Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-7, Issue-11, November 2025
DOI: 10.53469/jrse.2025.07(11).03

The Influence of Flocculant Type and Molecular Weight on the Dehydration Efficiency of Shield Slurry and Research on the Settlement Mode

Shifan Li, Shiwei Shen*

College of Construction Engineering, Jilin University, Changchun, 130026, China
**Correspondence Author*

Abstract: ***With the acceleration of urbanization in China, the slurry balance shield method is increasingly used in tunnel engineering, generating large amounts of high-moisture-content shield slurry that poses serious environmental threats. Dewatering is a key step for resource utilization of this slurry. This study systematically investigates the effects of different types (APAM, CPAM), molecular weights (8 million, 12 million, 16 million), and concentrations (0.1%–0.3%) of flocculants on the dewatering efficiency of silty clay shield slurry from the Changchun Metro Airport Line. Settlement experiments were conducted to analyze changes in sediment height and moisture content. Results show that anionic polyacrylamide (APAM) with a molecular weight of 16 million and concentration of 0.1% (Group A161) achieved the best dewatering performance. Additionally, a double-exponential decay model ($R^2 > 0.99$) was established for sediment height and equivalent moisture content over time, providing a reliable theoretical basis and prediction tool for practical flocculation dewatering processes.***

Keywords: Shield Slurry, Dewatering Efficiency, Flocculation Settlement, Anionic Polyacrylamide (APAM), Molecular Weight, Double-Exponential Decay model**.**

1. Introduction

The slurry balance shield tunneling method has been widely adopted in various tunnel construction projects in China due to its high degree of mechanization and strong adaptability to different soil conditions [1]. China's 14th Five-Year Plan emphasizes the "coordinated utilization of above-ground and underground space," indicating a sustained growth trend in future tunnel engineering projects [2]. Shield tunnel construction, characterized by high excavation efficiency and minimal impact on the surrounding environment, is extensively used in metro projects. Slurry, as an auxiliary engineering material, is widely employed in the shield tunneling process. However, the high viscosity of waste slurry presents a significant challenge for its treatment. Based on a conservative estimate using a shield tunnel diameter of 6 meters and a bulking factor of 1.5, shield tunneling generates 45,000 m³ of muck per kilometer of tunnel. The total muck volume produced by ongoing underground line projects amounts to 225 million m³ [10]. With the continued development of tunnel engineering, the slurry shield method is expected to generate large quantities of waste slurry with complex composition and high water content. Therefore, there is an urgent need to develop effective methods for treating this waste slurry.

Research has demonstrated the potential for resource utilization of shield tunnel muck [6–8], but efficient dewatering remains a critical prerequisite. The widely applied "flocculation-pressure filtration" process involves screening, flocculation settlement, and mechanical dewatering [4, 5], wherein flocculant selection is particularly crucial. Focusing on shield slurry from the Changchun Metro Airport Line, this study conducts flocculation settlement experiments using PAM-based flocculants. It systematically explores the effects of flocculant type, dosage, concentration, and molecular weight on settlement behavior, derives a predictive mathematical model, and investigates the underlying settlement mechanisms to offer practical guidance for dewatering operations.

This study investigates the flocculation and sedimentation of shield muck from the clay stratum of the Changchun Metro Airport Line using polyacrylamide (PAM)-based flocculants. The research systematically examines the sedimentation behavior by varying flocculant type, dosage, concentration, and molecular weight. The objective is to identify the optimal flocculant formula and dosage that yield the most effective dewatering results. Furthermore, a mathematical model for the sedimentation process is derived to elucidate the underlying mechanisms at different concentrations, ultimately providing an effective predictive model for practical flocculation and dewatering operations.

2. Experimental Scheme

2.1 Raw Materials

Table 1: Key physical parameters of shield slurry

Liquid limit (%)	Plastic limit (%)	Plastic index (%)	Maximum dry density (g/cm3)	Optimum water content (%)
34.84	18.64	16.20	2.00	11.37

Slurry was collected from a sedimentation tank of the Changchun Metro Airport Line. Basic physical properties were measured according to the "Standard for Soil Test Methods" (GB/T 50123-2019). The particle size distribution is shown in Figure 1, and other parameters are summarized in Table 1. The liquid limit and plastic limit were 34.84% and 18.64%, respectively, with a plasticity index of 16.20%. The maximum dry density was 2.00 g/cm³, and the optimal moisture content was 11.37%. Based on the particle size distribution and plasticity index, the soil was classified as silty clay.

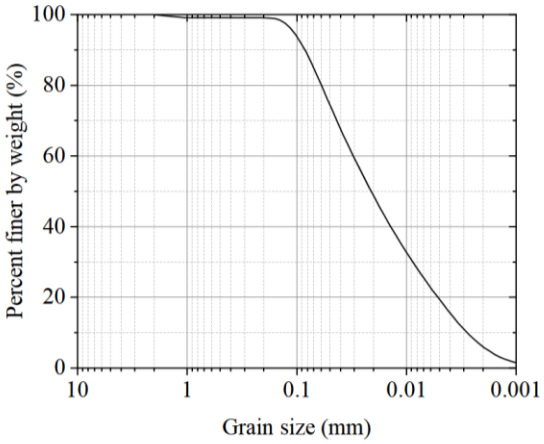

Figure 1: Particle gradation curve

To study settlement performance, commonly used industrial flocculants were selected: anionic polyacrylamide (APAM) and cationic polyacrylamide (CPAM).

2.2 Test Methods

Flocculation experiments were performed on slurry from the same batch. Steps included: 1. Sample preparation: Slurry was air-dried, crushed, and sieved to obtain particles <2 mm. 2. Slurry preparation: Air-dried soil and water were mixed at a specific ratio and stirred for over 30 minutes to ensure homogeneity. 3. The two flocculants were prepared as solutions (listed in Table 2) using an overhead mechanical stirrer. To ensure complete dissolution of the flocculants, the stirring time exceeded 30 minutes. The rotational speed was maintained between 100 and 300 r/min to protect the integrity of the polymer long chains of the flocculants. 4. Settlement column test: To simulate field conditions, 300 mL of prepared slurry was placed in a cylinder, and 40 mL of flocculant solution was added. Sediment interface height was recorded at intervals, and moisture content was measured after 2 hours.

Table 2: Experimental groups

NO.	Types of flocculants	Molecular weight (M)	Concentration (%)
C081		8	0.1
C082		8	0.2
C083		8	0.3
C121	Cationic	12	0.1
C122	polyacrylami	12	0.2
C123	de (CPAM)	12	0.3
C161		16	0.1
C162		16	0.2
C163		16	0.3
A081		8	0.1
A082		8	0.2
A083		8	0.3
A121	Anionic	12	0.1
A122	polyacrylami	12	0.2
A123	de (APAM)	12	0.3
A161		16	0.1
A162		16	0.2
A163		16	0.3

3. Results and Discussion

3.1 Flocculation Effects of Different Organic Flocculants

PAM-based flocculants primarily function through "adsorption bridging" and "charge neutralization." Adsorption bridging involves active groups on molecular chains adsorbing multiple suspended particles to form large, visible flocs that settle rapidly under gravity. Charge neutralization reduces electrostatic repulsion between particles by neutralizing surface charges, accelerating settlement.

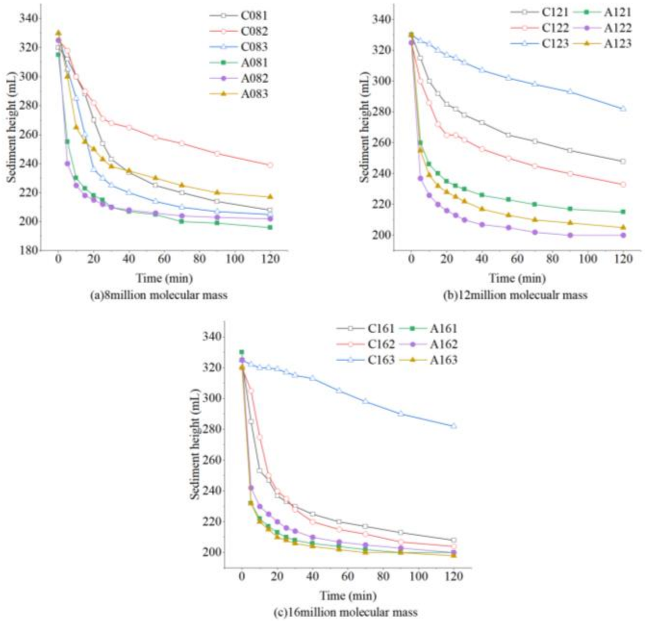

Figure 2: Sediment height variation with organic flocculants of different molecular weight

The variation in sediment height over time after flocculant treatment is shown in Figure 2. The flocculation process includes free settlement and compression consolidation stages. Initially, flocculants cause rapid aggregation of particles into flocs that settle under gravity. Later, upper flocs compress lower layers, expelling water through dendritic channels, with particles rearranging due to charge effects. The results show clear separation between supernatant and sediment within 30 minutes, with fast settlement rates. After 30 minutes, the sediment height decrease slows.

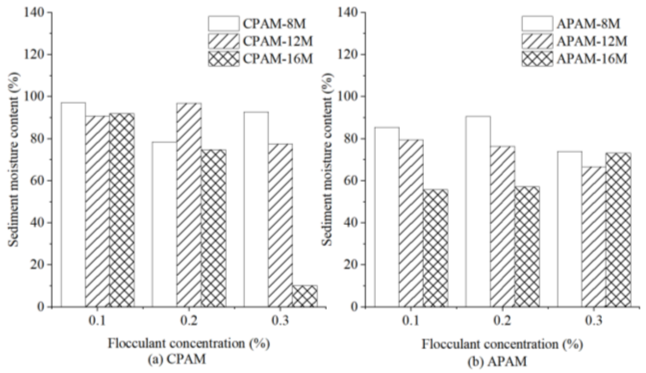

Figure 3: Moisture content of sediment after conditioning with different organic flocculants

Higher molecular weight flocculants generally yield faster settlement and lower final sediment heights. For CPAM, charge neutralization dominates; excessive dosage introduces electrostatic repulsion and inhibits bridging by encapsulating particles. Thus, at 0.3% concentration, higher molecular weights worsen performance. The dominant mechanism of APAM is the "bridging effect," which is relatively less dependent on charge density. Therefore, the higher the molecular weight, the better the flocculation performance.

Comparing Figure 2(c) and Figure 3(b), Groups A161, A162, and A163 have similar final sediment heights, but A161 has lower final moisture content. Overall, A161 exhibits the best comprehensive dewatering performance.

3.2 Mud Height-Time Relationship Model

The final sediment moisture content was lower than the initial slurry moisture content (120%). To quantitatively analyze the effect of flocculant concentration, the sediment height h(t) over time t was modeled. For the best-performing groups (A161, A162, A163), nonlinear curve fitting was performed using Origin software, as shown in Figure 4. A double-exponential decay model was used, with parameters in Table 3. The model fits well ($R^2 > 0.99$), effectively predicting sediment height trends and providing a reference for practical settlement processes.

Table 3: Parameters of the fitting curve equation

Concentration (%)	y0	K1	n1	K2	n2	R²
0.1	200.07238 ±0.54581	92.96888 ±30.92303	2.04186 ±0.48963	31.62894 ±2.57793	22.95078 ±2.58486	0.99989
0.2	200.5221 ±0.90137	79.95604 ±26.11034	2.54355 ±0.6638	38.54113 ±2.77532	29.42807 ±3.71329	0.99982
0.3	198.828 ±0.57857	84.92541 ±23.595	2.57078 ±0.59592	29.61733 ±3.62306	22.05995 ±3.24086	0.99987

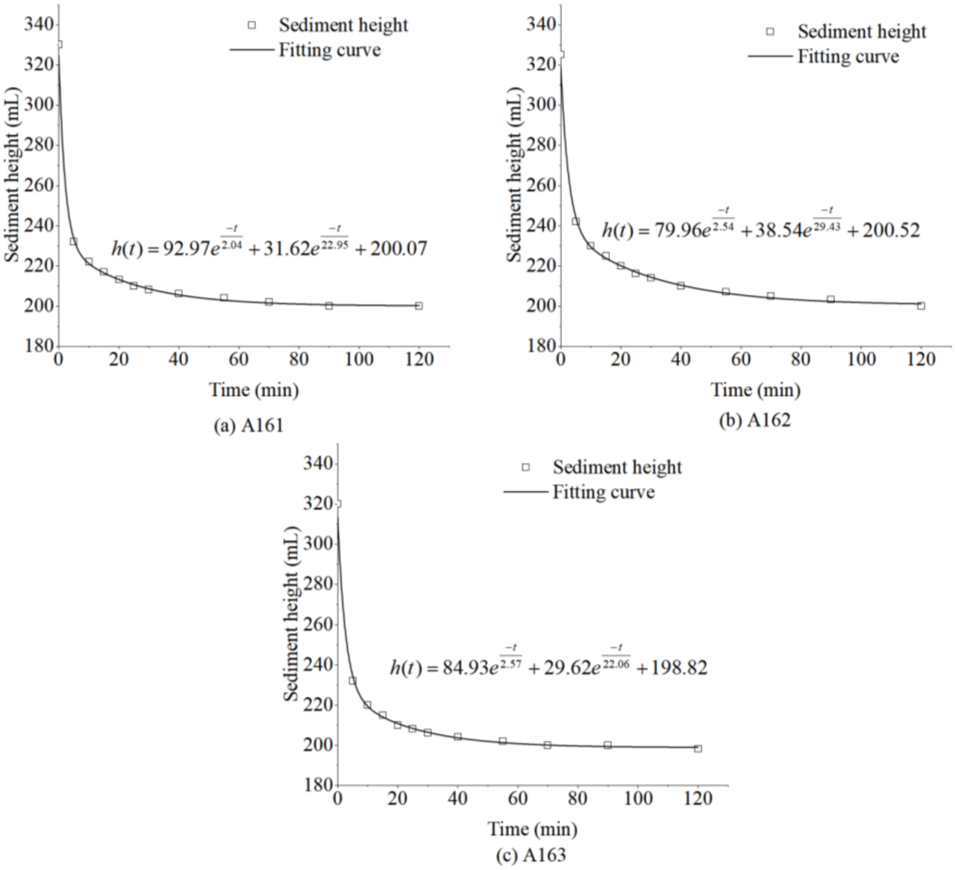

Figure 4: Fitting curve for sediment height versus time with the addition of flocculant solutions at different concentrations

3.3 Equivalent Moisture Content Prediction Model

For a direct assessment of the dewatering efficiency, the equivalent moisture content at each time point was calculated based on the sediment height, the initial moisture content of the prepared slurry, and the mass and solute fraction of the flocculant solution. The calculation method is as follows.

Total mass of dry matter in the slurry:

$$m_s = m_{soil} + m_{fl}^{f} = \frac{v_0 \rho}{1+\omega_0} + c_f \cdot m_f \quad (1)$$

where: v_0 is the volume of the prepared slurry; ρ is the density of the slurry; ω is the mass fraction of the solute in the flocculant solution; m_f is the mass of the flocculant solution.

Total mass of water in the slurry:

$$m_w = m_w^0 + m_w^f = \rho v_0 - m_s + \left(1 - c_f\right) m_f \quad (2)$$

Mass of supernatant at time t:

$$v(t) = \rho_w \cdot [\, v_1 - h(t)] \quad (3)$$

where: ρ_w is the density of water (usually taken as a 1 g/cm³); V_0 is the initial volume of the slurry after adding the flocculant solution; $h(t)$ is the sediment height at time t.

To enhance the reliability of the formula, the slurry density was corrected by incorporating the final measured moisture content, while neglecting the small amount of residual sludge particles in the supernatant. A predictive formula for the equivalent moisture content of the sediment at time t was ultimately derived as follows:

$$\omega(t) = \frac{m_0+m_s+(1-c_f)m_f-v_1+h(t)}{m_s+c_f m_f} \quad (3)$$

Calculate the equivalent moisture content of the three sets of date A161, A162, and A163 using formula (4), and perform curve fitting. The resulting fitting curves are shown in Figure 5, with the corresponding parameters listed in Table 4. The high R^2 values (all greater than 0.99) validate the effectiveness of the mathematical model in predicting the variation of equivalent moisture content over time. This model provides a theoretical tool for the dynamic monitoring of slurry dewatering status at engineering sites.

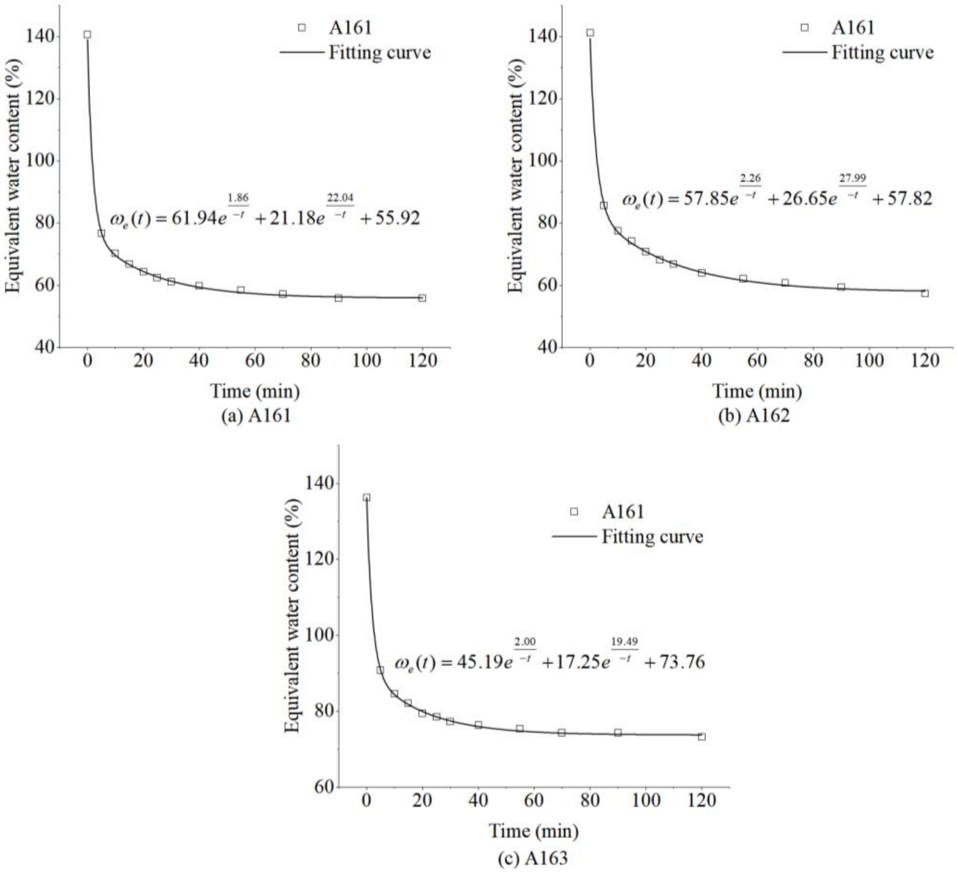

Figure 5: Fitting curves of equivalent moisture content versus time with the addition of flocculant solutions at different concentrations

Table 4: Parameters of the fitting curve equation

Concentration (%)	ω_{min}	K1	n1	K2	n2	R^2
0.1	55.92423 ±0.34876	61.943 ±15.67796	1.8577 ±0.35683	21.18411 ±1.48572	22.0375 ±2.25063	0.99993
0.2	57.82049 ±0.58694	54.8476 ±14.85715	2.25927 ±0.51692	26.65253 ±1.68907	27.98984 ±3.22644	0.99988
0.3	73.76293 ±0.28474	45.18998 ±1.55661	2.00459 ±0.19241	17.24552 ±1.38515	19.49122 ±2.13526	0.99963

4. Conclusion

This study investigates the enhancement of sludge dewatering performance using different types of organic flocculants through laboratory simulations of the field dewatering process. An optimal flocculant type and dosage were identified through comparative analysis, and the experimental data were fitted to derive the following conclusions.:

1) APAM generally outperforms CPAM in dewatering, with APAM at 16 million molecular weight and 0.1% concentration (A161) achieving optimal settlement speed, sediment height, and final moisture content.

2) CPAM effectiveness decreases with overdosing, likely due to electrostatic repulsion from excess positive charges inhibiting bridging.

3) A double-exponential decay model ($R^2 > 0.99$) for sediment height over time effectively predicts slurry settlement.

4) The derived equivalent moisture content formula provides theoretical support for dynamic monitoring and prediction in practical engineering.

This research offers experimental data and mathematical models for optimizing shield slurry dewatering, contributing to the resource utilization of shield slurry.

References

[1] Xiao Mingqing. Representative Projects and Development Trend of Underwater Shield Tunnels in China[J]. Tunnel Construction, 2018,38(03):360-367.

[2] Chen Ke, Liu Tianrui, Yang Zhao. Research Status and Future Prospects of Shield Tunneling Attitude Control Technology[J]. Tunnel Construction, 2024, 44(06): 1154-1164.

[3] Wang, D., et al. Sedimentation Behavior of Organic, Inorganic, and Composite Flocculant-Treated Waste Slurry from Construction Works. 2021.

[4] Guo Weishe, et al. Status quo and prospect of harmless disposal and reclamation of shield muck in China[J]. Tunnel Construction, 2020,40(8):1101.

[5] Min, F., et al. Laboratory Study of Flocculation and Pressure Filtration Dewatering of Waste Slurry. Advances in Civil Engineering, 2020.

[6] Hu, Y.X., et al. Preliminary study on preparation of unfired bricks using filter cake from tunnel muck. Journal of Building Engineering, 2022.

[7] Chen, S.B., et al. Research on Preparation and Performance of Clay-Based Shield Tunnel Nonsintered Bricks. Advances in Materials Science and Engineering, 2021.

[8] Guo Aifeng, et al. Study on Preparation and Performance of Unfired Bricks from Muck[J]. Non-Metallic Mines, 2021,44(03):99-102.

[9] Zhu, H., et al. Preparation of chitosan-based flocculant for high density waste drilling mud solid-liquid separation. Journal of Applied Polymer Science, 2012.

[10] Yang, L., Duan, W. J., et al. Research and application of environmental protection treatment mud dewatering technology for shield tunneling slag. Chinese Journal of Engineering Machinery, 2023, 21(6): 537-542, DOI:10.15999/j.cnki.311926.2023.06.007.