Polym Chem 42: 3708–3719, 2004

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INTRODUCTION

It has been known for some time that synthetic polymer microparticles and their combinations with natural counterparts can be used as carrier matrices in a wide variety of medical, biological, and biochemical applications, such as affinity chromatography, immobilization techniques, drug-delivery systems, and cell culturing.[1–3] The majority of these microparticles are based on polystyrene and its derivatives. Such polymer microparticles have different sizes (50 nm to 2 mm) and can be produced by various methods of synthesis, such as suspension, emulsion, precipitation, and dispersion polymerization.

The majority of the polymer particles with amine-functional groups are synthesized by emulsion polymerization. One example of this type of polymerization is described in a previous work;[4] amine-neutralized 4,4′-azobis(4-cyanopentanoic acid) was used as an initiator to synthesize amine-functional uncrosslinked particles.

A well-known process that provides crosslinked polymer particles with a narrow size distribution in toner preparation employs a solid colloidal stabilizer to control both the particle size and particle size distribution.[5–8] One example of this type of process[8] is described in U.S. Patent 5,427,885, which pertains to a suspension polymerization pro-

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cess in which a solid colloidal stabilizer is used to limit the coalescence of droplets containing polymerizable monomer in an aqueous medium. In that process, a water-soluble polyvalent metal salt is reacted with an alkali metal hydroxide in the aqueous phase to form a water-insoluble metal hydroxide colloid. Specifically, water-soluble $Al_2(SO_4)_3$ was reacted with sodium hydroxide at pH > 7 to produce *in situ* water-insoluble $Al(OH)_3$ to stabilize particles. In the presence of water-insoluble $Al(OH)_3$ as the suspension stabilizer, the immiscible polymerizable liquid was sheared to form small droplets suspended in an aqueous medium. The concentration and size of the colloid determined the size of the droplets. The colloid performed this function by adhering to the droplets at the water/monomer interface to form a layer on the surface of the droplets. After the monomer droplets had coalesced with other droplets and had grown to a particular diameter, the presence of the layer of colloidal stabilizer particles on the surface of the droplets prevented them from further coalescing and increasing in diameter. In this way, all of the droplets tended to grow to approximately the same diameter, so that upon polymerization the resulting polymer particles had a narrow size distribution.

Most of the microparticles used in the medical and biological applications mentioned previously have amine-functional groups as reactive sites. The syntheses of some amine-functional microparticles with various synthesis methods have been reported in the literature. In general, these synthesis methods can be divided into two groups. The most common one involves modifying the preformed functional microparticles with amine-containing reactants. Some examples of this include the modification of chloromethyl styrene[9] and glycidyl methacrylate[10] containing microparticles with poly(ethylene imine) and ammonia, respectively.

The second approach is to use tertiary-amine- or blocked-amine-containing copolymerizable monomers. In a previous publication, Tuncel et al.[11] reported the synthesis of monosize polystyrene microparticles carrying functional groups on their surface. In their study, the synthesis of tertiary-amine-functional and acid- and hydroxyl-functional microparticles was carried out with polystyrene latex particles as the seed and a mixture of styrene and acrylic comonomers comprising a functional monomer with the desired functional group. In another study,[12] butoxycarbonyl blocked *p*-amino styrene was used during the synthesis. Aminated microparticles were obtained by the simple removal of the Boc-protective group under acidic conditions followed by neutralization; this produced *p*-amino styrene/styrene copolymers.

In recent years, the number of reports on the preparation of functionalized particles by emulsion or suspension techniques has been growing rapidly.[13–21] In one of these publications,[13] the synthesis of cationic latex particles with surface amino groups by a multistep batch emulsion polymerization was reported. In this study, an amino-functionalized monomer such as aminoethyl methacrylate hydrochloride was used in the third and fourth steps to produce latices with amino surface groups. In another study,[14] latex particles consisting of styrene and aminoethyl methacrylate hydrochloride were grafted with hydrophilic hairs by a reversible addition–fragmentation chain-transfer technique.

As mentioned previously, a number of articles have been published in the field of amine-functional microparticle preparation, and it has been known for some time that these microparticles can be used in a variety of applications. However, no published report on the direct synthesis of active hydrogen-containing amine-functional crosslinked microparticles was found in our literature survey.

The main objective of this study was to prepare secondary-amine-functional crosslinked polymer microparticles with an unblocked amine-functional copolymerizable monomer via single-pot polymerization. The microparticles were prepared by the suspension polymerization method with 2-(*tert*-butylamino)ethyl methacrylate (tBAEMA) as the amine-functional monomer and styrene and divinylbenzene (DVB) as the comonomer and crosslinker, respectively. Styrene and DVB were chosen because of their hydrophobicity, and as mentioned previously, the majority of the microparticles used as carrier matrices were based on these two monomers.

EXPERIMENTAL

Materials

Styrene (Sigma–Aldrich, Steinheim, Germany) and DVB (containing a 65% mixture of *m*- and *p*-isomers of DVB and 33% ethylvinylbenzene isomers; Merck, Hohenbrunn, Germany) were purified by being passed through activated aluminum oxide (Al_2O_3) and were kept in a refrigerator.

tBAEMA (97%) was obtained from Aldrich (Milwaukee, WI). 2,2′-Azobis(2-methylpropionitrile) (AIBN; Merck) was kept refrigerated and was crystallized from methanol and used as the initiator. Sodium dodecyl sulfate (SDS; 98%; Sigma–Aldrich) was used without further purification. Aluminum sulfate [$Al_2(SO_4)_3 \cdot 10H_2O$; Aldrich] and activated Al_2O_3 (acidic; Brockmann I; Sigma–Aldrich) were used as received without further purification. Absolute ethanol was purchased from Riedel-de Haën (Sigma–Aldrich, Seeize, Germany) and was used without further purification. Deionized water used in all the experiments.

Preparation of the Microparticles

The secondary-amine-functional crosslinked microparticles were synthesized in glass polymerization vessels (120-mL) with screw caps with two different methods. In the first method, an aqueous dispersion medium was prepared through the dissolution of the desired amount of an electrolyte such as $Al_2(SO_4)_3$ within 50 mL of distilled water. The proper amount of the water-insoluble initiator was dissolved within the monomer mixture. The prepared aqueous and organic solutions were charged to the polymerization vessel, and the reaction mixture was flushed with bubbling nitrogen. The vessel was subsequently capped. The reaction vessel was then put in a water bath shaker (Gyrotory 676, Scientific Co., Inc., New Brunswick, NJ) at room temperature. It was shaken for 45 min at the selected shaker rate. Then, the water bath was heated to the polymerization temperature, and the reaction mixture was held at this temperature for the necessary period of time. The polymerization conditions are tabulated in Table 1.

The second method used to prepare the secondary-amine-functional crosslinked microparticles was similar to the first procedure, except that a proper amount of SDS was added to the aqueous dispersion medium. The polymerization conditions are summarized in Table 2. In both sets of experiments, the monomer-to-water ratio was 6:50, and the pH was approximately 10.

To remove the stabilizer(s) and unreacted monomers, we applied an extensive cleaning procedure. First, the microparticles were separated from the aqueous phase by the decantation of the supernatant after centrifugation of the dispersion at 6000 rpm for 10 min with a Hettich Universal 32 bench-top centrifuge. Then, the microparticles were redispersed and centrifuged, and the liquid phase was decanted with 0.01 M HCl, water, 0.001 M NaOH, and water (50 mL, five times each). The microparticles were redispersed in ethanol (50 mL) and centrifuged, and the liquid phase was decanted. After the washing was repeated five times with ethanol, the microparticles were dried at 50 °C *in vacuo* to a constant weight.

Yield of the Microparticles

The microparticle yield was determined gravimetrically as follows:

$$\text{Microparticle yield}(\%) = (W_p/W_m) \times 100 \quad (1)$$

where W_p and W_m are the weight of the recovered dry microparticles and the total weight of the monomers initially charged in the reactor, respectively.

Swelling Ratio

The swelling ratios of the microparticles were determined as follows. The dry microparticles (ca. 3 g) were weighed within a cylindrical glass tube (50 cm long and 6 mm in diameter). The height of the unswelled microparticles was measured, after they were packed, by the bottom of the tube being tapped. After 5 mL of 0.3 M HCl was added to the tube, the microparticles were allowed to swell at room temperature for 24 h with occasional shaking, and then the height of the swollen microparticles was measured. The swelling ratio was calculated as follows:

$$\text{Swelling ratio}(\%) = \left(\frac{H_s - H_0}{H_0}\right) \times 100 \quad (2)$$

where H_s is the height of the swollen microparticles (mm) and H_0 is the height of the dry microparticles (mm). All the swelling experiments were carried out in aqueous HCl because of the insignificant swelling of the amine-functional and crosslinked microparticles in deionized water.

Microparticle Characterization

Optical microscopy photomicrographs were taken on an Olympus BH2 microscope. A drop of a dilute microparticle dispersion in water was spread onto a glass surface and dried in a dust-free environment at room temperature. The particle size and distribution were calculated via the measurement

Table 1. Experimental Conditions and Their Effects on the Yield, Available Amine Content, Swelling, Particle Size, and Particle Size Distribution for Suspension Polymerization in the Presence of $Al_2(SO_4)_3$[a]

Experiment	Shaking Rate (cpm)	tBAEMA (wt %)	DVB (wt %)	EVB[b] (wt %)	STY[c] (wt %)	$AI_2(SO_4)_3$ (wt %)	AIBN (wt %)	Yield (wt %)	Nitrogen Content (wt %)	Amine Content by Elemental Analysis (wt %)	Available Amine by Titration (wt %)	Swelling Ratio (%)	Average Size (μm)	PDI (D_w/D_n)
Effect of the Shaking Rate														
1	180	25	25	13.5	36.5	0.83	0.33	—	—	—	—	—	—	—
2	240	25	25	13.5	36.5	0.83	0.33	69	1.82	24.1	20.2	10.0	189	1.04
3	270	25	25	13.5	36.5	0.83	0.33	67	1.82	24.1	20.8	10.0	150	1.10
4	300	25	25	13.5	36.5	0.83	0.33	65	1.83	24.2	21.0	10.1	106	1.15
Effect of the DVB Concentration														
5	300	25	5	2.7	67.3	0.83	0.33	—	—	—	—	—	—	—
6	300	25	17.5	9.1	48.4	0.83	0.33	48	1.81	23.9	19.6	12.2	75	1.29
7	300	25	20.0	10.8	44.2	0.83	0.33	50	1.82	24.1	20.0	11.7	93	1.21
Effect of the tBAEMA Concentration														
8	300	5	25	13.5	56.5	0.83	0.33	70	0.36	4.7	4.3	1.9	140	1.30
9	300	50	25	13.5	11.5	0.83	0.33	55	3.63	48.0	41.2	32.5	73	1.22
Effect of the AIBN Concentration														
10	300	25	25	13.5	36.5	0.83	0.17	71	1.83	24.2	22.7	9.9	132	1.27
11	300	25	25	13.5	36.5	0.83	0.66	70	1.82	24.1	22.1	10.0	100	1.32
Effect of the $Al_2(SO_4)_3$ Concentration														
12	300	25	25	13.5	36.5	1.67	0.33	61	1.83	24.2	21.0	10.4	59	1.10
13	300	25	25	13.5	36.5	2.49	0.33	68	1.83	24.2	22.1	10.3	52	1.07

[a] Polymerization time = 10 h; polymerization temperature = 78 °C.
[b] Ethylvinylbenzene.
[c] Styrene.

Table 2. Experimental Conditions and Their Effects on the Yield, Available Amine Content, Swelling, Particle Size, and Particle Size Distribution for Suspension Polymerization in the Presence of SDS and $Al_2(SO_4)_3$[a]

Experiment	tBAEMA (wt %)	DVB (wt %)	EVB[b] (wt %)	STY[c] (wt %)	SDS (wt %)	$Al_2(SO_4)_3$ (wt %)	AIBN (wt %)	Yield (wt %)	Nitrogen Content (wt %)	Amine Content by Elemental Analysis (wt %)	Available Amine by Titration (wt %)	Swelling Ratio (%)	Average Size (μm)	PDI (D_w/D_n)
Effect of the tBAEMA Concentration														
14	0	25	13.5	61.5	0.17	0.46	0.33	—	—	—	—	—	—	—
15	5	25	13.5	56.5	0.17	0.46	0.33	74	0.36	4.7	4.3	2.0	254	1.07
16	10	25	13.5	51.5	0.17	0.46	0.33	81	0.72	9.5	8.1	3.8	161	1.18
17	15	25	13.5	46.5	0.17	0.46	0.33	72	1.10	14.5	13.1	6.1	159	1.13
Effect of ths SDS Concentration														
18	5	25	13.5	56.5	0.35	0.46	0.33	72	0.36	4.7	4.3	2.1	225	1.09
19	5	25	13.5	56.5	0.83	0.46	0.33	71	0.35	4.6	4.2	2.1	190	1.09
20	5	25	13.5	56.5	1.67	0.46	0.33	—	—	—	—	—	—	—
Effect of the AIBN Concentration														
21	5	25	13.5	56.5	0.17	0.46	0.58	80	0.36	4.7	4.3	2.0	161	1.11
22	5	25	13.5	56.5	0.17	0.46	0.83	79	0.36	4.7	4.4	2.1	131	1.28
Effect of the DVB Concentration														
23	5	5	2.7	87.3	0.17	0.46	0.33	—	—	—	—	—	—	—
24	5	12.5	4.3	78.2	0.17	0.46	0.33	58	0.35	4.6	4.2	2.5	159	1.29
25	5	20	10.8	64.2	0.17	0.46	0.33	70	0.36	4.7	4.2	2.3	195	1.21

[a] Polymerization time = 6 h; polymerization temperature = 78 °C; shaking rate = 180 cpm.
[b] Ethylvinylbenzene.
[c] Styrene.

of the diameter of the particles. For statistical representation, at least 200 microparticles were measured for each sample from various numbers of photographs. Two types of average particle size were calculated: number-average (D_n) and weight-average (D_w):

$$D_n = \frac{\sum N_i D_i}{\sum N_i} \quad (3)$$

$$D_w = \frac{\sum N_i D_i^4}{\sum N_i D_i^3} \quad (4)$$

where N_i is the number of particles with diameter D_i (μm). The particle size distribution was characterized by the polydispersity index (PDI) and calculated as D_w/D_n. In this report, the calculated D_n values are reported as the average particle size.

The tBAEMA contents on the surface of the prepared polymer microparticles were determined by acid–base titration. For this purpose, dried microparticles (1.0 g) were added to 10 mL of a 0.3 M HCl solution, and the mixture was held at room temperature for 16 h in a tightly sealed glass container. The mixture was filtered, and 5 mL of the filtrate was titrated with a 0.1 M NaOH solution. The tBAEMA contents on the surface of the microparticles in terms of the weight percentage were calculated as follows:

$$\text{tBAEMA}(\%) = \frac{[V_{HCl}M_{HCl} - 2(M_{NaOH}V_{NaOH})] \times 10^{-3} \times 185.3}{w} \times 100 \quad (5)$$

where w is the weight of the sample (g) and V_{HCl} and V_{NaOH} and M_{HCl} and M_{NaOH} are the volumes and molarities of HCl and NaOH, respectively. The weight percentage of tBAEMA in the polymers is reported as the available amine throughout the rest of this article.

The total amount of tBAEMA in the microparticles (wt %) was also calculated from the nitrogen content of the microparticles determined with a CHNS-932 elemental analyzer (Leco Instruments, United States) and is reported as the amine content by elemental analysis.

RESULTS AND DISCUSSION

$Al_2(SO_4)_3$-Stabilized Suspension Polymerizations

Various types of stabilizers are being used to prevent the agglomeration of monomer droplets in suspension polymerizations. These include water-soluble organic polymers, electrolytes, and water-insoluble inorganic compounds. To synthesize amine-functional individual and spherical particles, a process known as *limiting the coalescence* in patent literature has been used.[5–8] In this process, water-soluble inorganic compounds can be used as dispersion stabilizers to produce small particles with narrow size distributions. Tamaki et al.[5] carried out suspension polymerizations in the presence of dispersion stabilizers selected from a group consisting of aluminum hydroxide, ferric hydroxide, titanium hydroxide, and thorium hydroxide. Wada et al.[6] used a dispersant selected from a group consisting of an orthophosphate, a pyrophosphate, and a polyphosphate and an anionic surfactant. During the synthesis of hard crosslinked particles for milling media,[7] poly(2-methylaminoethanol adipate) and a colloidal dispersion of silica were used as stabilizers. In another patent application,[8] water-soluble $Al_2(SO_4)_3$ was used at a pH greater than 7 to produce *in situ* water-insoluble $Al(OH)_3$ to stabilize particles.

In this study, water-soluble $Al(OH)_3$ was used at a pH of about 10 because of the amine-functional monomer, and colloidal $Al(OH)_3$ was formed *in situ* from water-soluble $Al_2(SO_4)_3$ to stabilize particles.

Effect of the Shaking Rate

The stirring rate in suspension polymerization affects the stability of the monomer droplets in the aqueous phase and determines the particle size and particle size distribution. In this part of the study, four different shaking rates (i.e., 180, 240, 270, and 300 cpm) were applied during the synthesis of microparticles, whereas the other polymerization conditions were kept constant (experiments 1–4, Table 1). The average size of the microparticles decreased as the rate increased from 240 to 300 cpm. At a shaking rate of 180 cpm, the resulting polymer particles were fused and could not be characterized. The fusing of the microparticles at a low shaking rate indicates that the shaking rate may not be sufficient to establish droplet stabilization. At higher shaking

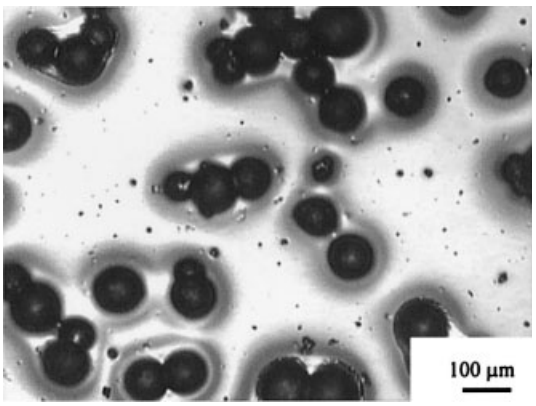

Figure 1. Representative optical micrograph of particles prepared at a shaking rate of 300 cpm (experiment 4, Table 1; magnification = 100×).

rates, the formation of individual and spherical microparticles was observed. A optical micrograph and a histogram indicating the size distribution of the microparticles produced at 300 cpm are shown in Figures 1 and 2, respectively. Individual and spherical microparticles were obtained with different sizes. A decrease in the average particle size with increasing shaking and stirring rates is described in the literature for different suspension polymerization systems.[22–26] Tuncel[22] reported that the properties of beads did not change significantly with the stirring rate, but the average particle size decreased with an increasing stirring rate. The PDI values showed that the size distribution was slightly narrower with lower shaking rates and broader with higher shaking rates. The total amine content of the microparticles was found to be about the same by elemental analysis, but the available amine on the surfaces showed a slight difference. This slight difference in the amine content on the surface of the particles had an insignificant effect on the swelling ratios. The presence of about 80% charged tBAEMA on the outer surface of the particles may be due to the hydrophilicity of this monomer. A similar phenomenon has been reported for particles containing 2-hydroxyethyl methacrylate.[27]

Effect of the Crosslinking Agent Concentration

We investigated the effect of the crosslinking agent concentration for the $Al_2(SO_4)_3$-stabilized system by changing the crosslinking agent concentration and keeping the other conditions constant (experiments 4–7, Table 1). The produced polymerization product with 5 wt % DVB was obtained as a flake, probably because of an insufficient amount of the crosslinker to maintain the stability of the particles at a shaking rate of 300 cpm. When the DVB concentration was increased from 5 to 17.5 and 20 wt %, individual spherical microparticles were obtained. As noted before, individual and spherical microparticles were observed at a 25 wt % DVB concentration also. The average size and the yield percentage of the microparticles increased as the crosslinker concentration increased. The increase in the particle size with increasing DVB concentration may be related to previous studies presented by Tuncel.[28] The increase in the yield of the resulting microparticles with the crosslinking agent concentration may be explained as follows: a higher conversion of the monomers into the crosslinked polymer in the presence of a higher amount of the crosslinker and, at a low concentration of DVB, the formation of smaller particles may lower the recoverable amount of the polymer because of the loss of some of the products during the extensive cleaning steps. The available amine content of the resulting polymers did not change significantly as the crosslinker concentration increased. However, the PDI value increased from 1.15 to 1.29 as the DVB concentration decreased from 25 to 17.5% with respect to the total monomer weight. The broader particle size distribution at a lower DVB content may be attributed to the coalescence of some small microparticles into larger ones. As expected, the swelling ratio of the particles con-

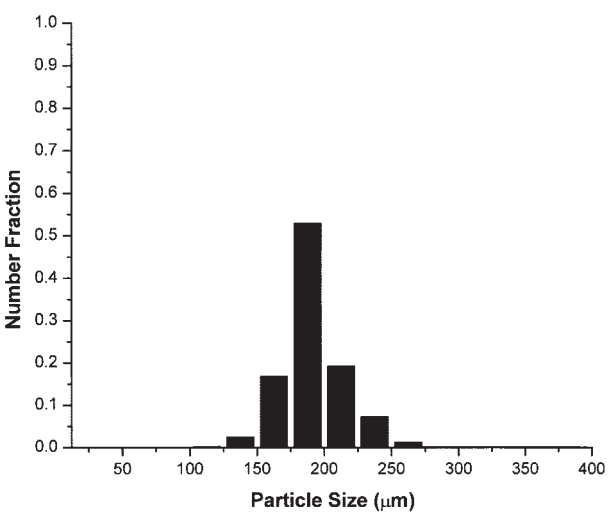

Figure 2. Particle size distribution of particles prepared at a shaking rate of 300 cpm (experiment 4, Table 1).

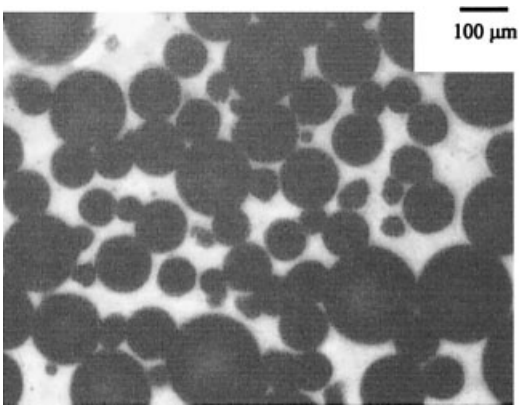

Figure 3. Representative optical micrograph of microparticles prepared in the presence of 5 wt % tBAEMA (experiment 8, Table 1; magnification = 100×).

taining lower amounts of DVB was higher because of less crosslinking.

Effect of the Amine Concentration

In this set of experiments, the tBAEMA concentration was varied between 5 and 50 wt % (based on the total monomers), whereas the other polymerization conditions were kept constant at a shaking rate of 300 cpm (experiments 4, 8, and 9, Table 1). An increase in the average size of the microparticles was observed with decreasing tBAEMA concentration. The yield of the microparticles also increased from 55 to 70 wt % as the tBAEMA concentration decreased from 50 to 5 wt %, and this may be attributed to a loss of smaller particles during the cleaning process. The amine content on the surfaces of the produced microparticles was about 80% of the charged tBAEMA amount. An optical micrograph and a histogram indicating the size distribution of the microparticles produced with 5 wt % tBAEMA are shown in Figures 3 and 4, respectively. The particles were obtained in a spherical form with different sizes. No systematic effect of the tBAEMA concentration on the PDI values of the microparticles was observed. The lowest PDI value was obtained with a 25% tBAEMA concentration. The swelling ratio, as expected, increased with increasing tBAEMA concentration.

Effect of the Initiator Concentration

We investigated the effect of the initiator concentration on the properties of the microparticles by varying the AIBN concentration while keeping the other polymerization parameters fixed (experiments 4, 10, and 11, Table 1). The initiator concentration did not affect the average particle size significantly. Also, no systematic effect of the AIBN concentration on the PDI values was observed. Yields between 65 and 71% and available amine contents between 21 and 22.7% were obtained in the studied initiator concentration range. The total amine content of the microparticles and the swelling ratios did not show any significant changes. A similar effect of the initiator concentration on the average particle size and yield percentage has been reported in the literature.[24]

Effect of the $Al_2(SO_4)_3$ Concentration

To examine the effect of $Al_2(SO_4)_3$, its concentration was varied between 0.83 and 2.49 wt % (with respect to the monomers), whereas the other polymerization parameters were kept constant (experiments 4, 12, and 13, Table 1). Although the yield percentage and amine content did not change significantly, the average size decreased dramatically. This sharp decrease in the average particle size may be explained by the better stabilization of the droplets and microparticles and the prevention of their agglomeration. The polydispersity of the microparticles was also affected minimally by the variation of the $Al_2(SO_4)_3$ concentration. The PDI values slightly decreased from 1.15 to 1.07 when the $Al_2(SO_4)_3$ concentra-

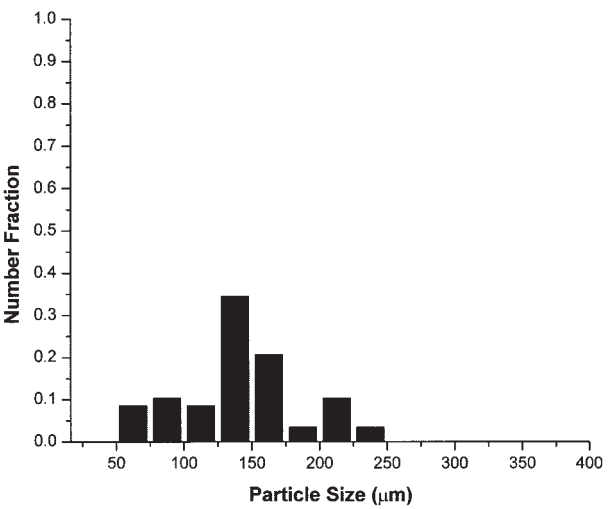

Figure 4. Particle size distribution of microparticles prepared in the presence of 5 wt % tBAEMA (experiment 8, Table 1).

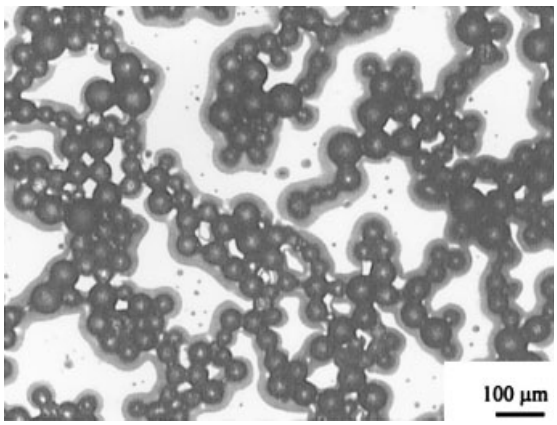

Figure 5. Representative optical micrograph of microparticles prepared in the presence of 1.67 wt % $Al_2(SO_4)_3$ (experiment 12, Table 1; magnification = 100×).

tion was increased three times. The swelling ratios of the particles did not show any significant changes as the $Al_2(SO_4)_3$ concentration increased. An optical micrograph and a histogram indicating the size distribution of the microparticles prepared with 1.67 wt % $Al_2(SO_4)_3$ are given in Figures 5 and 6, respectively.

SDS- and $Al_2(SO_4)_3$-Stabilized Suspension Polymerizations

SDS and similar surfactants are not proper stabilizers for conventional suspension polymerization because they cannot form a protective film at the surface of the droplet. In this part of the study, the effect of SDS as a costabilizer in the preparation of the microparticles was investigated.

Effect of the Amine Concentration

The effect of the tBAEMA concentration on the yield percentage, amine content, swelling ratio, and average particle size was explored through variations in the tBAEMA concentration between 0 and 15 wt % with respect to the total weight of the monomers, whereas the other polymerization parameters were kept constant (experiments 14–17, Table 2). An attempt to prepare amine-free microparticles with SDS- and $Al_2(SO_4)_3$-costabilized suspension polymerization resulted in individual beads of 1–2 mm. In this experiment, the white color of the suspension mixture at room temperature disappeared at the polymerization temperature, and the mixture became colorless (water-clear). In experiment 14, a polymerization product was not obtained in the form of microparticles. However, with the addition of an amine-containing monomer to the mixture, the suspension mixture was white at the polymerization temperature, and individual particles were obtained. The average size of the produced microparticles decreased to less than two-thirds as the amine concentration was increased from 5 to 15 wt % in the monomer mixture. As the hydrophilicity of the droplet increased with the tBAEMA content, the particle size decreased. A similar effect was also reported[22] with poly(ethylene glycol) methacrylate (number-average molecular weight = 366) as a comonomer for the preparation of microparticles. An optical micrograph and a histogram indicating the size distribution of the prepared microparticles with 5 wt % tBAEMA are given in Figures 7 and 8, respectively. The yield percentage and PDI values showed some variation with the tBAEMA concentration. However, the particle size was reduced as the tBAEMA concentration was increased from 5 to 15 wt % with respect to the monomers. The available amine content of these particles was approximately 80 wt % with respect to the theoretical amine content. Again, this may be explained by the hydrophilicity of tBAEMA. As expected, the swelling ratios increased with the tBAEMA content.

Effect of the SDS Concentration

The stabilizer concentration is one of the most important parameters in suspension polymerization for controlling the particle size. In the ab-

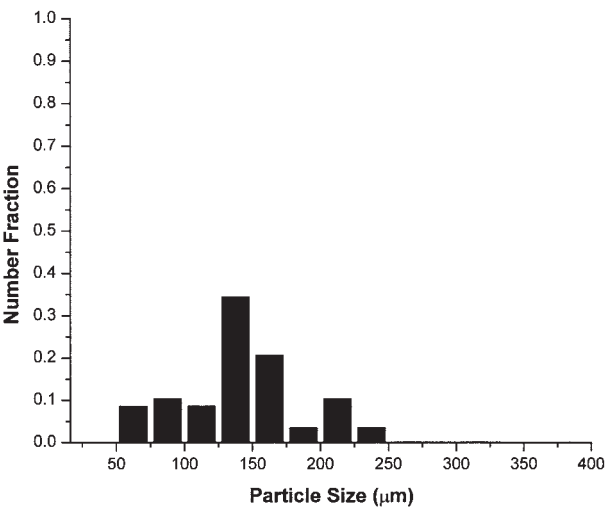

Figure 6. Particle size distribution of microparticles prepared in the presence of 1.67 wt % $Al_2(SO_4)_3$ (experiment 12, Table 1).

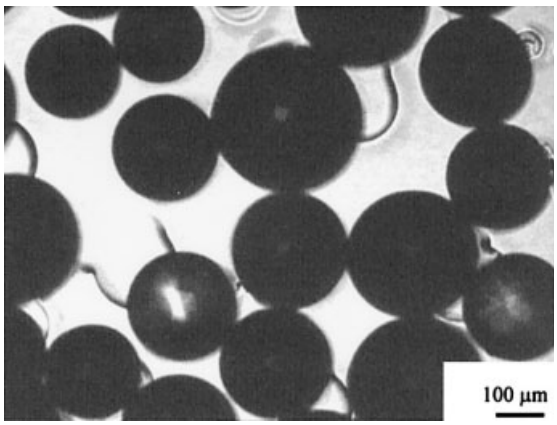

Figure 7. Representative optical micrograph of microparticles in the presence of 5 wt % tBAEMA (experiment 15, Table 2; magnification = 100×).

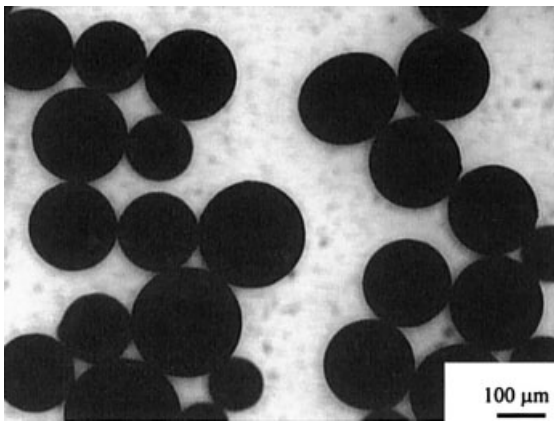

Figure 9. Representative optical micrograph of microparticles prepared in the presence of 0.83 wt % SDS (experiment 19, Table 2; magnification = 100×).

sence of sufficient stabilizer, the smaller droplets coalesce easily during the hardening stage. This causes the formation of larger and irregular particles. To explore the effect of the stabilizer concentration on the available amine content, particle size and particle size distribution, we varied the concentration of SDS, keeping the other parameters constant (experiments 15 and 18–20, Table 2). Except for a decrease in the particle size, almost no effect on the produced particle properties, such as the amine content, swelling ratio, and PDI values, was observed as the SDS concentration increased from 0.17 to 0.83 wt % with respect to the monomers. However, when the SDS concentration was increased to 1.67 wt %, a coagulated product was obtained, which could be attributed to the high concentration of SDS as an improper stabilizer for suspension polymerization. An optical micrograph and a histogram indicating the size distribution of the microparticles prepared with 0.83 wt % SDS are depicted in Figures 9 and 10, respectively. Spherical and individual microparticles were produced in this set of experiments. The available amine contents, yield percentages, swelling ratios, and PDI values of the produced microparticles were not affected significantly by the variations in the SDS concentration. The average particle size decreased with

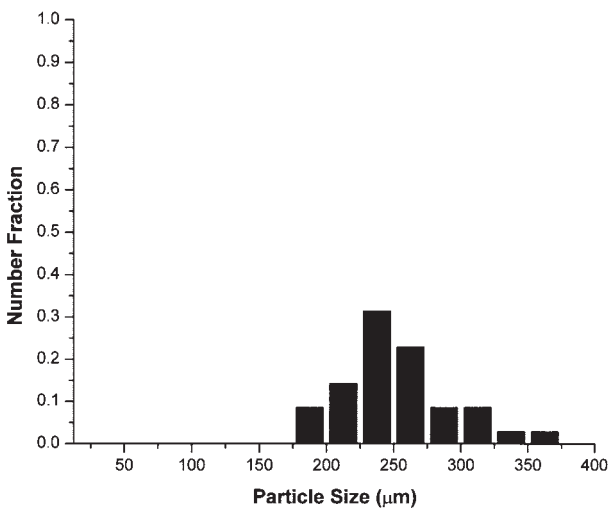

Figure 8. Particle size distribution of microparticles in the presence of 5 wt % tBAEMA (experiment 15, Table 2).

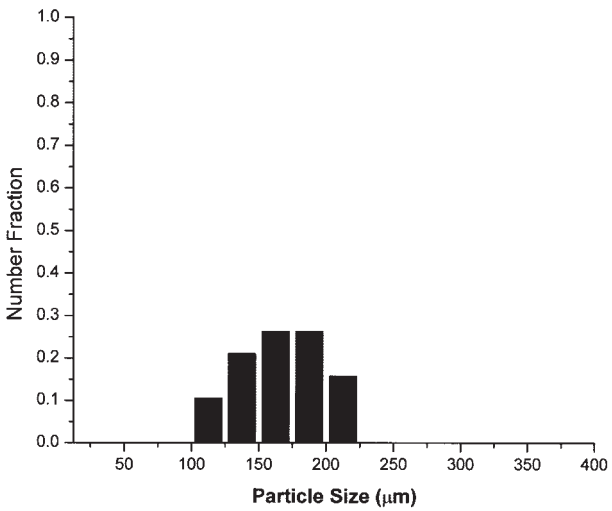

Figure 10. Particle size distribution of microparticles prepared in the presence of 0.83 wt % SDS (experiment 19, Table 2).

increasing SDS concentration, as stated in related literature.[3,23,24] Tuncel and Piskin[24] showed that the stabilizer concentration did not affect the yield percentage, although the particle size decreased significantly.

Effect of the Initiator Concentration

We investigated the effect of the initiator concentration on the properties of the produced microparticles by varying the AIBN concentration while keeping the other polymerization parameters fixed (experiments 15, 21, and 22, Table 2). There was no appreciable change in the available amine and total amine contents of the produced microparticles from variations in the initiator concentration. However, the yield percentage, polydispersity, and average particle size were affected. The average particle size decreased by about one-half as the initiator concentration was increased from 0.33 to 0.83 wt %. The decrease in the average particle size may be related to previous studies.[24] As the AIBN concentration increased, the number of produced radicals increased. A higher free-radical concentration increased the rate of polymerization and reduced the period of the sticky stage, which caused smaller particle formation. The yield percentage increased about 5% for the same variation in the initiator concentration. The variation in the AIBN concentration had an insignificant effect on the swelling ratios.

Effect of the Crosslinking Agent Concentration

The DVB concentration was increased from 5 to 25 wt % (with respect to the monomer), whereas the other polymerization parameters were kept constant. (experiments 15 and 23–25, Table 2). At a very low DVB concentration (5 wt %), microparticles were fused. Again, this may be explained by the fact that low-crosslinking sites could not maintain the dimensions of the particles. When the DVB concentration was increased from 12.5 to 25 wt %, the particle size increased from 159 to 254 μm and the yield increased from 58 to 74%. Again, the changes in the yield may be explained by a higher conversion in the presence of a higher amount of the crosslinker and the loss of some of the smaller products during the extensive cleaning process. The total and available amine contents remained nearly the same. Also, the swelling ratios were not affected significantly.

CONCLUSIONS

In this study, the synthesis of secondary-amine-functional microparticles with various amine contents and degrees of crosslinking by single-pot suspension polymerization was explored. Also, the effects of some polymerization parameters on the swelling ratios, amine content, particle size, and its distribution were investigated for two differently stabilized systems.

In the first system, aluminum sulfate was used to stabilize and prevent the agglomeration of the particles. In this system, the synthesis of secondary-amine-functional individual and spherical crosslinked microparticles was possible under certain polymerization conditions. As the shaking rate and the concentrations of the initiator, amine, and $Al_2(SO_4)_3$ increased, the average particle size decreased. However, as the crosslinking agent concentration increased, the average particle size decreased. Particles within the size range of 50–200 μm were obtained with the $Al_2(SO_4)_3$-stabilized system.

In the second method, a proper amount of SDS was used in the aqueous dispersion medium as a costabilizer. Again, individual and spherical crosslinked microparticles were obtained within the size range of about 130–250 μm. The average particle size decreased with increasing amine, stabilizer, and initiator concentrations. The average particle size increased with increasing crosslinking agent concentration.

From the amine content determinations by elemental analysis and acid–base titration, we concluded that the surface of the hydrophobic polymer microparticles was covered by a hydrophilic layer of tBAEMA.

Future studies should be performed with other stabilizers [e.g., poly(vinylpyrrolidone)] and sparingly soluble inorganic salts (e.g., Al_2O_3) to explore the preparation of uniform particles. Also, the effectiveness of these microparticles in biomedical applications (e.g., cell culturing) should be investigated.

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