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STUDY ON STRENGTH BEHAVIOR OF CEMENT STABILIZED SLUDGE REINFORCED WITH WASTE CORNSILK FIBER

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ABSTRACT: This study was carried out to investigate the strength behavior of cemented sludge reinforced with cornsilk fiber considered as a by-product from corn. Hence, a series of unconfined compression test was conducted at different levels of water, cement, and fiber content. Water contents considered in this study were 40, 50, and 60%; cement content used for sludge stabilization was changed from 5 to 40 kg/m^3; meanwhile, fiber content was used at different levels from 5 to 30 kg/m^3. In addition, the relationship between failure strength and the amount of water, cement, and fiber was investigated in the present work. The experiment results showed that there was an improvement in failure strength, failure strain, ductility, and stiffness with fiber inclusion. Besides, stiffness improvement was based on the amount of cement used. The relationship between failure strength with and without fiber inclusion and water, fiber, and cement content was described as following power or exponential function with a strong correlation coefficient. It was concluded that there was a good performance of cornsilk fiber in reinforcing cemented sludge. Furthermore, the utilization of waste material to modify soft soil or sludge will bring about many benefits not only for geotechnical engineering but also for the environment and social economy.

Keywords: Soil Stabilization, Fiber Reinforced Soil, Fiber-Cement Stabilized Soil, Cornsilk Fiber.

1. INTRODUCTION

Soft soil or sludge produced from construction sites or disaster areas is generally discarded to the natural environment. It causes many environmental issues and increases the project cost because of discharge fee inclusion. In addition, the use of borrowed soil material from another site is uneconomical for the overall cost of the construction project. Hence, it is necessary to modify or recycle local soil. Nowadays, an attractive method to deal with these problems is fiber-cement stabilized soil method, which is belonged to chemical and mechanical stabilized soil categories [1].

There are two fiber categories consisted of synthetic and natural fibers, which are classified based on their nature. Synthetic fibers are more concerning by many researchers compared with natural fibers due to high performance in structural concrete as well as soil reinforcement [2]–[4]. Nevertheless, from sustainable and economical points of view, natural fibers are better than synthetic fibers because of their renewable, available, and cheap resources. Furthermore, some researchers have been already confirmed the workability of natural fiber in ordinary concrete, mortar composites and soil stabilization [5]–[10].

Currently, cornsilk is a by-product from corn, which is the third most cultivation in the world [11], so the yield of cornsilk every year is redundant and it is easily obtained from the cultivated field. The use of cornsilk fiber in cemented sludge results in lower construction cost and environmental issue improvement. In addition, there is no research work on the utilization of cornsilk in fiber reinforcing cemented sludge. Therefore, the cornsilk fiber was focused as fibers to improve the sludge in this study.

Consoli et al. [12], [13] reported that the effect of parameters such as the amount of cement, the porosity, etc. to the unconfined compressive strength and the splitting tensile strength of fiber reinforced cement-soil (FRCS) mixture could be described following a power function. The porosity-to-cement ratio is a proper parameter to evaluate the tensile and compressive strength of FRCS mixture. Since the kind of fiber in previous studies was synthetic fiber, there are some differences with natural fiber such as bonding surface. Therefore, it is necessary to check the parameters affecting on strength behavior when using natural fibers.

The aim of this study is to understand the mechanical properties (i.e. failure strength, ductility, stiffness) of fiber-cement stabilized sludge with a different amount of cornsilk fiber at the different water and cement contents. Besides, the relationship between failure strength of cement stabilized sludge with and without fiber and the water-cement-fiber ratios is also considered in this study.

2. EXPERIMENTAL WORKS

2.1 Materials

2.1.1 Sludge

In order to carry out the systematic experiments, a large amount of sludge is necessary. However, it is difficult to obtain a large amount of actual sludge. Hence, artificial sludge was used in this study. The imitation sludge sample is composed of Kasaoka clay, silt, and water. The ratio of clay and silt in the sludge mixture is 40:60 in dry mass. This ratio was decided according to the previous research [14]. The water content in sludge was used at different levels of 40, 50, and 60% by weight of soil in dry mass. Chemical properties of Kasaoka clay and silt are shown in Table 1. Physical properties of soil composed of clay and silt are shown in Table 2. Grain particle size of soil is also shown in Fig. 1.

Table 1 Chemical properties of clay and silt

Compound	Clay (%)	Silt (%)
SiO_2	77.9	69.1
Al_2O_3	12.9	20.2
Fe_2O_3	2.08	5.46
CaO	1.88	0.91
MgO	0.28	0.807
MnO	0.072	0.027
Na_2O	1.97	1.48
K_2O	2.42	2.75

Table 2 Physical properties of soil

Properties	Values
Grain size analysis	
Gravel (%)	0
Sand (%)	8.10
Silt (%)	83.5
Clay (%)	8.50
Specific gravity	2.47
Atterberg limits	
Liquid limit (%)	46.1
Plastic limit (%)	29.4
Plasticity index (%)	16.7
Soil classification	
USCS	OL
AASHTO	A-7-6
Compaction parameters	
Optimum moisture content (%)	30.8
Maximum dry unit weight (kN/m^3)	12.9
Unconfined compression strength (kN/m^2)	72.9

2.1.2 Cement

The kind of cement used in this study was GEOSET 200, which was provided by Taiheiyo Cement Corporation. It is consistent with a wide variety of purposes, including both shallow and deep stabilization of soft ground, as well as the solidification of sludge and bottom-layer soil. Chemical and physical properties of GEOSET 200 are shown in Table 3.

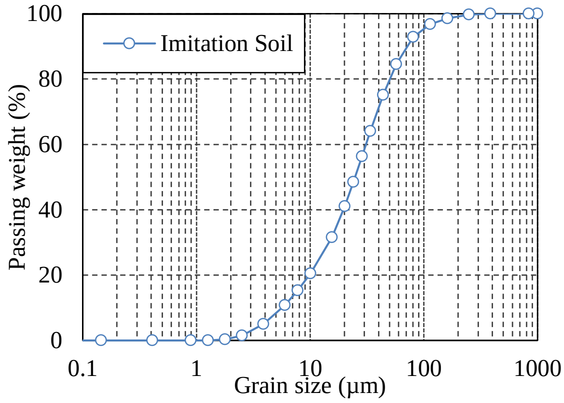


Fig.1 Grain size distribution curve

Table 3 Chemical and physical properties of GEOSET 200

Properties	Values
Chemical compound	
SiO_2 (%)	23.6
Al_2O_3 (%)	7.76
Fe_2O_3 (%)	1.83
CaO (%)	53.9
MgO (%)	3.35
SO_3 (%)	6.53
Physical properties	
Specific surface (cm^2/g)	3.68
Specific gravity	3.01

2.1.3 Fiber

The fiber used in this study was cornsilk as shown in Fig. 2, which is classified as a single fiber. They were provided by Thanh Binh Company, Vietnam. The length, diameter, and water absorption of cornsilk fibers were approximately 10 mm, 0.3 mm, and 4 cc/g, respectively.

Fig.2 Cornsilk fiber used in this study

2.2 Preparation of Samples

The sludge was modified by adding cement and fibers. The water content of sludge (W) and the additive amount of cement (C) and fibers (F) are shown in Table 4. The procedure to make specimens for testing is as follows. (1) Adding fibers and cement into the sludge and mixing until obtaining homogenous mixture. (2) Curing the mixtures in oven at 20±3 degree Celsius for 3 days to get modified sludge. (3) Making specimens by compacting the modified sludge in a standard steel mold of 50 mm in diameter and 100 mm in height. (4) Curing the specimens having the diameter of 50 mm and the height of 100 mm for 7 days [15].

Table 4 Additive amount of cement and fiber

Number Series	Water content (W) (%)	Additive amount of cement (C) (kg/m^3)	Additive amount of fiber (CS) (kg/m^3)
1	40	5	0
2			10
3			20
4			30
5		10	0
6			10
7			20
8			30
9		15	0
10			10
11			20
12		20	0
13			10
14			20
15			30
16		25	0
17			10
18			20
19	50	30	0
20			5
21			10
22			15
23			20
24			25
25		35	0
26			5
27			10
28			15
29		40	0
30			10
31			20
32	60	30	0
33			10
34			20
35		35	0
36			10
37			20
38		40	0
39			10
40			20

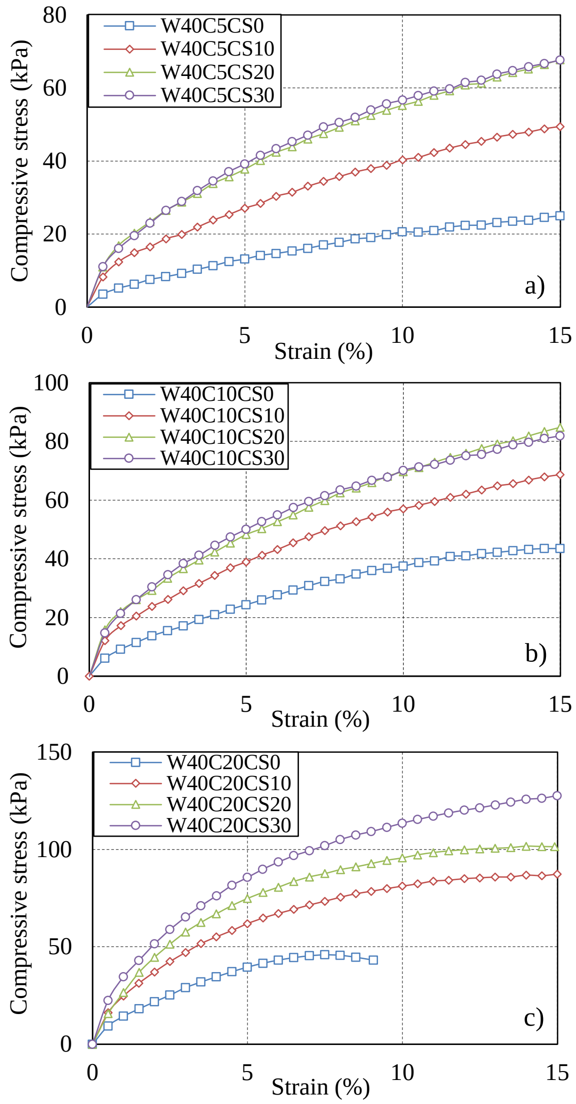
2.3 Testing Program

Unconfined compression tests with a load controlled 2 kN maximum load and an axial displacement rate of 1 mm/min were carried out according to ASTM D1633 [16] on the specimens of 50 mm in diameter and 100 mm in height. The curing time of samples used in this test was 7 days. According to ASTM D2166 [17], the maximum strain is limited to 15%, so the test would be performed until the displacement reaching 15 mm approximately.

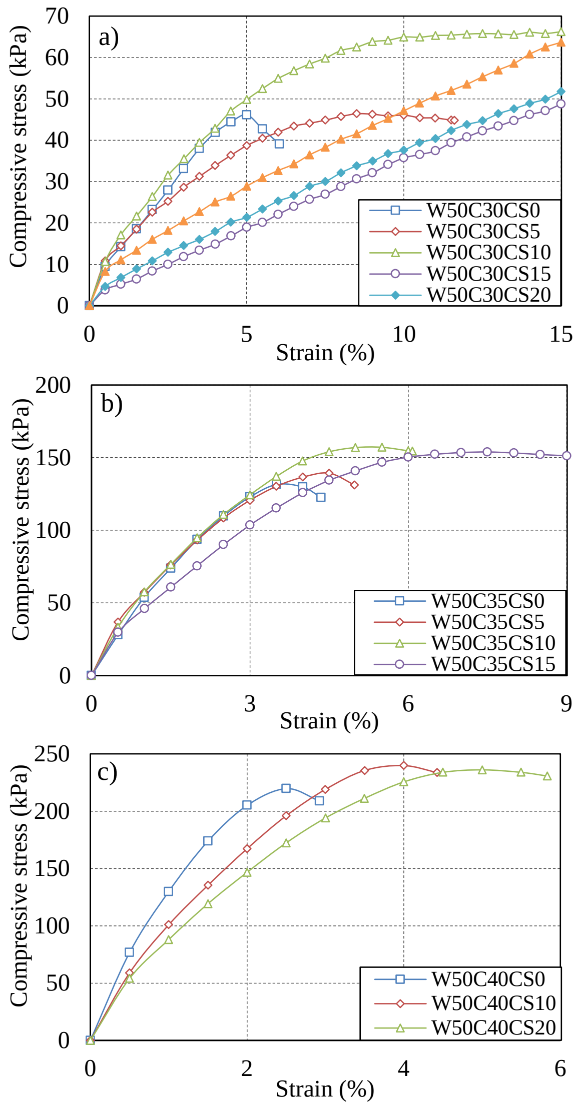
3. RESULTS AND DISCUSSION

3.1 Unconfined Compression Test

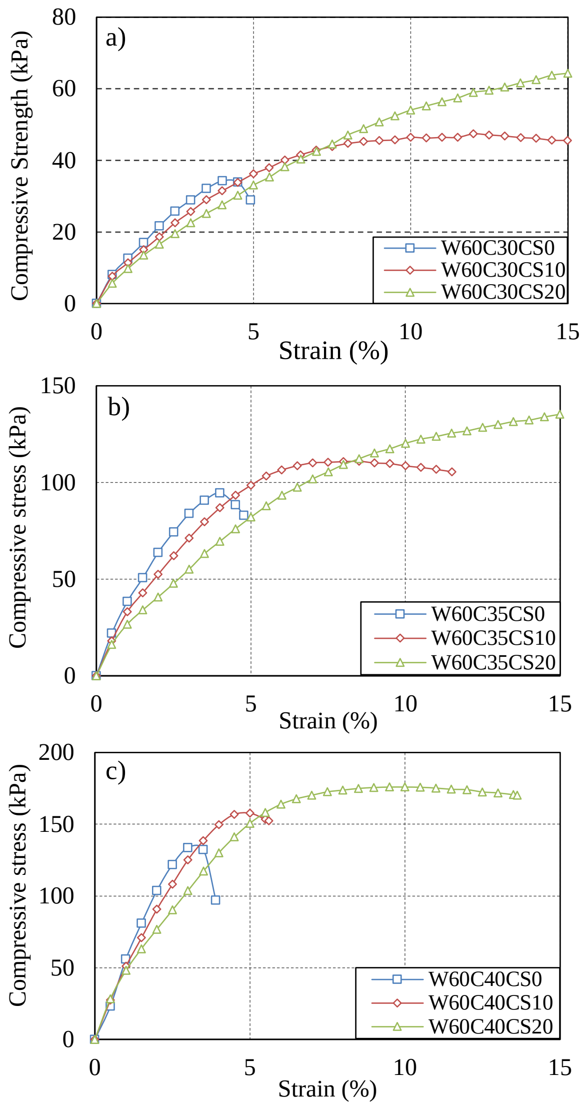
Figs. 3, 4, and 5 show the stress-strain curves of all mixtures. Name of each mixing condition is abbreviated following W, C, and F.



Figs.3a, 3b, 3c Stress-strain curves at water content of 40%



Figs.4a, 4b, 4c Stress-strain curves at water content of 50%



Figs.5a, 5b, 5c Stress-strain curves at water content of 60%

For example, W40C5CS0 indicates that the amount of water, cement, and fiber used in the admixture is 40%, 5 kg/m^3, and 0 kg/m^3, respectively. From these figures, it is clear that there was an improvement of stress as well as strain with fiber inclusion comparing with sludge stabilized by cement only.

The trend of stress-strain curve for mixtures with and without fiber inclusion after obtaining peak stress point was different. For sludge reinforced with cement only, the stress decreased significantly after peak stress causing suddenly structural failure. On the other hand, the stress gradually decreased for cemented sludge reinforced with fibers. Especially, the stress-strain curve tendency still increased after the strain reached 15% in some cases such as W40C10CS30, W50C30CS20, etc.

Ductility behavior of soil can be defined as the maximum axial strain of stress-strain curve [1]. Many previous studies had already confirmed that the behavior of cemented soil with fiber inclusion is changed from brittle to ductile [18], [19]. As can be seen in Figs. 3, 4, and 5, the addition of cornsilk fiber considerably improved the ductility behavior of soil. It is consistent with previous studies mentioned above. In other words, the effect of cornsilk fiber on ductility is not different compared with other natural or synthetic fibers.

Secant modulus is also an important parameter to evaluate the stiffness behavior of the materials and can be determined from the unconfined compression test. It is defined as the ratio of stress and strain at any point on the stress-strain curve. Hence, secant modulus at the strain of 2% for all mixtures was determined. The results from Figs. 6 and 7 show that there were two trends of secant modulus. The first one was for using a small amount of cement (5, 10, and 20 kg/m^3). The effect of cement on soil behavior was not much, so modulus values at the strain of 2%.

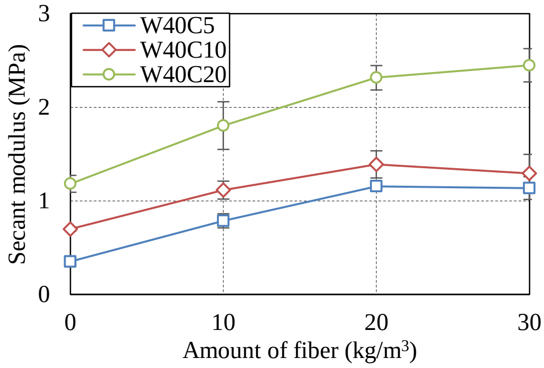


Fig. 6 Relationship between secant modulus and fiber content at strain of 2% and water of 40%

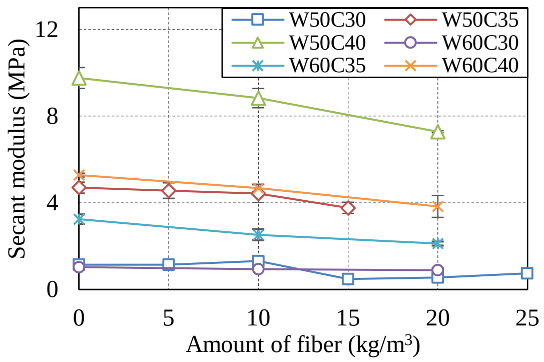
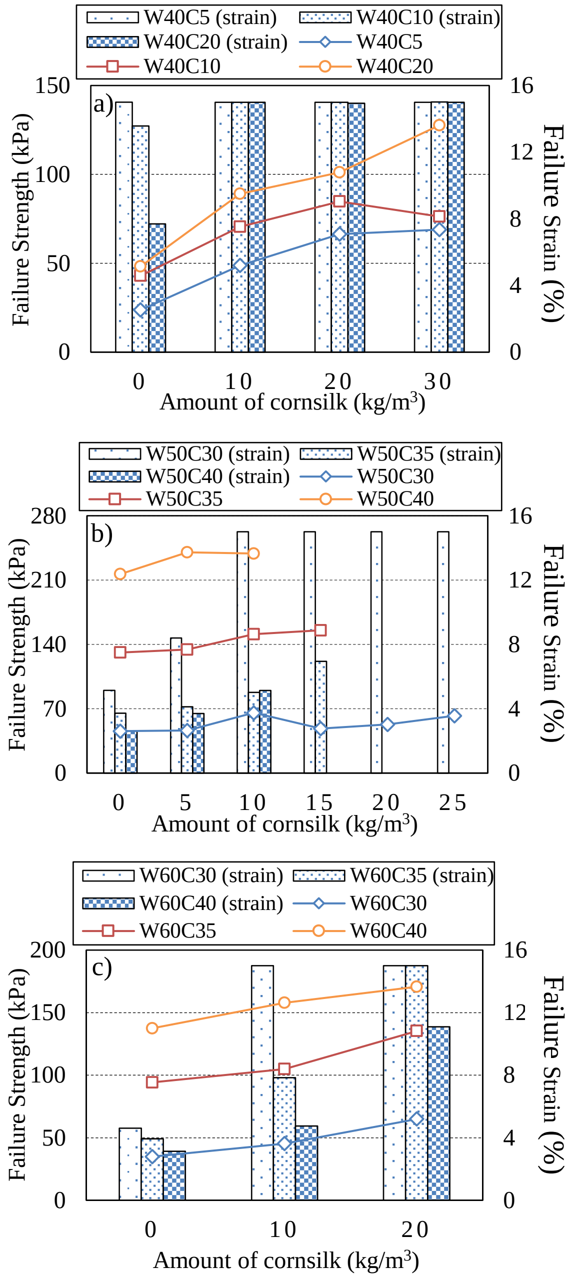


Fig.7 Relationship between secant modulus and fiber content at strain of 2% and water of 50% and 60%

increased with increasing fiber content. It can be concluded that the effect of fiber was not only making specimen more ductile but also improving the stiffness of sample. The second tendency is that the secant modulus decreased with increasing fiber content. It is in agreement with the results of previous studies [20], [21]. A reasonable explanation for the second trend is the use of a large amount of cement (30, 35, and 40 kg/m^3). In a word, the increase or decrease of secant modulus of cemented sludge with fiber inclusion is based on the amount of cement used.

The effect of fiber content on failure strength and strain with variations of cement and water content was also considered. Failure strength was a peak stress point in the stress-strain curve of each mixture. In general, both failure strength and strain increased with increasing amount of fibers, it can be readily observed in Fig. 8. The influence of fiber inclusion with variations of fiber content in increasing failure strength is as follows. 1) For W40 with C5, C10, and C20; from 64.2 to 190.6%. 2) For W50 with C30, C35, and C40; from 1.9 to 43.8%. 3) For W60 with C30, C35, and C40; from 14.8 to 85.9%. These results indicate that the addition of cornsilk fiber caused a significant improvement in the failure strength of cemented sludge.



Figs.8a, 8b, 8c Relationship between failure strength and strain and additive amount of cornsilk with different additive amount of water and cement

3.2 The Relationship between Failure Strength and Parameters Affecting on Strength Characteristics

In this part, the relationship of the failure strength ratio ($\sigma_{f,c}/\sigma_c$) and terms of three parameters (the water content (W%), the cement content (C%), and the fiber content (F%)) is considered. Where, $\sigma_{f,c}$ and σ_c are the failure strength with fiber inclusion and without fiber inclusion at the same mixing conditions, respectively. Only the best 2 terms of W, C, and F are shown in Figs. 9 and 10 due to the limitation of page.

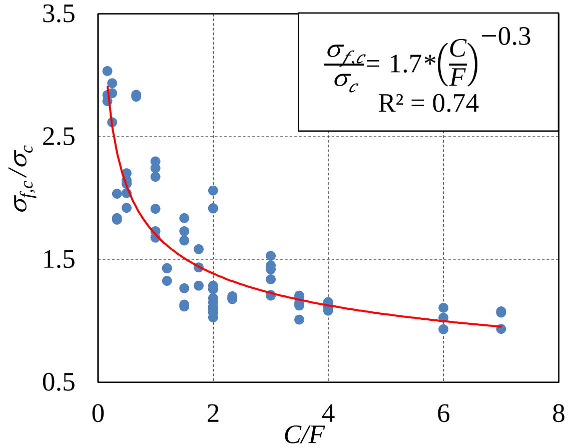


Fig.9 Correlation of $\sigma_{f,c}/\sigma_c$ and *C/F*

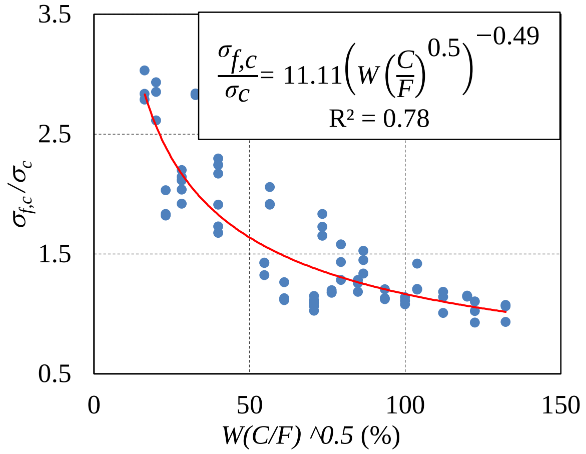


Fig.10 Correlation of $\sigma_{f,c}/\sigma_c$ and *W(C/F) ^0.5*

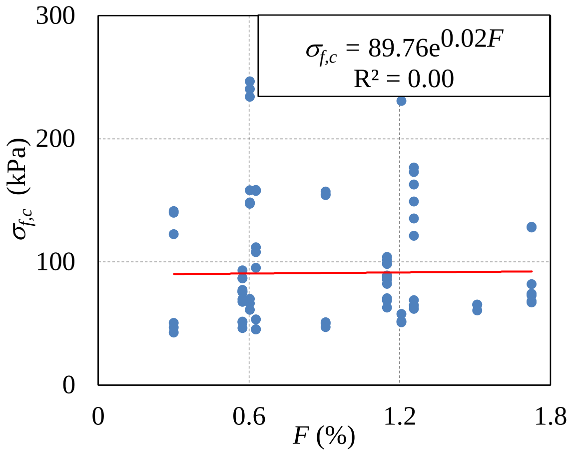


Fig.11 Correlation of $\sigma_{f,c}$ and *F*

Fig. 9 shows the relationship between ($\sigma_{f,c}/\sigma_c$) and *C/F* and the fitted curve for $\sigma_{f,c}/\sigma_c$ ratio as a function of *C/F* ratio. It can be observed that *C/F* ratio had a significant effect on $\sigma_{f,c}/\sigma_c$ ratio. A quite good correlation as "Eq. (1)" with a correlation coefficient of 0.74 can be seen in Fig. 9.

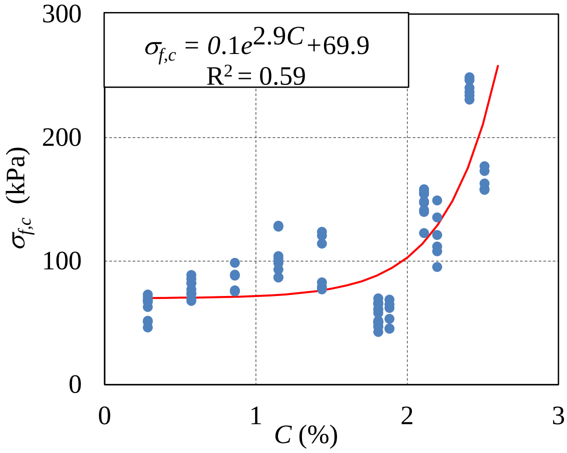


Fig.12 Correlation of $\sigma_{f,c}$ and *C*

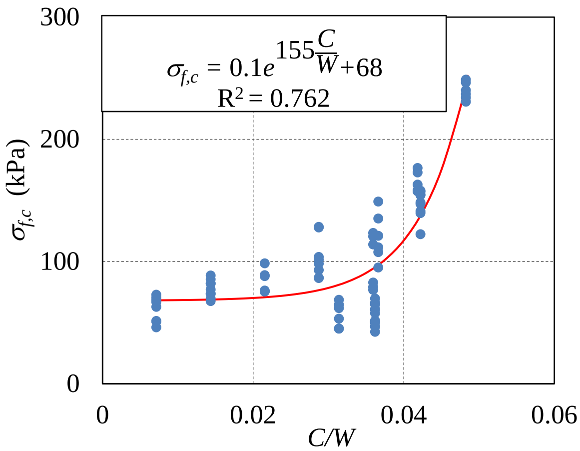


Fig.13 Correlation of $\sigma_{f,c}$ and *C/W*

Fig. 10 shows the experimental data and fitted curve for $\sigma_{f,c}/\sigma_c$ ratio as a function of *W(C/F) ^0.5* ratio. As a result, a better function as "Eq. (2)" following the term of *W(C/F) ^0.5* for describing failure strength ratio was found with a correlation coefficient of 0.78.

Consoli et al. [22] found some parameters such as cement content, porosity, etc. affecting noticeably on failure strength of cemented soil reinforced with synthetic fiber. However, the amount of fiber content was fixed at 3%. Therefore, it is quite difficult to determine the effect of fiber inclusion [23]. In addition, there is no research on the parameters as water, cement, and fiber content controlling the failure strength of cemented soil reinforced with natural fibers. Therefore, this section also evaluates the relationship between failure strength and parameters such as water, cement, and fiber content with different levels of water, cement, and fiber content.

$$\frac{\sigma_{f,c}}{\sigma_c} = 1.7 \times \left(\frac{C}{F}\right)^{-0.3} \quad (1)$$

$$\frac{\sigma_{f,c}}{\sigma_c} = 11.11\times\left(W\left(\frac{C}{F}\right)^{0.5}\right)^{-0.49} \quad (2)$$

$$\sigma_{f,c} = 0.1e^{2.9C} + 69.9 \quad (3)$$

$$\sigma_{f,c} = 0.1e^{155.0\left(\frac{C}{W}\right)} + 68.0 \quad (4)$$

$$\sigma_{f,c} = 0.1e^{155.7\left(\frac{C}{W}F^{0.02}\right)} + 67.0 \quad (5)$$

The present work considers the correlation of failure strength with fiber inclusion ($\sigma_{f,c}$) and parameters as *W*, *C*, *F*, *C/W*, *C/F*, and *F/W*. It was confirmed through analysis that there was no correlation between $\sigma_{f,c}$ ratio and parameters of *W*, *F*, *C/F*, and *F/W*. A representative case shown in Fig. 11 indicates no correlation was between $\sigma_{f,c}$ and *F*. as Meanwhile, Figs. 12 and 13 show the experimental data and fitted curve for $\sigma_{f,c}$ as a function of *C* and *C/W*, respectively. It is clearly observed that there was a weak relationship of $\sigma_{f,c}$ and *C* following "Eq. 3" with correlation coefficient of 0.59. A strong association with a coefficient value of 0.762 is $\sigma_{f,c}$ and *C/W* as "Eq. 4".

Besides, an equation following three variables including *W*, *C*, and *F* for using in the pre-feasibility study of real construction works such as predicting the failure strength of modified soil should be proposed. As can be seen in Fig. 14, a quite good equation "Eq. 5" with a correlation coefficient of 0.764 is proposed for predicting failure strength of cemented sludge reinforced with cornsilk fiber.

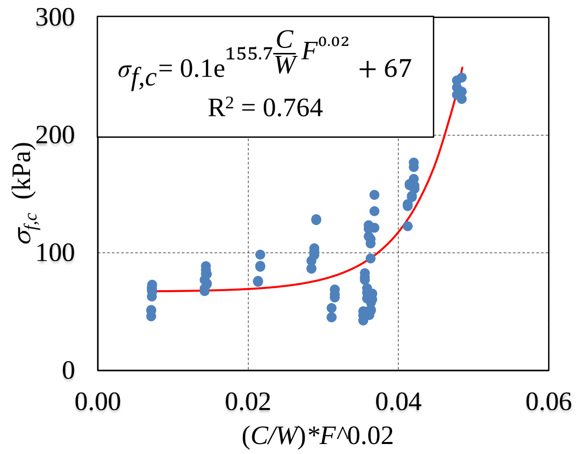


Fig.14 Relationship of $\sigma_{f,c}$ and (*C/W*)**F*^0.02

4. CONCLUSIONS

A series of experiments was carried out to investigate the effect of cornsilk fiber on cemented sludge stabilization. The effect of fiber addition with variations of water, cement, and water content on unconfined compressive strength, stiffness, and ductility was evaluated. In addition, the effect of parameters such as *W*, *C*, *F*, *C/W*, *C/F*, and *F/W*, etc. on ($\sigma_{f,c}$) and $\sigma_{f,c}/\sigma_c$ ratio was examined. According to experimental results in the present work, it can be concluded as follows.

The addition of fiber in cemented sludge caused the increase of failure strength in general. The most efficient increases in failure strength for W40 with C5-C20, W50 with C30-C40, and W60 with C30-C40 were 190.6, 43.8, and 85.9%, respectively. Fiber inclusion caused the change of cemented sludge behavior from brittle to ductile. The failure strength and ductile behavior increased with increasing an amount of fiber. The effect of fiber addition on stiffness property was based on the amount of cement. When a large amount of cement used, fiber inclusion caused a decrease of stiffness. Meanwhile, stiffness increased with using a small amount cement.

The failure strength of cement stabilized sludge reinforced with cornsilk fiber had a weak and strong correlation with the term of *C* and *C/W*, respectively. The failure strength ratio with and without fiber inclusion could be significantly described as functions following *C*/*F* ratio and the term of *W(C/F) ^0.5*. In addition, the equation described as a function of the term of (*C/W*)**F* ^0.02 can be used for predicting failure strength of modified sludge.

These conclusions mean that it is possible for using cornsilk fiber in cemented sludge reinforcement to improve mechanical properties. It is significant for points of view on engineering, economic, and environment. Furthermore, the number of research works studied on natural fiber is limited. Therefore, cornsilk fiber should be considered to study and use for modifying soft soil or sludge in future.

5. AUTHOR'S CONTRIBUTIONS

The experiments were carried out by Khiem Quang Tran as part of his Ph.D. research, under the supervision of Prof. Hiroshi Takahashi and Asst. Prof. Tomoaki Satomi. The manuscript was prepared by Khiem Quang Tran and revised by Prof. Hiroshi Takahashi and Asst. Prof. Tomoaki Satomi.

6. ETHICS

The corresponding author confirms that this article is original. The content of this paper is unpublished material. The manuscript had been approved by the other authors. There are no ethical issues and conflict interest on this article. The present paper is not under consideration for publishing in any other journal.

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