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Research Paper

Consideration of quality control standards through splitting tensile strength evaluation of plate-like improved soil

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ABSTRACT

The Saga lowlands in Kyushu, Japan, face significant settlement issues in embankments due to the high compressibility, sensitivity, and low permeability of Hasuike and Ariake clays. To address these challenges, a combination of columnar and plate-like ground improvement techniques is used. However, natural disasters, such as earthquakes, have revealed the inadequacies of current quality control methods, leading to structural failures. This study aims to enhance quality control for plate-like improved soil constructed using slurry methods by organizing field data based on design standard tensile strength (σ_{tk}), field standard tensile strength (σ_{tf}), and lab standard tensile strength (σ_{tl}). It also investigates the relationship between unconfined compressive strength (*qu*) and splitting tensile strength (*σt*) through laboratory experiments. Hasuike clay was treated with varying binder dosages and a water-cement (*W/C*) ratio of 1, to evaluate the strength ratio (*α*) between *qu* and *σt* after 28 days of curing. Key findings show that setting σ_{tl} at 2.0 times σ_{tf} effectively minimizes the risk of falling below σ_{tk}, thereby enhancing soil performance. Laboratory results indicate that the strength ratio *α* for Hasuike clay varies with cement content, showing mean values between 0.12 and 0.15, with optimal combinations yielding values from 0.21 to 0.28, which is higher than the empirical standard of 0.1. Conversely, less favorable combinations with minimum values resulted in *α* values between 0.05 and 0.07, which should be carefully considered when designing plate-like improved soil. These results underscore a statistical and systematic approach to quality control in ground improvement projects to ensure the durability and stability of soil structures in challenging environments like the Saga lowlands.

1.Introduction

In recent years, combining columnar and plate-like ground improvement techniques has become increasingly popular to address settlement issues in embankments in the Saga lowlands of Kyushu, Japan. The region's Hasuike and Ariake clays are known for their high compressibility, sensitivity, and low permeability, posing significant challenges for civil engineers [1], [2], [3]. To mitigate these issues, the Deep Mixing Method (DMM) is often applied [4], [5], [6]. However, natural disasters, such as the Kumamoto earthquake in 2016, revealed the insufficiency of current quality-control methods, as evidenced by the deformation and collapse of improved columns [7] [8].

Ensuring the quality control of plate-like improved soil, where layers of soil are treated with a

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cement-based binder to form plate-like structures, remains a critical issue. Currently, no standardized quality control measures exist for this type of soil in construction. Evaluating the ratio between unconfined compressive strength (*qu*) and splitting tensile strength (*σt*) is one approach to address this challenge, as it establishes significant correlations between these parameters [9], [10], [11]. Assessing splitting tensile strength is crucial for preventing lateral bending failures in DMM constructions.

Initially, powdered cement-based binders were used for plate-like improvements [12], but recently, slurry comprising water and cement-based binders has become the predominant method. Despite these advancements, further scientific exploration is needed to align this methodology with current engineering practices in road embankment construction.

This study organizes field data based on design standard tensile strength (σ_{tk}), field standard tensile strength (σ_{tf}), lab standard tensile strength (σ_{tl}), and the defective rate of 10% (Usui et al., 2024). It also investigates the relationship between *qu* and *σt* through controlled laboratory experiments [13], using the Brazilian test method [14], [15] on Hasuike clay and slurry with different binder dosages (C=80 kg/m³, 110 kg/m³, and 140 kg/m³) and a water-cement ratio (W/C) of 1, mixed for 10 minutes. After a 28-day curing period, the specimens underwent unconfined compressive and splitting tensile tests according to Japanese Geotechnical Society guidelines [16].

Statistical analysis of the data determined the optimal splitting tensile strength and strength ratio (α) variations. The design standard tensile strength for improved soil is defined as σ_{tk} /1.5 = 80 kN/m². To ensure σ_{tf} surpasses a one-sided risk of 10% relative to σ_{tk} with a coefficient of variation (*CVf*) of 0.25, the strength ratio σ_{tf}/σ_{tk} is established at 1.5, resulting in σ_{tf} = 120 kN/m². Based on empirical data, the strength ratio σ_{tl}/σ_{tf} is set at 3.0 (*σt*l = 360 kN/m²). This study found that for plate-like improved soil constructed using the slurry method, even when the indoor standard tensile strength (σ_{tl}) is set at 2.0 times(σ_{tl}= 240 kN/m²) the field standard tensile strength the probability of falling below the design standard tensile strength (σ_{tk}) is extremely low. This promotes efficient exploration of the mechanical behavior and performance characteristics of the improved soil.

The strength ratio α (*σt*/*qu*) for Hasuike clay varied from 0.12 to 0.15 based on mean values. Combinations of minimum *qu* and maximum *σt* yielded α values between 0.21 and 0.28, while maximum *qu* and minimum *σt* resulted in α values between 0.05 and 0.07. These findings should be considered in the design of plate-like improved soil to ensure optimal mechanical performance.

2.Plate-like improved soil in Saga lowland

2.1 Powder-based binder methods for Plate-like improved soil

Fig. 1 illustrates the concept of soft ground countermeasures conditions for embankments and roads construction. In Saga Lowland area, a construction method combining columns and plate-like improved soil with a thickness of t = 1.0m has been widely used since around 2004 for embankments with heights ranging from 2 to 3 meters.

Table 1 presents the quality control standards for plate-like improved soil constructed using powder-based construction involves the dispersion and mixing of cement-based binder, with design standards for tensile strength (σ_{tk}), field standards for tensile strength (σ_{tf}), and indoor standards for tensile strength $(\sigma_{t\ell})$ established as quality control measures based engineers' experiences [4], [5], [6] (Floating Foundation Research Association 2005).

To ensure that (σ_{tf}), surpasses a one-sided risk of 10% relative to (σ_{tk}), with a coefficient of variation (*CVf*) of 0.25, the strength ratio σ_{tf}/σ_{tk} is established at 1.5. Additionally, based on empirical data, the strength ratio σ_{tl}/σ_{tf} is set at 3.0. This determination aims to ensure a 90% confidence level (assuming a normal distribution) that the actual tensile strength will equal or exceed (σ_{tk}), considering the variability of the data indicated by the coefficient of variation *CVf* = 0.25 [4], [5], [6].

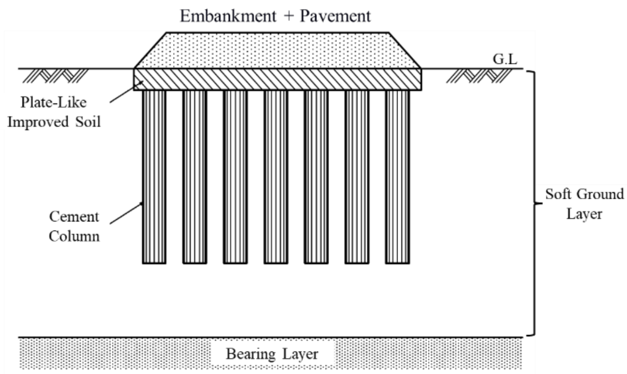

Fig. 1: Concept of soft ground countermeasures for embankments with floating foundation

When using Powder-based binder method, with design standards for tensile strength (σ_{tk}), field standards for tensile strength (σ_{tf}), and indoor standards for tensile strength $(\sigma_{t\ell})$ established as quality control measures-based engineers' experiences. Design Standard Tensile Strength in Saga lowland for improved soil is σ_{tk} ／1.5＝80, Field Standard Tensile Strength, to ensure that (σ_{tf}), surpasses a one-sided risk of 10% relative to (σ_{tk}) , with a coefficient of

Table 1: Quality Control Standards for Plate-like improved soil Constructed Using Powder-based Methods.

Design Standard Tensile Strength σ_{tk} (kN/m^2)	Field Standard Tensile Strength σ_{tf} (kN/m^2) (1)	Lab Standard Tensile Strength $\sigma_{t\ell}$ (kN/m^2)
σ_{tk} ／1.5＝80	120(2)	3.0 σ_{tf} ＝ 360(3)

(1) The field strength of the slab was determined using the average value.

(2) To ensure that σ_{tf} exceeds a one-sided risk of 10% for σ_{tk} under a coefficient of variation (*CVf*) of 0.25 σ_{tf}/σ_{tk} = 1.5 was adopted.

(3) Based on empirical data.

variation (*CVf*) of 0.25, the strength ratio σ_{tf}/σ_{tk} is established at 1.5 with σ_{tf} = 120 kN/m^2. Additionally, based on empirical data, the strength ratio σ_{tl}/σ_{tf} is set at 3.0. but this study discovered that regarding the indoor standard tensile strength σ_{tl} for plate-like improved soil constructed using slurry, even when set at 2.0 times the field standard tensile strength (σ_{tf}), the probability of falling below the design standard tensile strength σ_{tk} is extremely low. based on empirical data, engineers aim higher strength of the improved soil with an additional level of assurance, which lacks a systematic exploration of the mechanical behavior and performance characteristics in an efficient manner.

In the Saga lowland, the design standard tensile strength for improved soil is defined as σ_{tk} ／1.5 ＝80kN/m². To ensure that (σ_{tf}) surpasses a one-sided risk of 10% relative to (σ_{tk}), with a coefficient of variation (*CVf*) of 0.25, the strength ratio σ_{tf}/σ_{tk} is established at 1.5, resulting in (σ_{tf}) = 120 kN/m². Additionally, based on empirical data, the strength ratio σ_{tl}/σ_{tf} is set at 3.0. This study discovered that for plate-like improved soil constructed using the slurry method, even when the indoor standard tensile strength σ_{tl} is set at 2.0 times the field standard tensile strength (σ_{tf}) instead of 3 times (σ_{tf}), the probability of falling below the design standard tensile strength (σ_{tk}) is extremely low.

2.2. Embankment failure in Saga prefecture

The coastal lowlands of Ariake are characterized by two types of cohesive soil layers: non-marine Hasuike layer and marine Ariake clay layer. These cohesive soil layers are known for their high compressibility and low shear strength, making them weak ground conditions that require careful consideration during embankment construction. Natural disasters such as earthquakes have the potential to cause damage to these structures [12]. On June 23rd, 2016, deformation occurred in improved columns due to the impact of the Kumamoto earthquake and heavy rainfall, resulting in the collapse of the road between Ashikari Minami and Ashikari IC in the coastal area of Ariake as shown in Fig. 2 [7]. The failure is attributed to the incomplete solidification of the improved columns illustrated in Fig. 2 and 3 [7], [17].

This case suggests that the current quality-control method employed by Saga Prefecture in Japan [8] is insufficient to ensure the quality of field-constructed columns [7]. The likely failure mechanism involves defects in some columns in Rows F, G, and H, leading to relatively larger settlements at those locations, which in turn induced larger bending moments in the columns of Rows A–E. The increased bending moments may have caused tensile cracks in the columns, resulting in significant lateral displacement. Consequently, tensile cracks could have developed in the embankment fil [18]. Subsequently, heavy rainfall triggered the collapse of the embankment [7] .

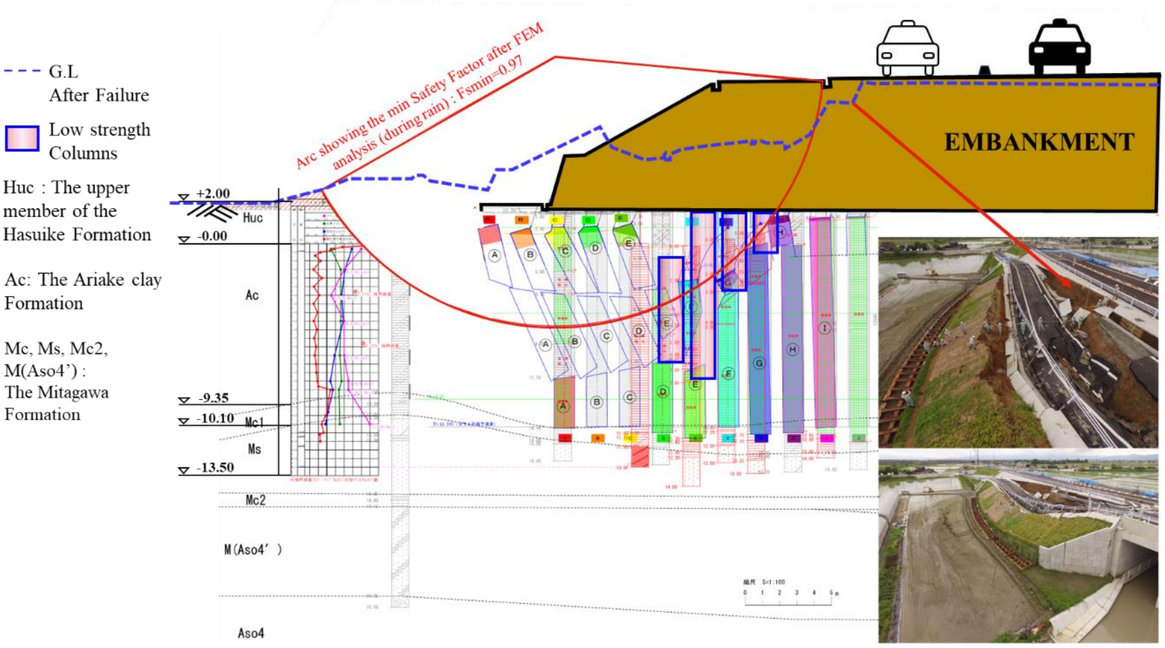

Fig. 2: Post-failure of the road Ashikari Minami and Ashikari IC in the coastal area of Ariake (Saga prefecture). (June 23rd, 2016)

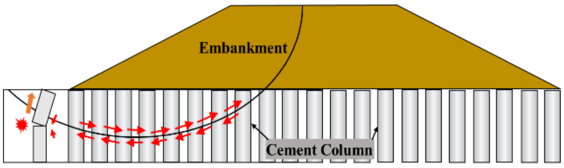

Fig. 3: Shear failure (adapted from shrestha et al. (2015) [17])

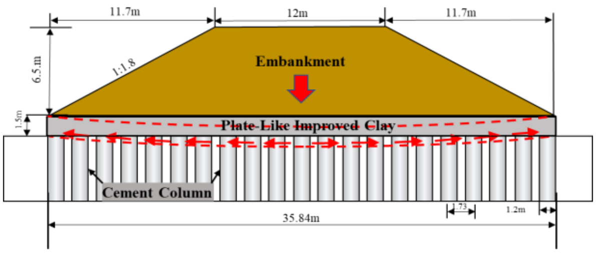

Fig. 4: Deep Mixing Methods approach and Tensile resistance of plate-like improved clay

3.Materials and methods

3.1 Field data

3.1.1 Splitting Tensile Test for Plate-like Improved Soil Constructed Using Slurry Method

In the Saga Lowland area, where soft ground conditions prevail in medium to high embankments, the predominant method for ground improvement involves the use of plate-like improved soil with a thickness (t) of 1.5m. These plate-like structures are constructed using a slurry composed of cement-based solidifying agents and water. The quality control data utilized in this study were collected from a construction section approximately 2km long, situated along a road with embankments of medium to high height.

Fig. 5 shows the locations of collected boring data for quality control measures, this plate-like improved soil data encompasses 30 constructions field contractors, covering an overall construction area of approximately 40,000m^2. These measures adhere to criteria established in the preceding section, with design standard tensile strength σ_{tk} set at 80kN/m^2, and indoor standard tensile strength σ_{tl} at 3.0 times σ_{tf}, equaling 360kN/m^2. In terms of quality control frequency, splitting tensile tests are conducted roughly three times per construction section, covering scales ranging from 1,000m^3 to just under 5,000m^3. Each quality control test involves conducting splitting tensile tests on three specimens obtained from the top, middle, and bottom sections of the slab. These tests are executed following the guidelines outlined in "JIS A 1113:2018 Method of Test for σt of Concrete," with a total of 110 tests performed throughout the construction section.

3.1.2 Indoor Tensile Strength σ_{tl} for Slurry Construction by contractors

Construction contractors are responsible for performing splitting tensile tests both on-site and within their respective laboratories. This dual approach is crucial for cross verifying the tensile strength obtained in the field with the indoor standard tensile strength, thereby ensuring the robustness of the constructed structures. On-site splitting tensile tests are conducted to provide immediate feedback on the quality of the construction process, allowing for real-time adjustments and ensuring that the tensile strength meets the predefined standards.

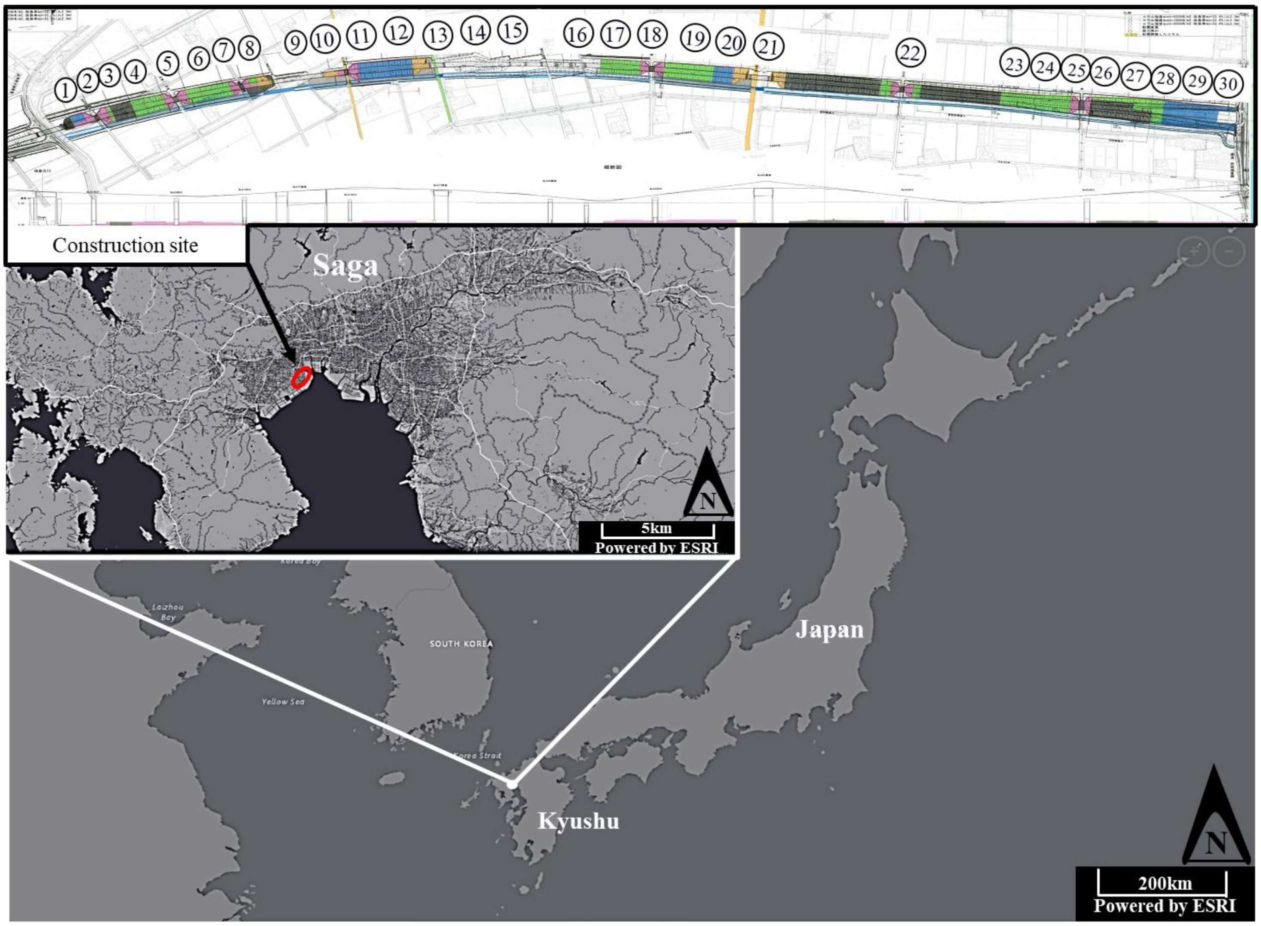

Fig. 5: locations of collected boring data in Saga lowland in Kyushu, the southern island of Japan.

These tests are performed on specimens extracted from various sections of the constructed slab, ensuring comprehensive coverage and accurate assessment of the tensile properties across the entire structure. Simultaneously, contractors conduct controlled splitting tensile tests within their laboratory settings. These indoor tests are essential for cross-validation purposes. The laboratory environment allows for more precise control over testing conditions, minimizing external variables that might affect the results. By comparing the field tensile strength (σ_{tf}) with the indoor standard tensile strength (σ_{tl}), contractors can ascertain the consistency and reliability of the tensile properties of the plate-like improved soil.

3.2 Laboratory Experiments

3.2.1 Basic soil properties of Hasuike clay

We focus on the Hasuike clay, which is collected from Kase-cho, Saga City. The Hasuike clay represents the upper layer of the soil profile in the study area [1], [2], as shown in fig. 5. To evaluate the properties of this cohesive soil, we present the relevant findings in Table 2. The state variables of cohesive soils provide their engineering behavior. In particular, the liquidity index (I_L), an important parameter that characterizes the consistency and workability of cohesive soils. In the case of Hasuike clay, the liquidity index (I_L) is found to be greater than 1, indicating that the soil exhibits characteristics of soft clay and has a high degree of mixability and blendability.

This is a type of cohesive soil found in the upper layer of the Saga lowland [1], [2]. It is characterized by its fine-grained composition and significant clay content. The soil particle density (ρ_s) of 2600 kg/m³, suggests a relatively heavy mineral composition. The soil has a very high natural water content (*Wn*) of 124.1%, more than its dry weight, indicating it is highly saturated and has a significant amount of water retention. A high liquid limit (*LL*) of 91.8%, suggests the soil is very plastic and can hold a lot of water before behaving like a liquid. The Plastic Limit (*PL*) of 39.1%, shows considerably lower than the liquid limit, showing a wide range of plasticity. A Plasticity Index (*IP*) of 52.7, shows a high plasticity index indicates the soil has a large range of moisture content over which it remains plastic.

An activity value of 1.32 indicates that the clay is highly active, meaning it is very sensitive to changes in moisture content. Wet Density (ρ_t) of 1376 kg/m³, represents the density of the soil in its natural, wet state. This value reflects a compactness or is densely packed when saturated, which can affect its permeability, compressibility, and other engineering characteristics. Dry density (ρ_d) of 6200 kg/m³, shows a lower dry density suggests a high void ratio and porosity in its natural state. The Void Ratio (*e*) of 3.250. represents the ratio of the volume of voids to the volume of solid particles in the soil. A high void ratio indicates the soil has a lot of pore space, which is consistent with its high natural water content. The degree of Saturation (*Sr*) of 99.3% indicates the percentage of the soil's voids that are filled with water. This value means the soil is nearly fully saturated.

Hasuike clay, found in the upper layer of the Saga lowlands, is predominantly composed of clay and silt with minimal sand and no gravel. It has a high natural water content and plasticity, as indicated by its high liquid limit and plasticity index. The soil particles are relatively dense, but the soil itself has a low dry density and a high void ratio, suggesting it is highly porous and saturated. The high degree of saturation and liquidity index further indicates that Hasuike clay is very soft high compressibility, sensitivity, and low permeability [1], [3], making it challenging for construction but essential to understand for effective ground improvement techniques.

Table 2: Basic soil properties

Site name		Kase machi, Saga City
Type of cohesive soil		Hasuike clay (Upper layer)
Grain size distribution	Gravel (%)	0.0
	Sand (%)	0.9
	Silt (%)	43.7
	Clay (%)	55.4
Soil particle density ρ_s (kg/m^3)		2600
Natural water content *Wn*(%)		124.1
Liquid limit *LL* (%)		91.8
Plastic limit *PL* (%)		39.1
Plasticity index *PI*		52.7
Activity A		1.32
Wet density ρ_t (kg/m^3) (JGS 0821 2020[8)])		1376
Dry density ρ_d (kg/m^3)		620
Void ratio *e*		3.250
Degree of saturation *Sr* (%)		99.3
Liquidity index I_L		1.6

3.2 Cement-based binder

Table 3 provides details on the cement-based binder known as Ustabiler 10 (US10), specifically formulated for the cohesive soils commonly found in the Saga lowland area [2]. US10 was developed to tackle difficult soil types and site conditions that are not easily stabilized using conventional Ordinary Portland Cement (OPC). As illustrated in Fig. 6, US10 offers significant advantages, positioning it effectively within a comparative framework that highlights its application, properties, and effectiveness relative to other materials.

Table 3 presents a chemical composition comparison between Ordinary Portland Cement and US10. US10 is particularly noted for its ability to facilitate rapid setting, which enhances early strength development in cement slurry. This characteristic is largely due to its high sulfur trioxide (SO_3) content, a key component of gypsum (Calcium Sulfate Dihydrate, $CaSO_4 \cdot 2H_2O$) [19]. Gypsum, used as an additive during the clinker grinding process, contains water in its molecular structure and consists of approximately 23.3% calcium and 18.5% sulfur [20]. Compared to ordinary Portland cement, US10 has a lower silicon content and a higher SO_3 content, leading to a higher ettringite content in the binder. This increased ettringite content helps incorporate soil moisture as crystalline water as shown in Table 3.

The use of US10 in this study significantly enhances the early strength, stiffness, and durability of soil, making it suitable for a wide range of engineering applications across various soil types and environmental conditions. Its versatility and cost-effectiveness make US10 an attractive option for budget-conscious projects, promoting its widespread adoption in soil stabilization and ground improvement efforts throughout Saga Prefecture.

Table 3 Test results of US-10

Tests \ *Type of Cement*		Ustabiler 10 (US10)
Density (kg/m^3)		2980
Specific surface area (m^2/kg)		3.900
Chemical composition (%)	Silicon Dioxide (SiO_2)	17.27
	Aluminum Oxide AlO_2)	4.93
	Iron (III) Oxide (Fe_2O_3)	2.72
	Calcium Oxide CaO)	60.73
	Magnesium Oxide (mgO)	1.27
	Sulfur Trioxide (SO_3)	7.50

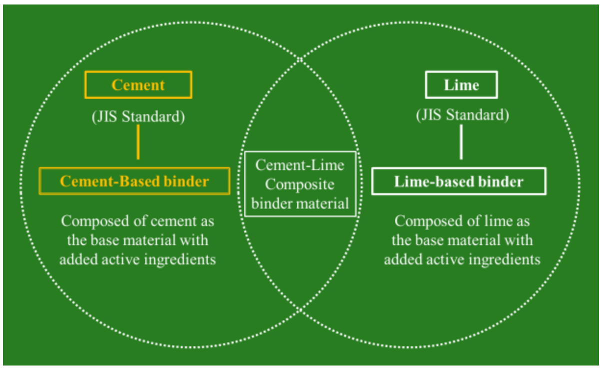

Fig. 6: Categorization of the cement-based binder [21]

Table 4: Chemical Composition of Ordinary Portland Cement and Cement-based Binder

Chemical Composition	Ordinary Portland Cement (%)	Cement-based Binder （US-10） (%)
SiO_2	21.4 ~ 22.6	17.27
Al_2O_3	4.3 ~ 5.7	4.93
Fe_2O_3	2.5 ~ 3.3	2.72
CaO	63.0 ~ 64.7	60.73
MgO	0.8 ~ 2.7	1.27
SO_3	1.7 ~ 2.4	7.50

3.3 Experimental method

3.3.1 Specimens preparation

The experimental method employed in this study aimed to evaluate the mechanical properties of the Hasuike clay, specifically its *qu* and *σt* after improvement with cement-based binder. Fig. 7 and 8 present the steps encompassing the mixing bowl, molds and mixing conditions were adopted to prepare and test the specimens.

Hasuike clay samples representing the upper layer of the soil profile were collected from Kase-cho, Saga City. In Saga prefecture, because of the nature of the clay soil, studies have been made to establish Guidelines for Construction Design and implementations, but there are no specific standards. The regulations these choices of mixing ratio are related the application methods on the field of the soil cement column by engineers and practitioners after many years of experiences, which usually involved the use of 110 kg/m^3 with W/C=1 and assured the desired strength of soil cement column in Saga prefecture.

For this study cement-based binders designed for general soft cohesive soils were selected for the improvement of the clay. Three different binder dosages, C=80 kg/m^3, 110 kg/m^3, and 140 kg/m^3, were considered as well as the water-cement (W/C) ratio equal to 1. Using these three ranges of amount of cement, it gives us an overview about the strength development at three different stages based on the amounts of cement.

To determine the required number of specimens and the percentage increase in preliminary tests, the volume of improved soil per batch (referred to as the volume of one mix) were taken into consideration [2]. Per batch basically obtains 12 specimens as shown in Fig. 7. The wet density of the soil sample is determined to be ρ_t =1376 kg/m^3. The calculations for the volume of the soil sample and the amount of cement-based binder are performed using Equation 1 and 2, respectively. The calculation for the volume of the soil sample is obtained as follows:

Soil sample required = Specimen volume x Number of specimens x Wet density ρ_t x Premium ratio
Eq. (1)

Similarly, the calculation for cement-based binder is given by:
Cement-based binder required = Volume of specimen x Number of specimens x Amount of cementitious solidifier x Premium ratio
Eq. (2)

A total of 144 specimens were prepared, with 48 specimens for each binder dosage as shown in Fig. 8. The specimens were molded into cylindrical shapes using a plastic mold with dimensions of 0.05m x 0.1m [22]. To ensure proper compaction and eliminate air voids, the molds were tapped on a rubber plate. The mass of each molded specimen was carefully checked to minimize variations between specimen's weight.

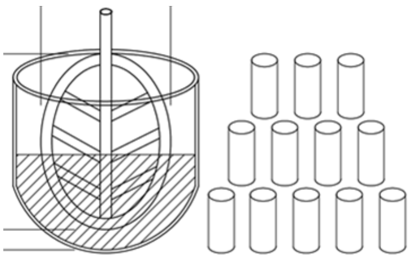

Fig. 7: Mixing bowl and molds

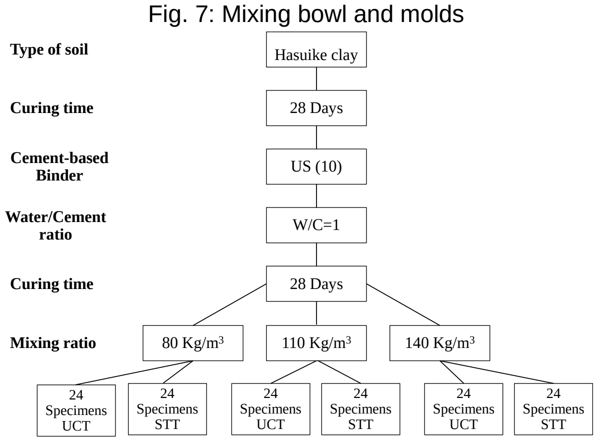

Fig. 8: Mixing conditions

3.3.2 Splitting tensile test.

The splitting tensile test followed Brazilian test method. Tensile stress increases with the increase in radial compressive force and specimens deteriorate along the direction of the applied force (Liao et al. 2020). This test is relatively simple and needs only a standard cylindrical test specimen and a loading assembly. From the cured specimens, specimens were cut with a length (L) ranging from D0.05m×L0.1m, following the standard "Tensile strength test of rocks by splitting (JGS 2551-2001)" [23]. The cutting process ensured that the length-to-diameter (L/D) ratio specimens ranged from 0.8 to 1.0, as shown in fig. 9e.

The detailed steps of specimen preparation are shown in fig. 9. Following these steps from (a) to (i), specimens were carefully managed throughout the whole process to avoid any breaking, damaging or deformations in specimen's shapes.

(a): Soil + cement + water was weighted based on the amount of the mixing condition.

(b); (c): The bowl was moved to the stirring machine and specimens were molded after 10minutes of stirring time.

(d): Specimens underwent a curing time of 28 days in a constant temperature room.

(e); (f); (g): Using a grinder, specimens were cut into L0.04m to L0.05m, and size were checked.

(h): Splitting tensile test.

(i): Unconfined compression test

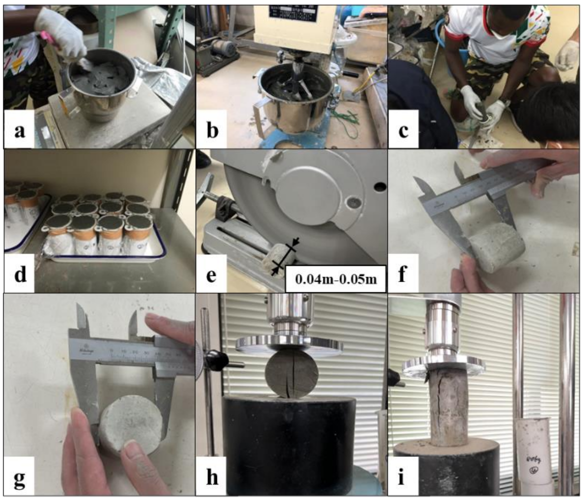

Fig. 9: Detail steps for specimen's preparation

The splitting tensile tests were conducted by placing the specimens between two parallel loading plates and applying vertical compression at a strain rate of 1% per minute relative to the specimen diameter (D) as shown in fig. 9h.

During the test, the compressive force (P) acting on the specimens was recorded, and the resulting tensile stress (σt) was calculated using the following equation.

$$\sigma t = 2F / (\pi \times D \times L) \quad \text{Eq. (3)}$$

Here, σt represents the σt (kN/m^2), F represents the maximum value of compressive force (kN), D represents the diameter (m), and L represents the length (m).

3.3.3 Unconfined compression test

After a curing period of 28 days, unconfined compression tests were conducted on the prepared specimens. The specimens were placed in a testing machine and subjected to axial loading until failure. The compressive force (P) acting on the specimens was measured throughout the test.

The *qu* was determined by dividing the maximum compressive force by the cross-sectional area of the specimen.

3.3.4 Data analysis

The strength ratio of unconfined compressive and σt of plate-like improved soil was investigated through different kinds of combinations as shown in fig. 10. But finally, we rely on the mean, maximum and minimum values.

For the data analysis, we used Excel and for better analysis as shown in the graphs.

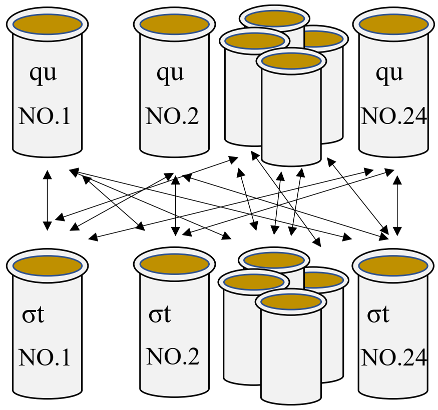

Fig. 10: Relationship between *qu* and σt

4. Results and discussion

4.1 Field Data

Fig. 11 displays the outcomes of the splitting tensile tests described above for field data. The results reveal an average value of 443kN/m^2, with a maximum value of 693kN/m^2 and a minimum value of 165kN/m^2. Notably, the minimum value surpasses the σ_{tk} specified in Table 1. Table 5 presents the results of the χ2 (chi-squared) test applied to the results depicted in Fig. 11. This test serves to assess the nature of data distribution, aiding in the decision-making process between hypotheses regarding data distribution characteristics. Based on the obtained χ2 values, with χ02 = 4.67 < χ2 = 15.51, it is concluded that the results in Fig. 11 conform to a normal distribution. Moreover, the relatively low coefficient of variation for field data (*CVf*) observed in Fig. 11, at *CVf* = 0.24, compared to past experiences with ground improvement techniques employing slurry, falls within a relatively low range.

Table 5: Chi-squared Test Results for Split Tensile Tests

Statistical Parameter (Sample Characteristics)		Rejection condition	
Number of sample (n)	110	Significance Level (α_0)	0.05
Average (kN/m^2)	442.87	Degrees of Freedom (*φ*)	8
Standard deviation (s)	104.0	χ^2	15.51
χ_0^2	4.67		

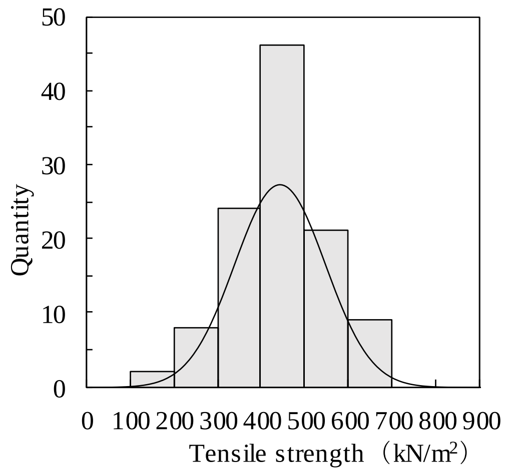

Fig. 11: Results of Split Tensile Tests

Table 6 outlines the results of the reliability verification concerning *CVf* using the F-test. This test assesses data dispersion, enabling decisions regarding differences in variances between the coefficient of variation (*CVf*) and *CVf*. The results indicate no significant difference between *CVf* = 0.25 (as specified in Table 1) and *CVf*, supporting their general equivalence.

The results obtained from Fig. 11 were depicted in Fig. 12 in the form of a frequency distribution curve, labeled as D, represented by solid lines. Analyzing the trend of curve (D), it revealed an exceedingly low probability, at 0.02%, of σ_{tk}= 80kN/m^2 (as per Table 1) being surpassed. Additionally, considering σ_{tl} = 3.0 × σ_{tf} as per Table 1, assuming σ_{tl} = 2.0 × σ_tf as the standard for columns constructed using slurry, the curve D/1.5 was evaluated by dividing D by 1.5, illustrated as dashed lines in Fig. 12.

The average value of curve D/1.5 was determined to be 295kN/m2, with a standard deviation (s) of 69kN/m2. Despite this, the likelihood of σ_{tk}= 80kN/m^2 (as per Table 1) being undershot remained minimal, at 0.10%, significantly below the typical concern of a 10% defect occurrence rate in ground improvement techniques utilizing slurry. Summarizing the findings discussed above, they can be presented in the proposed format shown in Table 7.

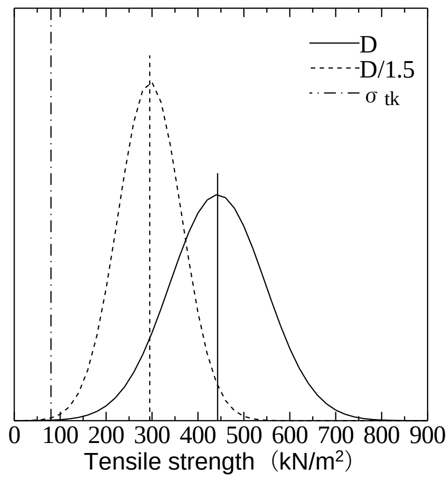

Fig. 12: Frequency Distribution Curve of Split Tensile Test

Table 6: F-test for Coefficient of Variation (*CVf*) in the Results of Split Tensile Tests

Statistical (Sample Characteristics)	Parameter	Rejection condition	
Number of sample (n)	110	Significance Level (α_0)	0.01
Average (kN/m^2)	442.87	Degrees of Freedom (*φ=n-1*)	109
Standard deviation (s)	104.0	*F-value*	1.342
Field coefficient of Variation (*CVf*)	0.24	*CVf*	0.25
Sum of Squared Deviations of Strength (S)	1189653.577	CVf^2	0.0625
Sum of Squared Coefficients of Variation (Sv)	6.065	$CVf^2 \cdot f$	0.084
Unbiased Variance of Coefficients of Variation ($V^2\sigma t_f$)	0.056		

Table 7: Proposed Quality Control Standards for Plate-like improved soil Constructed Using Slurry Method

Design Standard Tensile Strength σ_{tk} (kN/m^2)	Field Standard Tensile Strength σ_{tf} (kN/m^2) (1)	Lab Standard Tensile Strength $\sigma_{t\ell}$ (kN/m^2)
$\sigma_{tf}/1.5=80$	120(2)	$2.0\sigma_{tf}=$ 240(3)

(1) The field standard tensile strength of the slab is determined using the average value of all field tensile tests conducted.

(2) Since a coefficient of variation (*CVf*) of 0.25 was obtained in the split tensile tests, σ_{tf}/σ_{tk} = 1.5 is adopted to ensure that σ_{tf} exceeds a one-sided risk of 10% for σ_{tk}.

(3) Proposed values based on the quality control data used in the study.

4.2 Laboratory Experiments

The experimental results and discussion focus on the relationship between cement-based binder content (C) and the *qu* and *σt*. Fig. 13 illustrates the relationship between cement-based binder content (C) and the *qu* and *σt*. It shows that as the binder content increases, both *qu* and *σt* exhibit increased variability under the same conditions. Notably, the variability is more prominent in *σt* compared to *qu* as shown in table 8, by statically considering the coefficient of variation of the laboratory experiments (COV) based on the mean values. The COV of *σt* is quite high compared to qu. We acknowledge the limitations of the observed variability, which can be attributed to the additional shaping required for the specimens used in the splitting tensile test. This introduces uncertainties and makes them more susceptible to eccentric loads, ultimately leading to higher variability [24] in the *σt* [25] .

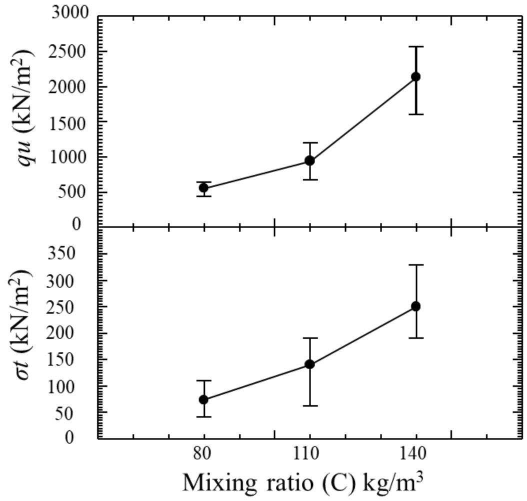

Fig. 13: Relationship between Mixing Ratios

To analyze the correlation between *qu* and *σt*, Fig. 14 is presented, accompanied by Table 8, which provides the strength ratio α between *qu* and *σt*. It is important to note that due to the preparation of 12 specimens per mixing for both the unconfined compressive test and the splitting tensile test in each mixing bowl, a simple plot of *qu* specimens for *σt* specimens is not feasible. Consequently, various combinations of values arise between the two parameters as shown in fig. 10.

The investigation reveals that α values, representing the strength ratio based on mean values, vary as follows: from 0.12 to 0.15 for different cement content C, from 0.21 to 0.28 for combinations with the minimum unconfined compressive strength *qu* value and maximum splitting tensile strength *σt* value, and from 0.05 to 0.07 for combinations with the maximum *qu* value and minimum *σt* value. Generally, α values around 0.1 or higher are commonly used for the analysis of splitting tensile failure based on empirical practices.

Table 8 provides more understanding for quality control of plate-like improvement structures. For future research based on this finding, it suggests that if the *qu* specimens and *σt* specimens can be guaranteed to be consistent, α values like those in the black dots in table 8 may be obtained. In situations where ensuring consistency among the specimens poses a challenge, it may become necessary to employ quality control measures based on the minimum α values, represented by the blue dots.

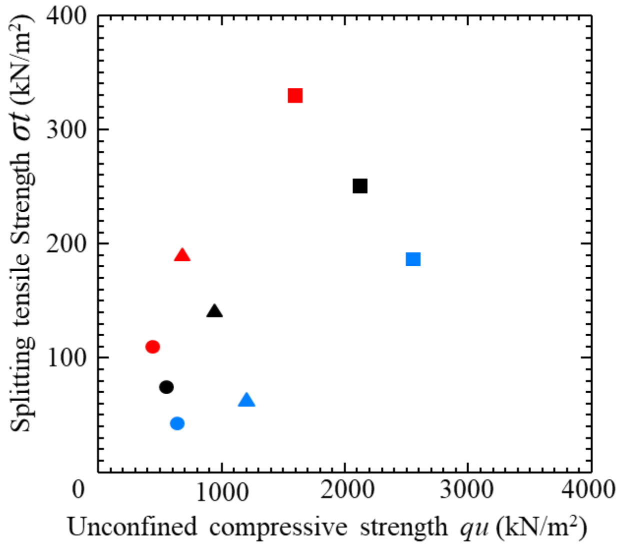

Fig. 14: Relationship between *qu* and *σt*

Future investigations on the comparative analysis between *qu* and *σt* should establish standardized criteria to address the fluctuations in *α* values resulting from the combination of both specimen types, as demonstrated in this research.

Overall, these findings contribute to a better perception of the relationship between *qu* and *σt* in the context of plate-like soil improvement. It emphasizes the importance of quality control measures and the need for standardized criteria to ensure reliable assessment and implementation of improvement techniques in geotechnical engineering applications regarding plate like improved soil.

Table 8: Strength Ratio *α* of *qu* and *σt* linked to the legend in Fig. 14

Cement (kg/m³)	COV Mean *σt*／*qu*	Mean value	Maximum value	Minimum value
		σt／*qu*	*σt*／*qu*	*σt*／*qu*
80	0.16/0.13	0.13 (●)	0.25 (●)	0.07 (●)
110	0.21/0.14	0.15 (▲)	0.28 (▲)	0.05 (▲)
140	0.28/0.08	0.12 (■)	0.21 (■)	0.07 (■)

4.3 Limitations

Based on the analysis of quality control data in the Saga Lowland area, proposed quality control standards for plate-like improved soil constructed using slurry have been suggested. Variations in values are more pronounced for *σt* compared to *qu* for the Hasuike clay. These observed limitations and uncertainties in variability may stem from the additional shaping required for specimens used in the splitting tensile test, rendering them more susceptible to eccentric loads. We propose that standardization of techniques is imperative to mitigate variations in strength ratio values.

5. Conclusion

This study underscores the need for stringent quality control in using plate-like improved soil techniques for ground improvement in the Saga lowlands. The unique properties of Hasuike and Ariake clays necessitate robust measures for structural stability. Field data were organized based on design, field, and lab standard tensile strengths (σ_{tk}, σ_{tf}, $\sigma_{t\ell}$), and actual laboratory experiments with varying cement content and with W/C=1. After 28 days of curing, the strengths were assessed. Evaluating the ratio between unconfined compressive strength *qu* and splitting tensile strength *σt* is crucial to prevent lateral bending failures and ensure effective quality control. They key findings in this study are:

The use of a slurry method and setting the σ_{tl} at 2.0 times the σ_{tf}, minimizes the risk of falling below the σ_{tk}, thereby enhancing the mechanical performance of the improved soil in an optimum and efficient manner. This approach is satisfactory for sustainable development goals (SDGs) as it reduces the amount of cement required.

Laboratory data demonstrated that the strength ratio *α* (*σt*/*qu*) for Hasuike clay varies with cement content, showing mean values between 0.12 and 0.15. Optimal combinations of *qu* and *σt* yielded *α* values ranging from 0.21 to 0.28, significantly exceeding the empirical value of 0.1 and enhancing the understanding of the mechanical behavior and performance characteristics of plate-like improved specimens. Conversely, less favorable combinations with minimum values resulted in *α* values between 0.05 and 0.07, which should be carefully considered when designing plate-like improved soil.

This study underscores the importance of systematic evaluation and quality control in ground improvement projects, advocating for the adoption of scientifically informed practices to ensure the durability and stability of soil structures in challenging environments like the Saga lowlands.

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