Research Paper/Technical Note/Review Article

Effect of Water-Cement Ratio and Liquidity Index on the Deep Mixing Method using Cement Slurry: A Case Study of Kaolin Clay Powder.

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ABSTRACT

The liquidity index is a crucial factor in geotechnical engineering used to assess soil behavior under varying loading conditions. It provides valuable information about a soil's deformability when subjected to loads, which is vital for structural and foundation design. In the domain of soil-cement, especially within the deep mixing method (*DMM*), various factors influence the strength of cement-stabilized soft soils. These factors include water content, cement content, water-cement ratio (*W/C*), and soil consistency. Notably, a lower W/C ratio tends to result in higher unconfined compressive strength (q_u). In the case of the Saga lowland, where soft cohesive soil with high compressibility and low strength is prevalent, the standard practice employs a *W/C* ratio of 1.0 with a cement content of 110 kg/m³ for most projects. However, this research introduces an innovative approach: utilizing a W/C ratio of 1.5 with the same cement content of 110 kg/m³, through laboratory experiments. It investigates the effects of Liquidity Index (I_L), instead of soil sensitivity, and the water-cement ratio on the unconfined compressive strength of specimens prepared using commercial kaolin clay powder. These specimens are prepared with varying initial water content (W_i), determined based on the liquid limit value (W_L), to achieve different soil states. As a result, there is a slight reduction in strength, but it is more uniformly distributed. This approach is designed to bolster support for the existing infrastructure in the Saga lowland. The significance of this study in the field of DMM lies in advocating for an increased *W/C* ratio to ensure not only the quality of the mixture but, more importantly, the uniformity of strength within the columns. In this context, the optimal ratio depends on a soil candidate consistency parameter, such as its I_L.

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1. Introduction

Some cohesive soils such as Ariake clay have a high sensitivity ratio [1] and suffer a drastic decline in strength once they are disturbed [2]. That is why soil improvement is necessary when poor geotechnical conditions are encountered for the intended purpose. The deep mixing method (*DMM*) can increase the strength and decrease the compressibility of soft ground, and thereby improve stability and reduce settlement of embankments and levees [3].

Adding binder to clay soil provides a moderate improvement of its geotechnical properties. For environmental purpose and for quality of mixing when using traditional binders such as cement, wet method leads to more homogenous structure of soil-cement material, which is caused by longer mixing phase and presence of applied water [4].

DMM applied in Lowland areas in Japan, depending on the project is empirically set at *W/C*=1.0, with an amount of cement C and a design standard strength ($\bar{q}_u$) range respectively between 50~150 kg/m^3 and 500~1000 kN/m^2 [5]. However, there is a prevalent reluctance among engineers to increase the water content (*W/C*>1) due to concerns about potential vertical and horizontal displacement of improved soil columns resulting from excess water.

In our current understanding, the consideration of a *W/C* ratio of 1.5 has not been fully explored in investigating unconfined compressive strength (UCS), mixture quality, and, more importantly, the uniformity of strength within columns in correlation with the design standard strength ($\bar{q}_u$) of the DMM in Lowland areas in Japan, using Kaolin clay as the basic soil. Thus, there is limited information about handling specimens made of commercial kaolin clay powder in correlation with the design standard strength ($\bar{q}_u$) of DMM, and previous research has not clearly addressed UCS by focusing on quality control in terms of uniform strength in the geotechnical engineering field. Consequently, this study aimed to fill this research gap.

Until now, studies have predominantly focused on the effects of specimen size on the *UCS* of *DMM* [6], the effects of water/cement ratio on properties of cement-stabilized clay for wet deep mixing application [7, 8], and on 'deep mixing column group reinforcement by a shallow mixing layer beneath an embankment,' which involved UCS tests and kaolin slurry made by mixing kaolin powder with 100% water content [9].

Through the experiments, we emphasize the preparation of specimens with varying initial water content (W_i), adjusted based on the liquid limit value (W_L), thus offering different achievable soil states with Liquidity Index (I_L) as a landmark. Therefore, the purpose of this study is to explore the influence of the water-cement ratio on the unconfined compressive strength of specimens made of commercial kaolin clay powder.

The findings of this study demonstrate that by employing a *W/C* ratio of 1.5, leading to a slightly reduced in strength but ensuring uniform distribution, offers enhanced support for current infrastructure. The innovation lies in increasing the *W/C* ratio for optimal mixing under high I_L conditions, coupled with adjusting the cement quantity, C, to meet the design standard strength ($\bar{q}_u$) of *DMM* in Lowland areas in Japan.

2. Background and rationale

Figure 1 shows non-solidification in the implementation of DMM on a construction site. And table 1 is about comparison of cohesive soil properties on this site and on the Saga Lowland. Observations from this construction site reveal a notable difference between the characteristics of soft cohesive soil in this site and that of Saga lowland. Specifically, the soil at this site exhibits lower liquidity (I_L<1) and compressibility indexes, while Saga lowland soil presents with a higher liquidity index (I_L>1) and greater compressibility. Moreover, the unconfined compressive properties differ, with the former displaying ductile fractures and the latter exhibiting predominantly brittle fractures.

When engineers apply for a fixed quantity of cement a ratio *W/C*=1.5 to Saga lowland soft clay, they achieve satisfactory soil-cement performance. However, using the same ratio, with a fixed quantity of cement in other locations results in unsatisfactory outcomes. The slurry binder fails to effectively mix with the ground, instead rising to the surface as shown in Figure1. b.
So, when I_L is less than 1 or approximately equal to 1, the pore water in the soil behaves as a special fluid, exhibiting characteristics of plastic state. On the other hand, when I_L is greater than 1, the pore water in the soil transforms into a general liquid.

This leads us to question whether very watery soil (I_L>1) is good for mixing, as the consistency of both, the slurry binder, and the soil, is quite similar when we use a water-cement ratio of 1.5 (*W/C*=1.5). On the other hand, when the soil is in a plastic state (with 0<I_L<1), mixing it with the slurry binder under *W/C*=1.5 conditions, become challenging because the two materials have different levels of fluidity. This can potentially result in problems with the quality of the mixture, as illustrated in figure 1.d.

Fig.1: Non-solidification in the implementation of DMM on a construction site.

Table 1. Comparison of cohesive soil properties on a site and on the Saga Lowland.

	Over-consolidation Ratio (OCR)	Plasticity Index (I_P)	Liquidity Index (I_L)	Compression Index (C_c)	Unconfined compressive property	Characteristics
Cohesive soil at this site	OCR > 1	High	$I_L < 1$	$C_c \leqq 1$	Ductile	Low sensitivity Low compressibility
Cohesive soil in Saga Lowland	OCR > 1	High	$I_L > 1$	$C_c >> 1$	Brittle	High sensitivity High compressibility

In short, IL is defined to understand the consistency and the compressibility of soil, and it is represented mathematically as the ratio of the difference between the natural water content of the soil and its plastic limit, to its plasticity index (I_P).

It's worth noting that W_i, W_L, and W_p are factors that can be applied to determine soil's consistency and compressibility. Soils with higher I_L values tend to be more compressible than those with lower I_L values. For instance, Ariake clay in the Saga lowland exhibits high sensitivity and compressibility. These clay types behave as solids when undisturbed but can liquefy when disturbed [10]. Given this, I_L emerges as a vital parameter providing insights into soil behavior under varying loading conditions, a critical aspect in the design of foundations and other structures. Engineers should not overlook its significance.

In this study, we employ kaolin clay powder to investigate the impact of the liquidity index and the water-cement ratio of the slurry binder on the mixture quality, with a focus on the distribution of unconfined compressive strength.

3. Materials, equipment, and methodology

3.1 Methodology

For this study, we use commercial kaolin powder as the soil sample. We define W_i as the adjusted initial water content of the soil sample and W_L as its liquid limit. W_i/W_L represents the ratio of W_i to W_L, and we examine this parameter with values from the set {0.8, 1, 1.5}. The *W/C* ratio is calculated as the ratio of Water to Cement and is explored using values from the set {0.5, 1.0, 1.5} as another parameter of interest in our study. The relationship between the ratio W_i/W_L and the liquidity index (I_L) of the material, which is defined to understand its consistency, is represented mathematically by equation [11].

$$I_L = \frac{W_i - W_p}{W_L - W_p} = \frac{W_i - W_p}{I_p} \quad [11]$$

Here, we have W_L=63%, and W_p=42% and the specific density ρ_s=2.6 g/cm^3. For the adjusted water W_i to make the powder in a certain initial condition. The link between this ratio (W_i/W_L) and IL is shown in table 2.

Table 2. relationship between liquidity index and adjusted initial water content.

Adjusted water content conditions	**Corresponding liquidity index**
W_i/W_L=	**I_L=**
0.8	0.4
1	1
1.5	2.5

The sample preparation process follows the guidelines outlined in *JGS* 0821-2009 [12], for soil specimen preparation.

The preparation process, from mixing to curing the specimens, is as follows:

Measure the required quantities of the sample, cement-based stabilizer, and the necessary amount of water for each specified *W/C* ratio.

Figure 2.b: mix the cement and water thoroughly at the specified *W/C* ratio. To ensure the conditions before mixing are met, place the solidifying material slurry in the mixing container, sandwiched between two layers of samples. Then, mix it vigorously using a mixer until a uniform stabilized material is obtained. The standard mixing time is approximately 10 minutes.

Figure 3.a: seal the mold with a sealing material to prevent moisture evaporation from the soil specimen. And allow the soil specimen to stand for the specified period in a temperature-controlled room, typically maintained at (20±3) °C, for a standard curing time of 28 days (*D28*).

Figure 3.b: the upper end surface of the soil specimen is covered with a polymer film. When filling the stabilized soil into the mold, divide it into roughly three layers, and remove air bubbles from each layer to prepare the soil specimen.

Figures 4.a, b: for the accelerated curing method (D1acm), the initial curing time in a temperature-controlled room is about 3 hours. Subsequently, the specimen is placed in a constant temperature water tank with hot water at a temperature of 55℃±5℃ for 20.5 hours, followed by a 0.5-hour post-curing time, totaling approximately 24 hours of curing time.

Figure 5.a, b: after the designated curing time, the specimens are used for various measurements and for Unconfined Compressive Test (*UCT*), which yielded the next results.

The statistical analysis of the obtained data offers valuable insights into the distribution of strength within the columns. To comprehend the uniformity of strength distribution, the coefficient of variation, a statistical measure reflecting the dispersion of data points around the mean, is employed in this analysis.

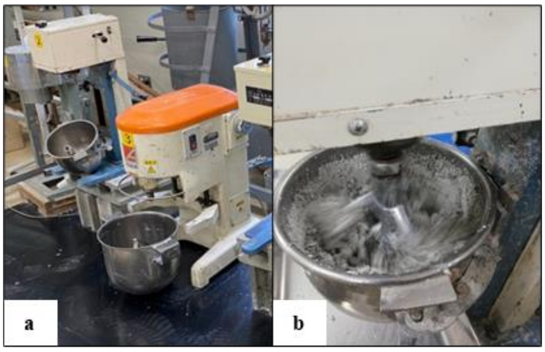

Fig.2: Electrically operated mixer

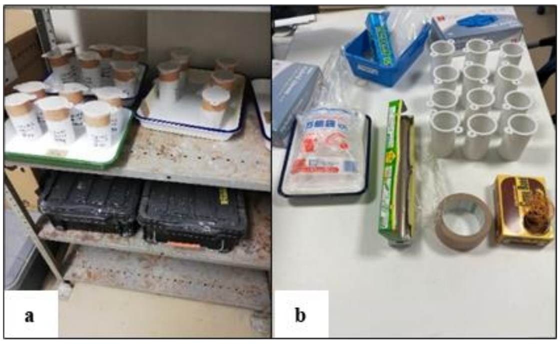

Fig.3: Temperature-controlled room, molds, and sealing materials.

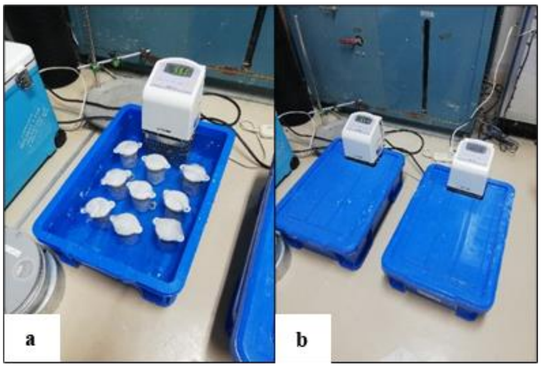

Fig.4: Constant temperature water tanks

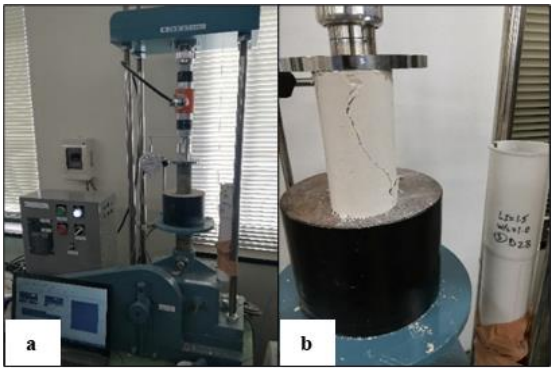

Fig.5: Load & displacement measurement device

3.2 Materials and equipment

Table 3 is showing the basic properties of the kaolin clay used in this study. Based on the grain size distribution, we observe that the clay particle content is 82%, confirming the material as clayey soil. The liquid limit represents the water-holding capacity of soil particles; in this case, we have a W_L of 63% with a plastic limit of W_p = 42%. A high liquid limit suggests high compressibility and shrinkage/swelling potential.

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Table 3. Basic properties of kaolin clay.

Grain size distribution	Gravel (%)	0
	Sand (%)	0
	Silt (%)	18
	Clay (%)	82
Soil particle density ρ_s (g/cm^3)		2.6
Liquid limit W_L (%)		63
Plastic limit W_p (%)		42

Mixing equipment: to ensure a homogeneous mixture, we use an electrically operated mixer. Additionally, we employ a mixer equipped with a drive unit, agitating blades, and mixing containers, as illustrated in Fig. 2, to uniformly blend the soil and stabilizer.

Molds: we use molds with standardized dimensions, featuring a 5cm diameter and 10cm height, to shape the soil-cement specimens. These molds are sealed with materials like polymer film (Fig. 3) to maintain a consistent moisture content.

Curing equipment: for the curing process, we utilize a temperature-controlled room set at (20±3) °C for standard curing periods of 7 days and 28 days (Fig. 3). In the case of the accelerated curing method, we employ an accelerated curing tank with constant-temperature water to prevent moisture loss due to temperature fluctuations (Fig. 4).

Unconfined compressive test (*UCT*) equipment: the *UCT* is performed using a load and displacement measurement device connected to a computer equipped with unconfined compressive test strength (*UCS*) data acquisition software. This setup records specimen information and real-time data, as depicted in Fig. 5.

4. Results and Discussion

4.1 Results

In our analysis, we consider the *UCS* at *D28* for each combination of W_i/W_L and *W/C* values as a function of strain (ε). Additionally, for both D1acm and *D28*, we examine UCS and wet density (ρ_t) for each combination of Wi/WL and *W/C*.

Table 4, presented below, demonstrates that the average UCS at D28 (q_{u28})for *W/C*=1.0 is slightly higher than for *W/C*=1.5. However, it is worth noting that the strength appears to be more evenly distributed when cement is applied at *W/C*=1.5, as indicated by the coefficient of variation. Another important observation is that the strength after 28 days of curing remains within the range of 500~1000 kN/m².

Table 4. Average UCS of kaolin clay improved with cement for $I_L > 1$ according to the accelerated curing method (q_{u1acm}), the 28 days of normal curing time (q_{u28}), and the coefficient of variation (CV).

W/C	**D1acm**		**D28**	
	q_{u1acm} (kN/m^2)	**CV** (%)	q_{u28} (kN/m^2)	**CV** (%)
0. 5	468.1	6.0	716.6	19.6
1.0	399.6	4.7	711.8	7.0
1.5	294.7	1.3	646.5	5.1

The following figure 6, shows the *UCS* of *D28* of all the three specimens numbered q_{u1} , q_{u2} and q_{u3} for each W_i/W_L and each *W/C* in function of strain ε. One can observe that for W_i/W_L=1, all the graphs are relatively close to each other, whatever the value of W/C= {0.5, 1.0, 1.5}.

However, for W_i/W_L=1.5, only the W/C=0.5 shows a larger gap between the UCS of the three specimens (q_{u1} , q_{u2} and q_{u3}). The graphs are relatively different from each other.

On the other hand, it is the opposite with W_i/W_L=0.8, where only the W/C=0.5 shows very close graphs. And the others (W/C= {1.0, 1.5}), the graphs are relatively different from each other.

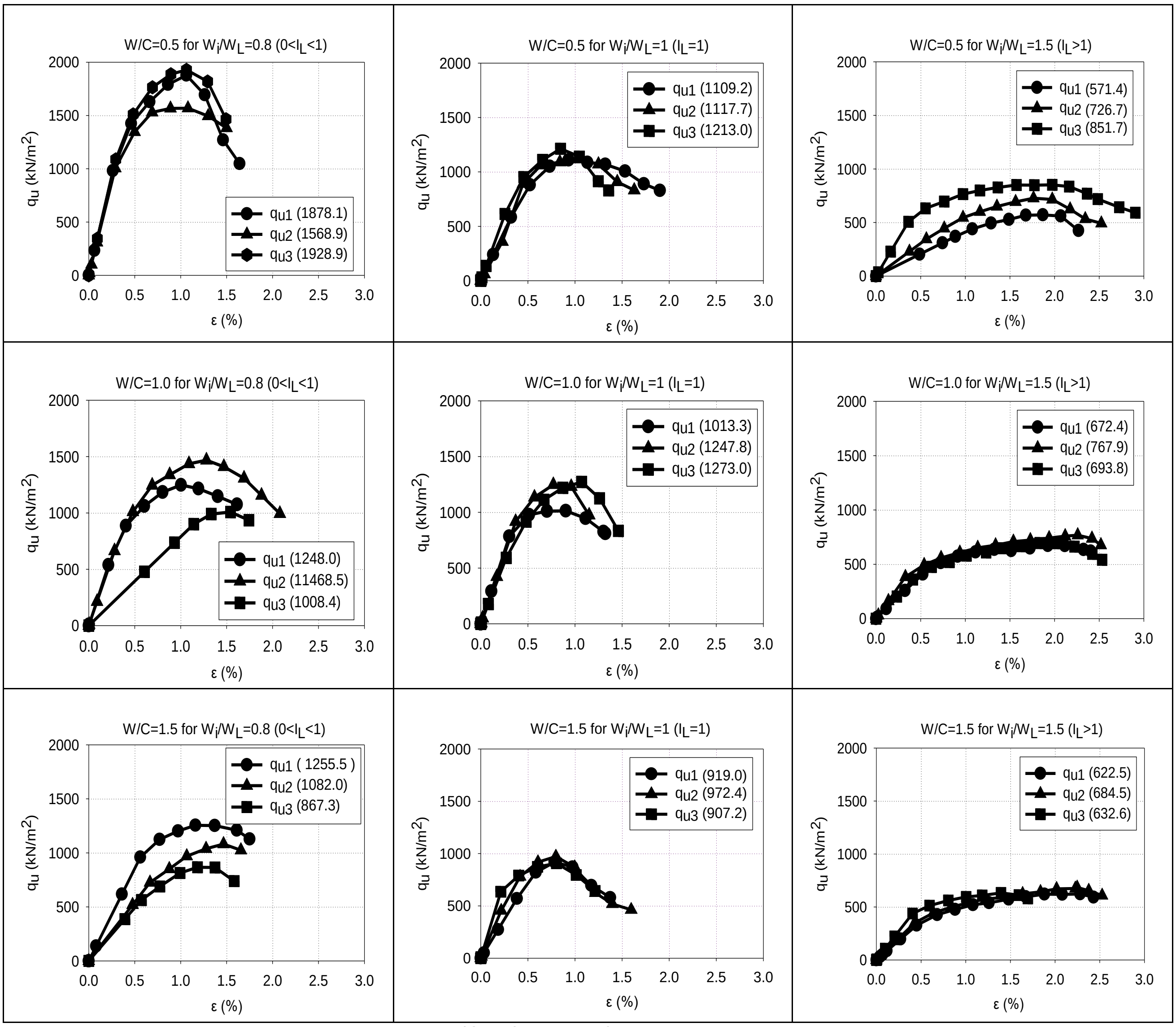

Fig.6: *UCS* of D28 for each W_i/W_L and each W/C in function of strain ε.

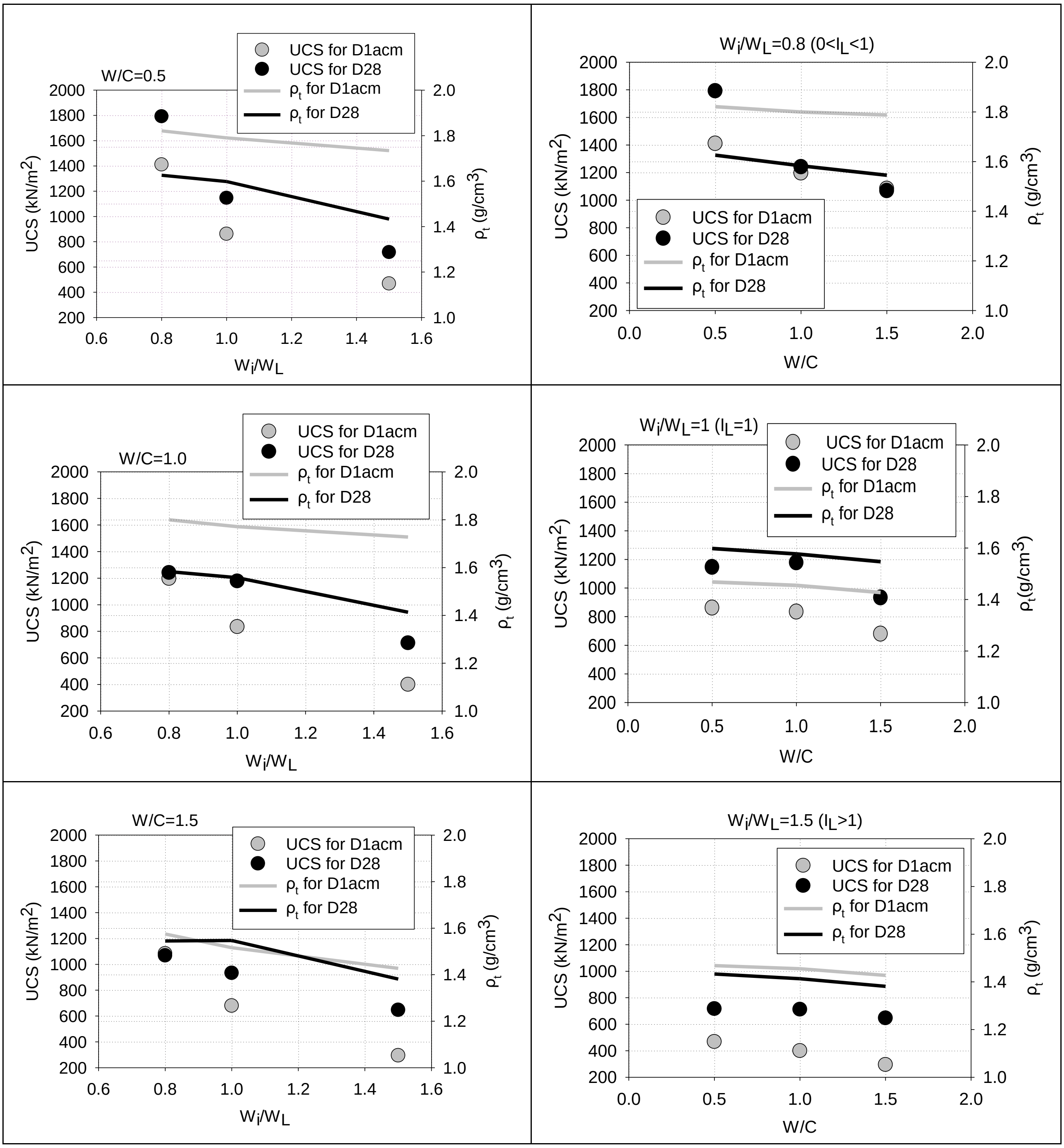

Fig.7: UCS and wet density ρ_t for each W_i/W_L and each W/C about D1acm and D28.

Figure 7 shows the UCS and wet density ρ_t for each W_i/W_L and each W/C about D1acm and D28. We can observe that UCS and ρ_t decrease when the parameters W_i/W_L and W/C increase, for D1acm as for D28. In addition, for each W_i/W_L the wet density ρ_t decreases linearly when W/C is increasing.

Then, Figure 8 shows the UCS (q_u) with standard deviation error bars in function of W_i/W_L and W/C for D1acm as for D28. We can observe that, there is:

A relationship of proportionality between UCS of D1acm and D28. UCS for D28 are greater than UCS for D1acm.

When W/C is increasing, only W/C=1.5 shows a lower error bar based on standard deviation value, for W_i/W_L= {1, 1.5} and the lowest for W/C=1.5 and W_i/W_L=1.5.

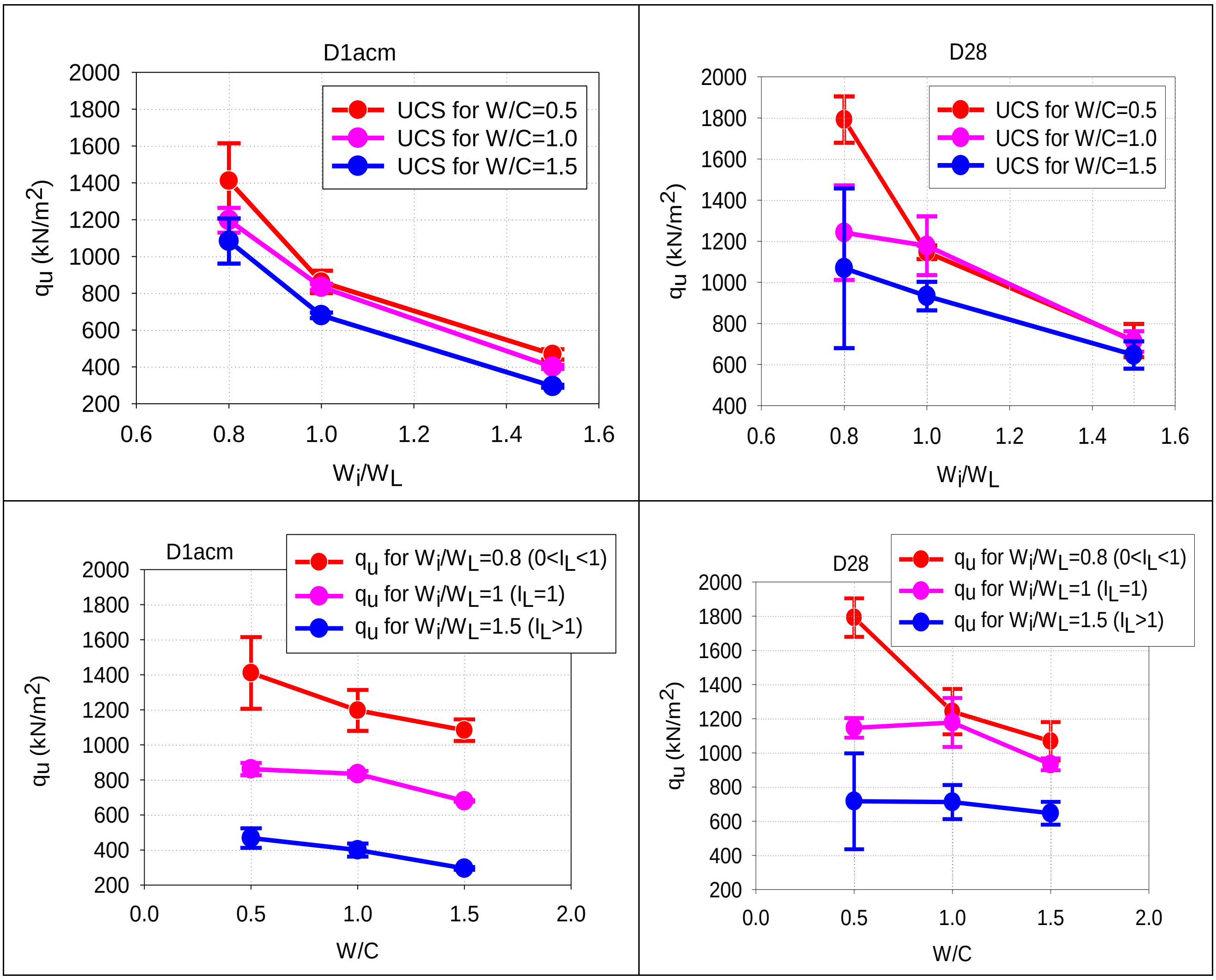

Fig.8: UCS with standard deviation error bars in function of W_i/W_L and W/C for D1acm and D28.

4.2 Interpretations and discussions

Figure 6 reveals that, when discussing the strength behavior in soil-cement specimens, a curing period of 28 days (*D28*) is appropriate. This choice aligns with the observation in [13] that longer curing times result in higher strength.

For cases where W_i/W_L equals {1, 1.5}, the samples exhibit characteristics like soft cohesive soils with I_L≥1, akin to soft marine clays found in lowlands. Specifically, when W_i/W_L=1.5, I_L reaches 2.5, which is consistent with the often-high liquidity index of Ariake clays, extending up to 4.6 [14].

Notably, for W_i/W_L=0.8, indicating I_L<1, *W/C*=0.5 yields the most favorable conditions as evidenced by the graph trends.

A detailed analysis of Figure 6 shows that when W_i/W_L ≥1, the sample behavior resembles that of soft marine clay, such as Ariake clay. However, the gap between the graphs of W_i/W_L=1.5 and *W/C*=0.5 suggests that the lowest W/C value does not uniformly and evenly distribute strength within the specimens. While decreasing *W/C* can enhance strength, as suggested by [5, 15, 8], it must also be well-distributed within the soil-cement columns to ensure their safety and effectiveness.

For Figure 7, the decrease in strength and wet density with increasing of W_i/W_L and *W/C* values is primarily due to the rise in water content within the samples, a phenomenon corroborated by previous research, such as [16] for sand and [17] for soft marine clay. While it's a common perspective that increased water content weakens soil resistance, it's essential to consider not only mechanical strength but also the workability and uniformity of soil-cement columns.

Finally, Figure 8, represented by the standard deviation error bars, illustrates that the coefficient of variation for strength in the accelerated curing method is lower than in the 28-days normal curing time. Additionally, there's is a relationship of proportionality between *UCS* of 28 days of curing and *UCS* of one-day accelerated curing method, in the sense that $q_{u28} = \alpha \times q_{u1acm}$, where $\alpha \in [1,2]$ is the coefficient of proportionality. So, the accelerated curing method can be applied to predict how the strength of 28 days of curing is going to be.

Notably, soft cohesive clay with high water content (W_i/W_L=1.5) and high compressibility, such as Ariake clays (with I_L=2.5), exhibit the best strength distribution when improved with cement at *W/C*=1.5.

The lowest coefficient of variation under these conditions suggests that *W/C*=1.5 is the most suitable for improving strength distribution within soil-cement columns for deep improvement of soft cohesive soils using cement as a binder when the liquidity index is greater than one. This finding contradicts some previous recommendations, such as W/C in the range of 0.6~0.8 for soft marine clays in Singapore [8], *W/C*=1.0 for soft Bangkok clays [15], and Ariake clays [5], our results indicate that *W/C*=1.5 yields the lowest coefficient of variation for strength.

Since *DMM* does not involve any compaction post-completion (the material is presumed to be self-compacting), often requiring a substantial amount of water to attain the fluidity necessary for the self-compacting nature of the soil-cement mixture. Bergado et al. assert that the final water content of the mixture should be at least equal to the liquid limit (W_L) of the virgin soil [7]. And for to some authors, when the initial (natural) water content of the soil (W_i) is greater than W_L, cement can be added in powder form using compressed air, termed the dry method. Conversely, when W_i is less than W_L, cement can be injected in the form of a slurry (wet mixing) [18, 19]. The novelty introduced by this study lies in the recommendation that when $W_i > W_L$, it is advisable to consider a *W/C* ratio greater than 1, indicating the addition of more water to the material.

5. Conclusion

This laboratory study investigated the influence of water content and water-cement ratio on the unconfined compressive strength of specimens using commercial kaolin clay powder. Different initial water content values (W_i) were adjusted based on the liquid limit value (W_L) or the liquidity index (I_L) to achieve various soil states.

In the domain of the *DMM* for cement-stabilized soft soils, multiple factors such as water content, cement content, water-cement ratio (*W/C*), and soil consistency can affect strength. While it's generally observed that smaller *W/C* ratios result in greater unconfined compression strength (q_u), our study revealed several important considerations:

- For kaolin clay in a plastic state (0<I_L<1), *W/C*=0.5 is suitable for deep mixing soil-cement.
- When kaolin clay transitions from a plastic state to a liquid state (I_L>1), the wet density decreases with increasing W/C.
- The use of cement slurry leads to a more homogeneous structure of soil-cement material due to a longer mixing phase and the addition of water.
- Successful on-site mixing requires alignment in fluidity between the soil and the slurry binder. I_L helps understand the soil's state before applying the favorable *W/C* ratio for good mixing.
- *W/C*=1.5 with a cement amount of *C*=110kg/m^3 results in slightly lower but uniformly distributed strength within soil-cement columns, enhancing their ability to support infrastructure. Increasing *C* while maintaining *W/C*=1.5 can boost strength under better mixing conditions.
- In soft cohesive soil conditions with a high liquidity index (I_L >2), the optimal *W/C* value for achieving stable soil-cement material with compressive strength in the range of 500~1000 kN/m^2 is *W/C*=1.5, with a cement amount of *C*=110kg/m^3.

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