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Investigating the Properties and Determinants of Underwater Anti-Dispersive Cementitious Soil with Kaolin: An Experimental Approach

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Abstract: Pile foundations, as one of the main foundation forms for bridges and offshore wind power structures, are prone to scour pits around them under the long-term action of water flow, leading to a decrease in bearing capacity. Traditional pile foundation scour prevention measures, such as the construction of protective jetties and riprap protection, are cumbersome and ineffective. Considering the inevitable generation of a large amount of spoil in engineering construction, by optimizing the performance of cement-stabilized soil, it is expected to use the discarded spoil for pile foundation scour management. Aiming at the underwater anti-dispersive cement-stabilized soil based on kaolin, 67 sets of single-factor rotation experiments were carried out to study the effects of changes in the addition of anti-dispersive agents ethylene-vinyl acetate copolymer (EVA), hydroxypropyl methylcellulose (HPMC) from 0‰ to 1‰, cement content from 8% to 14%, and water content from 1.4 to 2 times the liquid limit on the anti-dispersion performance, fluidity, and 7d and 28d unconfined compressive strength of the cement soil. The results show that the anti-dispersive agent HPMC can maximize the anti-dispersion performance of the cement soil, with the addition increased from 0‰ to 1‰, the anti-dispersion performance of the cement soil increased by 76.1%, but the fluidity decreased by 54.0%, and the strength of the 28d age cement soil increased by about 52.9%. Anti-dispersive agents can be added to quickly improve the anti-dispersion performance of the cement soil in pile foundation scour management, but attention should also be paid to its weakening effect on the fluidity of the cement soil; the increase in water content has the greatest impact on the fluidity of the cement soil, with the water content increased from 1.4 times the liquid limit to twice the liquid limit, the fluidity increased by 80.3%; the cement content increased from 8% to 14%, the unconfined compressive strength of the cement soil increased by more than double, and the anti-dispersion performance increased by 26.8%. Based on the experimental results, the recommended mix ratio of kaolin-based cement soil for pile foundation scour repair is: 0.75‰ EVA addition, 1.6 times the liquid limit water content, 10% cement content.

Keywords: Kaolin; Cement soil; Fluidity; Anti-dispersion; Unconfined compressive strength; Water content

1 Introduction

With the continuous increase in societal energy demands, offshore wind power equipment has gradually emerged to avoid occupying too much land resource [1]. Studies by scholars have shown that the columnar structures carrying wind power equipment can change the surrounding water flow patterns [2, 3], leading to local scour around the piles, affecting the pile's bearing capacity and the safety of the superstructure, thereby leading to safety incidents [4, 5]. Currently, the more widely applied and mature pile foundation scour repair methods include the construction of protective jetties and the riprap protection techniques [6], but constructing jetties can easily damage the pile foundation, and placing large loose stones (riprap) will consume a large amount of sand and gravel resources. Meanwhile, the environmentally friendly advantage of microbial reinforcement technology can solve stability issues facing the foundation [7], but this technology is still in the laboratory stage. Considering the large amount of waste soil generated during urban development is difficult to dispose of, its resourceful recycling and treatment align with the concept of ecological environmental protection. Cement-stabilized soil materials, with their high density and good integrity, therefore, optimizing the working performance of cement-stabilized soil to use waste soil for pile foundation scour management has broad prospects.

Many scholars have conducted in-depth studies on the scour protection of stabilized soil pile foundations. For instance, Li et al. [8] studied the erosion resistance characteristics of stabilized soil by analyzing the relationship between the erosion coefficient and the initiation shear stress, providing a new method for assessing the erosion resistance characteristics of flow-state stabilized soil, which compensates for the lack of assessment indicators for erosion resistance characteristics of stabilized soil. Zhou et al. [9] proposed four protective schemes specifically based on the different depths and ranges of scour pits around a single pile foundation, and used multibeam to test the protective effect of stabilized soil, proving that the stabilized soil protective layer can resist the scour of high-speed water flow. Although the superiority of the stabilized soil protection scheme was verified, there is a lack of related research on the more optimal mix ratio of cement-stabilized soil. Other scholars have studied the effects of adding admixtures to cement soil materials on their properties. Wang et al. [10] found that a 3% metakaolin admixture could maximize the unconfined compressive strength of cement soil by replacing cement with metakaolin in equal amounts to make cement soil blocks. Therefore, to improve the working performance of cement soil and apply it more effectively to pile foundation scour management, it is worth considering the addition of certain admixtures to the cement soil.

Some scholars have added certain anti-dispersants to concrete to improve its underwater working performance. For example, Khayat [11] prepared several mixtures of underwater anti-dispersive self-compacting concrete with two different types of anti-dispersants and conducted control experiments with concrete without admixtures. The results showed that the self-compacting concrete with anti-dispersants could significantly reduce scour loss. Ye [12] explored the impact of UWB-II type underwater anti-dispersant on the properties of underwater anti-dispersive concrete through experiments, and the results showed that the UWB-II type anti-dispersant could significantly enhance the strength and anti-dispersion of the concrete at a certain dosage, but excessive dosage would significantly reduce fluidity. The above studies mainly discussed the impact of anti-dispersants on the underwater anti-dispersion of concrete; however, the working performance of underwater anti-dispersive cement soil still needs further study.

To advance the application of underwater anti-dispersive cement-stabilized soil technology in pile foundation scour management, single-factor rotation experiments are designed and conducted to explore the effects of anti-dispersant type, dosage, cement content, and water content on the anti-dispersion performance, fluidity, and compressive strength of kaolin-mixed cement soil, and to screen out cement soil mixtures that meet the practical engineering needs of pile foundation scour resistance. This lays a foundation for future research and has guiding significance for related engineering fields.

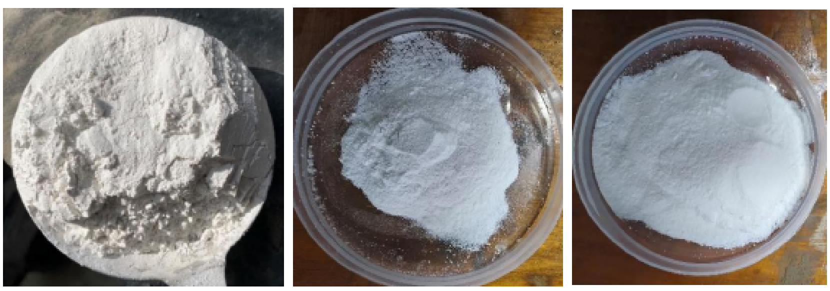
2 Experimental Materials and Scheme

2.1 Experimental Materials

The soil used is commercial kaolin, which has a fine particle size and exhibits the properties of a soft, cohesive soil. The basic physical and mechanical properties are shown in Table 1, and the experimental soil is shown in subgraph (a) of Figure 1. The cement material selected is Conch brand ordinary Portland cement, with a grade of P.O42.5, and the material parameters are shown in Table 2.

Table 1. Physical and mechanical properties of soil samples

Type of Soil	Proportion	Liquid Limit w_L	Plastic Limit w_P	Plasticity Index I_P
Kaolin	2.63	49.0	23.8	25.2



(a) Kaolin (b) EVA (c) HPMC

Figure 1. Some experimental materials

Table 2. Physical and mechanical properties of cement

Dry Density $/\mathrm{g/m^3}$	Fineness /%	Initial Setting Time /min	Final Setting Time /min	Stability	Flexural Strength $/\mathrm{MPa}$	Compressive Strength $/\mathrm{MPa}$
3.10	1.1	120	220	Qualified	9.2	50.3

Based on the formation mechanism of water-soluble polymers, anti-dispersants are divided into three main categories: natural, semi-synthetic, and synthetic polymers [13]. Natural polymers include xanthan gum, starch, etc.; semi-synthetic polymers include HPMC, cellulose ether derivatives, etc.; synthetic polymers include polyacrylamide, EVA. Under existing conditions, EVA and HPMC were selected as anti-dispersants. EVA is a hydrophilic polymer that, at higher concentrations, can entangle and adsorb onto cement and soil particles, enveloping free water to increase the cohesion and stability of the cement soil matrix [14]; HPMC belongs to the cellulose polymer category, with a long-chain structure. When mixed into the cement slurry, it adsorbs onto the surface of cement particles, forming a hinge effect that enhances the cohesiveness of the cement slurry [15, 16]. Anti-dispersant samples are shown in subgraph (b) and subgraph (c) of Figure 1.

2.2 Sample Preparation

According to the designed experimental scheme, the required amounts of soil, cement, water, and anti-dispersants were calcualted and weighed for the sample preparation. A mixer was used to mix the weighed soil, cement, and anti-dispersants evenly, the measured water was gradually added in small amounts, mixing thoroughly for 1 minute each time until the cement soil appears uniformly moistened. Then the flowability and anti-dispersion tests were condcuted immediately. After the experiments, the mixed soil samples were filled into the mold in multiple layers, compacting the sample manually with vibration and using a trowel for tamping. Excess cement soil was removed from the top of the mold to make the surface smooth and flat, and then covered with a plastic film to rest. The specimens were demolded after resting at room temperature for 48 hours. After demolding, the specimens were placed in water for curing according to the Specification for Mix Proportion Design of Cement Soil (JGJT 233-2011) [17], and then the unconfined compressive strength test was carried out after curing. The mix ratio of the cement soil is shown in Table 3.

Table 3. Mix ratio of cement soil

Cement Content α_c(%)	Type of Anti-Dispersant	Anti-Dispersant Dosage α_a(‰)	Water Content α_w	Age $t(d)$
8	HPMC	0	1.4 w_L	7
10	EVA	0.25	1.6 w_L	28
12		0.5	1.8 w_L	
14		0.75	2 w_L	
		1		

2.3 Experimental Scheme

Based on the existing conditions and the experimental protocols, this study designed a flowability test to measure the spread of freshly mixed cement soil to reflect its flowability, an anti-dispersion test to measure the turbidity of the suspension after the cement soil is immersed in water to reflect its anti-dispersion performance, and an unconfined compressive strength test to measure the unconfined compressive strength of different samples to reflect their mechanical properties.

2.3.1 Flowability test

The flowability test of cement soil is conducted following the standards stipulated in the Gypsum Based Self-Leveling Floor Compound JCT1023-2007 [18]. The test mold uses a metal hollow cylinder with an inner diameter of (30±0.1) mm and a height of (50±0.1) mm. The test plate uses a flat glass plate with an area larger than 300mm×300mm, as shown in subgraph (a) of Figure 2. The flowability test mold was placed horizontally in the center of the flat and smooth test plate, the mold was filled with the prepared sample, the excess cement soil was scraped off from the top of the mold, and then the mold was quickly lifted vertically upwards by 50mm-100mm, allowing the sample to flow freely on the test plate. After 4 minutes, the diameters in two perpendicular directions were measured and their arithmetic mean was taken as the flowability measurement value. A larger measurement value indicates better flowability of the cement soil.

2.3.2 Anti-dispersion test

A portable turbidity meter, model SGZ-200B, is used for the anti-dispersion test, as shown in subgraph (b) of Figure 2. Its working principle is: light emitted from a light source is irradiated onto the sample, and the scattered light is received. The photoelectric sensing element converts the received scattered light intensity signal into an electrical signal, which is then amplified and converted from analog to digital, and the turbidity value is displayed on the screen in NTU units. For the test, prepare a 500ml beaker and add 400ml of water to it. Then, slowly drop 100g of cement soil from above the water surface. After the drop, let the beaker stand for 5 minutes, gently extract the upper layer of the suspension with a pipette as the test sample, and quickly proceed with the test. Measure twice and take the arithmetic mean as the final determination value. A smaller determination value indicates better anti-dispersion performance of the cement soil.

2.3.3 Unconfined compressive strength test

The testing instrument is an SHT4305 microcomputer-controlled servo universal testing machine, with the loading diagram shown in subgraph (c) of Figure 2. During the test, the loading is carried out at a displacement control loading rate of 1mm/min until the sample is completely destroyed. When the maximum or minimum value of 3 specimens differs from the average value by no more than 10%, that average value is taken as the strength value; if the test value of an individual specimen exceeds or falls below the average value by more than 10%, that specimen is discarded, and the compressive strength is calculated based on the average value of the remaining specimens. The specimen size is a cylindrical sample with a diameter of 50mm and a height of 100mm.

(a) Flowability test mold and test plate (b) SGZ-200B turbidity meter (c) Unconfined compressive strength test

Figure 2. Testing instruments

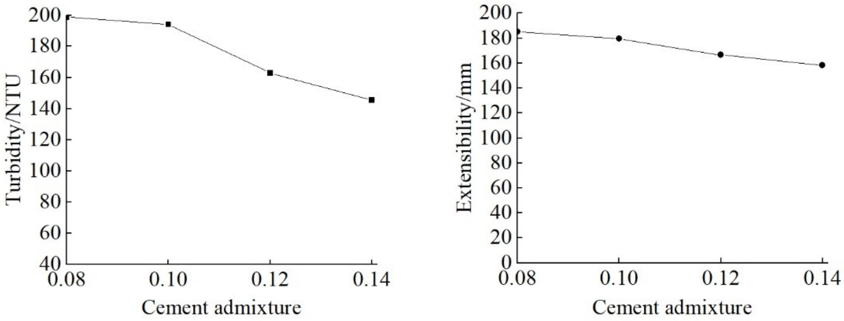
3 Experimental Results and Analysis

3.1 Anti-Dispersion and Flowability Tests

When cement soil is used underwater for resource utilization, such as filling underwater pits or scour pits, it needs to have certain anti-dispersion properties to prevent it from being dispersed by water flow during underwater pouring. In practical construction processes, underwater pouring of cement soil often uses the tremie method for pumping [19], and the fluidity of the cement soil must meet certain requirements. If the fluidity of the cement soil is poor, it may cause blockages during construction. According to the Gypsum Based Self-Leveling Floor Compound JCT1023-2007, the spread of the sample four minutes after preparation should be greater than 130mm. This section will study the effects of water content, cement content, type of anti-dispersant, and dosage on the development of anti-dispersion and fluidity of cement soil by adjusting these factors.

3.1.1 Impact of cement content

Figure 3 shows the relationship between the turbidity of the cement soil suspension, the spread of the cement soil, and the cement content when the water content is twice the liquid limit. As shown in subgraph (a) of Figure 3, the turbidity of the suspension gradually decreases as the cement content increases. When the cement content is 8%, the turbidity is 198.95NTU, and when the content increases to 14%, the turbidity drops to 145.5NTU, showing a decrease of 26.8%. This is related to the hydration reaction of cement, as during the hydration reaction, viscous soil particles can physically adsorb CaO from the cementitious substances. The $Ca(OH)_2$ in the matrix is in an unsaturated state, reducing the hydrated calcium silicate and hydrated calcium aluminate [20], thereby promoting the formation of ettringite, which can enhance the stability of the cement soil and reduce the turbidity of the cement soil suspension. Therefore, under a certain water content, increasing the cement content can enhance the anti-dispersion performance of the cement to a certain extent.



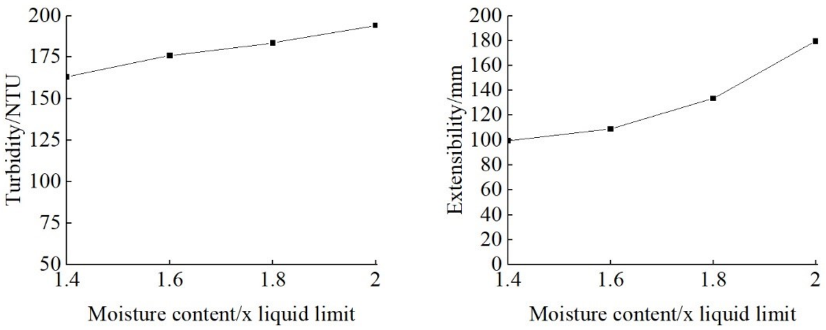
(a) Turbidity change with cement content (b) Spread change with cement content

Figure 3. Impact of cement content on turbidity and spread

As shown in subgraph (b) of Figure 3, when the cement content is 8%, the spread is 185.0mm, and when the content increases to 14%, the spread decreases to 158.5mm, showing a decrease of 14.3%, which is a small decrement. The higher the cement content, the higher the proportion of cement that can react with water, consuming more water, and reducing the proportion of free water. Therefore, the spread of the cement soil will decrease, leading to poorer fluidity of the cement soil.

3.1.2 Impact of water content

Figure 4 shows the relationship between the turbidity of the cement soil suspension, the spread of the cement soil, and the water content when the cement content is 10%. As shown in subgraph (a) of Figure 4, with the increase in water content, the turbidity of the suspension gradually increases. When the water content is 1.4 times the liquid limit, the turbidity of the suspension is 163.11NTU, and at 2 times the liquid limit, the turbidity reaches 194.31NTU, showing an increase of 19.1%. Increasing the water content of the cement soil raises the proportion of water present in the form of free water. Water molecules attach to the surfaces of soil and cement particles, completely enveloping them, delaying the process of cement hydration, and forming a smooth layer of water film on the surface of material particles, reducing the cohesion between particles, hence resulting in an increase in suspension turbidity.

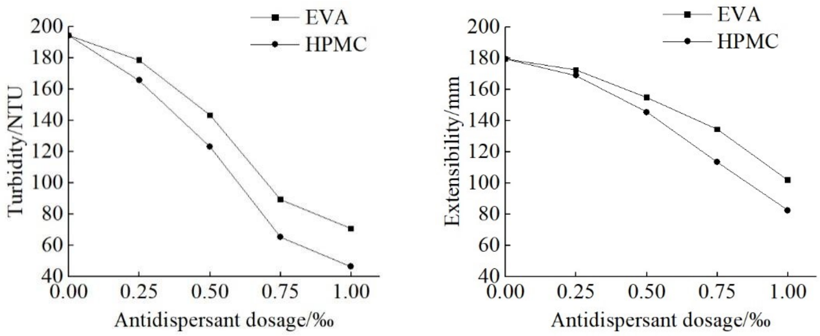


(a) Turbidity change with water content (b) Spread change with water content

Figure 4. Impact of water content on turbidity and spread

3.1.3 Impact of anti-dispersants

Figure 5 shows the relationship between the turbidity of the cement soil suspension, the spread of the cement soil, and the two types of anti-dispersants and their dosages. As shown in subgraph (a) of Figure 5, the addition of two different anti-dispersants significantly reduces the turbidity of the freshly mixed cement soil suspension. When HPMC is used as the anti-dispersant, when its dosage is increased from 0‰ to 1‰, the turbidity drops from 194.31NTU to 46.52NTU, showing a reduction of 76.1%, while using EVA reduces the turbidity by 66.6%, with HPMC showing a more pronounced improvement in the anti-dispersion of cement soil. On one hand, the ether and hydroxyl groups in HPMC molecules and the carboxyl groups in EVA molecules bind with water molecules through hydrogen bonding and fixate to the periphery of water molecules, macroscopically increasing the viscosity of the water [21, 22]. On the other hand, the polar interactions between anti-dispersant molecules increase the contact area with other particles, adsorbing and enveloping the surfaces of fine soil and cement particles, forming a relatively stable networked gel structure, improving the cohesion between soil and cement particles [23], thus reducing the turbidity of the cement soil suspension.



(a) Turbidity change with anti-dispersant dosage

(b) Spread change with anti-dispersant dosage

Figure 5. Impact of anti-dispersant dosage on turbidity and spread

As shown in subgraph (b) of Figure 5, the addition of anti-dispersants gradually reduces the spread of cement soil. Without anti-dispersants, the spread of cement soil is 179.5mm. When the dosage of HPMC increases to 0.25‰, 0.5‰, 0.75‰, and 1‰, the spread respectively decreases by 5.8%, 13.1%, 17.8%, and 17.3%. The negative impact of EVA on the fluidity of cement soil is slightly less. The introduction of anti-dispersants leads to the formation of a more stable gel network structure within the cement soil, increasing its viscosity. The degree of viscosity change is determined by the molecular weight of the anti-dispersant and the number of functional groups it carries [24], thus incorporating HPMC with a higher molecular weight results in a greater reduction in the spread of cement soil.

3.2 Unconfined Compressive Strength Analysis

Cement soil is usually considered a brittle material and has lower mechanical properties compared to other cement-based materials such as concrete. When used for pile foundation scour resistance or filling scour pits, the cement soil hardened around the pile foundation can easily crack and break under the action of wave flow or when the pile foundation is subjected to significant horizontal loads, failing to meet engineering requirements. Wang et al. [25] found that soil samples with an unconfined compressive strength of 300kPa could resist water flow erosion at 3.14m/s after curing. This section will explore the impact of water content, cement content, type of anti-dispersant, and dosage on the development of unconfined compressive strength of cement soil by adjusting these factors.

3.2.1 Analysis of orthogonal experimental results

Figure 6 shows the relationship between the unconfined compressive strength of cement soil at ages of 7d and 28d and the cement content. When the water content is twice the liquid limit, the unconfined compressive strength of cement soil at both 7d and 28d ages increases with the increase in cement content, with a small difference in the rate of strength increase between the two ages. At a 7d age, when the cement content is 8%, the compressive strength is 72.3kPa. After increasing the cement content to 14%, the compressive strength rises to 184.1kPa, showing an increase of about 154%. The compressive strength of cement soil materials depends on the quantity and uniformity of cement hydration products within the matrix. With higher cement content, the quantity of hydration products like AFt, AH3, and C-S-H gel increases, connecting to form a network framework within the cement soil [26], making the internal structure of the cement soil dense and stable, and thus increasing the unconfined compressive strength. According to the trend of compressive strength changes shown in the figure, it can be observed that as the cement content increases, the increase in strength will gradually stabilize.

3.2.2 Impact of water content

Figure 7 presents the curves fitted with a quadratic function for the unconfined compressive strength of cement soil at two ages. The linear correlation coefficient R2 is above 0.99 for both curves, indicating a good fit. The fitted curves show that the unconfined compressive strength of cement soil at both ages decreases with an increase in water content, but the rate of change gradually slows down. When the water content is 1.4 times the liquid limit, the unconfined compressive strength of cement soil at 7d and 28d ages are 440.13kPa and 1224.36kPa, respectively. As the water content increases, the evaporation of excess free water causes many capillary pores to form inside the cement soil, reducing its compressive strength.

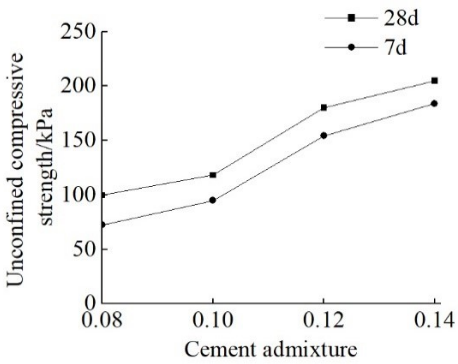


Figure 6. The change of unconfined compressive strength with cement content

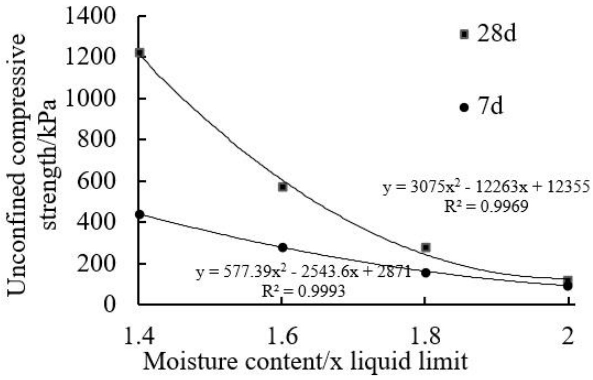
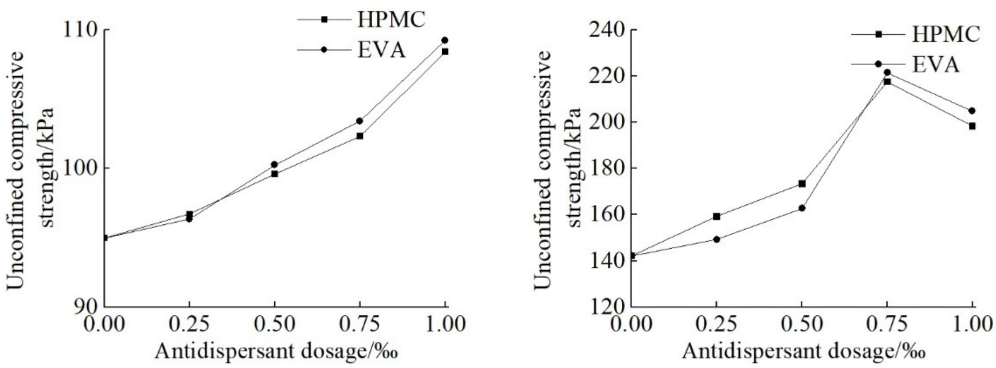


Figure 7. The change of unconfined compressive strength with water content

After the water content increases to twice the liquid limit, the unconfined compressive strength decreases to 94.98kPa and 118.25kPa, respectively, decreasing by 78.5% and 90.3%. Moreover, when the sample is axially compressed, the free water and capillary water inside the cement soil, through the interface between hydration binders, reduce the van der Waals forces between them, weakening its compressive strength [27]. At the same time, the exudation of excess water weakens the effect of water content, hence the decrease in compressive strength of cement soil slows down.

3.2.3 Impact of anti-dispersants



(a) Change of 7-day unconfined compressive strength with anti-dispersant dosage

(b) Change of 28-day unconfined compressive strength with anti-dispersant dosage

Figure 8. Impact of anti-dispersant dosage on unconfined compressive strength

Figure 8 shows the relationship between the unconfined compressive strength of cement soil at 7d and 28d ages with two types of anti-dispersants and their dosages. Under the incorporation of two different types of anti-dispersants, there is not much difference in the compressive strength of cement soil at 7d or 28d ages. As shown in subgraph (a) of Figure 8, at 7d age, the compressive strength generally increases linearly with the increase in anti-dispersant dosage, such as when EVA dosage increases from 0‰ to 0.25‰, 0.5‰, 0.75‰, 1.00‰, the strength respectively increases by 1.5%, 4.1%, 3.3%, 6.1%. This is because the anti-dispersants act in water, further enhancing the cohesion within the cement soil, making the structure denser and increasing its strength.

As shown in subgraph (b) of Figure 8, at 28 days, the compressive strength initially increases with the addition of anti-dispersant and then decreases, reaching a maximum value when the dosage is 0.75‰. This is because as the amount of anti-dispersant increases, air is inevitably mixed into the cement soil during mixing, forming many micro-bubbles inside, which increases the porosity and flexible polymers [28] in the cement soil. When the cement soil matrix is compressed, they cannot act as rigid supports like the hydration products of cement, effectively weakening the cement soil matrix. Considering both practicality and economy, a 0.75‰ anti-dispersant dosage is identified as the optimal amount for enhancing the strength of cement soil.

3.2.4 Analysis of orthogonal experimental results

Previous sections have shown that controlling individual factors has a significant impact on the compressive performance of cement soil. However, the joint effect of multiple factors remains to be tested. Therefore, an orthogonal analysis experiment was conducted on the 28-day unconfined compressive strength of cement soil. The experiment involved four factors: type of anti-dispersant (EVA, HPMC), anti-dispersant dosage (0.25‰ to 1‰), water content (1.4 wL to 2 wL), and cement content (8% to 14%). Based on the results of the experiment, an analysis was carried out based on the range of strength corresponding to each factor [29]. The range value R reflects the degree of change in compressive strength of cement soil with the level change of factors, with a larger R value indicating that the factor is a major influencer on compressive strength.

Figure 9 shows the range impact of each factor on the 28-day unconfined compressive strength of kaolin-based cement soil. The relationship between the range values of each influencing factor is: $R_{\text{water content}} > R_{\text{anti-dispersant dosage}} > R_{\text{cement content}} > R_{\text{type of anti-dispersant}}$. This indicates that for the 28-day aged kaolin-mixed cement soil, changes in water content show significant variability in strength impact. The reason for this situation may be due to the high level of water content range in the kaolin strength test, which leads to a higher degree of dilution of the cementitious material in the matrix. It is difficult to ensure uniformity of the samples during actual pouring, resulting in greater dispersion of the 28-day unconfined compressive strength data. Therefore, targeted optimization of water content can achieve better target values for the compressive performance of 28-day aged cement soil.

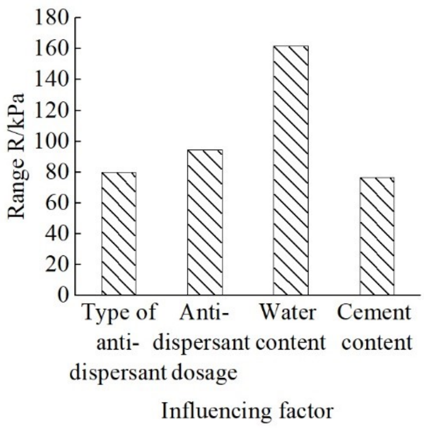


Figure 9. Analysis of the range of unconfined compressive strength

4 Conclusions

This paper designed and conducted experiments on the mix ratio of underwater anti-dispersive cement-stabilized soil based on kaolin, focusing on the anti-dispersive performance, fluidity, and mechanical properties of cement-stabilized soil and their influencing factors. The results revealed the variation laws of these key properties with changes in the type and dosage of anti-dispersants, cement content, and water content.

(1) Anti-dispersants have a significant impact on the anti-dispersive property of cement soil, with HPMC showing a more pronounced improvement. The addition of 1‰ HPMC reduced the turbidity of the cement soil suspension by 76.1% and increased the 28-day strength by 52.9%. However, while anti-dispersants increase the viscosity of cement soil, they reduce its fluidity, with 1‰ HPMC reducing the fluidity of cement soil by 54.0%.

(2) The fluidity of cement soil significantly improves with increased water content, but excessive water reduces its compressive strength. When water content increased from 1.4wL to 2wL, fluidity increased by 80.3%, while compressive strength decreased by 78.5%.

(3) Increasing the cement content enhances the strength and anti-dispersive property of cement soil. An increase in cement content from 8% to 14% more than doubled the unconfined compressive strength and reduced the turbidity of the cement soil suspension by 26.8%. However, an increase in cement also leads to higher water consumption, negatively affecting the fluidity of cement soil.

(4) Based on the experimental results and considering anti-dispersiveness, fluidity, and unconfined compressive strength, it is recommended for pile foundation scour repair to use a kaolin-based cement soil mix ratio of 0.75‰ EVA dosage, 1.6 times the liquid limit water content, and 10% cement content. It is recommended that this ratio be used as a reference for further trial mixes and selection in engineering projects.

(5) Based on a series of experiments, this study proposes a cement soil mix ratio based on kaolin with certain underwater anti-dispersive properties. Considering the variety of anti-dispersants currently available and the common use of mineral powder, water-reducing agents, and other materials to enhance the properties of mixtures in engineering, further work is needed to optimize the selection of anti-dispersants and the mix ratio through a multi-component approach, thereby providing beneficial references and technical support for engineering practice.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] Z. Sun, S. Wang, X. Y. Su, and J. Y. Rao, "Building an offshore wind power integrated supply and consumption system to help achieve dual-carbon strategy goals," *Chin. Consult. Eng.*, vol. 2023, no. 10, pp. 33–36, 2023. https://doi.org/10.3969/j.issn.1009-5829.2023.10.007

[2] F. C. Ting, J. L. Briaud, H. C. Chen, R. Gudavalli, S. Perugu, and G. Wei, "Flume tests for scour in clay at circular piers," *J. Hydraul. Eng.*, vol. 127, no. 11, pp. 969–978, 2001. https://doi.org/10.1061/(ASCE)0733-9429(2001)127:11(969)

[3] B. M. Sumer and J. Fredsøe, "Scour around pile in combined waves and current," *J. Hydraul. Eng.*, vol. 127, no. 5, pp. 403–411, 2001. https://doi.org/10.1061/(ASCE)0733-9429(2001)127:5(403)

[4] Q. Q. Xiang, Y. D. Li, K. Wei, S. Y. Wang, and C. R. Yao, "Review of bridge foundation scour," *J. Southwest Jiaotong Univ.*, vol. 54, no. 2, pp. 235–248, 2019. https://doi.org/10.3969/j.issn.0258-2724.20170373

[5] Z. F. Dong, J. Guo, and J. J. Wang, "Summary and prevention countermeasures of bridge collapses," *Shanghai Highw.*, vol. 2, no. 2, pp. 30–32, 2009. https://doi.org/10.3969/j.issn.1007-0109.2009.02.009

[6] Y. M. Chiew, "Scour protection at bridge piers," *J. Hydraul. Eng.*, vol. 118, no. 9, pp. 1260–1269, 1992. https://doi.org/10.1061/(ASCE)0733-9429(1992)118:9(1260)

[7] Y. D. Liu and Q. Liu, "Prospects of microbial consolidation technology in foundation treatment applications," *Constr. Saf.*, vol. 34, no. 10, pp. 12–14, 2019. https://doi.org/10.3969/j.issn.1004-552X.2019.10.004

[8] Z. Y. Li, G. L. Dai, and S. Du, "Experimental study on scour resistance characteristics of fluid cured soil for offshore wind power foundation," *J. Southeast Univ.*, vol. 53, no. 4, pp. 647–654, 2023. https://doi.org/10.3969/j.issn.1001-0505.2023.04.010

[9] M. Q. Zhou, P. Li, X. Q. Luo, Y. W. Shi, and H. T. Zhang, "Application of solidified soil in scour protection of foundations in offshore wind power engineering," *J. Waterway Harb.*, vol. 44, no. 2, pp. 264–269, 2023. https://doi.org/10.3969/j.issn.1005-8443.2023.02.015

[10] P. Y. Wang, Y. L. Yang, L. H. Wang, and X. H. Bai, "Influence of metakaolin on strength and permeability coefficient of cement soil," *Sci. Technol. Eng.*, vol. 18, no. 10, pp. 112–116, 2018. https://doi.org/10.3969/j.issn.1671-1815.2018.10.019

[11] K. H. Khayat, "Effects of antiwashout admixtures on fresh concrete properties," *Mater. J.*, vol. 92, no. 2, pp. 164–171, 1995.

[12] K. Ye, "Research on high-performance offshore underwater non-dispersive concrete," Master's thesis, Yangzhou University, 2016. https://doi.org/10.7666/d.Y3131187

[13] T. Kawai, "Non-dispersible underwater concrete using polymers–the production, performance and potential of polymers in concrete," in *5th International Congress on Polymers*, Brighton, 1987, p. 523.

[14] Y. F. Wang, Q. B. Chen, X. J. Mei, S. B. Yao, L. Chen, and W. B. Su, "Study on preparation and properties of sulphoaluminate silicate anticorrosive mortar doped with eva rubber powder," *Chin. J. Colloid Polym.*, vol. 40, no. 1, pp. 3–7, 2022. https://doi.org/10.13909/j.cnki.1009-1815.2022.01.001

[15] B. Ma, Y. Peng, H. Tan, S. Jian, Z. Zhi, Y. Guo, and X. He, “Effect of hydroxypropyl-methyl cellulose ether on rheology of cement paste plasticized by polycarboxylate superplasticizer,” *Constr. Build. Mater.*, vol. 160, pp. 341–350, 2018. https://doi.org/10.1016/j.conbuildmat.2017.11.010

[16] L. Cai, M. L. Wu, F. S. Luo, D. L. Yang, B. Li, C. Wang, and T. S. Zhang, “The influence of hydroxypropyl methylcellulose on the properties of permeable concrete,” *Highway*, vol. 66, no. 12, pp. 355–362, 2021.

[17] Fujian Academy of Building Research, “Specification for Mix Proportion Design of Cement Soil (JGJ/T233-2011).” Beijing: China Architecture & Building Press, 2011.

[18] Beijing Building Materials Academy of Science Research, *Specification for Mix Proportion Design of Cement Soil (JC/T 985-2005)*. Beijing: Tongji University Press, 2005.

[19] Z. C. Tang, “Underwater concrete pouring methods and scour hole repair construction technology,” *Shaanxi Water Resour.*, vol. 2015, no. S1, pp. 58–60, 2015. https://doi.org/10.3969/j.issn.1673-9000.2015.z1.028

[20] H. C. Sun, “Study on the mechanical properties and microstructural characteristics of sludge solidified soil with low cement content,” Master’s thesis, Zhejiang University, 2020.

[21] K. Wu, W. Kang, L. L. Xu, A. Hecker, H. M. Ludwig, and P. M. Wang, “Influence of hydroxyethyl methyl cellulose on early hydration of calcium sulfoaluminate cement,” *J. Chin. Ceram. Soc.*, vol. 48, no. 5, pp. 615–621, 2020. https://doi.org/10.14062/j.issn.0454-5648.20190625

[22] J. Liu, “Research on anti-dispersant for underwater non-dispersive concrete,” Master’s thesis, Hunan University, 2005. https://doi.org/10.7666/d.y832575

[23] K. L. Qian, Y. Peng, G. R. Zhao, and P. M. Wang, “Comparison on morphology of ettringite transformed by different cellulose ethers at early ages,” *J. Chin. Electron Microsc. Soc.*, vol. 39, no. 3, pp. 268–273, 2020. https://doi.org/10.3969/j.issn.1000-6281.2020.03.007

[24] P. D. J. Cano-Barrita and F. M. León-Martínez, “Biopolymers with viscosity-enhancing properties for concrete,” in *Biopolymers and Biotech Admixtures for Eco-Efficient Construction Materials*, 2016, pp. 221–252. https://doi.org/10.1016/B978-0-08-100214-8.00011-7

[25] J. Wang, J. Xie, Y. Wu, C. Wang, and F. Liang, “An investigation of the effect of utilizing solidified soil as scour protection for offshore wind turbine foundations via a simplified scour resistance test,” *J. Mar. Sci. Eng.*, vol. 10, no. 9, p. 1317, 2022. https://doi.org/10.3390/jmse10091317

[26] C. Z. Qu, “Finite element analysis of the performance of cement-soil mixing pile retaining structure for foundation pits,” Master’s thesis, Xiangtan University, 2007. https://doi.org/10.7666/d.d131542

[27] C. A. Ross, D. M. Jerome, J. W. Tedesco, and M. L. Hughes, “Moisture and strain rate effects on concrete strength,” *Mater. J.*, vol. 93, no. 3, pp. 293–300, 1996. https://doi.org/10.14359/9814

[28] H. Feng and Q. J. Zhu, *Concrete Admixtures Engineering Application Handbook*. Beijing: China Architecture & Building Press, 1999.

[29] X. W. Ma, *Mathematical Theory of Orthogonal Design*. People’s Education Press, 1981.