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Experimental study on the thixotropic strength of the marine soft clay from the Yangtze River estuary

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Soft clay in the offshore area of the Yangtze River estuary has been investigated considering its basic physical properties. Forty-five unconfined compressive strength tests were conducted on the remolded marine soft clay to investigate the impacts of curing time T, water content w, plasticity index I_P, and clay particle content ρ_c on the thixotropic static shear strength ratio A_s of the marine soft clay from the Yangtze River estuary. Results show that the stress−strain curves were primarily strain hardening and strain softening curve types. Unconfined compressive strength q_u increased with an increase in T. All specimens with different basic physical properties were capable of thixotropic strength recovery. When $T = 0−28$ days, A_s increased rapidly, while for $T > 28$ days, A_s of most specimens increased slightly or tended to stabilize. The impacts of w, I_P and ρ_c on A_s do not follow a consistent pattern, but there is a strong correlation between A_s and w/w_L (w_L is the liquid-limit water content). For $w/w_L < 0.75$, A_s increased with increasing w/w_L, whereas for $w/w_L \geq 0.75$, A_s decreased with increasing w/w_L. We proposed a simple and widely applicable power function prediction model for the As of the soft clay from the Yangtze River estuary.

KEYWORDS

marine soft clay, thixotropic strength, unconfined compressive strength tests, prediction model, physical properties

1 Introduction

Soft clays are widely distributed across marine sites around the world. Due to their unique sedimentary environment and consolidated state, the basic physical properties of marine soft clays differ substantially from those of terrestrial soils (Wu et al., 2023; Xiao et al., 2024). These differences are characterized by their low strengths, high porosity ratios, low permeability, high sensitivity, and high compressibility. Once disturbed, the structure

of a marine-deposited soft clay is damaged, leading to a substantial decrease in its strength and flow behavior, thereby exhibiting thixotropy. In 1927, Peterfi first introduced the concept of "thixotropy," which is used to describe a reversible phenomenon where a colloidal solution can be transformed from a liquid state to a solid state and then from a solid state to a liquid state. When the clayey soil is disturbed by external forces, it gets remolded, leading to a decrease in strength. However, after being left undisturbed for a certain period under constant temperature and humidity conditions, its strength increases. For example, during the installation of a pile or a suction anchor, the *in situ* marine clay is damaged and transformed into a remolded soil. After a marine structure such as a pile, anchor, or cable is installed, the lateral strength of the remolded soil around its foundation will increase over time due to thixotropy. Part of this strength can provide sufficient frictional resistance for the pile or suction anchor in the early stage. The thixotropy of soft clays is important for the design of anchored foundations. For example, Kul'Chitskii (1975) found that about one month after disturbance, the strength of the soil around the pile was about twice that of the soil when it was first disturbed. Therefore, if the contribution of the thixotropy of the clay to the soil strength is taken into account in the design of the foundations for actual marine engineering sites, a significant amount of costs can be saved.

For a long time, many scholars have conducted extensive research on the thixotropy of soils involved in the geotechnical engineering field. Boswell (1949) conducted a thixotropy study on a large number of sediments in the geotechnical engineering field, and found that except for clean sands and gravels (Ma et al., 2024a; Ma et al., 2024b; Ma W. et al., 2024; Qin et al., 2024), most materials exhibited various degrees of thixotropy. Soft clays, in particular, exhibited higher thixotropy compared to other materials, and these thixotropic properties are commonly observed (Dullaert and Mewis, 2006; Seng and Tanaka, 2012; Shahriar et al., 2018; Peng et al., 2021a; 2021b; Ren et al., 2021). Moretto (1948) conducted unconfined compressive strength tests on four different clays and found that all four clays were capable of thixotropic strength recovery, with some of them recovering nearly to the strength levels of *in situ* clays. Alam et al. (2021) conducted unconfined compressive and direct shear tests, and found that the thixotropic strength of a clay mainly depends on its liquid limit, activity, clay particle content, and initial grain structure. Shahriar and Jadid (2018) conducted one-dimensional consolidation tests, and found that the yield stress of dredged clays increased with increasing thixotropic time, and they developed a prediction model for the yield stress ratio of dredged clays with different initial water contents. Tang et al. (2022) investigated the changes of mechanical properties of the clay from Zhanjiang during the thixotropic process. They quantitatively analyzed the relationships between the thixotropic time and the cohesion, internal friction angle, and initial tangential modulus, and developed the Duncan-Chang model that considers the thixotropy of clay. Yang et al. (2021) investigated the impacts of thixotropy and reconsolidation on the undrained shear strength and shear modulus of marine clays, and found that reconsolidation counteracted the increase in shear strength and shear modulus caused by thixotropy. Wei et al. (2023)

identified significant thixotropy in loess and demonstrated that the increase in thixotropic strength of loess during the thixotropic process was due to increased cohesion and frictional force in the soil structure. Ren et al. (2024) conducted fall-cone tests and found that the thixotropic strength of a deep-sea clay increased rapidly in the early stage and then its increase slowed down with increasing thixotropic time. They also observed that during the thixotropic process, the microstructure of the clay changed from a dispersed structure with parallel-aligned particles to a well-flocculated dispersed structure.

The thixotropic properties of marine soft clays are crucial for maintaining the bearing capacities of offshore engineering foundations in the early stage, and deserve the attention of the engineering community during the designing of offshore engineering foundations (Ren et al., 2021). Although the above studies on the thixotropy of soft clays have achieved certain results, there is a lack of research on the thixotropy of the soft clay in the offshore area at the Yangtze River estuary due to its complex regional variations. In particular, there is a lack of analytical research on the impacts of its physical and mechanical properties on its thixotropy. In addition, there are few prediction models for the thixotropy of soft clays. Given the shortcomings of the above studies, we focused on water content w, plasticity index I_P, clay particle content ρ_c, and curing time T, and conducted unconfined compressive strength tests to measure and analyze the thixotropy of the marine soft clay from the Yangtze River estuary. The research findings can provide reference data for the early-stage bearing capacities of actual engineering foundations at the Yangtze River estuary, and also help us understand more deeply the unique engineering properties of marine soft clays.

2 Test plan

2.1 Test materials and preparation of specimens

The specimens were taken from the offshore waters of the Qidong section of the Yangtze River estuary. The physical properties, including water content w, specific gravity G_s, natural density ρ, and plasticity index I_P, were determined according to ASTM D2487-11 (2017); ASTM D854 (2014); ASTM D2216-982 (2019); ASTM D1556/D1556M (2015), and ASTM D4318 (2017), respectively. The results are summarized in Table 1. The measured I_P and w of the *in situ* soil were used as the basic physical properties

TABLE 1   Basic physical properties of the marine soft clay.

ID	w/%	Δw_0/%	ρ/ g·cm^{-3}	G_s	w_L/%	w_P/%	I_P
1	45	-0.5~0.3	1.68	2.72	50.0	24.6	25.4
2	45	1.0~1.4	1.81	2.69	60.1	25.1	35.0
3	45	0.2~0.5	2.14	2.68	70.6	26.3	44.3
4	40	0.0~0.3	2.03	2.71	57.8	23.6	35.2
5	35	0.75~1.2	1.77	2.70	64.8	29.2	35.6

for the remolded specimens in the tests. The remolding procedure is as follows: 1) Dry, crush, and sieve the *in situ* soil (sieve pore size 0.25 mm); 2) Weigh the predetermined mass of soil (keeping the dry density at 1.5 g/cm³), add the corresponding mass of water according to the specified *w*, and mix thoroughly until the mixture becomes a uniform soil paste; 3) Fill the prepared uniform soil paste into a standard triaxial specimen-saturation mold in eight layers, and ensure high consistent compaction and uniform height for each layer; 4) Wrap the prepared cylindrical specimens with a diameter of 50 mm and height of 100 mm in plastic wrap, and store them a constant temperature and humidity environment (humidity of 98%, and temperature of 20°C) for curing times of 0, 7, 14, 28, and 60 days. Before the test, check the water contents of the cured specimens layer by layer. The difference between the cured water content and the initial water content Δw_0 should not exceed 1.5% for the test to proceed.

2.2 Test instrument and test plan

The unconfined compressive strength test is one of the common indoor tests for studying the thixotropic properties of clays. In this test, an electric strain-controlled unconfined pressure gauge was used, and specimens with an I_P of 25.4, 35, and 44.3, respectively, were selected. Specimens with different I_P values were prepared with water contents of (*w*) 35%, 40%, and 45%, respectively. Considering the impact of time on the thixotropic properties of the remoded marine soft clay, five different curing times (*T*) of 0, 7, 14, 28, and 60 days were used to investigate their impacts on the thixotropic properties. Taking the above factors into account, we conducted a total of 45 unconfined compressive strength tests. The specific test conditions are shown in Table 2.

3 Analysis of test results

The thixotropic static shear strength ratio A_s is defined as follows:

$$A_s = \frac{q_{u,t}}{q_{u,0}} \qquad (1)$$

where $q_{u,t}$ is the unconfined compressive strength q_u with a curing time of *T*, and $q_{u,0}$ is the q_u with a curing time of 0. A_s reflects the recovery of the thixotropy static shear strength with any *T*. It is used to indicate the strength of the specimen. The q_u and A_s of the specimens under different test conditions are shown in Table 3. The value of q_u is defined as the peak strength when the specimen

experiences a brittle failure, or the strength corresponding to a strain of 15% when the specimen experiences a plastic failure.

Figure 1 shows the axial stress–strain curves for the remodeled marine soft clay with different *T* values. As shown in the figure, the stress–strain curves are of two types: Strain hardening and stress softening curves. With $I_P = 25.4$, all the stress–strain curves for the specimens with *T* = 0, 7, 14, 28 and 60 days are strain hardening stress–strain curves. With $I_P = 35.0$, *w* = 35% or $I_P = 44.3$, *w* = 35%, the stress–strain curves for the specimens are strain softening stress–strain curves with the increase of *T*. With $I_P = 35$, *w* = 45%, the stress–strain curves for the specimens gradually changed from strain hardening to strain softening stress–strain curves with the increase of *T*, in which case the primary failures are cracks on the surface. The main reasons for the different development patterns are the following. When the *w* of a specimen is low and its I_P is high, its soil particles are fine and surface water film is thin. The water inside the specimen is mainly bound water, thereby resulting in tightly connected soil particles and a high unconfined compressive strength which will cause the specimen to experience a considerable brittle failure once a failure occurs. Conversely, as its *w* increases and I_P decreases, the water inside the specimen is mainly free water and the bound water film becomes thicker. The water on the surface of the soil particles acts as a lubricant, which reduces the frictional resistance between them. This would result in a lower unconfined compressive strength, which will cause the specimen to experience a plastic failure once a failure occurs, and cause the stress to decrease or increase at a slower pace. It is noteworthy that with *T* = 0 days, all the stress–strain curves for the specimens are strain hardening stress–strain curves. As *T* increased, the axial stress–strain curves gradually changed to strain softening stress–strain curves, developing a relationship similar to the drained axial stress–strain relationship in over consolidated clays. This is mainly because with *T* = 0, the main factors affecting q_u are the hardness and the newly formed structure of the soil. As the *T* increases, the thixotropic effect leads to a rearrangement of the soil particles, thus increasing the contact between them, and gradually forming a new structure. Under an external load, soil particles are compressed and slide, leading to the complete disappearance of its structural integrity, which ultimately results in a strain softening failure.

3.1 Recovery of the thixotropic strength

To investigate the impact of *T* on the unconfined compressive strength q_u of the remolded marine soft clay, Figure 2 shows the q_u-*T* curve. As shown in the figure, under the influence of the thixotropic effect, the q_u of all specimens increased with the increase of *T*. All the specimens were capable of thixotropic strength recovery, with q_u increasing rapidly in the early stage, and its increase slowing down in the later stage. With $I_P = 35.0$ and *w* = 45%, the q_u increased from 2.16 kPa to 3.25 kPa as the *T* increased from 0 to 60 days, marking a 50.18% increase in q_u, and the highest thixotropic strength recovery capability. With $I_P = 35.0$ and *w* = 35%, the q_u increased from 5.37 kPa to 6.52 as the *T* increased from 0 to 60 days, marking a 21.34% increase in q_u, and the lowest thixotropic strength recovery capability. In general, the

TABLE 2 Test conditions for the unconfined compressive strength tests.

I_P	*w*/%	*T*/day
25.4	35、40、45	
35.0	35、40、45	0 7 14 28 60
44.3	35、40、45	

TABLE 3 Results of unconfined compressive strength tests.

| w/%	I_P	T/ day	q_u/ kPa	A_s	w/%	I_P	T/ day	q_u/ kPa	A_s	w/%	I_P	T/ day	q_u/ kPa	A_s
35	25.4	0	2.845	1.000	40	25.4	0	1.483	1.000	45	25.4	0	1.216	1.000
		7	3.307	1.162			7	1.625	1.096			7	1.288	1.059
		14	3.575	1.257			14	1.715	1.156			14	1.337	1.100
		28	3.894	1.369			28	1.785	1.204			28	1.437	1.182
		60	4.055	1.425			60	1.891	1.275			60	1.493	1.228
	35.0	0	5.374	1.000		35.0	0	2.845	1.000		35.0	0	2.164	1.000
		7	5.544	1.042			7	3.220	1.132			7	2.578	1.191
		14	5.958	1.088			14	3.526	1.239			14	2.772	1.281
		28	6.395	1.150			28	3.696	1.299			28	3.000	1.386
		60	6.521	1.213			60	3.915	1.376			60	3.250	1.502
	44.3	0	9.046	1.000		44.3	0	5.800	1.000		44.3	0	3.891	1.000
		7	9.217	1.019			7	5.979	1.031			7	4.110	1.056
		14	9.362	1.035			14	6.200	1.069			14	4.234	1.109
		28	9.530	1.054			28	6.374	1.099			28	4.593	1.180
		60	9.654	1.067			60	6.662	1.149			60	4.789	1.231
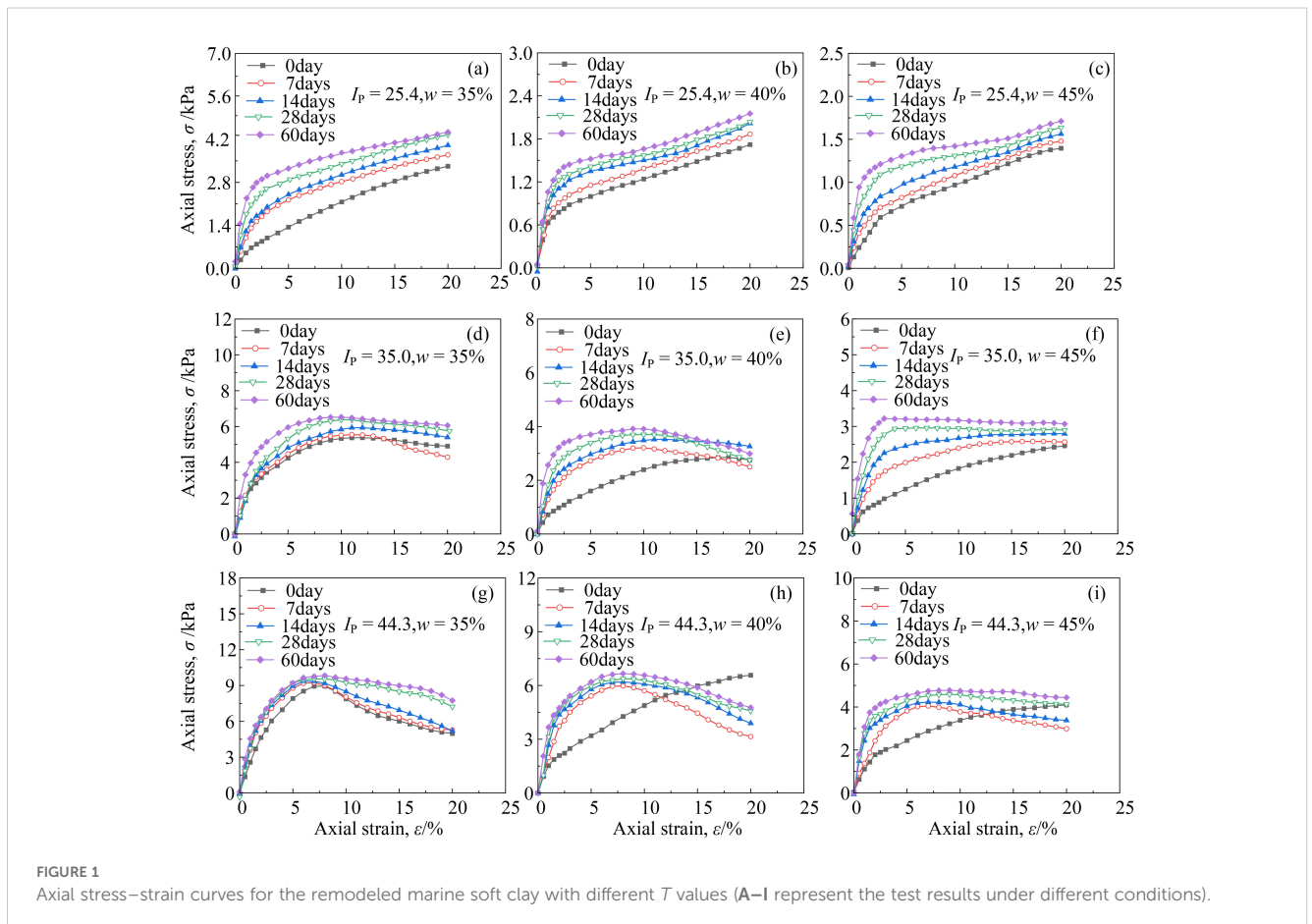
FIGURE 1
Axial stress–strain curves for the remodeled marine soft clay with different T values (**A–I** represent the test results under different conditions).
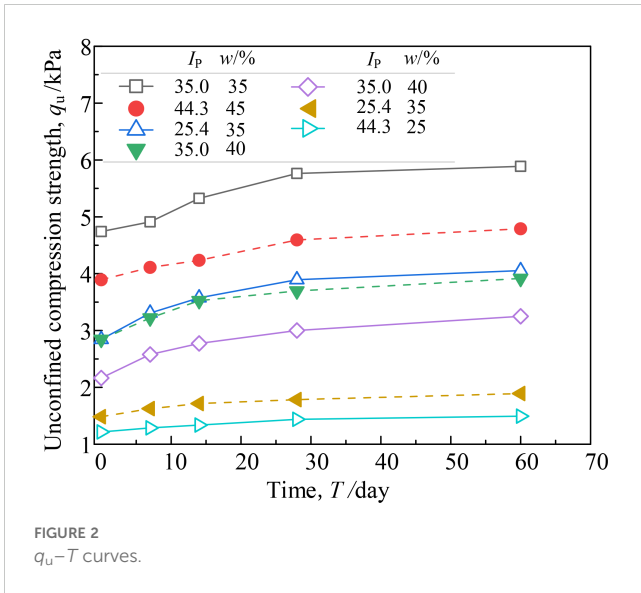
FIGURE 2
q_u–T curves.

remodeled marine soft clay under different test conditions showed different levels of thixotropic strength recovery capability. The q_u increased with increasing T, but this does not imply that the q_u would increase infinitely within an infinitely long curing time. For instance, the specimen with $I_P = 25.4$ and $w = 35\%$ was measured to have a q_u of 4.05 kPa after 60 days of curing, which is substantially lower than the strength of its *in situ* clay, i.e., 14.69 kPa.

Figure 3 shows the A_s–T curves for the remolded marine soft clay under different test conditions. With $T = 0$–28 days, A_s increased rapidly; with $T > 28$, A_s of most specimens increased slightly or tended to stabilize. However, with $I_P = 35$, and $w = 45\%$, A_s of the specimens continued to increase after 28 days, demonstrating a high thixotropic strength recovery capability. With $T = 60$ days, the A_s of the specimen with $I_P = 35$, and $w = 45\%$ was the highest, i.e., 1.5, among all specimens; the A_s of the specimen with $I_P = 25.4$, and $w = 35\%$ was the second highest, i.e., 1.4; the A_s of the specimen with $I_P = 45$, and $w = 35\%$ was the lowest,
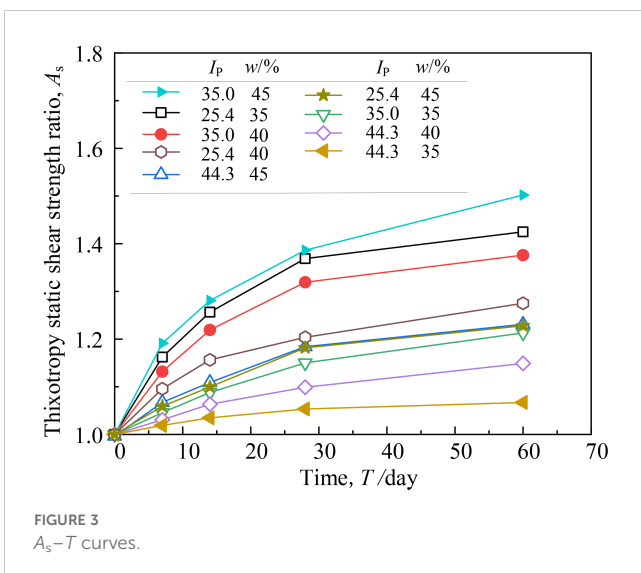
i.e., 1.2; the A_s values of the remaining specimens were in the range of 1.2–1.4. In general, the thixotropy of a soft clay is a prolonged and continuous process.

Figure 4 shows the A_s-T curves for the soft clay from the Yangtze River estuary and clayey soils from other regions Taihu Lake (Wang et al., 2015), Zhanjiang (Zhang et al., 2017), and South China Sea (Yang and Andersen, 2016). The figure also contains data for three pure clay minerals: montmorillonite, illite, and kaolin (Skemption and NorThey, 1952). As shown in the figure, with $T < 14$ days, the A_s of the clay from the Yangtze River estuary is close to those of the clay from Zhanjang and illite; with $T > 14$ days, the A_s of the clay from the Yangtze River estuary is higher than that of illite, but lower than that of the clay from Zhanjang. With $T = 0, 7, 14, 28, 60$, and 100 days, the A_s of the clay from the Yangtze River estuary is significantly lower than those of the marine clay from the South China Sea, montmorillonite, and clay from Taihu Lake, and its A_s variation curve clearly lies below the curves for the clays from these three regions, indicating a lower thixotropic strength recovery capability of the clay from the Yangtze River estuary. In addition, the A_s values of the three pure clay minerals differed considerably. Despite increasing T, Kaolin showed no thixotropic effect with an A_s being close to 1.0. The A_s of illite increased linearly but with a lower thixotropy, and reached approximately 1.35 with $T = 100$ days. Montmorillonite showed the highest thixotropy compared to the other two clay minerals, with its A_s peaking at 2.75 with $T = 100$ days.

The thixotropic static shear strength ratio A_s is defined as the ratio of the strength with a curing time of T to the strength with a curing time of 0. This ratio can reflect the variation in the static shear strength of a soil over the curing time, and is used to evaluate the variation in the thixotropic strength. A_s can be used to indicate the relative variation in the static shear strength, rather than the absolute variation. Based on this, to further evaluate the absolute variation in the static shear strength of the remolded marine soft clay under the influence of the thixotropic effect, the following equation is used to define the thixotropy static shear strength recovery ratio B_s:
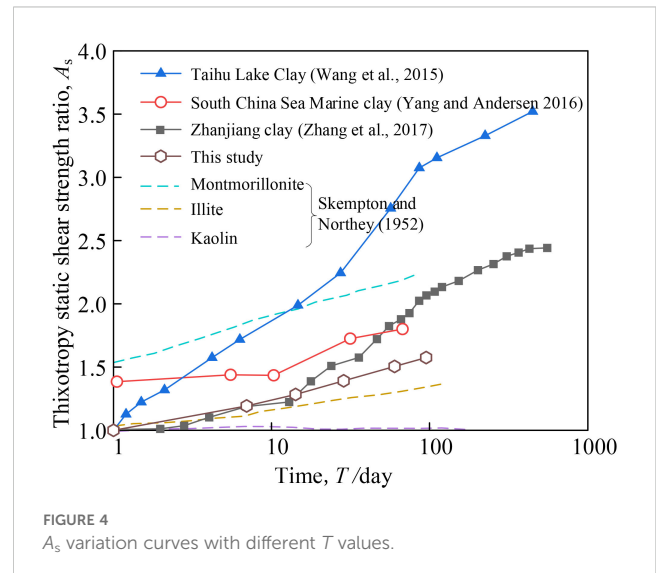

FIGURE 3
A_s–T curves.

FIGURE 4
A_s variation curves with different T values.

$$B_s = \frac{S_{u,t} - S_{u,0}}{S_u - S_{u,0}} \times 100\% \qquad (2)$$

B_s can represent the percentage ratio of the strength recovered during the thixotropic process to the strength lost due to disturbance (Zhang et al., 2017). Figure 5 shows the B_s–T curves for the specimens under different test conditions. As shown in the figure, the two specimens with the highest and lowest B_s also have the highest and lowest A_s, respectively. However, not all test conditions show a one-to-one correspondence in their arrangement. A comparison of Figures 3 and 5 shows that a specimen with a high A_s does not necessarily have a high B_s (e.g., the specimen with $I_P = 25.4$ and $w = 35\%$), while a specimen with a low A_s has a high B_s (e.g., the specimen with $I_P = 35$ and $w = 35\%$). This is mainly related to the differences in the basic physical properties of the specimens. When the soil is disturbed by external factors, the cohesion between soil particles and the balance system of anions and cations are disrupted, leading to the destruction of the naturally formed soil structure, and a decrease in soil strength. Although its thixotropy will recover some strength, the recovery is limited. In this study, the thixotropy static shear strength of the soft clay from the Yangtze River estuary recovered after 60 days of curing only accounted for 3.1%–16% of the strength lost due to disturbance. This indicates that even with a long curing time, it is difficult for a clayey soil to restore to its *in situ* strength, reflecting the fact that all clayey soils are partially thixotropic (Zhang et al., 2017).

3.2 Impact of I_P on A_s

Figure 6 shows the I_P–A_s curves with different T values. A_s shown in figure, with $w = 35\%$, the A_s of the specimens with different T values decreased with the increase of I_P. The specimens with $w = 35\%$ and $I_P = 44.3$ had the lowest A_s in the range of 1.02–1.07 during a curing time of 7–60 days; the specimen with $w = 35\%$ and $I_P = 25.4$ had an A_s in the range of 1.16–1.43 during a curing time of 7–60 days. With $w = 40\%$ or $w = 45\%$, the A_s of the specimen first increased and then decreased with the increase of I_P. Hence, with different w values, the impact of w on A_s does not follow a
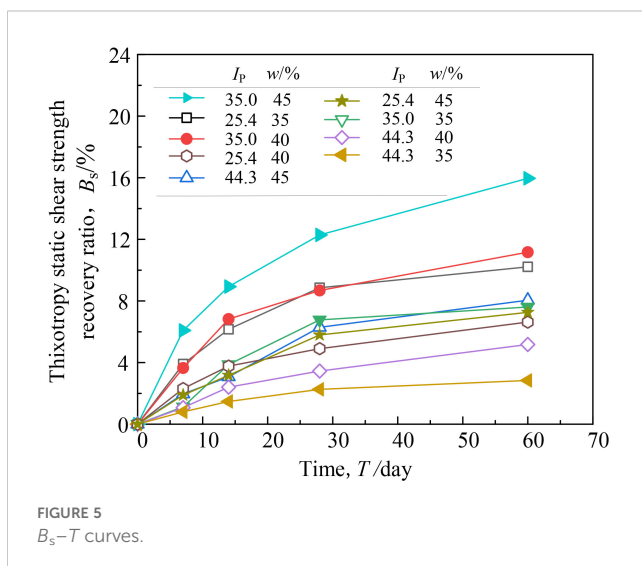
monotonic pattern. This is mainly related to the structural differences between different clay minerals. When w is moderate, a higher I_P means a larger specific surface area, which facilitates particle rearrangement and exchange of ions. These influencing factors can, to a certain extent, promote the occurrence of the thixotropic effect in soft clays. In addition, with the same I_P, the A_s of all the specimens increased with the increase of T. With $T = 7$ days, the A_s of each specimen was the lowest, and with $T = 60$ days, the A_s of each specimen was the highest.

3.3 Impact of ρ_c on A_s

Figure 7 shows the A_s–ρ_c curves with different T values. ρ_c is the proportion of the mass of particles with a diameter < 0.005 mm to the total mass. This value reflects the fineness of the soil particles and their ability to adsorb bound water. As shown in the figure, with $w = 35\%$, A_s increased with increasing ρ_c during a curing time of 7, 14, 28 or 60 days; with $w = 40\%$ or $w = 45\%$, A_s increased first and then decreased with increasing ρ_c with different T values. The specimen with $w = 45\%$ and $\rho_c = 35.6$ reached its highest A_s of 1.5 with $T = 60$ days, while the specimen with $w = 35\%$ and $\rho_c = 33.8$ had an A_s of only 1.02 with $T = 7$ days. In general, the impact of ρ_c on A_s does not follow a monotonic pattern. The higher the ρ_c, the higher the capacity of the soil to adsorb bound water, and with an appropriate w, the more likely the soil particles will be rearranged to form a new structure more favorable for thixotropy.

3.4 Impact of w on A_s

Mitchell (1960) pointed out that w is a major parameter affecting the thixotropic properties of soils. Figure 8 shows the A_s–w curves for the remolded marine soft clay with different T values. With $I_P = 25.4$, A_s decreases with increasing w with different T values; with $I_P = 25.4$ or $I_P = 45$, A_s increases with increasing w with different T values. Hence, with different I_P values, the impact of w on A_s does not follow a monotonic patter. In addition, with the same w, A_s increases with increasing T.

In summary, the impacts of w, I_P and ρ_c on A_s do not follow a monotonic pattern. In addition, due to differences in surface area and mineral composition, soils vary in their capacity to adsorb bound water. With the same w, in a specimen with a high I_P, all the water may be bound water, while in a specimen with a low I_P, a significant portion of water may already be free water. Investigating the impact of w or I_P on the thixotropic static shear strength ratio A_s may not fully explain the thixotropic properties of a marine soft clay. Therefore, we introduced the normalized water content w/w_L, which can comprehensively reflect the combined impact of w and I_P on A_s. It is analogous to the liquidity index, which can comprehensively reflect the hardness of a soil. Normalized water content w/w_L is an important parameter for assessing the thixotropic properties of clayey soils, and many scholars have studied its impacts on A_s. Skemption and NorThey (1952) reported that with $w/w_L < 1$, A_s would decrease with decreasing w. Mitchell (1960) found that when w/w_L is in the range of 0.56–
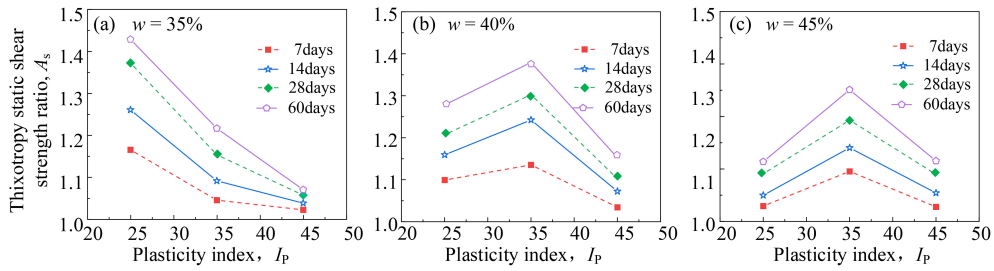
FIGURE 5
B_s–T curves.

FIGURE 6

A_s−I_P curves for the remolded marine soft clay with different T values (**A−C** represent different moisture contents).
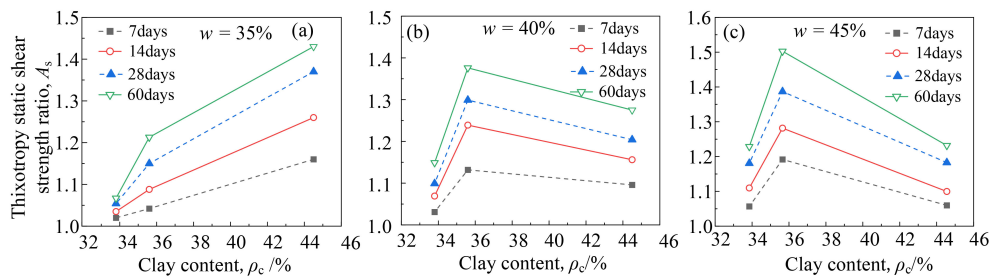

FIGURE 7

A_s−ρ_c curves for the remolded marine soft clay with different T values (**A−C** represent different moisture contents).

0.74, soils exhibit a significant thixotropic effect. Shahriar and Jadid (2018) found that with $w/w_L = 0.75$, the A_s of a soil will reach its highest value. Based on the above research findings, the threshold value of the normalized water content w/w_L with respect to its impact on A_s is 0.75. However, due to differences in the basic physical properties of the marine soft clay, to investigate the impact of w/w_L on the A_s of the remolded marine soft clay, the A_s–w/w_L curves with different T values are shown in Figure 9. It can be observed that with different T values, A_s first increased and then decreased with increasing w/w_L. With $T = 7$ days, A_s was the lowest. With $T = 60$ days, w/w_L increased from 0.5 to 0.75, and A_s increased from 1.07 to 1.43; with $w/w_L > 0.75$, A_s decreased, and with $w/w_L = 0.95$, A_s decreased to 1.23. This indicates that with $w/w_L = 0.75$, A_s was the highest. The above results are consistent with the findings of Shahriar and Jadid (2018) regarding the impact of w/w_L on A_s. However, due to complex regional variations and differences in

basic physical properties of the marine soft clay, A_s values of the marine soft clay with different w/w_L ratios differ from one another.

w/w_L can comprehensively reflect the thickness of the electric double layer as well as the relative contents of bound water and free water in a soil, thereby affecting the thixotropic properties of the soil. Mitchell (1960) hypothesized the mechanism of thixotropy in soils, suggesting that after the soil is disturbed to a remolded state, a significant amount of energy remains in the soil. This energy induces the rearrangement of particles and the movement of water molecules until the energy is dissipated, and the internal structure of the soil reaches a state of equilibrium. In addition, the attraction between soil particles is closely related to the spacings between them. Even slight changes in spacings can considerably impact the soil strength. Therefore, with a constant w/w_L, particle movement is the primary factor in strength recovery. For a soft clay, when its w/w_L is low ($w/w_L = 0.5$), there is less free water between
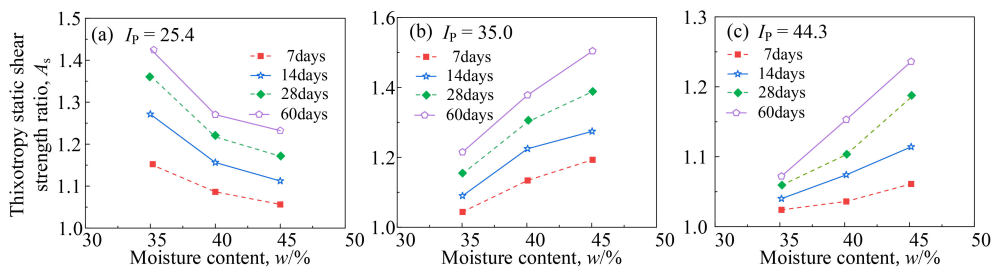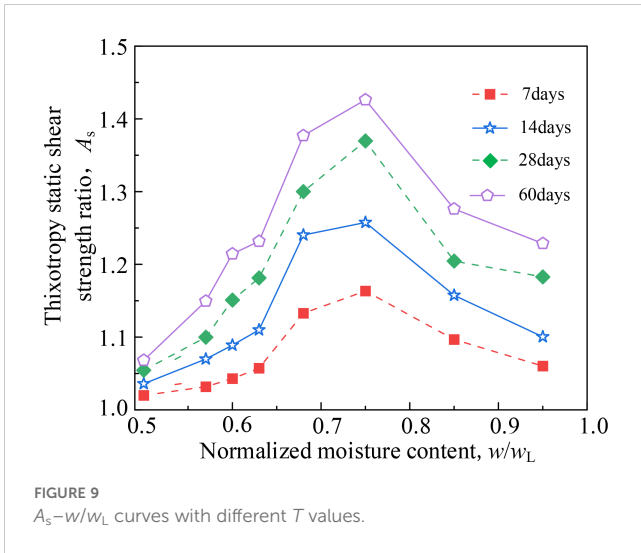

FIGURE 8

A_s−w curves for the remolded marine soft clay with different T values (**A−C** represent different plasticity indices).

FIGURE 9

A_s−w/w_L curves with different T values.

soil particles, and most of the water is bound water. The bound water films around the soil particles are very thin, and bound water is affected significantly by the electric field, thus resulting in a strong attraction between particles, which makes it difficult for the soil particles to spontaneously rearrange during the thixotropic process, thereby leading to a lower thixotropic strength recovery capability of the soil. When the normalized water content is moderate ($w/w_L \approx 0.75$), the amount of free water between particles increases. During the thixotropic process, free water flows through the inter-particle pores, carrying clay particles to fill the pores. The thickness of the electric double layer around clay particles is moderate, and the spacings between particles are appropriate. This allows for more spontaneous movement and rearrangement of particles, facilitating the formation of a new flocculated structure, and thereby leading to a higher thixotropic strength recovery capability of the soil. When the normalized water content is high ($w/w_L > 0.75$), there is a significant amount of free water between soil particles, and the thickness of the electric double layer increases, which increases the spacings between particles. This would result in a very weak attraction during the thixotropic process, making it difficult for

the particles to form a new flocculated structure, thereby leading to a lower thixotropic strength recovery capability of the soil.

4 Prediction model for the thixotropic static shear strength ratio

A_s is an important parameter used to characterize the recovery of the thixotropy static shear strength of a soft clay under static loading. In practical engineering, it would be cost saving if the contribution of A_s to the strength of the clay is taken into account. In order to facilitate the design and construction of actual engineering sites, it is necessary to establish relationships between the thixotropic static shear strength ratio A_S and the parameters. This study analyzed a total of 45 tests in the test plan, and developed a power function model between the thixotropic static shear strength ratio and the curing time as shown in Equation 3:

$$A_s = \arctan\left(BT^C\right) + 1 \qquad (3)$$

where A_s is the thixotropic static shear strength ratio; T is the curing time; B and C are the fitting parameters. Equation 3 was used to fit the A_s of the remolded marine soft clay from the Yangtze River estuary. Table 4 lists the values of As of the specimens under different test conditions as well as the values of the fitting parameters calculated using Equation 3.

In summary, the impact of w/w_L on A_s depends on a threshold value of 0.75. With $w/w_L < 0.75$, A_s increases with the increase of w/w_L; with $w/w_L > 0.75$, A_s decreases with the increase of w/w_L. Therefore, to better distinguish between the two scenarios, Figure 10 shows the A_s−T curves with $w/w_L \leq 0.75$ and $w/w_L \geq 0.75$, respectively. As shown in Figure 10, the overall fitting results are better when the power function model is used for fitting. Under certain thixotropic static conditions, the prediction equation for A_s proposed in this section is both reliable and effective.

Currently, there are few prediction models for A_s, and there are significant differences among different sites. To verify the applicability and accuracy of the prediction model proposed in this paper, Figure 11 shows the A_s- T curves for the clayey soils from

TABLE 4 Values of A_s and corresponding fitting parameters of the remolded marine soft clay.

| w /%	I_P	w/w_L	A_s					B	C	R^2
			0day	7days	14days	28days	60days			
35	25.4	0.75	1.000	1.162	1.257	1.369	1.425	0.976	0.095	0.970
	35.6	0.6	1.000	1.042	1.088	1.150	1.213	0.908	0.070	0.997
	44.3	0.5	1.000	1.019	1.035	1.054	1.067	0.977	0.022	0.993
40	25.4	0.85	1.000	1.096	1.156	1.204	1.275	0.959	0.069	0.997
	35.2	0.68	1.000	1.132	1.239	1.299	1.376	0.956	0.091	0.976
	44.3	0.57	1.000	1.031	1.069	1.099	1.149	0.932	0.050	0.996
45	25.4	0.95	1.000	1.059	1.100	1.182	1.228	0.918	0.072	0.980
	35.6	0.76	1.000	1.191	1.281	1.386	1.502	0.964	0.108	0.999
	44.3	0.63	1.000	1.056	1.109	1.180	1.231	0.932	0.069	0.985
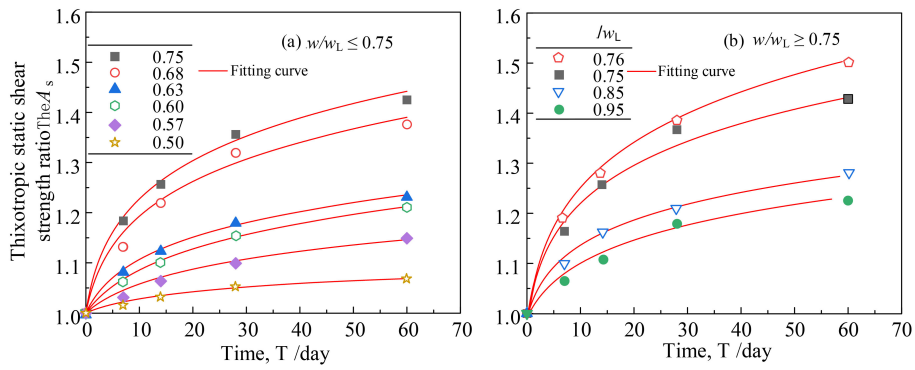
FIGURE 10
A_s−T curves with different w/w_L ratios for the remolded marine soft clay (**A, B** represent different w/w_L).

four different regions Bangladesh (Shahriar and Jadid, 2018), the South China Sea (Yang and Andersen, 2016), Taihu Lake (Wang et al., 2015), and Zhanjiang (Zhang et al., 2017). Using Equation 3 to fit the data revealed that the fitting results were excellent, with all R^2 values greater than 0.95, while the lowest R^2 value for the clay from the South China Sea clay was still 0.954. This indicates that using Equation 3 to evaluate the As of clays from different sites is advantageous due to its simplicity and broad applicability.

5 Conclusion

In this study, we conducted 45 unconfined compressive strength tests on the remolded marine soft clay from the Yangtze River estuary.

By analyzing its axial stress–strain curves, thixotropic strength recovery capability, and the impacts of curing time T, water content w, plasticity index I_P, and clay particle content ρ_c on its thixotropic static shear strength ratio A_s, we drew the following conclusions:

1. A_s values increased with an increase in T. For $T = 0–28$ days, the A_s increased rapidly, whereas for $T > 28$, A_s increased slightly or tended to stabilize. All specimens were capable of thixotropic strength recovery. Furthermore, a specimen with a high A_s does not necessarily have a high thixotropy static shear strength recovery ratio B_s. There is no one-to-one correspondence between the two.

2. The impacts of w, I_P, and ρ_c on A_s do not follow a consistent pattern, but there is a strong correlation between A_s and $w/$
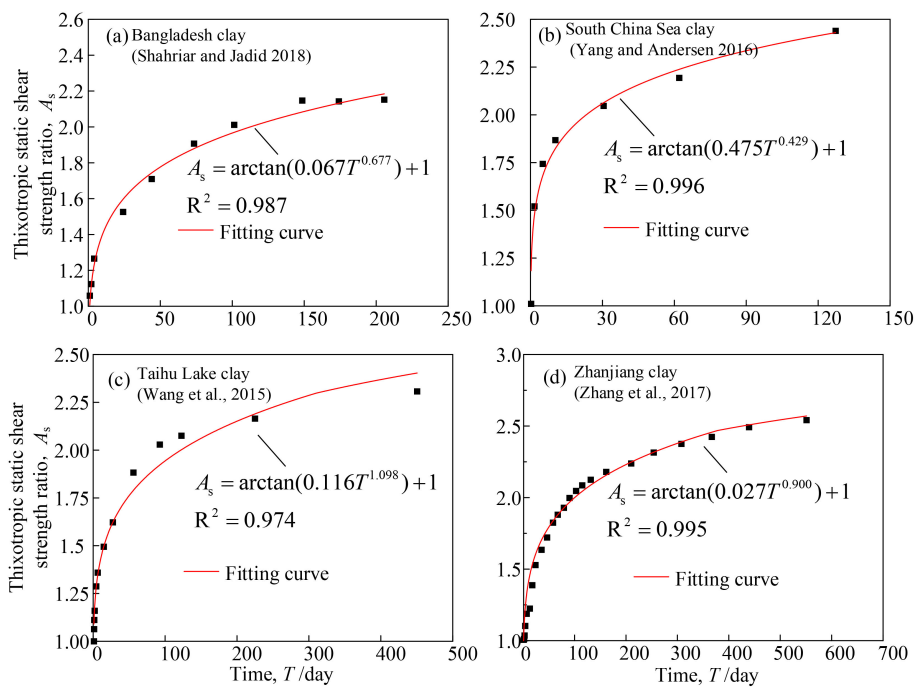

FIGURE 11
A_s−T curves for clays from different sites (**A−D** represent different regions).

w_L (w_L is the liquid-limit water content). A_s increased and decreased with increasing w/w_L for $w/w_L < 0.75$ and $w/w_L > 0.75$, respectively.

3. The A_s of the remodeled soft clay is affected by the coupling effect of w, I_P and T. We proposed a power function prediction model for the A_s of the soft clay from the Yangtze River estuary and verified its applicability.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

Funding

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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