Environmental Science and Pollution Research (2021) 28:12613–12627
https://doi.org/10.1007/s11356-020-11242-9

RESEARCH ARTICLE

Solidification effect of river bottom sediments after flocculation via different composite flocculants

Linzhu Sun[1] · Yunyun Zheng[1] · Xiaoniu Yu[1,2]

Received: 11 July 2020 / Accepted: 12 October 2020 / Published online: 21 October 2020

Abstract
The main problem in the reduction of river bottom sediments is to solve the dewatering of the rive sediments. The reduction of river bottom sediments is usually dehydrated by natural air drying and requires more time and economic costs. Different proportions of composite flocculants and curing agents have been developed to the reduction of river bottom sediments according to the requirements of the project. Two or more flocculants were mixed with the rive sediments. Therefore, anionic polyacrylamide (PAM), polyaluminum chloride (PAC), polysilicate aluminum ferric (PSAF), and iron perchloride (IC) were selected for flocculation of river sediments. Through the sedimentation column test, the relationship between sedimentation amount and time was plotted, the turbidity value and pH value of the supernatant filtration supernatant were detected, and the flocculation effect of different flocculants was evaluated to obtain suitable groups of composite flocculants. The optimum ratio of two types of polyacrylamide with a molecular weight of 18 million and 23 million was 3:7. The turbidity of the supernatant of water could well be reduced by adding polysilicate aluminum ferric. Finally, the 6 groups of composite flocculants were determined according to the sedimentation and the turbidity value of the supernatant. The relative water content was maintained at about 60% before and after flocculation. At the same curing age, the compressive strength increased as the amount of curing agent increased after flocculation. At the same curing agent dosage, the overall solidification effect was reduced with increase of curing time after flocculation.

Keywords River bottom sediments · Flocculants · Turbidity value · Flocculation effect · Solidification effect

Introduction

The water in the sludge is in the form of bound water (Wang et al. 2019; Liang et al. 2020). The flocculation method of the river sediments is to discharge bound water between soil particles. The bound water is also called free water and exists between the flocs, which can be extruded from the flocs by mechanical dewatering (Wang et al. 2019). The flocculation agent can be used to encapsulate the colloid, solute, or particles suspended in the solution into a flocculent precipitate (solid-water separation), and can function as a purifying solution (Zhai et al. 2012; Niu et al. 2013; Zhao 2002). The void structure in the mud can be improved, the filtration channel can be increased by flocculation, and finally, the rapid dewatering to reduce the volume and mass of sludge by the filter press equipment will become the main method for treatment of river bottom sediments (Yuan et al. 2011; Lin et al. 2019; Lv et al. 2019; Wu et al. 2016; Chen et al. 2020). River sludge can be used for making brick, filling material, and road construction material by mixing curing agent after flocculantion (Lafhaj et al. 2008; Samara et al. 2009; Liu et al. 2018).

There are many classification methods for flocculants, which are divided into organic and inorganic flocculants according to their composition (Huang et al. 2020). Inorganic salt flocculants have been studied and developed for a long time and are now widely used in industry. According to the molecular weight of inorganic flocculants, it can be divided into two categories: low-molecular weight and high-molecular flocculants. Among them, low-molecular inorganic flocculants, which are low in price, rich in source, and easy to transport, still occupy a certain proportion

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Responsible Editor: Philippe Garrigues

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11356-020-11242-9) contains supplementary material, which is available to authorized users.

✉ Xiaoniu Yu
xnyu@wzu.edu.cn; xnyu09@163.com

[1] College of Civil Engineering and Architecture, Wenzhou University, Wenzhou 325035, China

[2] School of Environment, Tsinghua University, Beijing 100084, China

Table 1 Physical property of river sediments

Project No.	pH	Sand (%)	Dry matter (%)	Loss on ignition (%)	Organic matter (%)
N1	7.32	4.4	40.8	8.93	2.79
N2	7.54	4.08	39.5	8.56	2.76
N3	7.41	3.75	41	9.35	2.92
Mean	7.42	4.08	40.43	8.95	2.82

in industrial water treatment. However, large amount of residue and poor effect, the development of inorganic flocculants has basically gone from low molecular to high molecular due to large amount of use (Wang et al. 2019). At present, inorganic polymer flocculants commonly used are aluminum salts and iron salts (Niu et al. 2013). Compared with inorganic flocculants, organic polymer flocculants have low amount added, many types, obvious effects, and wide application range, and they produce large flocs, fast sedimentation speed, and short processing time. Sludge pollution can be handled easily after flocculation. Generally, organic polymer flocculants can be divided into two types: synthetic organic polymer flocculants and naturally modified polymer flocculants. The flocculation process and mechanism of organic polymers are a very complicated process, and its interpretation has many limitations. Organic polymer flocculants have a plurality of reactive functional groups, and multiple points in the molecular chain can be adsorbed on the surface of the particles (Suresha and Badiger 2019). Inorganic-organic polymer flocculants can save the dosage of flocculants, thus reducing the cost of sludge flocculation (Wang et al. 2019).

The flocculation effect of alum is mainly reflected in the influence of the aluminum hydroxide obtained by alum hydrolysis on the sludge character (Bache and Papavasilopoulos 2003). The relationship between the physical properties and the dewatering performance of flocs after flocculation shows that the test only obtains a weak relationship between the size and the optimum amount of flocculants, it is not difficult to find that the best dewatering performance is not obtained when the effective density and compactness of flocs are maximum (Zhao 2003). The size of iron salt flocs is smaller than that of aluminum salt flocs under the same control conditions, that is, the floc structure composed by iron salts can produce more free water, and the combined water content is less (Turchiuli and Fargues 2004). Therefore, the dewatering efficiency of sludge is high. In the paper, anionic polyacrylamide (PAM), polyaluminum chloride (PAC), polysilicate aluminum ferric (PSAF), and iron perchloride (IC) were selected to dehydrate river sediments. Next, two or more flocculants are mixed with river sediments. Finally, the 6 groups of composite flocculants were determined according to the sedimentation and the turbidity value of the supernatant in the sludge. River sediments could be solidified by the curing agent after flocculation.

Experiment and methods

Materials

River sediments were taken from the river section of the Hualong bridge in Wenzhou, China. Table 1 shows that the pH, average content of sand, dry matter, loss on ignition, and organic matter were 7.42, 4.08%, 40.43%, 8.95%, and 2.82%, respectively. Mineral composition of the sediments was analyzed by Philips PW 1400 spectrometer. Average contents of SiO_2, Al_2O_3, K_2O, Na_2O, CaO, and MgO were 60.04%, 16.87%, 2.47%, 0.53%, 1.16%, and 1.63% in the river sediments, respectively, as shown in Table 2. Polyacrylamide, polyaluminum chloride, chlorinated high iron, polymeric aluminum silicate iron, etc. were used in this study. Among them, polyacrylamide adopts ionic type as anionic polyacrylamide, and the molecular weight was 18 million and 23 million, regards as PAM-1 and PAM-2, respectively. Chemically pure of polyaluminum chloride (PAC-s) and analytical pure of iron perchloride (IC) were used and produced by Shanghai Zhanyun Chemical Co., Ltd. Polyaluminum chloride (PAC-h) was used and produced by Hefei Zicheng Environmental Protection Technology Co., Ltd. Polysilicate aluminum ferric (PSAF) was made by Henan Taiyuan Environmental Protection Technology Co., Ltd.

The cement in the curing test was ordinary Portland cement with a strength grade of P·O 42.5 and had a sieve balance of 2.90% through a 0.080-mm square hole sieve (China Jiande Sanshi Songtao Cement Co., Ltd.). The grade of fly ash was level II and purchased from China Wenzhou Jielong Insulation Material Co., Ltd. Lime was hydrated lime, produced by China Yiyang Zhenxin Chemical Co., Ltd. Bentonite was produced from Hexing Bentonite Factory,

Table 2 Determination of mineral content (%) in the sediments

Project No.	SiO_2	Al_2O_3	K_2O	Na_2O	CaO	MgO
N1	59.91	16.93	2.22	0.53	1.16	1.67
N2	60.03	16.83	2.95	0.54	1.23	1.65
N3	60.19	16.86	2.24	0.53	1.1	1.58
Mean	60.04	16.87	2.47	0.53	1.16	1.63

Table 3 Technology indicators of the mineral powder

Specific surface (m^2/kg)	Flow ratio (%)	Ignition loss (%)	Moisture content (%)	Chloride ion content (%)	Sulfur trioxide content (%)	Density (g/cm^3)
≥ 350	≥ 90	≤ 2.0	≤ 1	≤ 0.02	≤ 4.0	≥ 2.8

Anji County, Zhejiang Province, China. The mineral powder was purchased from a material processing plant in Wenzhou, China. Sodium sulfate was purchased from Zhejiang Zhongxing Chemical Reagent Co., Ltd., China. The technical indicators of mineral powder and ordinary Portland cement are shown in Tables 3 and 4. The curing agent was mainly composed of eight materials: mineral powder (48 g), fly ash (17 g), ordinary Portland cement (18 g), gypsum (9 g), lime (2.75 g), bentonite (yellow, 4 g), sodium sulfate (1 g), lignin (0.25 g), respectively. The mineral powder and fly ash are solid waste, which not only reduces the cost of solidification treatment but also utilizes solid waste. Therefore, the price of these materials was reasonable. In this test, the degree of water purification was considered by different flocculants, and quickly and accurately detected the turbidity of the water in the river sediments after flocculation. The turbidity of the supernatant was determined by the portable turbidity meter and was purchased from the American HACH Company (HACH 2100Q) and Shanghai Anting Electronic Instrument Factory, China (WZS-1000). The two instruments were used to detect the turbidity of the water, and finally obtained the average value of the two instruments, which could reduce instrument and measurement errors, ensure the validity of turbidity data, and improve measurement accuracy. The compressive strength test was carried out using the YAW-300 compressive strength tester at a rate of 2.4 mm/min. All tests were performed three times, and the arithmetic mean was plotted.

Content of flocculant materials

Content of flocculants materials is shown in Table 5. Table 6 shows the percentage of the mass of flocculants to the total mass of river sediments. The A, B, C, D, and E represent different content, types, and place of production of polyacrylamide, and L represents polysilicate aluminum ferric.

Table 4 Technology indicators of ordinary Portland cement

3 days of flexural strength (Mpa)	3 days of compressive strength (Mpa)	28 days of flexural strength (Mpa)	28 days of compressive strength (Mpa)
5.2	24.9	7.8	47.6

Table 5 Content of flocculants materials

No.	PAM-1	PAM-2	PSAF	Total content
A	1	-	-	1
B	-	1	-	1
C	0.5	0.5	-	1
D	0.3	0.7		1
E	0.7	0.3		1
L			1	1

The F, G, H, K, and M groups represented second time mix after the selection of PAM in the best effect after the end of the A–E group test (denoted as the Q group), as shown in Table 7. Flocculants used in the group F was compounded with the group Q and PAC-h. Flocculants used in the group G was compounded with the group Q and PAC-s. The group H was compounded the group Q and IC. The group K indicated that the Q group was compounded with the PSAF. The M group showed that the Q group was compounded with the lime.

In addition, the J, N, and P groups indicated that optimum formula was obtained after second compounding, and finally, the best formula of composite flocculants was obtained, as shown in Table 8. The group J indicated that the best PAC obtained from the F/G groups was compounded with Q and IC. The N group indicated that the Q group was compounded with the best K group and the best lime. The P group indicated the Q group was compounded with the best F/G group and lime. Finally, the best composite flocculants and materials

Table 6 Content of flocculants

No.	Content (%)	No.	Content (%)	No.	Content (%)
A0	0.02	C0	0.02	E0	0.02
A1	0.04	C1	0.04	E1	0.04
A2	0.08	C2	0.08	E2	0.08
A3	0.12	C3	0.12	E3	0.12
A4	0.16	C4	0.16	E4	0.16
A5	0.20	C5	0.20	E5	0.20
B0	0.02	D0	0.02	L0	0
B1	0.04	D1	0.04	L1	0.025
B2	0.08	D2	0.08	L2	0.15
B3	0.12	D3	0.12	L3	0.30
B4	0.16	D4	0.16	L4	0.60
B5	0.20	D5	0.20	L5	1

Table 7 Composition of composite flocculants

No.	PAC-s	PAC-h	IC	PSAF	Lime
F	-	√	-	-	-
G	√	-	-	-	-
H	-	-	√	-	-
J	-	√	√	-	-
K	-	-	-	√	-
M	-	-	-	-	√
N	-	-	-	√	√
P	-	√	-	-	√

ratio were obtained according to the comprehensive use cost and environmental pollution of flocculants.

Determination of the water content of river sediments

The drying method could be used to measure the water content in the river sediments. Firstly, the mass of the box was recorded as m_0. The 10–30 g of the river sediments was placed in the weighing box. At the same time, the mass of the river sediments in the box was recorded as m_1, accurate to 0.01 g. Secondly, the box was placed in an oven and the temperature was set to about 110 °C. The river sediments in the box were baked to a constant amount under a constant temperature, and the drying time should be greater than 8 h. Finally, the weighing box was taken out of the oven, and the box and dry soil quality was recorded as m_2, accurate to 0.01 g. The water content of the sample (w_1) was calculated by the following Eq. (1) to be accurate to 0.1%. Equation (1) was as follows (Zhu et al. 2013):

$$w_1 = \frac{m_1 - m_2}{m_1 - m_0} \times 100\% \tag{1}$$

in where w_1 represents relative water content; m_0 is the mass of aluminum box, g; m_1 is total mass of aluminum box and river sediments, g; m_2 is total mass of aluminum box and dried soil, g.

Consolidation of river sludge after flocculation

Firstly, the flocculated river sludge was mixed with different amount of composite curing agent and stirred for 5 min until the mixture was homogeneous. Next, the uniformly stirred mixture was placed in a previously prepared mold (70.7 mm × 70.7 mm × 70.7 mm) for molding. After 3 days, all samples were demolded and covered with geotextile for curing, so that the indoor temperature and humidity (temperature 20 ± 2 °C, humidity above 90%) met the maintenance requirements. The compressive strength of the samples was carried out after 7, 14, and 28 days.

Results and discussion

Relationship between time and sedimentation amount

Figure 1 shows that the maximum settlement of the comparison group was 30 ml when the settling time was 1000 min.

Table 8 Content of composite flocculants

No.	Content (%)	No.	Content (%)	No.	Content (%)	No.	Content (%)	No.	Content (%)
F0	0	G0	0	H0	0	M0	0	K0	0
F1	0.0016	G1	0.0016	H1	0.03	M1	0.03125	K1	0.025
F2	0.0039	G2	0.0039	H2	0.05	M2	0.0625	K2	0.05
F3	0.0063	G3	0.0063	H3	0.10	M3	0.125	K3	0.10
F4	0.0086	G4	0.0086	H4	0.30	M4	0.25	K4	0.15
F5	0.0109	G5	0.0109	H5	0.50	M5	0.5	K5	0.30
F6	0.0133	G6	0.0133	H6	1	M6	1		
F7	0.0156	G7	0.0156	P0	0				
J0	0	N0	0	P1	0.03125				
J1	0.03	N1	0.03125	P2	0.0625				
J2	0.05	N2	0.0625	P3	0.125				
J3	0.10	N3	0.125	P4	0.25				
J0	0	N4	0.25	P5	0.5				
		N5	0.5						
		N6	1.0						

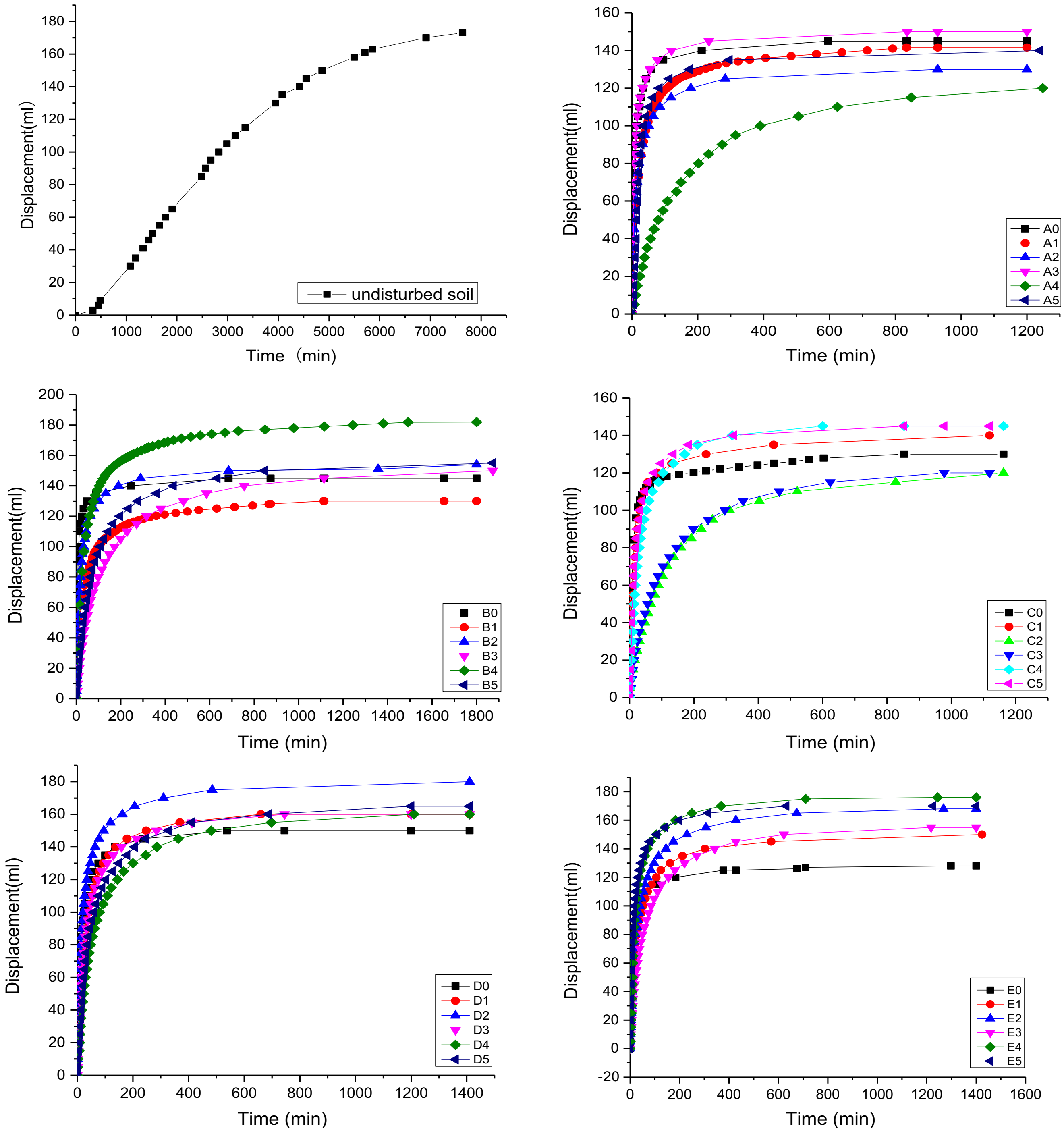


Fig. 1 Time-sedimentation curves of the A–E groups

After 8000 min, the sedimentation tends to stabilize and the final sedimentation amount is 230 ml. It was not difficult to find that the sedimentation rate without the flocculants was seriously affected by the reuse of sludge in the actual project in the later stage. According to the different types of flocculants, the sedimentation column test under different dosages was studied. The A3 is the most suitable dosage in the A series, and the dosage is 0.12%. Because the difference between B4 and B2 is too large, but the amount of polyacrylamide in the B4 group was too large, the B2 and B4 groups in the B series were considered to be suitable dosage, which was 0.08% and 0.16%, respectively. The dosages of the C4 and C5 were 3–4 times of the C1 group. The comprehensive dosage, cost, and treatment effect are considered.

The suitable dosage in the group C was the C1, and the total dosage of polyacrylamide was 0.04%. The optimum amount of the D series was recorded as the D2, and the total amount of polyacrylamide was 0.08%. Due to the excessive use of polyacrylamide, it would cause environmental pollution, the appropriate dosage in the group E was the E2, and the dosage is 0.08%. According to the best flocculation effect in the test A–E systems was the A3, B2, B4, C1, D2, and E2. The combination and dosage of polyacrylamide are shown in Table 9.

The relationship between the sedimentation time and the sedimentation amount of the A3, B2, B4, C1, D2, and E2 is shown in Fig. 2. The sedimentation of the D2 and B4 reached about 180 ml, and the sedimentation velocity of D2 was significantly faster than that of B4 before 500 min. The other groups were not comparable to the two flocculants in terms of sedimentation and sedimentation velocity. The D2 group was reduced by half compared with the E4 group. The reduced amount can effectively reduce the environmental pollution, and 30% PAM-1 was used instead of PAM-2 to reduce the cost. Therefore, the best way to add polyacrylamide was to blend PAM-1 with PAM-2 in a ratio of 3:7 with a total incorporation of 0.08%.

Figure 3 shows time-sedimentation curves of F, G, H, J, K, L, M, N, and P groups. The settlement and sedimentation velocity of the F6 group were significantly better than those of the other groups, in which the sedimentation amount reached 165 ml, and the amount of polyaluminum chloride was 0.0133%. The sedimentation amount and velocity of the G6 group were significantly better than other groups, in which the sedimentation amount reached 165 ml, and the amount of PAC was 0.0133%. It can be seen from the F and G series tests that the optimum amount of polyaluminum chloride was 0.0133%, and the sedimentation amount was 165 ml. Comparing F6 and G6, the overall sedimentation velocity of the F6 group was higher than that of the G6 group, as shown in Fig. 4. Therefore, the PAC-h was selected in the combination with the polyaluminum chloride in the later stage.

The sedimentation amount and velocity of the H0 group were significantly better than other groups, but it indicated that the IC was not incorporated into the blank group of PAM, and the other groups were far lower than the H0 group. The J0 indicated that the high concentration was not incorporated. The IC was only incorporated into the blank group of PAM and PAC. The remaining groups doped with the IC were much lower than the J0. Tests of the H and J series showed that the addition of PAM and IC had no significant effect on the flocculation speed and the water output, but the purification of water quality was improved. The incorporation of PAM and IC into PAC could slightly increase the water output, but the treatment effect was not good.

Table 9 Combination method and dosage of flocculants

No.	Combination method	Content (%)
A3	PAM-1	0.12
B2	PAM-2	0.08
B4	PAM-2	0.16
C1	PAM-1:PAM-2=1:1	0.04
D2	PAM-1:PAM-2=3:7	0.08
E2	PAM-1:PAM-2=7:3	0.08

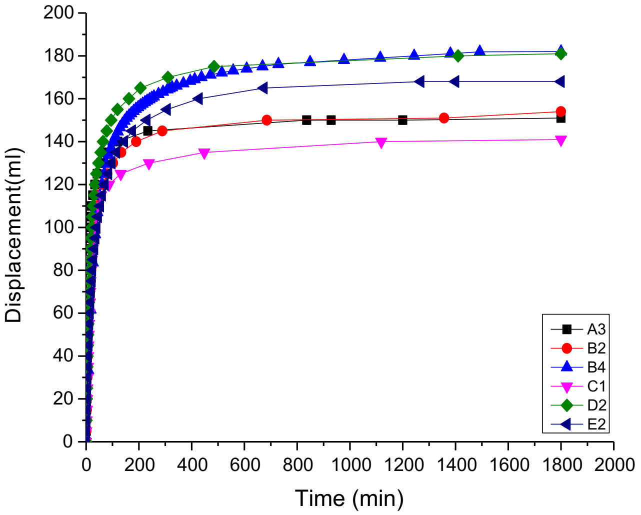


Fig. 2 Time-sedimentation curves of the A3, B2, B4, C1, D2 and E2

The results of the flocculation sedimentation test in the group L were within 3 days, and the group L indicated the PSAF was used. Figure 4 shows that the flocculation time of PSAF was longer and the flocculation effect was not obvious. The fastest flocculation rate was the L3, and the final settlement amount was 121 ml. The maximum settlement was the L2 group reached 124 ml and had not reach 60% of the maximum sedimentation amount. Therefore, the flocculation effect of the PSAF alone was inferior. In order to further investigate the flocculation characteristics of the PSAF, the K series test was carried out, in which a certain amount of PAM was incorporated, and then the PSAF was incorporated. The K0 and K2 groups were very similar in flocculation effect, according to Fig. 3, it was not difficult to find that the effect of the K2 group in purifying water quality was better than that of the K0 group (171 ml). At the same time, the sedimentation amount was175 ml when the K2 reached stability. The treatment effect of two flocculants composites was significantly better than that of the PSAF alone, and the optimum amount was 0.05%. Under the optimum dosage, the flocculants are continuously compounded, that is, a certain amount of lime was added, and the treatment effect of the composite flocculants was continuously discussed.

N0 means that no lime is incorporated, and only a blank group of PAM and PSAF was incorporated. The remaining group of lime was lower than the N0, the settlement of the N0 was 175 ml, and the other highest settlement of N series is 165 ml. At the same time, the curve

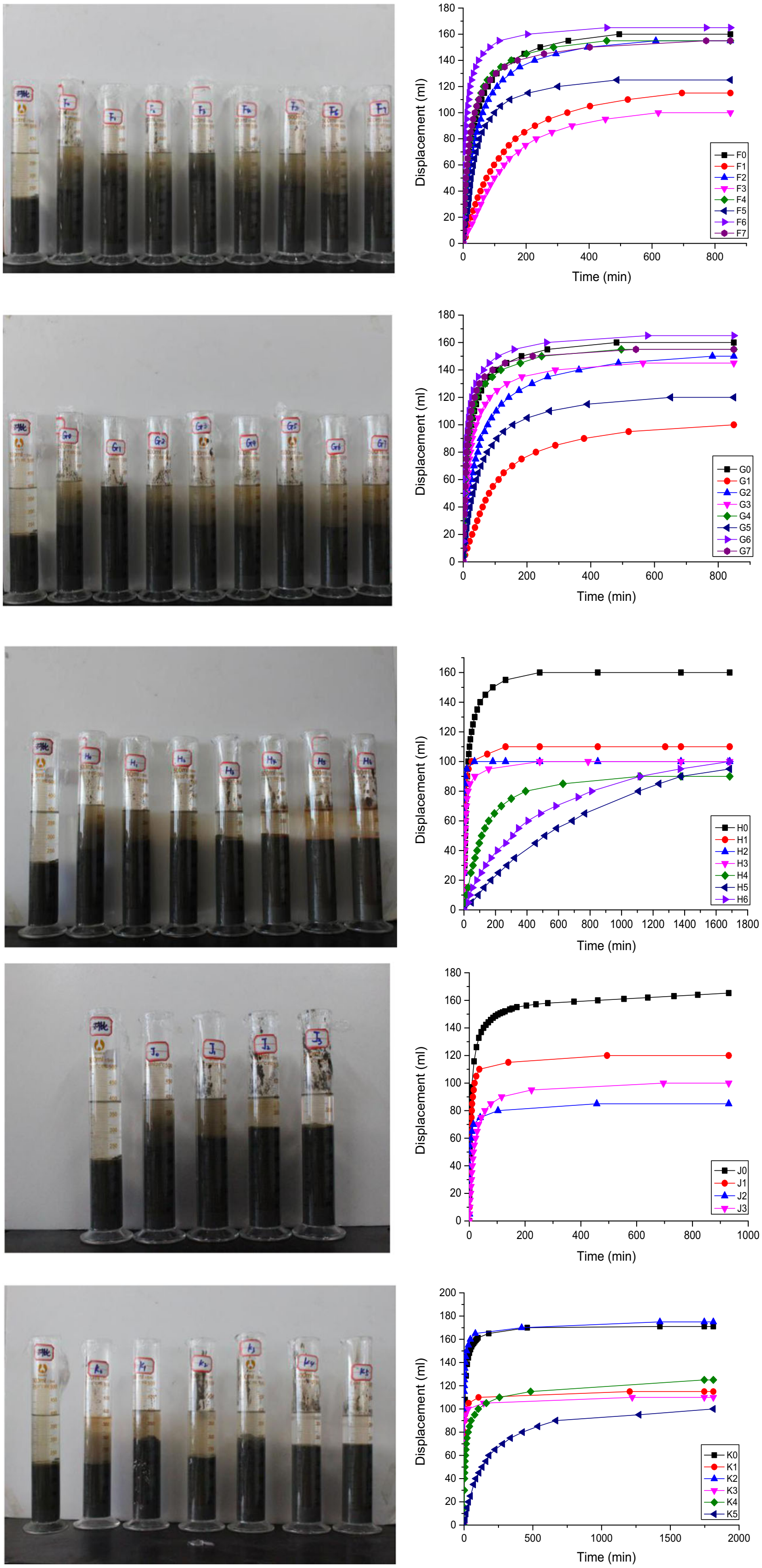


Fig. 3 Time-sedimentation curves of the F, G, H, J, K, L, M, N, and P groups

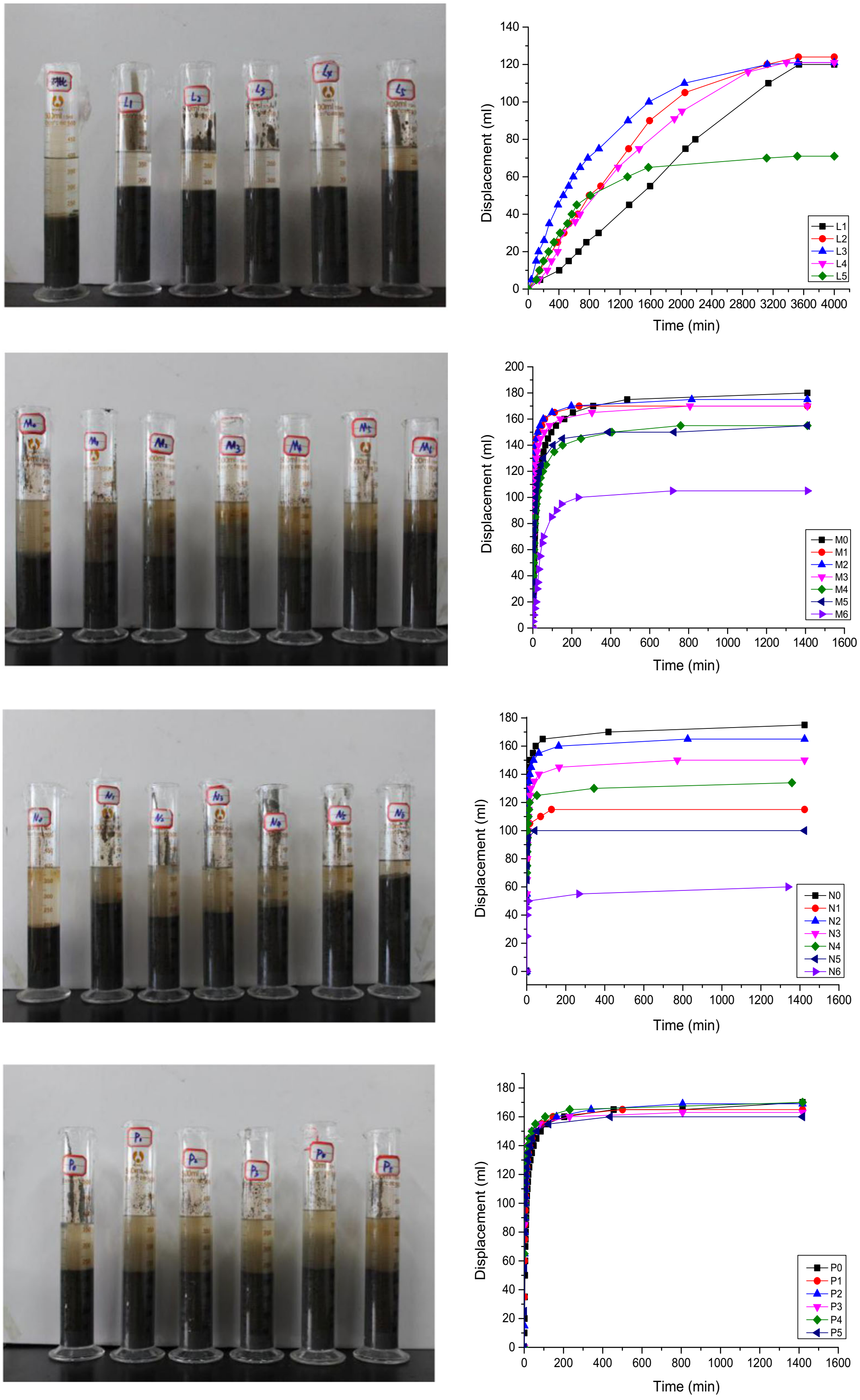


Fig. 3 (continued)

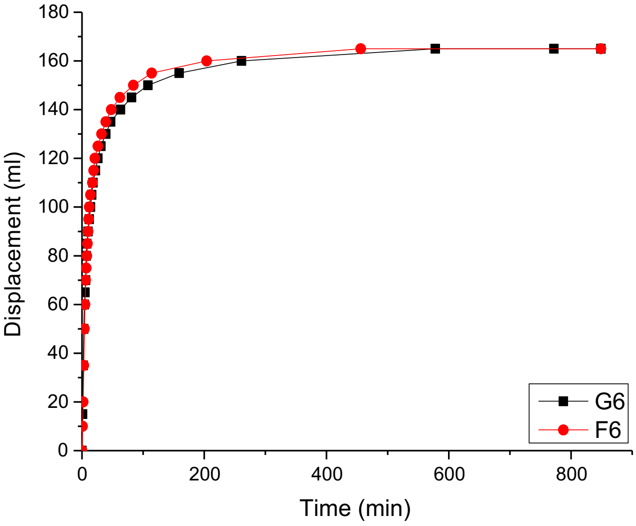


Fig. 4 Time-sedimentation curves of the F6 and G6

of N0 was the steepest and the sedimentation speed was the fastest before 200 min, so the addition of lime could not improve the sedimentation speed and flocculation effect, and could only achieve the effect of purifying water quality. Before 200 min, the curve of M2 was the steepest and the sedimentation speed was the fastest. At this time, the lime content was 0.0625%, but the final settlement was still lower than the M0, so the addition of lime could not significantly improve the sedimentation speed and flocculation effect. The P series indicated that the above-mentioned optimum PAM and PAC were incorporated and the added amount of lime and the flocculation effect were discussed. Figure 5 shows that the incorporation of lime had little effect on the displacement of the composite flocculants. The sedimentation of the 6 groups was between 160 and 170 ml. The settling velocity of each group in the first 200 min was basically the same by the mixing of lime. The flocculation effect of lime in the system was not significant.

Sedimentation amount and turbidity

Figure 5 shows the sedimentation amount and turbidity for each group when the settling column test reached stability. The overall turbidity of the B series was lower than that of the A series, and the turbidity was the highest when the average content was 0.08%, and the turbidity was the lowest when content was 0.02%. The increase in the amount of a single series of PAM did not have much effect on the reduction of turbidity. The average sedimentation of the A series was 138 ml with a standard deviation of 10 and a mean turbidity of 262 NTU with a standard deviation of 50.4. The average sedimentation of the B series was 153 ml with a standard deviation of 15.5 and a mean turbidity of 218 NTU with a standard deviation of 82. The overall sedimentation of PAM-1 was lower than that of PAM-2, and the turbidity was higher than that of PAM-2, but its overall discrete type was small and the turbidity was more stable. The average sedimentation of the C series was 134 ml with a standard deviation of 10.7 and a mean turbidity of 273 NTU with a standard deviation of 80.8. The D series has an average sedimentation of 163 ml, a standard deviation of 9, and a mean turbidity of 154 NTU with a standard deviation of 61.3. The average sedimentation of the E series was 158 ml with a standard deviation of 16 and an average turbidity of 231 NTU with a standard deviation of 64.5. The turbidity values of D series were much lower than those of A, B, C, E, and F series, which are 41%, 30%, 43%, and 33%, respectively. Therefore, the average sedimentation amount, turbidity, and discrete type can also obtain the best effect of polyacrylamide obtained when PAM-1 and PAM-2 are mixed according to 3:7. The overall discrete type is small, the turbidity, and more stable.

Groups F and G discussed the optimum amount of PAC on the basis of the D2 group. It could be clearly seen from Fig. 6 that the turbidity of both series reached the lowest value when the dosage was 0.0109%. At this time, sedimentation value of the F series was 125 ml, and G series was 120 ml. When the dosage is 0.0133%, the sedimentation of both series reaches the maximum value. At this time, the F series of turbidity was 216 NTU, and the G series of turbidity was 220 NTU. The addition of PAC also reduced the turbidity of the D series. Considering the combination of F series polyacrylamide and polyaluminum chloride, it could be used as a composite flocculants.

On the basis of the D2, the H group discussed the addition amount of IC and the flocculation effect. Figure 8 shows the addition amount of the IC and the flocculation effect on the basis of the F6 group. Figure 6 indicates that the incorporation of the IC could significantly reduce the turbidity of the turbidity upper layer solution (compared with the H0 and J0), and the maximum decrease was 97.3%, which was reduced from 300 NTU to 8.1 NTU. Figure 6 shows the addition of polyacrylamide and ferric chloride. When the amount was less than 0.05%, the incorporation of ferric chloride only reduced the turbidity of the solution by 37.6–54.7% and continued to increase the amount of IC, and the turbidity was significantly decreased, with a maximum reduction of 96.7%. The group J indicated the incorporation of polyacrylamide, polyaluminum chloride, and IC. It can be found that the amount of IC was increased, and the turbidity of the solution was continuously reduced to 8.1 NTU. However, the average sedimentation of the H series was 100 ml, and the average settlement of the G series was 118 ml from the perspective of flocculation, which was far lower than the sedimentation amount not added into the IC series, so the IC was not considered as flocculation of the composite flocculants.

The L group was the sedimentation amount and the turbidity test results of the PSAF alone show that the PSAF could significantly reduce the turbidity, and the reduction was about

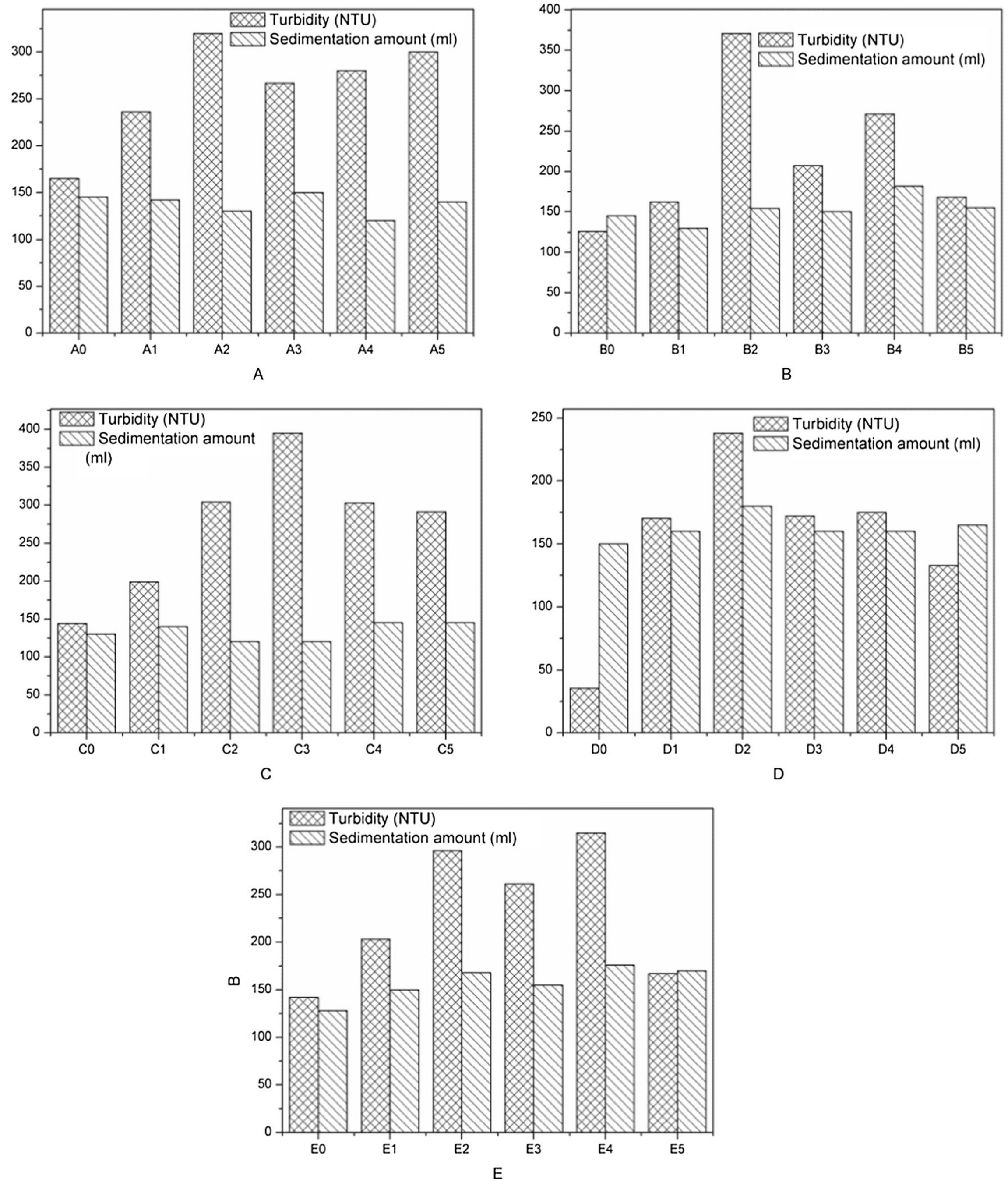


Fig. 5 Turbidity and sedimentation amount of A–E groups

97.5%, but it was also greatly reduced sedimentation amount of flocculation, and was reduced to a maximum of 71 ml with a 60% drop. In order to further investigate the flocculation effect of PSAF, the K series discussed the test results of PSAF on the basis of the D2 group. Among them, the turbidity decreased continuously, from the initial 234NTU to 8.1NTU, the reduction reached 96.6% with the addition of PSAF. From the sedimentation amount, the sedimentation amount of the K2 group was increased compared with the blank group. Continuing to add lime to the K2, and the N group was obtained after adding lime. It can be seen that the effect of lime content on the reduction of turbidity was obvious, and the influence on the settlement amount was also large. In summary, the flocculation effect of the PSAF alone was poor, and the flocculation effect was improved after compounding with polyacrylamide. Therefore, the PSAF could be used as one of composite flocculants materials.

The M series indicated that the effect of lime addition on the sedimentation amount and turbidity was discussed on the basis of the D2. When the lime content exceeded 0.125%, the

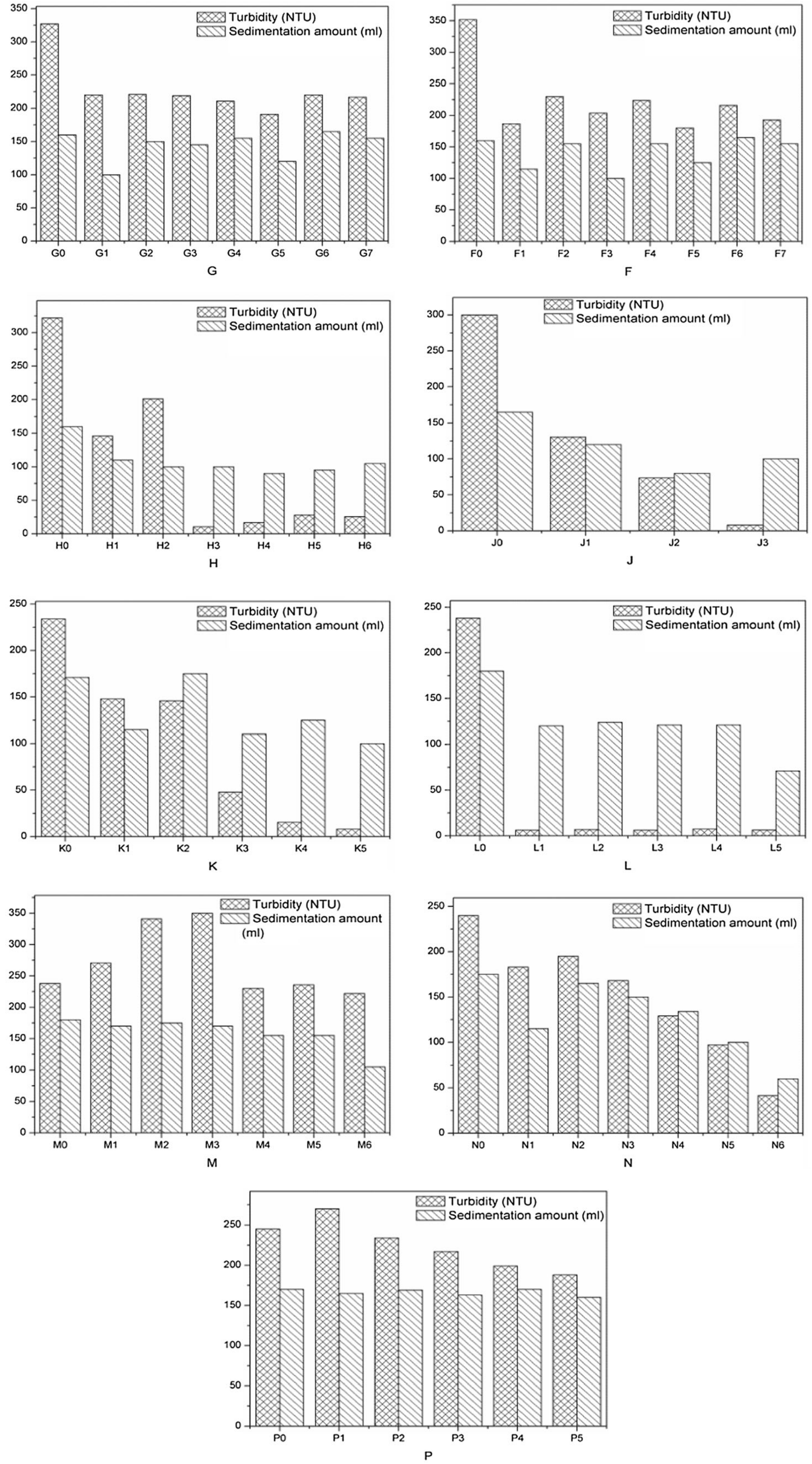


Fig. 6 Turbidity and settlement of G, F, H, J, K, L, M, N, and P groups

turbidity was improved, but it was not obvious, and the effect of flocculation and sedimentation was not improved. The group P indicated that the effect of lime addition on the sedimentation amount and turbidity was also discussed the basis of the D2 group. Figure 6 shows that the addition of lime had little effect on the displacement of the composite flocculants system, and the sedimentation amount after the addition was more than 160 ml. As the added amount of lime increased, the turbidity continued to decrease, with a maximum drop of 24%. In summary, the lime could be considered as one of the materials of the third composite flocculants.

According to the test of F, G, H, J, K, L, M, N, and P groups, 6 kinds of composite flocculants with obvious flocculation effect were selected from the settlement, sedimentation speed, and turbidity, as shown in Table 10. The no. 5 of composite flocculants had the lowest price and could meet actual engineering needs by comparison.

Flocculation process of inorganic-organic flocculants

Flocculation process of inorganic-organic flocculants is shown in Fig. 7 (Wang et al. 2019). The negatively charged river sediment was electrostatically combined with cationic flocculants or the cationic organic polymer flocculants. Electrostatic repulsion occurred between excess cations, which increased pore channels. The effect between the negatively charged river sediment and the non-ionic organic polymer flocculants was mainly through the hydrophobic group in the organic polymer flocculants chain embedded in the single soil particles to release the bound water. Inorganic-organic flocculants flocculate the river sediments mainly by the electrostatic repulsion between the inorganic ions and the organic group embedded in the single soil particles to increase the pore channel, and discharged the bound water under the mechanical dewatering.

Water content

Before the test, the soil sample was tested for the relative water content. After the test, the flocculation test was carried out. After the flocculation, the relative water content was again detected on the river sediments. The test results are shown in Fig. 8. Due to the randomness of each sampling, there was a slight error in the initial water content of each group of experiments, but the initial water content of the river sediments was maintained at about 60%. After sampling, the flocculation test was carried out. After the flocculation test, the river sediments were filtered and the water content was measured after 2~3 h. The water content after flocculation was maintained at about 60%, as shown in Fig. 8. Therefore, the relative water content was about 60% before and after flocculation.

Table 10 Combination method and dosage of composite flocculants

No.	PAM (%)	PAC-h (%)	PSAF (%)	Lime (%)
1	0.08	0.0133	-	0.0625
2	0.08	-	-	0.0625
3	0.08	-	0.05	0.0625
4	0.08	-	0.05	-
5	0.08	-	-	-
6	0.08	0.0133	-	-

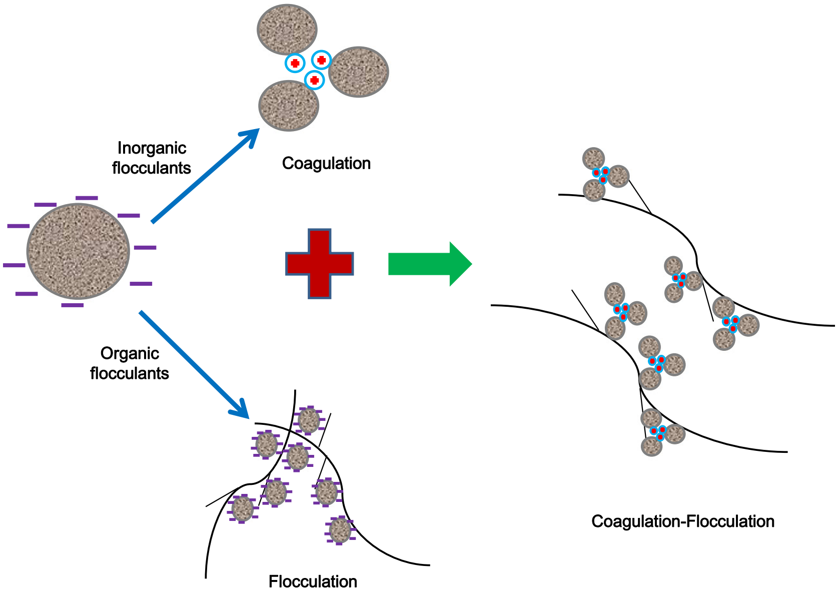
Consolidation of river sludge

Figure 9 shows compressive strength of river sediments solidified by curing agent at different ages after flocculation by 6 groups of composite flocculants. At the same curing age, the strength increases as the amount of curing agent increased. At the same curing agent dosage, the strength was reduced with increasing curing time after adding 5 of composite flocculants. The solidification strength of the soil sample was reduced by an average of 28%. The greater the blending amount, the more obvious the strength reduction, and when the blending amount was 25%, the requirement of 1.5 to 2.0 MPa could be satisfied (Fig. 9e). Compared with the absence of flocculates, the addition of composite polyacrylamide affected the consolidation effect, as shown in Fig. 5g.

The solidification test results of river sludge after flocculation used flocculants no. 2, no. 4, and no. 6 showed experiment results of flocculation after lime, polysilicate aluminum ferric, and polyaluminum chloride were sequentially added on the basis of flocculants no. 5, as shown in Fig. 9b, d, and f. The addition of lime reduced the consolidation effect by an average of 16%, with a maximum reduction of 44%. The addition of polysilicate aluminum ferric could increase the overall effect by an average of 24%, with a maximum increase of 53.3%. The addition of polyaluminum chloride reduced the consolidation effect by an average of 9.2%, with a maximum reduction of 145%.

Figure 9a and c indicate the test results of flocculation and solidification of flocculants no. 1 and no. 3, that is, the solidification test results were in sequence on the basis of flocculants no. 6 and no. 4 by adding lime. In the flocculants no. 1, the addition of lime reduced the overall solidification effect by an average of 14%, with a maximum reduction of 52%. In the flocculants no. 3, the addition of lime reduced the overall solidification effect by an average of 16%, with a minimum of 43%. The no. 1, no. 2, and no. 3 could reduce the strength of the specimens, which was not conducive to solidification treatment after flocculation. When the optimal curing time and curing agent dosage were respectively 7 days and 25%, it

Fig. 7 Flocculation process of inorganic-organic flocculants (Wang et al. 2019)

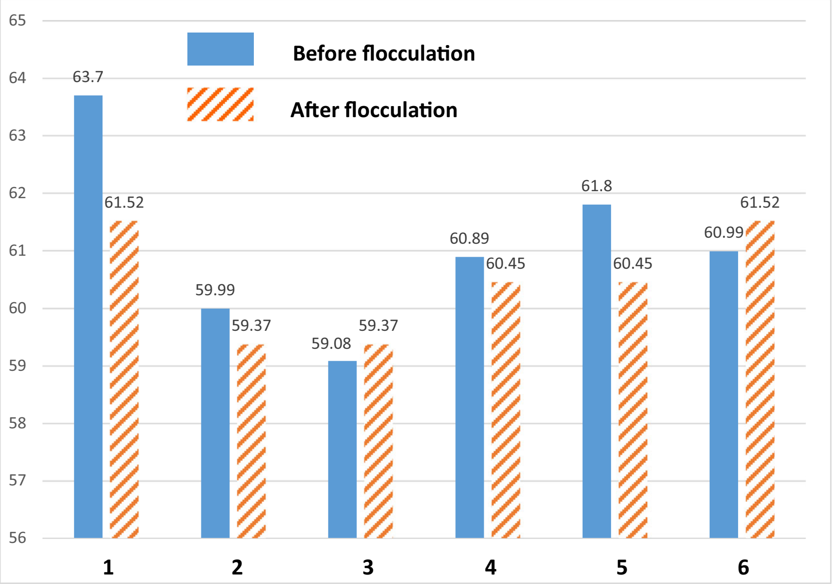


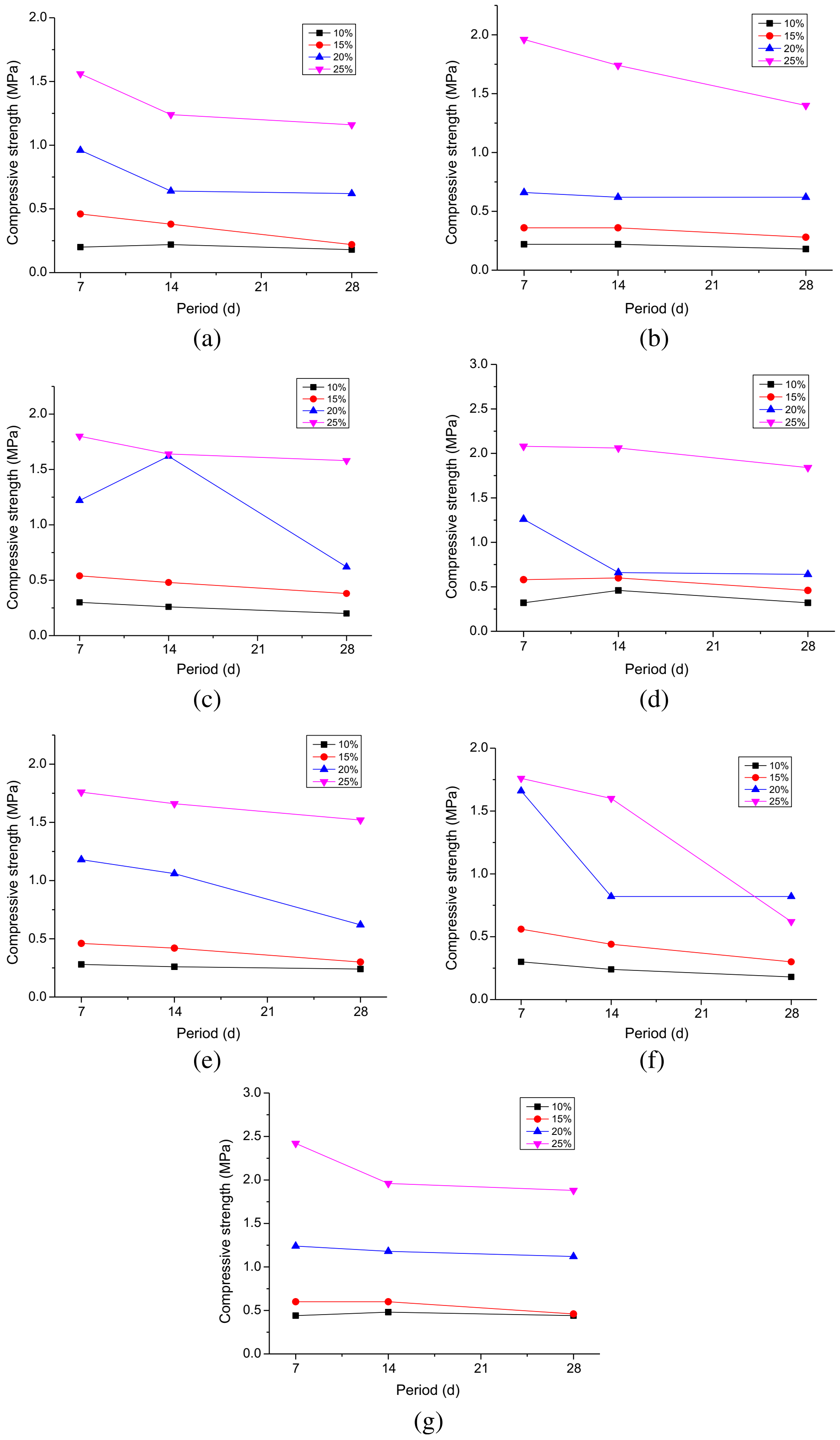
could meet the project strength requirements (1.5–2.0 MPa) (Fig. 9).

Conclusions

The optimum polyacrylamide was added by combining two types of polyacrylamide having a molecular weight of 18 million and 23 million in a ratio of 3:7. The total amount of two types of polyacrylamide was 0.08%. The best dosage was 0.12% in the A3 group in A series. The B2 and B4 in the B series were considered to be suitable dosages, which were 0.08% and 0.16%, respectively. The suitable dosage in the group C was the C1, and the total dosage of polyacrylamide was 0.04%. The optimum amount of the D series was recorded as the D2, and the total amount of polyacrylamide was 0.08%. The appropriate dosage in the group E was the E2, and the dosage was 0.08%. The optimum amount of polyaluminum chloride was 0.0133% in the F and G series. The average sedimentation amount, turbidity, and discrete type could further confirm that the best ratio of two types of polyacrylamide was 3:7. Therefore, the 6 groups of composite flocculants were obtained by two types of polyacrylamide mixing polyaluminum chloride (PAC), polysilicate aluminum ferric (PSAF), and lime. The addition of lime can reduce the overall solidification effect of river sediments. The compressive strength of river sediments could meet the project strength requirements when the optimal curing time and curing agent dosage were 7 days and 25%, respectively.

Fig. 8 Water content before and after flocculation





(a) (b) (c) (d) (e) (f) (g)

Fig. 9 Compressive strength of river sediments at different ages after flocculation. **a** No. 1 of composite flocculants. **b** No. 2 of composite flocculants. **c** No. 3 of composite flocculants. **d** No. 4 of composite flocculants. **e** No. 5 of composite flocculants. **f** No. 6 of composite flocculants. **g** No flocculants

Authors' contributions Xiaoniu Yu conceived and wrote the paper; Xiaoniu Yu and Yunyun Zheng performed the calculations and experiments; Xiaoniu Yu, Linzhu Sun, and Yunyun Zheng contributed in the discussion to analyze the results.

Funding This work is supported by the National Nature Science Foundation of China (51702238), the China Postdoctoral Science Foundation (2019M650715), the Opening Funds of Jiangsu Key Laboratory of Construction Materials (CM2018-02), and the Plan Project of Science and Technology of Wenzhou (No. S20150010), and the financial support is gratefully acknowledged.

Data availability The datasets and materials used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish All authors read and approved to publish the final manuscript.

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