Synthesis and characterization of a dewatering reagent: cationic polyacrylamide (P(AM–DMC–DAC)) for activated sludge dewatering treatment

Junren Zhu, Huaili Zheng*, Zhenzhen Jiang, Zhi Zhang, Liwei Liu, Yongjun Sun, Tiroyaone Tshukudu

Key laboratory of the Three Gorges Reservoir Region's Eco-Environment, State Ministry of Education, Chongqing University, 74 Shabei Street, Shapingba District, Chongqing 400045, China
Tel. +86 23 65120827; Fax: +86 23 65121769; email: ZHL6512@126.com

ABSTRACT

P(AM–DMC–DAC), one kind of ternary copolymerized cationic polyacrylamide, was synthesized using acrylamide (AM), methacryloxyethyltrimethyl ammonium chloride (DMC), and acryloxyethyltrimethyl ammonium chloride (DAC) by photopolymerization technique. The copolymer was characterized by means of Fourier transform infrared spectroscopy, thermal gravimetric analysis, and scanning electron microscopy. The optimum synthesis conditions were as follows: mass percentage of photoinitiator being 0.40%, mass percentage of solubilizer being 0.10%, inducing time being 1 h, pH value being 9.0, and mass ratio of AM/DMC/DAC being 4:3:3. At optimum conditions, the performance parameters of copolymer are as follows: thermal stability was $126.0 \, \mathrm{J \, g^{-1}}$, molecular weight was 1.28×10^7, cationic degree was 30.7%, coagulant dosage being $0.5 \, \mathrm{g \, kg^{-1}}$, and the filter cake moisture content (CMC) and filtrate residual turbidity were 65.7% and 3.73 NTU, respectively. Based on the evaluation of the sludge dewatering process, it was found that when the coagulant dosage was $1 \, \mathrm{g \, kg^{-1}}$, activated sludge initial pH value was 7.0, and rapid agitation speed was 120 rpm, CMC and turbidity were 63.5% and 2.95 NTU, respectively. In addition, charge neutralization and adsorption/bridging coagulation–flocculation mechanisms played an important role in sludge dewatering performance.

Keywords: Cationic polyacrylamide; Photopolymerization; Activated sludge dewatering; Characterization; Coagulation–flocculation process

1. Introduction

The activated sludge wastewater treatment processes produce large quantities of sludge, of which over 95% is water. Therefore, sludge treatment through water separation techniques before disposal is necessary to reduce the sludge volume and at the same time reduce transportation and handling costs [1]. Sludge dewatering has been pointed out as one of the most expensive and least understood processes [2]. Currently, mechanical pressure and centrifugation by mechanical dewatering are widely used dewatering methods; however, they are not effective enough to obtain high dehydration rate [3]. Thermal drying method is often considered more efficient, but it

*Corresponding author.

requires complicated devices and higher cost and may generate serious air pollution [4,5]. Coagulation/flocculation of sewage sludge with polyelectrolytes prior to dewatering is a commonly used method for enhancing dewaterability of sludge. There are two widely accepted flocculation mechanisms: adsorption/bridging and surface charge neutralization [6,7]. The sludge conditioned with cationic polyacrylamide performed better in fine particle capturing and in formation of larger flocs resulted in enhanced dewaterability while reducing the chance of overdosing [8]. Therefore, sludge conditioning as an economical and efficient dewatering technique can be effectively applied before applying mechanical pressure or centrifugation.

Based on the surface charge neutralization mechanism, flocculation occurs because the electrostatic force of repulsion between the charged particles is reduced. Therefore, the polyelectrolytes with high charge density (CD) are more effective in forming flocs through surface charge neutralization [9]. The stability of flocs is also dependent on the polyelectrolyte properties. On the other hand, some studies found the molecular weight (MW) was also an important factor for flocs stability [10]. High MW polyelectrolytes are helpful in forming large and loosely packed flocs, which are stable to shear and have significantly better filtration performance. In addition, polymer adsorption is an essential prerequisite for flocculation and MW plays an important role in adsorption/bridging [11]. Polyelectrolytes with high MW show better flocculation effect, with production of stronger flocs and lower turbidity filtrate. Up to now, most studies are focused on obtaining a dewatering reagent of high MW and high CD [12].

Cationic polyacrylamide can be prepared by copolymerization of acrylamide (AM) with a cationic monomer, such as dimethyldiallyl ammonium chloride (DMDAAC) [13]. The most popular polymerization reaction on copolymerization of AM is aqueous solution polymerization, which can be initiated by heat [13,14], microwave [15], γ rays [16], and ultraviolet (UV) [17]. Among them, polymerization through UV-induced initiation was believed to be the best way as it occurs quickly even at low temperature, while producing uniform MW distribution due to low energy and superior penetrability of UV. The P(AM–DMC) widely investigated in the wastewater treatment was prepared by cationic monomer of methacryloxyethyltrimethyl ammonium chloride (DMC) with AM [18]. The organic copolymers had enhanced flocculating performance with superior turbidity removal efficiency. There were less methyl-branched chains in acryloxyethyltrimethyl ammonium chloride (DAC) than in DMC, resulting in better hydrophobicity and

plasticity compared with DMC. Therefore, obtaining higher MW P(AM–DAC) was easier than P(AM–DMC). The MW and cationic degree of P(AM–DMC) were close to that of P(AM–DAC), whereas P(AM–DMC) had better flocculating performance and higher sludge dewatering efficiency. P(AM–DMC–DAC) is a ternary copolymerized cationic polyacrylamide containing two cationic monomers and one AM monomer. As a result, two cationic monomers were incorporated into the polymer molecule chain which results in two cationic monomer performances complementary advantages. Consequently, P(AM–DMC–DAC) has such advantages as high cationic degree, high MW, and superior sludge dewatering efficiency.

In this study, the synthesis and characterization of the sludge dewatering agent ternary copolymerized cationic polyacrylamide P(AM–DMC–DAC) were investigated. The copolymer was synthesized using one AM monomer and two cationic monomers (DMC and DAC) with different conditions by adjusting photoinitiator concentration, solubilizer concentration, pH value, and UV irradiation time. The property was tested using Fourier transform infrared spectroscopy (FTIR), thermal gravimetric analysis (TGA) and scanning electron microscopy (SEM). In order to optimize the polymerization condition, the effects of DMC, DAC, and AM weight ratio on sludge dewatering performance were investigated in the condition of high MW and CD. Finally, optimized sludge dewatering performance was investigated by comparing the coagulant dosage of P(AM–DMC–DAC).

2. Experimental

2.1. Material and instruments

The monomer AM was the superior grade (over 98.5%, w/w), cationic monomer DAC was the industrial grade (over 80%, w/w aqueous solution, 100% CD), and cationic monomer DMC was the industrial grade (over 78%, w/w aqueous solution, 100% CD), which were sourced from Guangchuangjing Import and Export Co., Shanghai, China. The photoinitiators for the synthesis of the hydrophily ally modified polyacrylamides, sodium hydrogensulfite (NaHSO$_3$), and potassium persulfate (K$_2$S$_2$O$_8$) were analytical pure grade. The other reagents used in the experiments were analytical grade, including acetone (C$_3$H$_6$O), urea (CO(NH$_2$)$_2$), sulfuric acid (H$_2$SO$_4$), and sodium hydroxide (NaOH). All aqueous solutions and standard solutions were prepared with deionized water. The purity of nitrogen gas was higher than 99.99%, which was used as the saturated gas for UV-induced polymerization reaction. The instruments used in the experimental setup were as follows:

(1) GY-500 Ultraviolet High Pressure Mercury Lamps, supplied by Tianyuanhuiteng CO., Beijing, China; double-glazed quartz cold trap was used to reduce heat effect by filtering most of the infrared (internal diameter 30 mm, external diameter 40 mm, and effective length 225 mm) was self-made. Heating jacket and HYD-7411 Intelligent temperature controller (PT100A thermocouple sensors) was supplied by Her instrument Co., Ltd., Shanghai, China.

(2) pH meter: Delta 320 pH meter was supplied by Mettler Toledo Instruments Co., Ltd., Shanghai, China.

(3) Scanning electron microscope was supplied by VEGA II LMU, TES-CAN, Chech.

(4) Turbidimeter HACH 2100Q was supplied by HACH, USA.

(5) Vacuum drying oven DZF-6021 was supplied by Jinghong experiment equipment Co., Shanghai, China.

(6) Malvern zetasizer Nano ZS90 was supplied by Malvern instruments Ltd., UK.

2.2. Sludge sample

The activated sludge samples used in this study were obtained from the gravity thickening pool of Tangjiatuo Wastewater Treatment Plant, Chongqing, municipal sewage treatment with capacity 300,000 m^3 per day. The sludge was black with fetor smell, characterized with dense crystal grains (moisture content = 95.5%, mass density = 1.02 kg L^{-1}, filtrate turbidity = 60.92 NTU, and pH value = 7.0).

2.3. Preparation of P(AM–DAC–DMC)

The dewatering reagent P(AM–DAC–DMC) was prepared with UV photon as the initiator to the

Fig. 1. Technical process of preparation for P(AM–DMC–DAC).

reaction. Firstly, *x* g AM, *y* g DMC, and *z* g DAC were added into the reaction vessel made of transparent quartz glass. Secondly, deionized water was added into the reaction vessel, resulting in the formation of a liquid mixture containing AM monomers and two times of cationic monomers. The aqueous solution was prepared with the concentration of monomers being 25%. Thirdly, several kinds of solubilizers and photoinitiators were quickly added into the aqueous solution. At the same time, the aqueous solution was purged with nitrogen for 30 min prior to activation of the UV source. Therefore, oxygen gas was fully removed from the aqueous solution before the reaction vessel was totally enclosed in the UV synthesis box. With the UV-induced polymerization that continued for a specified time, the polymer was produced and the aqueous solutions turned into a colorless transparent solid in the reaction vessel. The degree of polymerization increased after aging for more than 12 h at room temperature (Fig. 1).

The probable complex reaction mechanism was represented as follows:

Photoinduction was carried out in UV synthesis box made of stainless steel with UV source in the center of the box (Fig. 2). The UV lamp had a power of 500 W and light intensity of 1.76 mW cm^{-2}. During initiation, the reaction temperature was controlled at about 25℃ using a temperature sensor, which was inserted into the transparent quartz glass reactor.

2.4. Characteristics of P(AM–DMC–DAC)

The copolymer was purified using acetone for three times in order to obtain the pure solid of P(AM–DMC–DAC). Infrared spectroscopy (IR) was used to identify the structure of organic compounds of the copolymer powder. The IR samples were prepared with a KBr pellet before analysis using IR Prestige-21 infrared spectrometer (SHIMADZU, Japan). The TGA samples of the copolymer power were prepared by stripping, drying, and shattering. The TGA was carried out with the heating rate being 10℃ min^{-1}, nitrogen flow being 20 ml min^{-1} over a temperature range from 20℃ up to 600℃ on a DTG-60H synchronal thermal analyzer (SHIMADZU, Japan) to identify and quantitatively analyze the chemical composition of substances, while investigating the thermal stability of the copolymer. The relative MW of the product was determined using an Ubbelodhe viscosimeter. The morphology of the copolymer was observed through SEM. The electron samples were prepared by shattering, planishing, and sputtering Au. The electron samples were dried and the SEM images were taken through scanning electron microscope.

2.5. Dewatering experiments

The coagulation/flocculation experiments were carried out using a program-controlled jar test apparatus (ZR4-6, Zhongrun Water Industry Technology Development Co., Ltd., China) at room temperature. About 500 ml of sludge was transferred into a beaker. Under rapid mixing condition with the agitation speed being set as 120 rpm, predetermined amount of coagulant P (AM–DMC–DAC) was added. After 30 s, the speed was adjusted into 40 rpm slow speed for 1 min. After settling for 5 min, the sample was filtered with a funnel fitted with a qualitative filter paper and processed with vacuum filtration at a vacuum pressure of 5×10^5 Pa. The dewater performance of the P(AM–DMC–DAC) was investigated by measuring the moisture content of filter cake and the number of fine particles that remained in the suspension after flocculation. The amount of filter cake moisture content (CMC) was determined using Eq. (1).
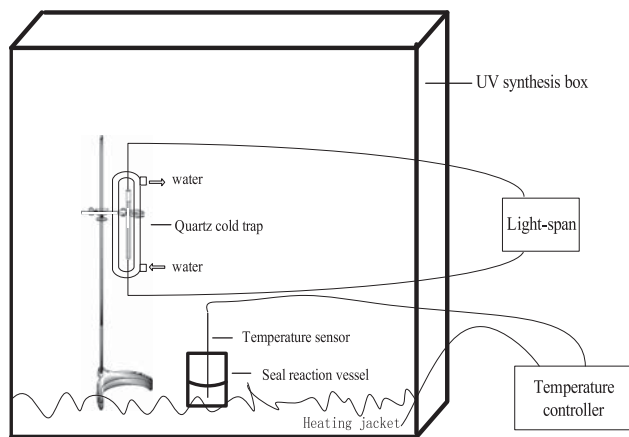
$$\text{CMC } (\%) = \frac{M_T - M_f}{M_T} \times 100 \tag{1}$$

M_T was the weight of the filter cake at the end of filtration and M_f was the weight of the filter cake after drying at 105℃.

The number of fine particles in filtrate was determined by measuring the residual turbidity. It was used to estimate the number of surplus sludge particles in filtration while analyzing the effect of particle aggregation. The copolymer dose which can give the lowest CMC and residual turbidity in the filtrate was considered as the optimum dosage.

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3. Results and discussion

3.1. Infrared spectra analysis

The possible chemical bonds when AM/DMC/DAC was adjusted as 6 g:2 g:2 g were examined using FTIR with KBr as dispersant (Fig. 3).

Fig. 3 shows that the absorption peaks were at 3427 cm^{-1} and 1129 cm^{-1} that were assigned to the stretching vibrations for –NH$_2$ bond in amide groups and C–O in ester groups, respectively. The asymmetric absorption peak at 2952 cm^{-1} is for –CH$_3$ and –CH$_2$. In addition, the characteristic absorption peaks at 1734 cm^{-1}, 1664 cm^{-1}, and 952.3 cm^{-1} were attributed to C=O in ester groups, C–N in amide groups, and
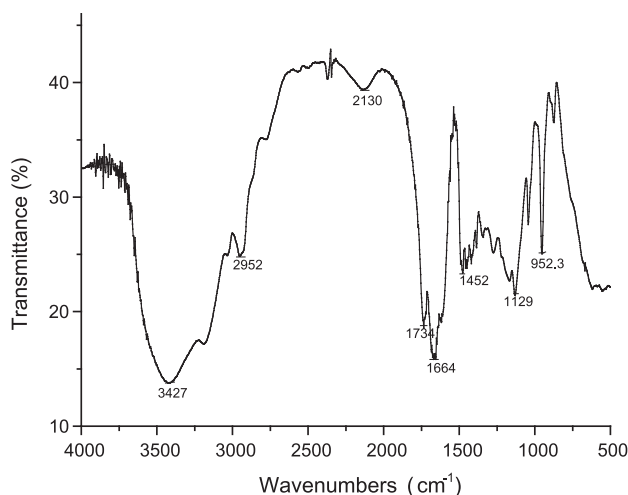

Fig. 2. Catalysis and synthesis device with UV.

Fig. 3. Infrared spectra of P(AM–DMC–DAC).

Fig. 4. TGA of P(AM–DMC–DAC).

quaternary ammonium groups, respectively. The absorption peak at $1452\,cm^{-1}$ is for $-CH_2$ flexural vibrations in $-CH_2-N-(CH_3)_3$ while the absorption peak at $>3000\,cm^{-1}$ is for $-OH$ stretching vibrations indicating that the broad peak and the twin peaks were overlapping. The reason is that the polymers have the ability for absorbing water and therefore can contain a small amount of bound water. Infrared spectral analysis indicated the product was prepared with AM, DAC, and DMC as raw materials. The qualitative analysis by comparing the size of the absorption peak area for absorption at $3427\,cm^{-1}$, $1664\,cm^{-1}$, $1734\,cm^{-1}$, and $952.3\,cm^{-1}$ indicated that the number of amide groups was much more than that of ester group and quaternary ammonium groups. The result is broadly in line with the composition of self-made products.

3.2. Thermal gravimetric analysis

The thermal stability of the P(AM–DMC–DAC) copolymer was determined by TGA, which was carried out using a DTG-60H synchronal thermal analyzer. The thermal gravimetric curve of P(AM–DMC–DAC) copolymer was shown in Fig. 4.

Fig. 4 shows the TGA diagram of the P(AM–DMC–DAC) copolymer indicating three stages of weight loss. The first weight loss occurred in the range 30–210°C, with a weight loss being about 7.99% of the total weight, corresponding to the evaporation of intra and intermolecular moisture [16,17]. The copolymer contained a large number of strong hydrophilic groups which could induce the sample to combine with water molecules. The second weight loss occurred in the range of 210–290°C, with a weight loss being approximately 17.58% of the total
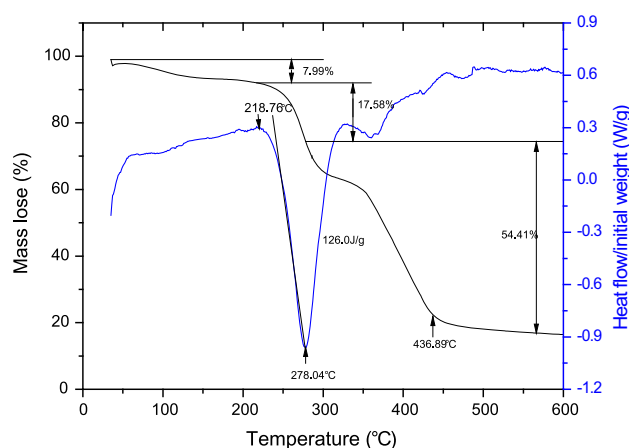
weight, corresponding to the imidization of the amide group and the thermal decomposition of methyl in the quaternary ammonium groups [18,19]. The third weight loss occurred in the range above 290°C, with a weight loss being 54.41% of the total weight. At temperatures above 450°C, the copolymer decomposed completely because of the thermal decomposition of the copolymer backbone. In addition, the thermal gravimetric curve stabilized above 450°C. The residual weight was only 20% of the initial weight of the test sample. The thermal gravimetric curve of the copolymer is shown in Fig. 3, presenting an obvious peak of heat absorption, corresponding to the imidization of the amide groups, and thermal decomposition by methyl of quaternary ammonium groups. The glass transition temperature and decomposition temperature of P(AM–DMC–DAC) were 218.76 and 278.04°C, respectively. The enthalpy value of the heat absorption peak was $126.0\,J\,g^{-1}$. Results of TGA analysis indicated that the copolymer had favorable thermal stability.

3.3. SEM result

The morphology of P(AM–DMC–DAC) was detected by the scanning electron microscopy, shown in Fig. 5.

The morphologies of P(AM–DMC–DAC) and P(AM–DAC) are shown in Fig. 5. In the size range of 50–200 μm, P(AM–DMC–DAC) was significantly smaller than P(AM–DAC), consequently it had far larger surface area that resulted in enhanced bridging/adsorption performance. While in the size range of 10 μm, it presented a compact gel network structure with a few cavities. It can be seen from Fig. 5(b) that the structure of P(AM–DAC) is compact and smooth,
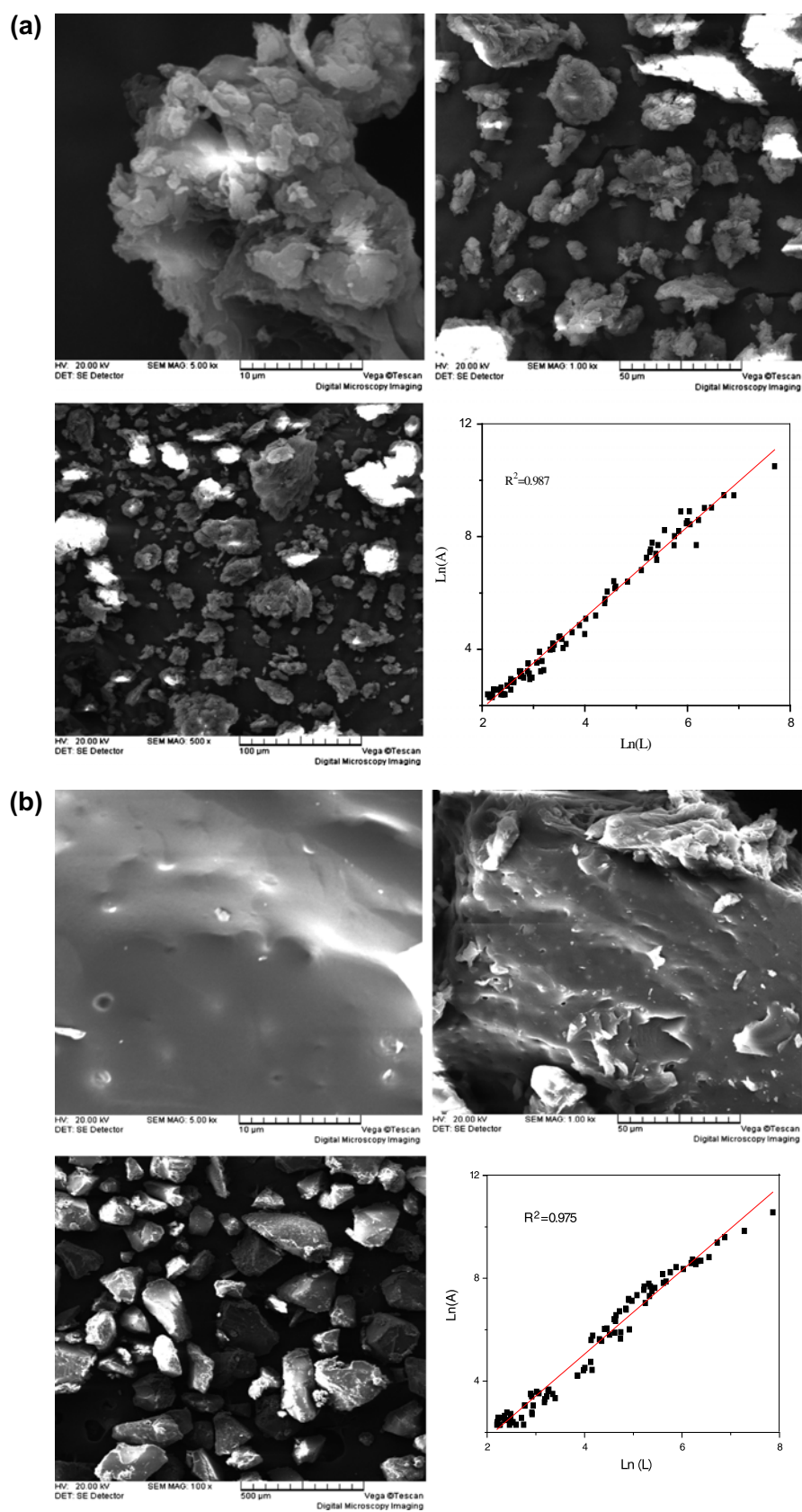
Fig. 5. SEM micrographs of (a) P(AM–DMC–DAC) and (b) P(AM–DAC).

similar to the shape of a chewing gum. The conclusions were drawn based on previous studies that the compact gel network structure was more favorable to coagulate colloidal particles and form bridge-aggregation among flocs compared with the smooth structure [20,21]. The larger and irregular hole in the network structure is good to play the bridge role for dewatering. Therefore, P(AM–DMC–DAC) had advantages in adsorption/bridging coagulation–flocculation for sludge dewatering.

The experimental results showed that the coagulant exhibited higher stability. Additionally, Fig. 5 also shows the degree of the linear correlation of the logarithm of perimeter (L) and area (A). According to the calculation result for fractal dimension using image-pro Plus 6.0 Software, the average fractal dimensions of P(AM–DMC–DAC) and P(AM–DAC) were 1.613 and 1.632, respectively. The difference of P(AM–DMC–DAC) and P(AM–DAC) in the average fractal dimension showed a different morphological structure, which would give an important indicator that the two chemicals might have different physical and chemical properties, and thus they showed significant difference in the actual application.'

3.4. Effect of the photoinitiator on MW

The effect of photoinitiator concentration was investigated by setting AM/DMC/DAC as 6 g:2 g:2 g, setting urea as 0.10% of monomer weight, adjusting the pH value of aqueous solutions as 7.0, and photopolymerization time as 60 min. MW (Fig. 6) was measured with the amount of initiator in the range of 0.25–0.50% of the monomer weight and the amount of initiators $NaHSO_3/K_2S_2O_8$ ratio in the range of 0.5 $\sim$ 2 (w/w).

Fig. 6 shows the highest MW of 1.06×10^7 was achieved when the $NaHSO_3/K_2S_2O_8$ ratio was 0.8:1 (w/w) and the dosage of initiator was 0.40% of monomer weight. The MW of P(AM–DMC–DAC) increased at the beginning and then decreased with the increase of initiator. If the initiator dosage was insufficient, the chain reaction could not proceed, creating the "Cage Effect," that resulted in the loss of initiator, which was not favorable for producing a product with higher MW. On the contrary, in the case of excess initiator, the system temperature increased sharply while inducing the chain reaction that resulted in initiator wastage. The excess heat produced during polymerization is not promptly lost by the reaction vessel resulting in implosion of the reaction; however, this was not conducive for producing a higher MW and high solubility product. The P(AM–DMC–DAC) product with the highest MW was produced at an initiator dosage of 0.40%. The initiator was produced using
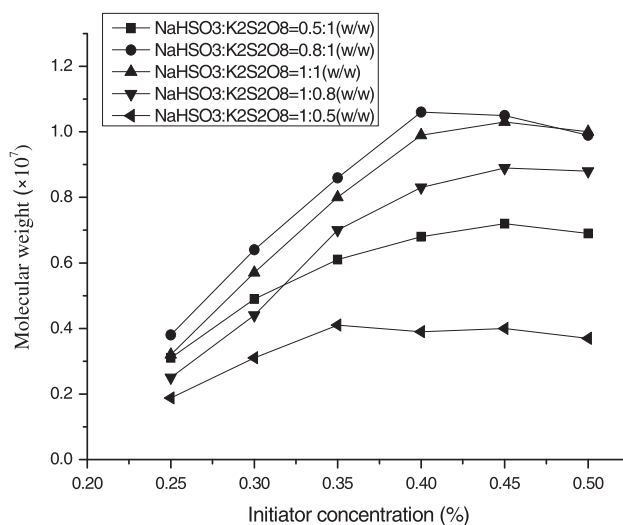

Fig. 6. Effect of the initiator on the MW.

$K_2S_2O_8$ as oxidant and $NaHSO_3$ as reductant. In the case where the dosage of the deoxidizer was equal or greater than the dosage of oxidant, the MW of product was not high. This was because excess reductant in the reaction vessel reacts with free radicals, which results in decreasing reaction reactivity. In addition, at $NaHSO_3:K_2S_2O_8$ ratio of 1:2 (w/w), the initiator efficiency deteriorates as the excess initiator decomposed. The free radicals and initiator reacts generating stable molecules while not producing fresh free radicals. Therefore, free radical decreased whereas the oxidants were consumed indicating a high MW product cannot be produced using excess oxidants. Based on the above, $NaHSO_3/K_2S_2O_8$ ratio of 0.8:1 (w/w) and the amount of initiator at 0.40% of monomer weight were adopted as the optimum conditions.

3.5. Effect of the solubilizer for MW

The effect of the solubilizer concentration was investigated by setting AM/DMC/DAC as 6 g:2 g:2 g, setting initiator concentration as 0.40% of the monomer weight, $NaHSO_3/K_2S_2O_8$ as 0.8:1 (w/w), adjusting the pH value of the aqueous solution as 7.0 and photopolymerization time as 60 min. MW and dissolution time (Fig. 7) were measured using urea as the solubilizer in the range 0–0.20% of the monomer weight.

Fig. 7 shows that P(AM–DMC–DAC) with the highest MW of 1.06×10^7 was produced using the amount of solubilizer equivalent to 0.10% of the monomer weight while the best solubility time of 5 h was achieved using solubilizer amount equivalent to 0.20% of monomer weight. The MW P(AM–DMC–DAC) increased first and then decreased with increasing
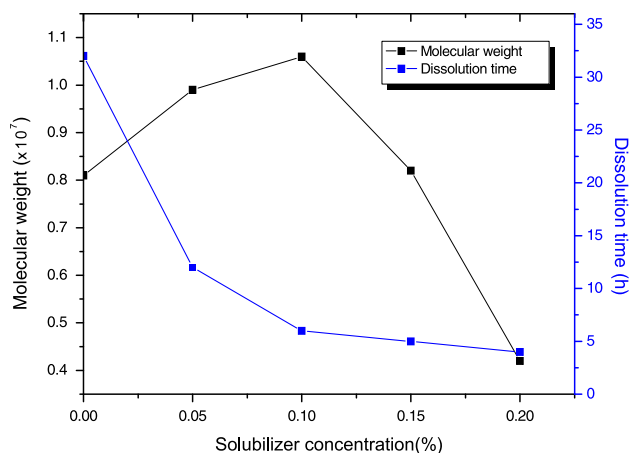
Fig. 7. Effect of the solubilizer on the MW and solubility.

Fig. 8. Effect of the time and pH on the MW.

amount of solubilizer. If the dosage of urea was insufficient, it takes part in the oxidation/reduction reaction as auxiliary reductant. The urea aids the "Kinetic Chain Length" growth for obtaining the higher MW product. However, excess urea increased the probability of chain transfer, which is not desired for producing a higher MW product.

The P(AM–DMC–DAC) dissolution time decreased with increasing solubilizer. Urea's active amide groups would react with large molecules' amide groups that effectively prevent the polymer cross-linking to take place, thus improving the product's water solubility. The addition of 0.10% of urea reduced the dissolving time from 36 h to 6 h whereas there was minimal change in the dissolving time as the amount of urea was increased above 0.10%. In addition, excess urea may influence the quality of the product. Based on the above, the amount of urea equaling 0.10% of the monomer weight was adopted as the optimum condition.

3.6. Effect of time and pH for MW

The effect of time and pH value on the reaction was investigated by setting AM/DMC/DAC as 6 g:2 g:2 g, setting initiator concentration as 0.40% of the monomer weight, $NaHSO_3/K_2S_2O_8$ as 0.8:1 (w/w), and urea as 0.10% of monomer weight. MW (Fig. 8) was determined for photopolymerization time in the range of 40–80 min and pH value of the aqueous solutions in the range of 6.0–10.0.

Fig. 8 shows that P(AM–DMC–DAC) with the highest MW of 1.24×10^8 was produced at pH value of 9.0 and reaction time of 60 min. The P(AM–DMC–DAC) MW increased with increasing photopolymerization time. Using UV to initiating the reaction, the
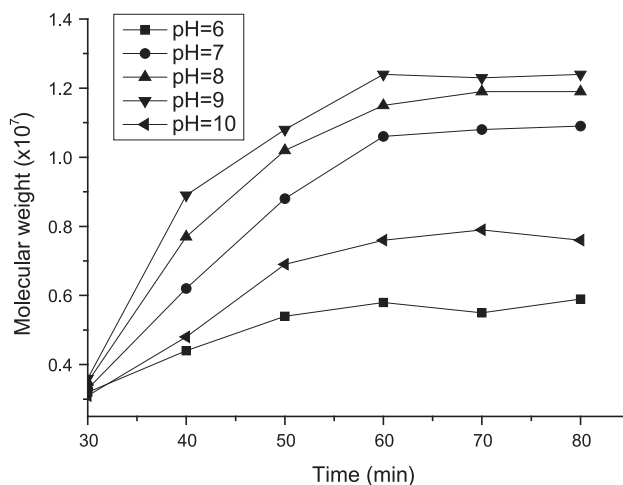
polymerization time was reduced from several hours to within an hour. The MW stabilized for photopolymerization with time period of more than 60 min. At high pH value, the decomposition rate of the photoinitiator improved resulting in changes to the structure of AM through hydrolyzing the AM's amido group while decreasing the activation energy of the reaction, thus improving the rate of polymerization. In addition, at high pH value, AM's amido hydrolysis into carboxyl increased the product viscosity. When the pH value attained 10.0, carbonium ion was instable. Considering the strong electrophile of carbonium ion, excess alkali is reactive to electrophilic reagent, which may inhibit polymerization and is not conducive for the product of cationic polyacrylamide. Based on the results listed above, pH value of 9.0 and reaction time of 60 min were adopted as the optimum conditions.

3.7. Effect of the component of P(AM–DMC–DAC) for MW and dewatering efficiency

The effect of the amount of monomers was investigated by setting initiator concentration as 0.40% of the monomer weight, $NaHSO_3/K_2S_2O_8$ as 0.8:1 (w/w), urea as 0.10% of the monomer weight, adjusting the pH value of the aqueous solution as 9.0, and photopolymerization time as 60 min. MW and dewatering (Table 1) were determined for varied weights of AM, DMC, and DAC. For dewatering test, the concentration of flocculants solution at 0.5 g/kg sludge was used.

According to Table 1, effect figure of cationic degree is depicted as follows:

Fig. 9(a) shows that as cationic degree increased, there was a gradual increase in the product MW. The

Table 1
Effect of varied weight of AM, DMC, and DAC

DAC:DMA:AM (w/w)	MW ($\times 10^7$)	Cationic degree (%) (mol/mol)	CMC (%)	Residual turbidity (NTU)
1:1:8	0.89	6.90	77.95	43.4
1.5:1.5:7	1.09	11.2	73.69	28.4
2:2:6	1.18	16.4	69.69	14.5
2:4:4	1.26	29.1	66.71	4.83
3:3:4	1.28	30.7	65.70	3.73
4:2:4	1.24	31.1	66.16	3.92
3.5:3.5:3	1.09	40.8	69.28	7.92
4:4:2	0.83	54.1	72.65	21.9
4.5:4.5:1	0.57	72.6	75.42	34.2

highest MW of 1.28×10^7 was achieved at cationic degree of 30.7%. It indicated if the cationic degree was low, content of AM with high activity was high, which would accelerate the rate of polymerization
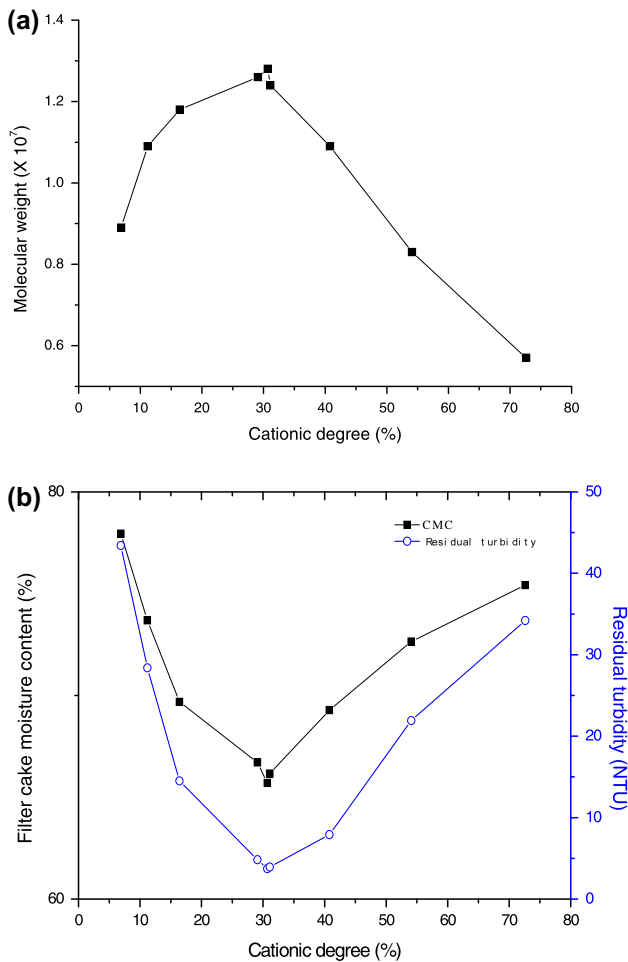
Fig. 9. Effect of cationic degree: (a) cationic degree for MW (b) cationic degree for CMC and residual turbidity.

and gel and cross-linking effect, resulting in decreased MW of the product. On the contrary, if the cationic degree was high, content of cationic groups with high activity was high, which caused the reaction induction period and the necessary waiting time before attaining the maximum polymerization temperature longer, resulting in incomplete monomer polymerization and decreased MW of the product [22]. Fig. 9(b) shows that with increasing cationic degree, the moisture content of the filter cake and filtrate turbidity decreased gradually until the cationic degree of 30%. In addition, as the cationic degree increased above 30%, there was an increase in filtrate turbidity and CMC. The reason is that with cationic degree of 30%, electrostatic repulsion was enhanced between polymer chain, resulting in polymer chain becoming more spread, which is good to effect the bridge; and high CD is more effective in the formation of flocs by surface charge neutralization [23]. However, CD above 30% was less effective in floc formation as there was a charge reversal by excess positive charge on the surface of sludge, resulting in repulsion between the particles and catioinc polyacrylamide (CPAM). Therefore, the best treatment efficiency was achieved at MW of 1.28×10^7 and cationic degree of 30.7%, where the CMC and filtrate residual turbidity were, 65.7% and 3.73 NTU, respectively.

3.8. Effect of coagulant dosage

The purpose of this experiment was to investigate the effect of the coagulant dosage on the surface charge of colloid, CMC, residual turbidity at sludge initial pH of 7.0, rapid agitation speed of 120 rpm, and rapid stirring time of 30 s [24]. The surface charge of colloid was determined according to the studies [25–27].

Fig. 10(a and b) illustrates the effect of coagulant dosage on CMC and residual turbidity. It shows that as the coagulant dosage increased, there was a gradual increase in the zeta potential value, and it almost reached the point of zero charge (0 mV) at a dosage of 1 g kg^{-1}. However, the zeta potential was positive for the dosages greater than 1.25 g kg^{-1}. In addition, Fig. 10 shows that with the increase of coagulant dosage, CMC, and residual turbidity decreased noticeably until the coagulant dosage of 0.5 g kg^{-1}. Furthermore, as the dosage increased above 1 g kg^{-1}, there was an increase in CMC and residual turbidity. CMC at a dosage of 0.5 g kg^{-1} was approximately the same as with the dosage of 1 g kg^{-1}, where the CMCs were 65.7% and 63.5%, respectively. Based on the dewatering efficiency while with the same time considering costs, the optimum dosage ranged from 0.5 g kg^{-1} to 1 g kg^{-1}. The best treatment efficiency was achieved at
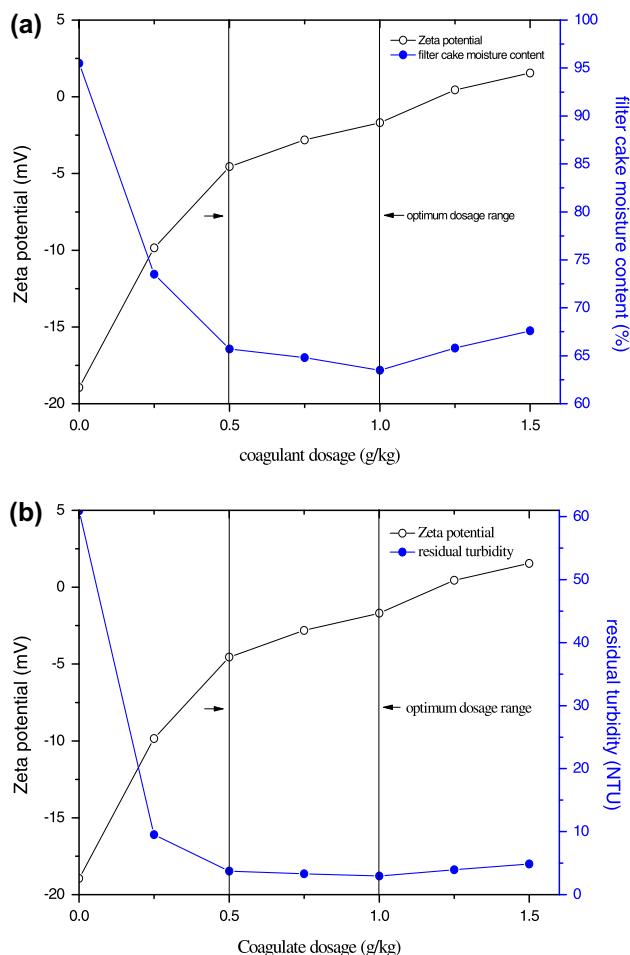
Fig. 10. Effect of coagulant dosage on zeta potential and (a) CMC (b) residual turbidity.

the formation of the ternary copolymerized cationic copolymers and the results for TGA analysis indicated that the copolymer had a favorable thermal stability. The SEM images suggested that the P(AM–DMC–DAC) had better adsorption/bridging ability than P(AM–DAC), which would result in a considerable dewatering performance during the sludge dewatering. The dosage experimental results showed that the surface charge of colloid was reduced up to $-1.68\,\text{mV}$ when the dewatering reagent dosage was $1\,\text{g kg}^{-1}$, meanwhile, the minimum CMC and turbidity of 63.5% and 2.95 NTU were achieved. The charge neutralization and the adsorption/bridging mechanisms played an important role in sludge dewatering performance.

Generally speaking, P(AM–DMC–DAC) is a novel sludge dewatering reagent with high efficiency and promising prospect for development. The next steps would be pilot test and economic feasibility research to provide technical support for its real application.

Abbreviations

AM	—	acrylamide
DMC	—	methacryloxyethyltrimethyl ammonium chloride
DAC	—	acryloxyethyltrimethyl ammonium chloride
FT-IR	—	fourier transform infrared spectroscopy
CPAM	—	cationic polyacrylamide
TGA	—	thermal gravimetric analysis
SEM	—	scanning electron microscopy
CD	—	charge density
MW	—	molecular weight
UV	—	ultraviolet
CMC	—	filter cake moisture content

the dosage of $1\,\text{g kg}^{-1}$, where the zeta potential values, CMC, and turbidity were $-1.68\,\text{mV}$, 63.5%, and 2.95 NTU, respectively. Based on the above, the charge neutralization played an important role in reducing the surface charge of colloid in the sludge dewatering.

4. Conclusions

The present work was aimed to present an experimental study on sludge dewatering treatment using cationic polyacrylamide as a modified dewatering reagent. Firstly, the cationic polyacrylamide (P(AM–DMC–DAC)) was prepared and characterized by some conventional methods such as FTIR, differential TGA, and SEM. The results showed that at the optimum conditions that the photoinitiator, solubilizer, inducing time, pH, and AM/DMC/DAC were 0.40%, 0.10%, 1 h, 9.0, and 4:3:3, respectively; it showed a strong sludge dewatering performance with higher MW of 1.28×10^7 and cationic degree of 30.7%. The IR analysis showed

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