Synthesis, Characterization, and Flocculation Performance of Anionic Polyacrylamide P (AM-AA-AMPS)

Jiangya Ma,[1] Huaili Zheng,[1] Mingzhuo Tan,[2] Liwei Liu,[1] Wei Chen,[1] Qingqing Guan,[1] Xiaokai Zheng[1]

[1]Key Laboratory of the Three Gorges Reservoir Region's Eco-Environment, State Ministry of Education, Chongqing University, Chongqing 400045, China
[2]Jiangmen Wealth Water Purifying Agent Co., Ltd., Guangdong 529000, China
Correspondence to: H. L. Zheng (E-mail: zhl@cqu.edu.cn)

ABSTRACT: In this study, a kind of anionic polyacrylamide (P(AM-AA-AMPS)) was synthesized using acrylamide (AM), acrylic acid (AA), and 2-acrylamido-2-methyl propane sulfonic acid (AMPS) under ultraviolet (UV) irradiation. The conditions of the polymerization reaction such as monomer mass ratio, solution pH value, EDTA concentration and urea concentration were investigated by using the single factor approach and an L_{16} (4^5) orthogonal array. The structure and morphologies of the copolymer were determined by nuclear magnetic resonance spectrometer (NMR), infrared spectrometer (IR) and scanning electron microscope (SEM). The results show P(AM-AA-AMPS) with the intrinsic viscosity of 1.5×10^3 mL g^{-1} was synthesized at optimal conditions: mass ratio, m(AM) : m(AA) : m(AMPS) of 70 : 10 : 10, pH value of 9.0, EDTA concentration of 0.10% and urea concentration of 0.20%. In addition, P(AM-AA-AMPS) had better flocculation efficiency than commercial PAM in sludge dewatering experiment; the minimum filter cake moisture content could be reduced to 65.1%. © 2013 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 129: 1984–1991, 2013

INTRODUCTION

Over the last decade, the increase in municipal and industrial wastewater purification activities lead to a dramatically increasing flow of sewage sludge.[1] Generally, large quantities of sewage sludge contain high moisture content (97–99%).[2] To reduce transport and disposal cost, treatment focuses on effectively reducing the moisture content of sludge. However, current dehydration methods are not efficient enough; the moisture contents of dewatered sludge achieved ranges between 70 and 80%.[2,3] The addition of chemical conditioners such as flocculants and coagulants helps the sludge particles to agglomerate into larger particles prior to solid–water separation.[4] Anionic polyacrylamide (APAM) as a kind of organic flocculants can produce adsorption/enmeshment in sludge dewatering.[5,6] The flocculation performance of APAM flocculants primarily depends on the molecular weight (MW).[7] In recent years, the quality of dewatering reagent has been promoted toward the direction of high molecular weight[8] while the intrinsic viscosity of polysaccharides is determined by molecular weight.[9] Therefore, APAM should be synthesized with high intrinsic viscosity to dehydrate effectively. However, although APAM with high intrinsic viscosity can play an important role in sludge dewatering, the dissolved time of

APAM also cannot be ignored. In fact, dissolving time for existing APAM products can reach 4h, which is too long in practical application. Thus, both intrinsic viscosity and dissolving time of APAM should be taken into account at the same time.

Anonic polyacrylamide can be prepared by copolymerization of acrylamide (AM) with anionic monomer, such as 2-acylamido-2-methyl propane sulfonic acid (AMPS).[10] In general, the most widely used reaction is aqueous solution polymerization. The reaction of aqueous polymerization commonly can be initiated by heat, γ rays, microwave, and ultraviolet (UV).[11,12] Compared with other methods, UV-initiation has many advantages, such as low reaction temperature, short reaction time, simple equipment, environmental friendly process, which can be easily industrialized.[13–15] UV-initiation as a new research technique in the synthesis of the PAM has been recognized for surface modification.[16,17] In this way, the specific surface area can be increased by the UV-initiation, which is favorable for promoting the adsorption and enmeshment ability in sludge dewatering. Therefore, UV-initiation was selected for the polymerization.

In this article, synthesis of the anionic polyacrylamide P (AM-AA-AMPS) was investigated using a new initiation system, UV irradiation. The copolymer was synthesized by AM and two anionic
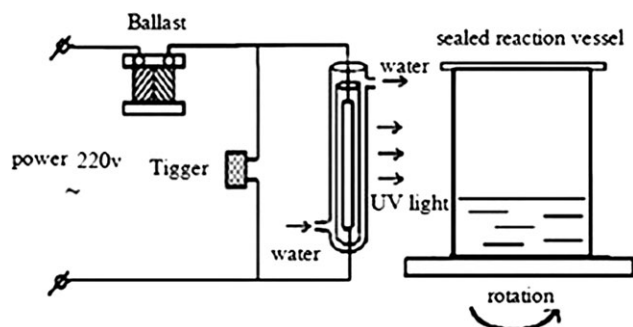
Figure 1. Sketch of the UV reaction device.

monomers acrylic acid (AA) and AMPS. And P (AM-AA-AMPS) was used in sludge dewatering as flocculation/coagulation. In addition, studies on the synthesis of P(AM-AA-AMPS) and its flocculation have not been reported yet while only the properties of the copolymer such as swelling behaviors and resistance to temperature have been studied before.[18] In this study, synthesis conditions such as mass ratio, pH value, ethylenediaminetetraacetic acid (EDTA) concentration and $CO(NH_2)_2$ (urea) concentration were investigated to obtain optimal polymer with high intrinsic viscosity and short dissolving time. The characterization was performed using nuclear magnetic resonance spectrometer (NMR), infrared spectrometer (IR) and scanning electron microscope (SEM). The orthogonal array design (OAD) has been used efficiently to show the way different parameters affect polymerization.[19,20] Therefore, to optimize the synthesis condition, orthogonal array design (OAD) was investigated. Finally, optimized sludge dewatering performance was tested by comparing effect of P (AM-AA-AMPS) and PAM on the filter cake moisture content under different coagulant dosages.

EXPERIMENTAL

Materials and Instruments

The monomer AM was sourced from Chongqing Lanjie Tap Water Company (Chongqing, China), AA from Chengdu Ke-long Chemical Reagent Corporation (Chengdu, China), and AMPS from Shouguang Chemical (Shandong, China). EDTA and urea were sourced from Chongqing Chuan-dong Chemical (Chongqing, China), while photo-initiator 2,2′-Azobis (2-methylpropionamide) dihydrochloride (V-50) was bought from Ruihong biological

technology (Shanghai, China). Sample of PAM was bought from Guanghui Chemical (Dalian, China).

The instruments used in the experimental set-up were as follows:

1. GY-500 Ultraviolet High-pressure mercury lamp was supplied by Tianyuanhuiteng (Beijing, China);
2. DZF-6021 Vacuum drying oven from Jinghong experiment equipment (Shanghai, China);
3. AVANCE 500 nuclear magnetic resonance spectrometer (NMR) from BRUKER Company (Germany);
4. 550Series II infrared spectrometer (IR) from Mettler Toledo instrument (Switzerland);
5. VEGA II LMU scanning electron microscope (SEM) from TES-CAN Company (Czech);
6. ZR4-6 Coagulation experiment blender from Shenzhen Zhongrun Water Industry Technology and Development (Shenzhen, China); and
7. HACH 2100Q Turbidmeter was supplied by HACH (USA).

Synthesis of the Copolymer

P(AM-AA-AMPS) was synthesized using three monomers AM, AA and AMPS in an aqueous solution. The reaction was carried out under UV irradiation, and the specific procedure is as follows. First, 7.0 ± 0.0001 g AM, 1.0 ± 0.0001 g AA as well as 1.0 ± 0.0001g AMPS were added into a reaction vessel. Then, deionized water was added to make the monomer ratio reach 40%. The mixture was stirred using a glass rod until the monomers dissolved completely. Next, the additives EDTA (0.1%, w/w, percentage of monomers' total weight) and urea (0.2%, w/w) were added to the vessel. The initial pH value of mixed solution is 1.2 and the pH value of the aqueous solution was adjusted to 9.0 using sodium hydroxide and hydrochloric acid. Under the protection of nitrogen gas, the photo-initiator V-50 (0.2%, w/w) was added to the solution. After purging with nitrogen gas for 15 min, the reaction vessel was sealed and transferred to the UV reaction device (Figure 1). The reaction time under UV irradiation was set for 1 h. Figure 2 shows the possible reaction scheme for polymerization.

Optimization of Synthesis Conditions

Single factor technique was used to determine optimum conditions for the four factors: monomer mass ratio, solution pH
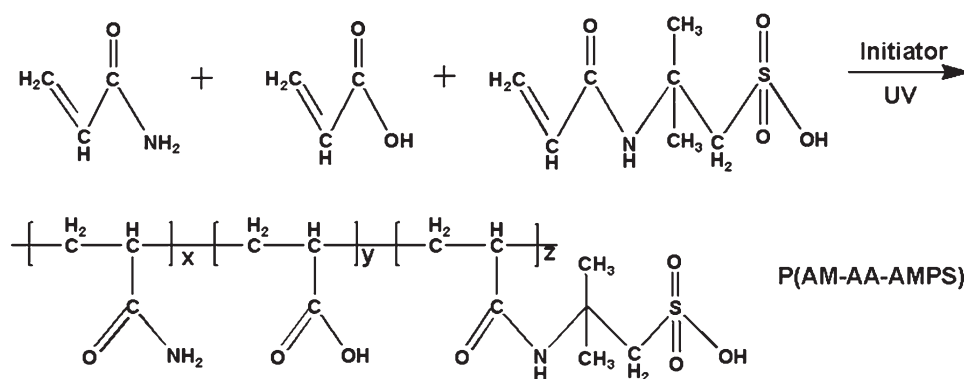

Figure 2. Possible reaction scheme of the synthesis.

Table I. Factors and Levels Establishment

Level	m(AM):m(AA): m(AMPS) (A)	pH (B)	Urea (C) /%[a]	EDTA (D)/%[a]
1	60 : 5 : 25	8	0.10	0.05
2	60 : 10 : 20	9	0.20	0.10
3	70 : 10 : 10	10	0.30	0.15
4	70 : 5 : 15	11	0.40	0.20

[a]w/w, percentage of monomers' total weight.

value, EDTA concentration and urea concentration. In addition, an orthogonal array L_{16} (4^5) (15 degrees of freedom) was used to determine optimum conditions and the significance of each factor. Table I shows the four factors at four levels for the orthogonal array design (OAD), with a dummy factor, E. The experiment was repeated three times and average results were reported.

Characterization of Copolymer

The copolymer was cut into particles and purified several times using acetone. Furthermore, the copolymer was dried for 24 h in a vacuum drying oven at 85°C before grounding into powder. The powdered product was dissolved with deuterium oxide (D_2O) as the solvent, before analyzes using ^{1}H NMR (Figure 3).
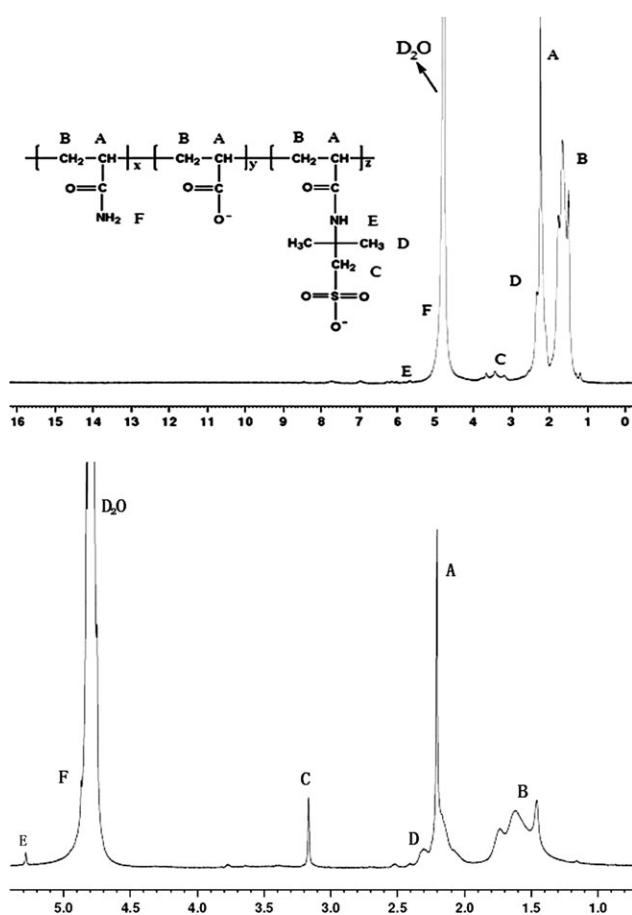
Figure 3. ^{1}H NMR spectrum of P (AM-AA-AMPS) with different intrinsic viscosity (a) 1000 mL g^{-1} and (b) 1500 mL g^{-1}.

IR spectrum was detected by the infrared spectrometer with KBr as the pellet, which is shown in Figure 4. In addition, after pretreatment with spray gold, the product morphology was determined using a scanning electron microscopy (SEM), and compared with the PAM which was bought from the market. SEM micrographs of P (AM-AA-AMPS) and PAM are shown in Figure 5.

Measurement of Intrinsic Viscosity

Different weight of copolymer were dissolved in 50 mL deionized water, before adding 50 mL of 2.0 mol L^{-1} NaCl solution to make aqueous solution samples with different concentration. The flow time of the samples were measured by Ubbelohde viscosity meter and digital stopwatch. The intrinsic viscosity [η] was evaluated from Huggins equation [eq. (1)].[7]

$$\eta_{sp}/c = [\eta] + K_H[\eta]^2 c \qquad (1)$$

Measurement of Dissolving Time

About 0.04 ± 0.002 g of the P(AM-AA-AMPS) was added to a 200-mL beaker as the reaction vessel. Then, 100 mL of distilled water was added into the reaction vessel, which was placed in an oscillator. The temperature of the oscillator was controlled at 30°C while the electrode of conductivity meter was inserted into the beaker to determine whether the products completely dissolved or not. If conductance value did not change in 3 min, the sample was considered completely dissolved. Finally, the time required for complete dissolving the sample was recorded.

Sludge Dewatering Experiments

To investigate flocculation performance, a program-controlled Jar-test apparatus was used for sludge dewatering experiments. The sludge samples came from the Dadukou Wastewater Treatment Plant of Chongqing. The sludge as characterized by a moisture content of 94.6%, mass density of 1.25 kg L^{-1}, and pH value of 7.3. About 500 mL of sludge was transferred into beakers before dosing with different dosage. The initial mixing speed was 100 rpm for 30 s before changing to a slow mixing speed of 50 rpm for 30 s. After flocculation, samples were filtered through a vacuum suction filter machine with the pressure of 5 × 10^5 Pa. The filter cake moisture content (CMC) was calculated using eq. (2), where M_r is the weight of filter cake at
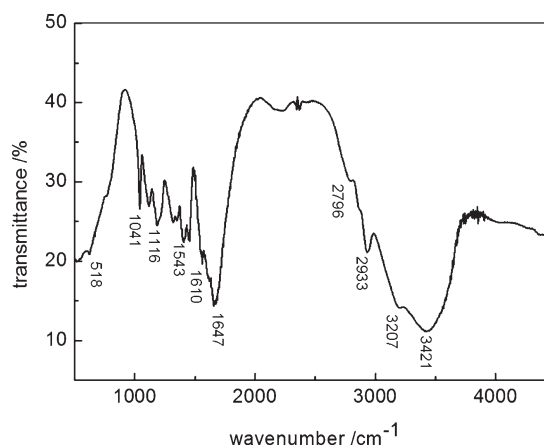
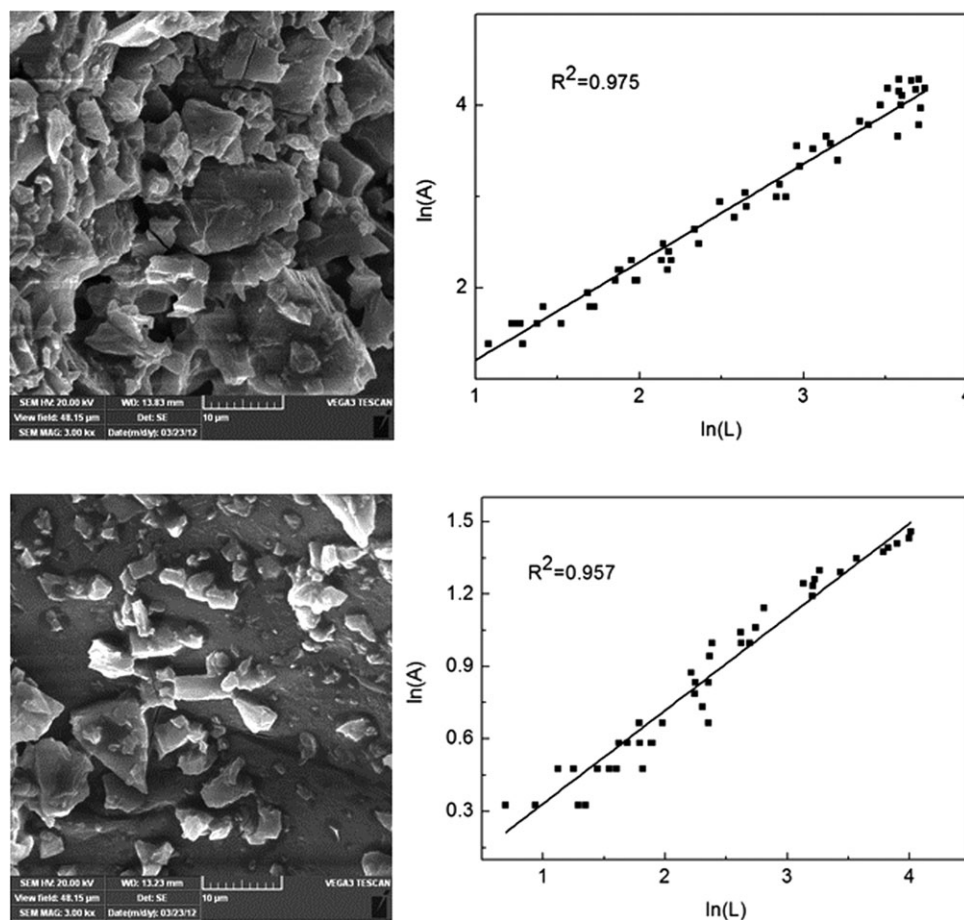**Figure 4.** IR spectra of copolymer.

Figure 5. SEM micrographs of (a) P (AM-AA-AMPS) and (b) the commercial PAM.

the end of filtration, and M_d is the weight of filter cake after drying at 105°C. According to the above steps, dewatering efficiency of P (AM-AA-AMPS) with different intrinsic viscosity and the PAM bought from the market were compared by investigating the filter cake moisture content under the different flocculants dosage.

$$CMC\% = \frac{M_r - M_d}{M_r} \times 100\% \qquad (2)$$

RESULTS AND DISCUSSION

Characterization of Copolymer

The characterization of the copolymer was investigated using a ^{1}H NMR while the possible chemical bonds present were examined using a FT-IR with KBr as dispersant.

Figure 3 shows ^{1}H NMR spectrum of P (AM-AA-AMPS) with different intrinsic viscosity, 1000 and 1500 mL g^{-1} respectively. It can be seen from Figure 3(a,b) that, two samples generally have a similar ^{1}H NMR spectrum. The resonance peak at $\delta = 4.75$ ppm which was attributed to the solvent D$_2$O.[21] The peaks at $\delta = 2.24$ and $\delta = 1.65$ ppm were derived from the proton at the methane group and methylene group of —CH$_2$—CH— in the AM, AA and AMPS.[7,16,22] Furthermore, the resonance peak at $\delta = 3.25$ and $\delta = 2.33$ ppm were ascribed to the proton at

the methylene group and methyl group —C(CH$_3$)$_2$CH$_2$SO$_3^-$ in the AMPS. However, compared to Figure 3(a), resonance peak of Figure 3(b) shows a difference at $\delta = 3.25$, which is resulted from the different AMPS dosage. Moreover, the peak at $\delta = 5.75$ ppm resulted from the proton of —NH— in the AMPS, but it has a low proportion in the copolymer according the integral of the area of the resonance spectrum.

Figure 4 shows the IR spectrum of copolymer. We can found that the absorption bands at 3421 cm^{-1} was ascribed to the —NH$_2$ groups of AM, and 3207 cm^{-1} was attributed to the —NH groups of AMPS. In addition, the absorption bands at 1647 and 1406 cm^{-1} were due to the —CH$_2$ and —CH groups respectively. As can be seen from Figure 4, the absorption bands at 1543 and 1610 cm^{-1} were attributed to the —COO— of AA. Furthermore, a series of adsorption bands at 1116, 1041, and 518 cm^{-1} were attributed to the —SO$_3^{-1}$ groups of APAM. In conclusion, the adsorption bands of AM, AA and AMPS all appeared in the copolymer.

Figure 5 shows the surface morphology of P(AM-AA-AMPS) and PAM. As shown in Figure 5, denser and larger sheet floccules were observed in the UV-initiated P(AM-AA-AMPS) whereas PAM shows looser and smaller floccules. In addition, Figure 5 also displays the linear correlation of the logarithm of perimeter (L) and area (A). Image-pro Plus 6.0 Software calculated the fractal dimension, which is the slope of the fitted curve. The

Table II. Effect of Mass Ratio Between Monomers on Intrinsic Viscosity

Sample	m(AM): m(AA):m(AMPS)	Intrinsic viscosity (mL g^{-1})	dissolving time (h)
1	50 : 35 : 5	635.81	3.0
2	50 : 30 : 10	689.24	3.5
3	50 : 25 : 15	752.58	2.5
4	60 : 15 : 15	824.63	3.0
5	60 : 10 : 20	1268.74	2.5
6	60 : 5 : 25	913.12	2.0
7	70 : 15 : 5	945.63	1.5
8	70 : 10 : 10	1537.49	1.5
9	70 : 5 : 15	1276.38	2.0

results shows the fractal dimension of P(AM-AA-AMPS) and PAM as 1.07 and 0.39, respectively. This big difference in morphological structure indicates the specific surface area of P(AM-AA-AMPS) is bigger than PAM, which is helpful for the bridging adsorption and enmeshment in sludge dewatering.

Effect of Mass Ratio Between Monomers on Polymerization
Mass ratio between monomers is one of the critical factors in the copolymerization. Therefore, synthesis experiments were carried out with nine different mass ratios m (AM) : m (AA) : m (AMPS), while solution pH at 9.0, EDTA concentration at 0.1% (w/w), and urea concentration at 0.2% (w/w) were kept constant.

Table II shows the highest intrinsic viscosity of copolymer can reach 1537.49 mL g^{-1} when the mass ratio m (AM) : m (AA) : m (AMPS) was 70 : 10 : 10. Because the reactivity ratio of AM is higher than AA and AMPS, therefore copolymer with higher intrinsic viscosity was obtained at high mass ratio of AM. In addition, anion groups such as sulfonic acid existing in AMPS can produce static repulsion, which is useful to chain growth in the copolymerization.[23] However, the resistance influence of side base in AMPS may have adverse effect on improving the intrinsic viscosity.[24] Consequently, the intrinsic viscosity will not be ideal with high or low mass ratio of AMPS. Furthermore, the dissolving time decreased to 1.5 h. Therefore, the

adopted optimum mass ratio of m (AM) : m (AA) : m (AMPS) was 70 : 10 : 10.

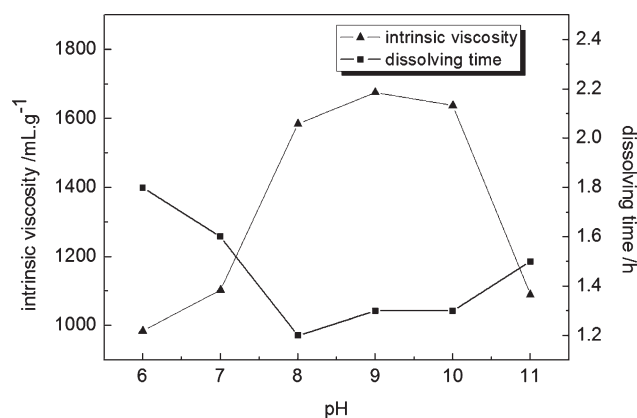**Effect of pH Value of Aqueous Solution on Polymerization**
The effect of pH value of aqueous solution on intrinsic viscosity was investigated by adjusting pH value from 6.0 to 11.0, while m(AM) : m(AA) : m(AMPS) ratio at 70 : 10 : 10, EDTA concentration at 0.1% (w/w), and urea concentration at 0.2% (w/w) were kept constant.

As shown in Figure 6, the intrinsic viscosity was high when the pH value changed between 8.0 and 10.0. This result is due to the hydrolysis of ─CO─NH─ in the alkaline environment.[25] In this case, the reaction solution will be negatively charged, leading to gravitational repulsion between electrostatic charges, which made polymerization easier because of the reduction of the reaction's activation energy. Increasing the pH value above 10 (pH > 10.0), will lead to branching of the molecular chain in the polymerization and ultimately reduce the intrinsic viscosity. Similar results were reported in the case of other aqueous synthesis systems.[18] In addition, Figure 6 shows the minimum dissolving time of 1.2 and 1.3 h at pH 8 and 9, respectively. Therefore, pH 9 was adopted as the optimal condition.

Effect of EDTA Concentration on Polymerization
In the polymerization system, small amount of impurities such as Cu^{2+} and Fe^{3+}, which have a negative impact on the reaction, may exist in the system. Therefore, in this experiment, the interference was eliminated by adding complexing agent EDTA. The effect of EDTA concentration on intrinsic was investigated in the range 0.05–0.30%, using m(AM):m(AA):m(AMPS) ratio of 70 : 10 : 10, solution pH-value of 9 and urea concentration of 0.2%.

Figure 7 shows the maximum intrinsic viscosity of 1.41×10^3 mL g^{-1} was observed at EDTA concentration of 0.10%. The results indicate EDTA played an important role in shielding impurities as the EDTA concentration increased from 0.05 to 0.10%. In this range, the intrinsic viscosity of the copolymer improved with increasing EDTA concentration. However, excessive EDTA in the reaction system will act as a chain transfer agent, which hinders the growth of the molecular chain, leading to a drop in the intrinsic viscosity of the copolymer.[26] This was observed as the EDTA concentration increased from 0.10 to

Figure 6. Effect of pH value of aqueous solution on intrinsic viscosity.
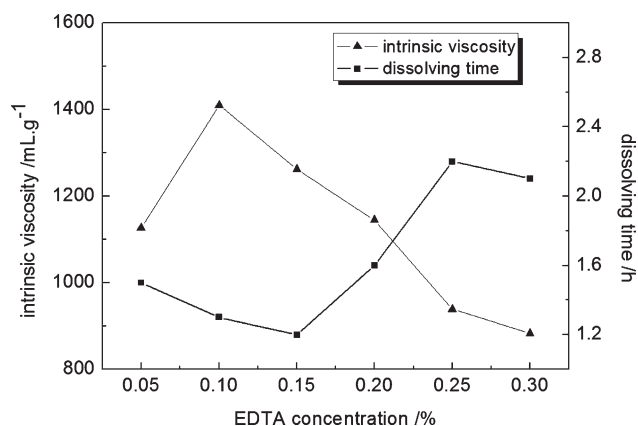
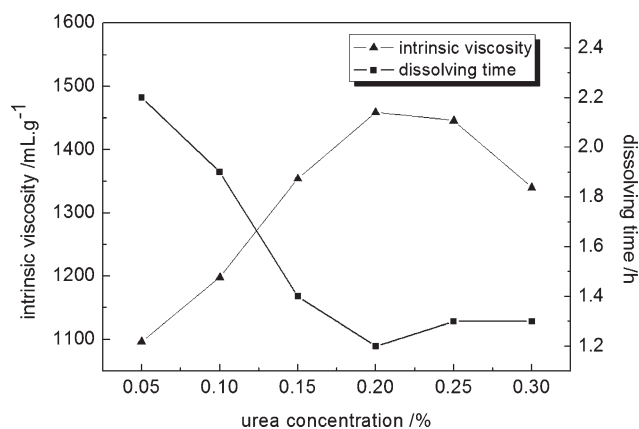**Figure 7.** Effect of EDTA concentration on intrinsic viscosity.

Figure 8. Effect of urea concentration on intrinsic viscosity.

0.30%. Moreover, dissolving time also increased due to the crosslinking in this process. Controlling the EDTA concentration controlled at a low level (0.10–0.15%), dissolving time reduced to 1.2 or 1.3 h. Therefore, 0.10% was adopted as the optimum concentration of EDTA.

Effect of Urea Concentration on Polymerization

In practical application, APAM product of high efficiency does not only require high intrinsic viscosity, but also good solubility. Urea can weaken the hydrogen bonding between side groups of the APAM molecular chain, resulting in the decrease of the intermolecular forces and the chance of the crosslinking. Therefore, urea was used as the solubilizer in the polymerization to reduce the dissolving time.[27] The effect of urea concentration on intrinsic viscosity was investigated in the range 0.05–0.30%, while m(AM) : m(AA) : m(AMPS) ratio at 70 : 10 : 10, solution pH at 9 and EDTA concentration at 0.1% (w/w) were kept constant.

Table III. Orthogonal Table L_{16} (4^5) and Experimental Results

No.	A	B	C	D	E[a]	intrinsic viscosity (mL g^{-1})
1	1	1	1	1	1	718.32
2	1	2	2	2	2	892.27
3	1	3	3	3	3	1027.95
4	1	4	4	4	4	934.71
5	2	1	2	3	4	1253.64
6	2	2	1	4	3	1091.30
7	2	3	4	1	2	1250.16
8	2	4	3	2	1	1369.80
9	3	1	3	4	2	1248.00
10	3	2	4	3	1	1340.03
11	3	3	1	2	4	1830.54
12	3	4	2	1	3	1662.11
13	4	1	4	2	3	1107.35
14	4	2	3	1	4	1179.75
15	4	3	2	4	1	1374.48
16	4	4	1	3	2	1152.36

[a] Dummy factor.

Table IV. Analysis of Variance (ANOVA) in the L_{16} (4^5) Matrix

Factor	Sum of squares (SS)	Degree of freedom	Mean square	F value	PC %
A	790696.25	3	263565.42	3.45[a]	72.55
B	216240.25	3	72080.08	0.95	19.84
C	40390.75	3	13463.58	0.18	3.71
D	42477.25	3	14159.08	0.19	3.90
Error	1089804.50				

[a] The critical F value is 3.29 ($P < 0.05$).

Figure 8 shows an increase in the intrinsic viscosity as the concentration of urea increased from 0.05 to 0.2%. However, as the urea concentration increased above 0.20%, the intrinsic viscosity decreased. Therefore, the highest APAM intrinsic viscosity of 1.46 $\times 10^3$ mL g^{-1} was achieved at urea concentration of 0.20%. The results indicate the chain transfer reaction accelerated at urea concentration above 0.20% resulting in the decrease in the intrinsic viscosity. In addition, Figure 8 shows a decrease in the dissolving time as the concentration of urea increased from 0.05 to 0.20% with a decrease thereafter. Therefore, the adopted optimum condition for the concentration of urea was 0.20%.

Analysis of Variance (ANOVA)

Table III shows the experimental results of orthogonal table L_{16} (4^5). The statistical testing of the parameters was performed using the Fisher's statistical test for ANOVA. Table IV shows the ANOVA results performed on the L_{16} (4^5) matrix. The mass ratio m(AM) : m(AA) : m(AMPS) was found to be significant at 95% confidence level by the F test as shown in Table IV, with P value less than or equal to 0.05 ($P < 0.05$) while solution pH, concentration of urea and EDTA were insignificant. In addition, the percentage contribution (PC%) of each factor to the polymerization reaction i.e., product intrinsic viscosity, was investigated using eq. (3). Table IV shows the mass ratio as the most important factor contributing to the intrinsic viscosity (72.55%), followed by solution pH value (19.84%), urea concentration (3.71%) and EDTA concentration (3.90%). Therefore, ANOVA results and percentage contribution indicate the mass ratio m(AM) : m(AA) : m(AMPS) has significant influence on the synthesis.

$$\mathrm{PPC}\% = \frac{\mathrm{ss}}{\mathrm{Error}} \times 100\% \qquad (3)$$

Where SS is the sum of squares and Error is the total sum of squares.

Table V. Average (K) at Each Level of Every Factor and Range of Intrinsic Viscosity

	A	B	C	D
K_1	893.31	1081.83	1198.13	1202.59
K_2	1241.23	1125.84	1295.63	1299.99
K_3	1520.17	1370.78	1206.38	1193.49
K_4	1203.48	1279.75	1158.06	1162.12
Range	626.86	288.96	137.56	137.87
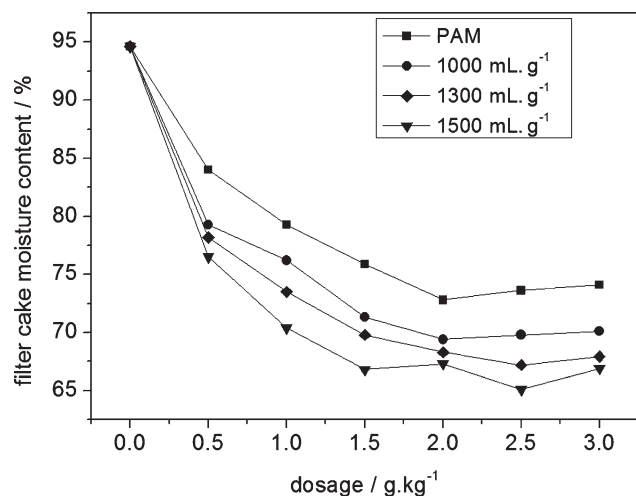
Figure 9. Effect of P (AM-AA-AMPS) with different intrinsic viscosity (1000, 1300, 1500 mL g^{-1}) and PAM dosage on filter cake moisture content.

Direct Observation Analysis

To confirm the optimum conditions from the single factor approach, the L$_{16}$ orthogonal array was used to determine optimum synthesis conditions. Table V shows the average intrinsic viscosity (K) for the four factors at four levels. The results indicate the optimum synthesis conditions from the orthogonal array are m(AM) : m(AA) : m(AMPS) at 70 : 10 : 10, solution pH value at 10, urea concentration at 0.20% and EDTA concentration at 0.10%. Compared with the single factor experiment, the optimum conditions are the same except for the solution pH, which changed from 9 to 10. However, Figure 6 shows a small difference in the APAM intrinsic viscosity between pH 9 and 10, and therefore solution pH of 9 was adopted as the optimum condition.

Flocculation Performance

The purpose of this experiment was to determine the effect of dosage on the filter cage moisture content using synthesized APAM and commercial PAM.

Figure 9 illustrates the effect of P(AM-AA-AMPS) with different intrinsic viscosity (1000, 1300, 1500 mL g^{-1}) and commercial PAM dosage on filter cake moisture content. It shows a decrease in the filter moisture content as the dosage increased to 2.5 g kg^{-1}. However, for dosages above 2.5 g kg^{-1}, the filter cake moisture content increased. The results indicates the filter cake moisture content as low as 65.1% could be achieved using P(AM-AA-AMPS) whereas 72.8% could be achieved using commercial PAM. Therefore, P(AM-AA-AMPS) was more efficient than commercial PAM in sludge dewatering. In addition, the intrinsic viscosity had an effect on the filter cake moisture content as the lowest moisture content was achieved using a high intrinsic viscosity synthetic APAM.

CONCLUSIONS

A novel UV-initiated polymerization anionic polyacrylamide (P(AM-AMPS)) was prepared for the sludge dewatering. The ^{1}H NMR and IR analysis shows the presence of functional

groups in ternary copolymers, proving that the copolymer was synthesized with AM, AA, and AMPS. SEM images provided the apparent morphology of the copolymer, which suggested P(AM-AA-AMPS) had a good adsorption and bridging ability. The optimization results showed the optimum conditions for mass ratio m(AM) : m(AA) : m(AMPS), solution pH value, EDTA concentration and urea concentration were 70 : 10 : 10, 9.0, 0.10% and 0.20% respectively. A series of experimental results show that the average molecular weight can be stabilized in 8×10^6. Analysis of variance indicates the mass ratio was the most significant factor. Compared with the commercial PAM, synthesized P(AM-AA-AMPS) with high intrinsic viscosity had a better flocculation performance on sludge dewatering.

REFERENCES

1. Akrama, M.; Jeremy, O.; Jean, V.; Hoadley, A. F. A. *Water Res.* **2011**, *45*, 2795.

2. Guanyin, Z.; Xiaofei, Y.; Haiyan, Z.; Hua, C.; Tiantao, Z.; Youcai, Z. *J. Environ. Sci.* **2011**, *23*, 1225.

3. Kouloumbos, V. N.; Schaffer, A.; Corvini, P. F.-X. *Water Res.* **2008**, *42*, 3941.

4. Ying, Q.; Thapa, K. B.; Hoadley, A. F. A. *Chem. Eng. J.* **2011**, *171* 373.

5. Johnson, A. C.; Martinez-Garcia, G.; Edyvean, R. G. *J. Desalination Water Treat.* **2010**, *16*, 39.

6. Nguyen, T. P.; Hankins, N. P.; Hilal, N. *Desalination* **2007**, *204*, 277.

7. Gui, Z.; Qian, J.; An, Q.; Xu, H.; Zhao, Q. *Eur. Polym. J.* **2009**, *45*, 1403.

8. Zheng, H.; Zhu, J.; Jiang, Z.; Ji, F.; Tan, M.; Sun, Y.; Miao, S.; Zheng, X. *Adv. Mater. Res.* **2012**, *414*, 172.

9. Burkus, Z.; Temelli, F. *Carbohydr. Polym.* **2003**, *54*, 51.

10. Yu, L.; Zhang, S.; Liu, W.; Zhu, X.; Chen, X. *J. Comput. Math.* **2007**, *41*, 2443.

11. Shokrieh, M. M.; Bayat, A. *J. Comput. Math.* **2007**, *41*, 2443.

12. Pal, S.; Ghorai, S.; Dash, M. K.; Ghosh, S.; Udayabhanu, G. *J. Hazard. Mater.* **2011**, *192*, 1580.

13. Deng, J.; Wang, L.; Liu, L.; Yang, W. *Progr. Polym. Sci.* **2009**, *34*, 156.

14. Bessem, K.; Ramzi, K.; Mhenni, M. F.; Sakli, F.; Belgacem, M. N. *Appl. Surf. Sci.* **2012**, *258*, 9737.

15. Di Gianni, A.; Amerio, E.; Monticelli, O.; Bongiovanni, R. *Appl. Clay Sci.* **2008**, *42*, 116.

16. Song, H.; Zhang, S.-F.; Ma, X-C.; Wang, D.-Z.; Yang, J.-Z. *Carbohydr. Polym.* **2007**, *69*, 189.

17. Mostak, A.; Mohammad, B. K.; Mubarak, A. K.; Shamsul Alam, M.; Anwar, H. K. *J. Power Sources.* **2011**, *196*, 614.

18. Bao, Y.; Ma, J.; Li, N. *Carbohydr. Polym.* **2011**, *84*, 76.

19. Diez, C.; Barrado, E.; Marinero, P.; Sanz, M. *J. Chromatogr.* **2008**, *1180*, 10.

20. Zhu, G.; Ju, H. *Anal. Chim. Acta.* **2004**, *506*, 177.

21. Zhu, G.; Wang, Y.; Zhu, W.; Zhu, K.; Xu, X.; Shen, Z. *J. Appl. Polym. Sci.* Available at: http://onlinelibrary.wiley.com/doi/10.1002/app.38327/pdf (accessed 30 AUG 2012).

22. Abdollahi, Z.; Frounchi, M.; Dadbin, S. *J. Ind. Eng. Chem.* **2011**, *17*, 580.

23. Pourjavadi, A.; Barzegar, S.; Zeidabadi, F. *React. Funct. Polym.* **2007**, *67*, 644.

24. Pourjavadi, A.; Hosseinzadeh, H.; Mazidi, R. *J. Appl. Polym. Sci.* **2005**, *98*, 255.

25. Lanthong, P.; Nuisin, R.; Kiatkamjornwong, S. *Carbohydr. Polym.* **2006**, *66*, 229.

26. Zhen, H.-B.; Xu, Q.; Hua, Y.-Y.; Cheng, J-H. *Chem. Eng. J.* **2012**, *209*, 547.

27. Li, M.-F.; Sun, S.-N.; Xu, F.; Sun, R.-C. *Eur. Polym. J.* **2011**, *47*, 1817.