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Influence of Water-Cement Ratio on the Strength Distribution inside a Soil-Cement Material

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Abstract: 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 soil candidate consistency parameters, cement content, water-cement ratio (W/C), mixing time, and curing time. Notably, a lower W/C ratio resulted in a higher unconfined compressive strength (q_u). However, in the context of improving soft and cohesive soils through DMM, a W/C ratio of 1.0 has conventionally been recommended due to its favorable resistance. In the case of the Saga lowland, where a soft cohesive soil with high compressibility and low strength is prevalent, the standard practice employs a W/C ratio of 1.0 with a selective amount of cement for different layers, in most projects. This research introduces an innovative approach: utilizing a higher W/C ratio of 1.5 with a cement content of 110 kg/m^3, to fulfill the standard strength requirement and above all, to have a well-distributed strength inside the material. This could prevent the lateral displacement of the soil-cement columns. Through laboratory experiments, this paper investigates the effects of increasing W/C on the strength distribution. As result, the comparison between the needle penetration strength ($q_{u_{NP}}$) of W/C= 1 and 1.5 showed that the latter represents a slight reduction in strength, but it is more uniformly distributed. This approach is designed to a 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 also, more importantly, the uniformity of strength within the soil-cement columns.

Keywords: *water-cement ratio; strength distribution; soil-cement material; needle penetration index*

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1. Introduction

The need for ground improvement is to develop engineering properties of soft soils which then provide stability and required bearing capacity. Deep mixed method (DMM) is employed for the improvement of these types of soil and to reduce settlement, stabilizing agents such as cement are used. Some of the Key benefits of this technique are, that it is economical, vibration-free, flexible in application, reduces construction time, and is an environment-friendly method. Some of the typical applications of this method are embankments on soft soils, bridge foundations and wind turbine foundations, slope stabilization, and cut-off walls and barriers [1].

DMM is a method which uses the soil already in place on a construction site to carry out geotechnical works by means of a mechanical mixer with a binder, here cement. It can increase the strength and decrease the compressibility of soft ground, and thereby improve stability and reduce settlement of embankments and levees [2,3,4].

Its economic and ecological aspects (no excavation) have made this method very attractive, especially in roads construction in lowland areas [5].

DMM, commonly used for embankment stability, is expected to withstand vertical compressive forces. However, considering the occurrence of bending tensile forces due to arc sliding during the collapse, the presence or absence of strength variations, known as variability, in the improved columns is believed to be an important factor in the quality assurance [6,7,8]. Furthermore, if the strength is not uniformly distributed inside the columns, the larger bending moments on these columns might cause tensile cracks and induce significant lateral displacement.

For its application in Saga lowland typically, common conditions are employed. A water/cement ratio of one (W/C=1.0) is defined, with an amount of cement-based binder addition (C) ranging between 50~150 kg/m^3, to meet the design standard strength ($\bar{q}_{uck}$) ranging between 500~1000 kN/m^2 [9,10]. However, lateral displacement of soil-cement columns, leading to a disturbance of surrounding soil, occurs sometimes [11,12,13].

Notably, our research explores the conditions of increasing W/C to 1.5 and checks its effect on the strength distribution inside the soil-cement columns. Since we already know that the reduction of W/C (less than one) or the increase of C leads to an increase in the strength [9,14,15,16] , this study aims to focus on two types of W/C to check using statistical consideration [17,18,19], the conditions of the strengths obtained from the needle penetration index, for a good quality of the soil-cement columns. The contribution of this study to the field of DMM is the perspective that increasing the W/C parameter also has an important effect on the quality of soil-cement columns, being able to reduce lateral displacements when the strength is uniformly distributed and conforms to the requirements. And therefore, invites engineers to be more flexible by considering a selective value of this parameter in the implementation of the DMM.

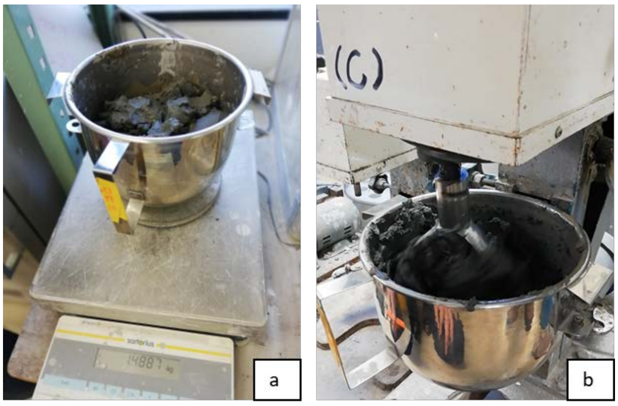

Figure 1. Mixing conditions

2. Materials and Methodology

2.1. Materials and Equipment

The clay soil of Saga prefecture called Ariake clay is a very soft sensitive clay located in the coastal plain around Ariake bay, the northwestern part of the island of Kyushu in Japan [20]. The mechanical properties of Ariake clay such as the unconfined compressive strength are between 3 kPa and 30 kPa for the upper layer of above 10 meters depth, and between 30-100 kPa for the lower layer, and the axial strain at failure, between 2% to 4% for the undisturbed soil [21,22,23].

Table 1 shows the basic properties of the clay used in this study. Based on the grain size distribution, we observed that the clay particle content is 83%, confirming the material as clayey soil. The liquid limit which represents the water-holding capacity of soil particles is LL=63.4% and plastic limit PL = 33.1%. A high liquid limit suggests a high compressibility and shrinkage/swelling potential.

Table 2 shows the chemical composition of the cement-based binder used (Ustabilizer 10). Ustabilizer 10 (Us-10) is particularly favored for its promotion of flash setting, contributing to early strength development in cement slurry.

Table 1. Geotechnical properties of an Ariake clay

Grain size distribution	Gravel (%)	0
	Sand (%)	1
	Silt (%)	16
	Clay (%)	83
Soil particles density ρ_s (g/cm^3)		2.626
Natural water content Wn (%)		109.61
Liquid limit (LL) (%)		64.2
Plastic limit (PL) (%)		33.1
Plasticity Index (PI)		31.1
Wet density ρ_t (g/cm^3)		1.478
Liquidity index (LI)		1.46

Table 2. Chemical Composition of the Cement-based Binder

Chemical compounds	Cement-based Binder（Us-10）(%)
SiO_2	18.04
Al_2O_3	4.99
Fe_2O_3	2.74
CaO	61.14
MgO	0.98
SO_3	6.88

Mixing equipment: to ensure a homogeneous mixture, we use an electrically operated mixer. We employ a mixer equipped with a drive unit, agitating blades, and mixing containers, as illustrated in Figure 1.b. to uniformly blend the soil and stabilizer.

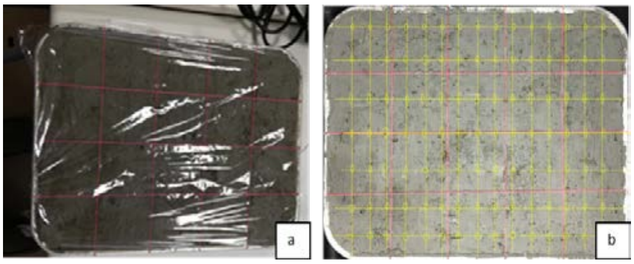

Figure 2. Solidifying material laid in a flat rectangular bowl with divisions to facilitate measurements

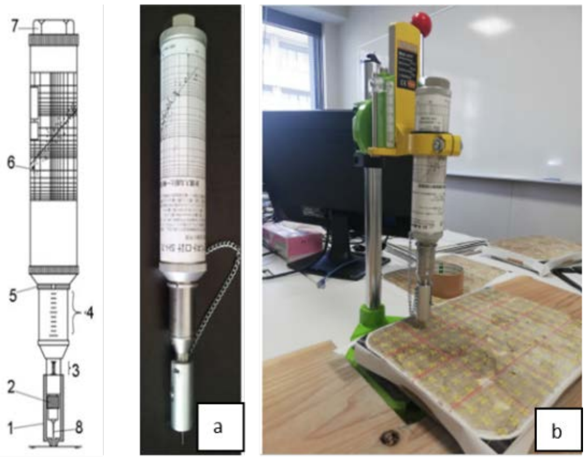

Figure 3. Needle penetrometer

Container to keep the solidifying material: the material is laid in a flat rectangular bowl of 27 × 21 × 3.5 cm^3 dimensions. Divisions are made to facilitate measurements with the needle penetrometer as depicted in the above Figure 2.

Needle penetration equipment: the needle penetration test is intended for the determination of the needle penetration index (NPI). This index value can be used to estimate other physico-mechanical properties of material with which NPI is correlated, for example uniaxial compressive strength (UCS) [24]. Figure 3.a depicts the needle penetrometer, and its parts as follows: (1) presser, (2) chuck, (3) penetration scale, (4) load scale, (5) load-indicating ring, (6) cap, (7) penetration needle, and (8) spring [25]. Figure 3.b shows the needle penetrometer with a mount vertically stood to facilitate the measurements.

2.2. Methodology

For this study, we consider for the three samples A, B and D with the two conditions of mixing time, such as the parameter t= {1 min;10 min}. Then, for the six flat rectangular bowl of solidifying material, we use the needle penetrometer to measure the needle penetration index (NPI) for each sample of the solidifying material.

For our study we note A, the sample with C=110 kg/m^3 amount of cement and W/C=1.0; B, the sample with C=110 kg/m^3 amount of cement and W/C=1.5; and D, the sample with C=80 kg/m^3 amount of cement and W/C=1.5. We also add some parameters like the mixing time t= {1 min; 10 min} and the curing time for all is 28-days.

So, the set of samples in our study is $\{At;\ Bt;\ Dt\}$. For instance, A_1 and B_{10} are respectively sample with C=110 kg/m^3 amount of cement and W/C=1.0 at 1 minute of mixing time, sample with C=110 kg/m^3 amount of cement and W/C=1.5 at 10 minutes of mixing time. D_{10}, is sample with C=80 kg/m^3 amount of cement and W/C=1.5 at 10 minutes of mixing time.

The sample preparation process follows the guidelines outlined in JGS 0821-2009 standard, for soil specimen preparation [26]. Preparation of the mixture to the curing of the specimens is done as follows:

- Weigh the sample, and the cement-based solidifying material, a predetermined amount of mixed water and specify the W/C ratio.
- Mix the cement and the kneading water sufficiently at the specified W/C ratio. To match the conditions before mixing, set the solidifying material slurry in the mixing container Figure 1.a so that it is sandwiched between two layers of samples.
- Mix with a mixer (as shows in Figure 1.b) to obtain a soil treated with a uniform cementitious solidifying material. The mixing time is 1 min and 10 min in this case.
- The soil treated with cement-based slurry is laid out in a flat rectangular bowl (Figure 2.a).
- After 28-days of curing, we took a picture of the surface and from that image on a sheet of paper, we made divisions to facilitate measurement with the needle penetrometer as shown on Figure 2.b.

Curing conditions: for the curing process, we utilize a temperature-controlled room set at (20±3)°C for standard curing periods of 28 days. After 28 days of curing, we performed the Needle Penetration Index (NPI) reading of the 100 points (Count) on each sample.

The needle penetration test was originally developed for easily predicting the unconfined compressive strength (UCS) of soft rocks [27]. However, it was possible for us to use it in this study because hard natural soils, stabilized soils and soft rocks are intermediate geo-materials between a hard rock and a soil. They include hard clays and clay-shales, hard residuals soils, lime stabilized clays, cement stabilized soils, soft sedimentary rocks, weak pyroclastic rocks, weakly cemented sandstones, and very weathered hard rocks [28,29]. Several relationships exist between NPI and the corresponding UCS (q_{uNp}), for this study we used the formula of Naoto et al, for hard claystone [30]:

$$q_{uNp} = 41.8 \times NPI - 4 \qquad (1)$$

3. Results and Discussion

3.1. Results

Figure 4 trend depicts for only 1 min of mixing time, the strength inside sample B is more uniformly distributed than inside sample A.

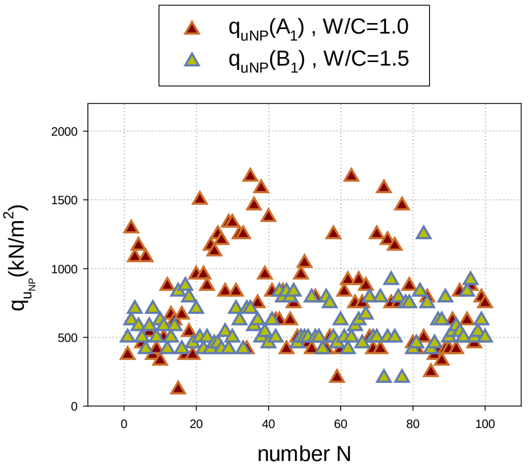

Figure 4. Strength distribution of samples A and B for 1min mixing time

Figure 5 shows that for 10 min of mixing time, the strength inside sample B is still well distributed than inside sample A.

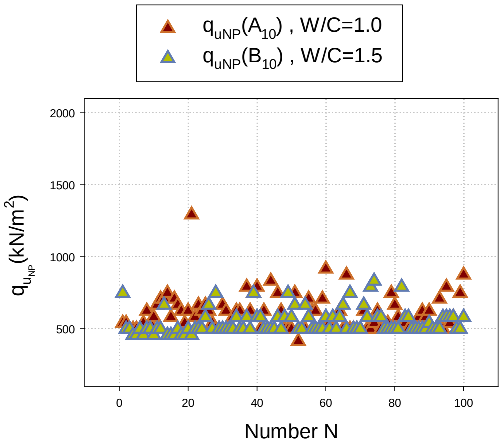

Figure 5. Strength distribution of samples A and B for 10 min mixing time

For Figure 6, the strength is not well distributed inside both samples A and D, for only 1 min of mixing time.

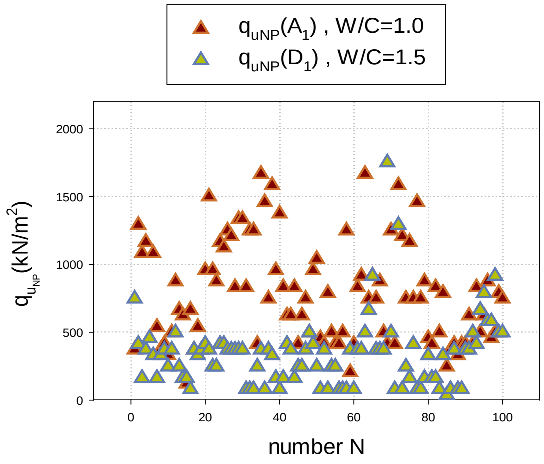

Figure 6. Strength distribution of samples A and D for 1min mixing time

But, Figure 7 shows that when the mixing time is 10 min, the uniformity of the strength distribution is improved inside both samples A and D. However, the strength is very low inside sample D.

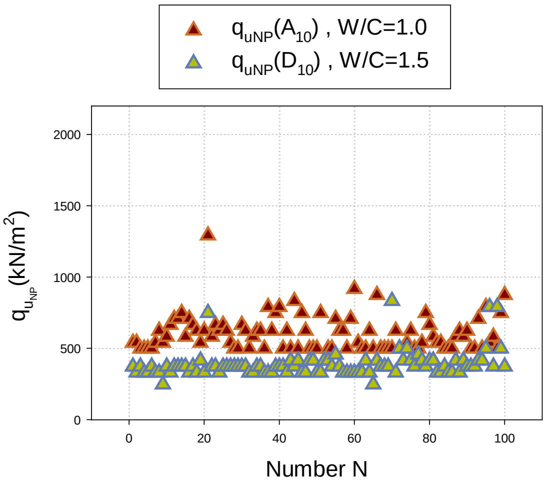

Figure 7. Strength distribution of samples A and D for 10min mixing time

As for Figure 8, the trend depicts that for only 1 min of mixing time, the strength inside sample B is more uniformly distributed than inside sample D. Sample D has low strength.

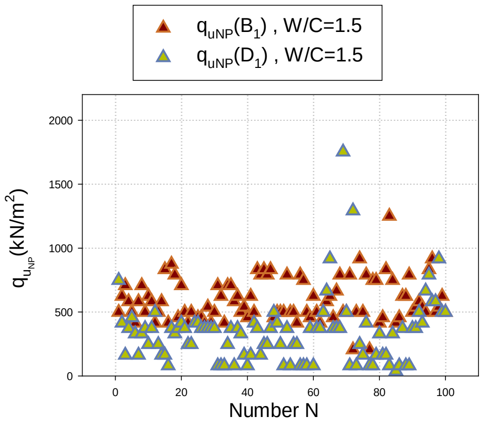

Figure 8. Strength distribution of samples B and D for 1min mixing time

And for Figure 9, it depicts that 10 min of mixing time, improved drastically the strength distribution inside the soil-cement for both, the sample B and sample D. But, sample D has low strength.

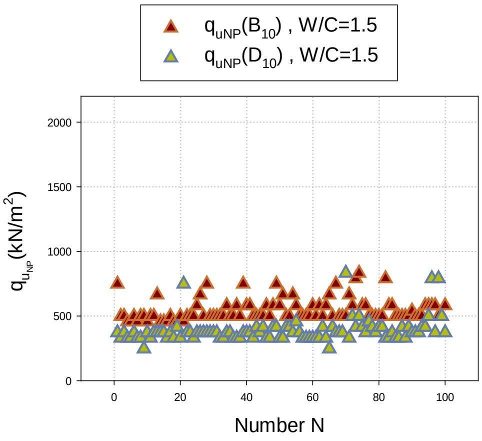

Figure 9. Strength distribution of samples B and D for 10min mixing time

3.2. Discussion

Figures 4 and 5 reveal that, when discussing the strength behavior of soil-cement samples, it is not only a curing period of 28 days that is appropriated, but also the mixing time. This choice aligns with the observation in [6,10] that the longer mixing and curing times resulted in a higher strength and well distributed. Figure 4 particularly reveals that since samples A and B have the same amount of cement C=110 kg/m^3, by increasing W/C to 1.5 (for sample B), it is helpful for the mixing conditions and leads to a better strength distribution inside the soil-cement material sample.

A detailed analysis of Figure 6 shows that only 1 min of mixing time is not sufficient to thoroughly mix the soil and slurry. Thus, the poor strength distribution inside the material is due to this. As for Figure 7, 10 min of mixing time improved the mixing conditions and the strength distribution. However, the strength cannot fulfill the requirement because it is very low. The quantity of cement incorporated into the material (C=80 kg/m^3) is not sufficient to improve the material. So, W/C can be used to control the strength distribution inside the soil-cement and C can be used for controlling the strength development.

Finally, Figures 8 and 9 reveal that when increasing W/C to 1.5 it is good for the mixing conditions if the mixing time is more than 1 min, about 10 min is required for a good mixing of the soil and the cement-based slurry. Samples B and D have both a W/C ratio of 1.5, but they differ from the amount of C. Respectively 110 kg/m^3 and 80 kg/m^3. Sample B after 10 min of mixing time shows the best conditions of a soil-cement in this study because the strength inside it is uniformly distributed and fulfilled the strength requirements.

4. Conclusion

The findings of this study demonstrate that employing a W/C ratio of 1.5, leading to a slight reduction of strength, compared to that of W/C=1.0, but ensuring uniform strength distribution, offers enhanced support for current infrastructure. The innovation lies in increasing the W/C ratio for optimal mixing under conditions of cement quantity $C \geq 110$ kg/m^3, to meet the design standard strength ($\bar{q}_u$) of DMM in lowlands. In the field of DMM for cement-stabilized soft soils, multiple factors such as water content, cement content, water-to-cement ratio (W/C), and soil's state can affect strength. While it's generally observed that smaller W/C ratios result in a greater strength ($q_{u_{NP}}$), our study revealed several important considerations:

- The use of cement slurry leads to a more homogeneous structure of soil-cement material due to a longer mixing phase.
- Successful mixing requires alignment in fluidity between the soil and the slurry binder. It is better to understand the soil's state before applying the favorable W/C ratio for good mixing and not always set W/C=1.0.
- 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-water content ($Wn > LL$), 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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