

# EFFECT OF ORGANIC MATTER ON LIME AND CEMENT STABILIZED ARIAKE CLAYS

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This study investigates the effects of organic matter on lime and cement stabilized Ariake clays with emphasis on their mechanical properties and microstructure. The study also focuses on the effect of humic acid, which is a part of organic matter, on the strength development of stabilized clays. The results show that the strength and the yield stress of lime stabilized clay with high humic acid are low due to the obstruction of the pozzolanic reaction. Consequently, the cementing products are not visible in the micrographs. The humic acid has a greater effect on the strength reduction of lime stabilized clay than that of cement stabilized clay. The effect of humic acid on strength of stabilized clays decreased with increasing salt concentration because the humic acid becomes inactive at higher salt concentration.

*Key Words* : Ariake clay, organic matter, lime and cement stabilized clays, humic acid, salt concentration, microstructure

## 1. INTRODUCTION

Ariake clay is highly sensitive soft clay deposited around the coast of the Ariake Bay in Kyushu Island, Japan. The properties of Ariake clay have been studied for more than three decades (Ariake Bay Research Group<sup>1</sup>), Fujikawa and Takayama<sup>9</sup>, and Onitsuka<sup>13</sup>). Its natural water content varies from 50 to 200%. Most of the Ariake clays are classified as CH, and have sensitivity of over 16. In particular, the liquidity index of the Ariake clay exceeds one. Owing to its very high water content and low shear strength, the disposal of surplus Ariake clay from the construction sites has become a serious problem.

An improvement of the surplus clays within a short period is necessary. The stabilized clay can be used as fill materials. A popular improvement method is by chemical additives such as lime or cement. Due to the cementation bond developing with time for cement or lime mixed clays, the shear strength of the clay increases. The strength increase of lime or cement stabilized clay is mainly obtained

by the formation of the cementing products such as CSH (CaO-SiO<sub>2</sub>-H<sub>2</sub>O) and CAH (CaO-Al<sub>2</sub>O<sub>3</sub>-H<sub>2</sub>O). These cementitious products were investigated by X-ray diffraction and a scanning electron microscope (SEM) by Kawamura and Diamond<sup>8</sup>, and Kamon and Nontananandh<sup>20</sup>. Moreover, it has been found that clay compositions such as soil gradation, types of clay minerals, organic matter, pH, sulphate, pore water in clay, etc. are the main factors controlling the bond strength (Clare and Sherwood<sup>2</sup>, Sherwood<sup>5</sup>, Thompson<sup>6</sup>, Kujala et al.<sup>22</sup>, and Onitsuka and Modmoltin<sup>26</sup>).

Organic matter is one of the predominant factors influencing the physical and the mechanical properties of clay. The organic matter in the clay is responsible for high plasticity, high shrinkage, high compressibility, low hydraulic conductivity, and low shear strength. It is generally accepted that the presence of the organic matter in the clay may lead to the detriment of the strength of lime and cement stabilized clays. In the case of lime stabilized clay, the influence of the organic matter on the lime reactivity is attributed to the obstruction of

pozzolanic reaction. Thompson<sup>6)</sup> proposed that the organic matter either prevents the dissolution of soil silica and /or alumina or combines with the lime added to the soil. In the case of the cement stabilized clay, the organic matter also affects the cementing process. The organic matter tends to coat the cement particles, preventing or retarding their hydration reactions (Kamon et al.<sup>15)</sup>). However, some studies have shown that not all of the organic compounds really have a negative effect on the cementing process (Young<sup>7)</sup> and Kamon and Nontananandh<sup>20)</sup>).

There is not much research concerning the effect and the mechanism of organic matter on lime and cement stabilized clays. The precise quantity of the organic matters interfering with lime or cement reaction cannot be accurately defined. In addition, adequate criteria have not been made available for distinguishing the low reactive clay. The low reactive soil is normally investigated in terms of the amount or type of the organic matter present.

The study attempts to comprehend the effect of organic matter on lime and cement stabilized Ariake clays. An experimental program was conducted to investigate on strength, compressibility, and microstructure of the stabilized clays. The test has been conducted on Ariake clays sampled from different areas in Saga Plain. The strength and the compressibility of the stabilized clays were investigated by unconfined compression and oedometer tests. The microstructure feature of the stabilized clays was observed by a scanning electron microscope (SEM). Due to the variety of general methods of measuring the organic matter content in soils, considerable attention was also given to the examination methods presently used as well as to establishing a reliable method for practical engineering.

The study focused on the effect of humic acid, a kind of organic matter, on the strength of lime and cement stabilized Ariake clays. To make sure that the clay sample containing different humic acid contents, the tests were conducted with inorganic clays mixed with the various amounts humic acid.

As salt concentration is known to be one of the dominant factors on the strength of the lime and the cement stabilized clays, this study also investigated the influence of the salt concentration on the detrimental effects of the humic acid.

## 2. EXPERIMENTAL INVESTIGATION

### (1) Soil sample

The Ariake clay samples used in this investigation were obtained from (a) Okawa area,

Table 1 Properties of Ariake clays.

Properties	Clay sample		
	Clay1	Clay2	Clay3
Water content, %	185.0	150.0	170.0
Liquid limit, %	142.7	133.0	150.0
Plasticity index	89.1	71.4	88.0
Specific gravity	2.48	2.62	2.56
Particle size distribution, %			
Sand	3	3	0
Silt	29	37	19
Clay	68	60	81
pH	6.0	7.6	8.0
Salt concentration (g/l)	0.7	15.4	23.1
Organic matter, % (Dichromate absorption) (JSF T 231-1990 <sup>17)</sup> )	1.1	1.1	1.1
Ignition loss, % (JSF T 221-1990 <sup>16)</sup> )	8.0	7.3	10.0
Humus content (JSF T 232-1990 <sup>18)</sup> )	1.94	1.67	2.35
Humic acid, %	1.60	0.25	0.31
Fulvic acid, %	0.34	1.42	2.04

Fukuoka Prefecture, (b) Ashikari area, Saga Prefecture, and (c) Isahaya Bay, Nagasaki Prefecture designated as Clay 1, Clay 2, and Clay 3, respectively. Clay 1 was sampled at 1.0 m depth under the bottom of the rivulet. Clay 2 and Clay 3 were sampled at 3.0 m depth from the ground surface. The properties of Ariake clays are shown in Table 1.

### (2) Sample preparation for unconfined compression and oedometer tests

Quick lime and ordinary Portland cement were applied for the stabilization. Mixing and preparation of specimens were performed in accordance with the method of making and curing non-compacted stabilized soil specimens (JGS 821-2000<sup>24)</sup>) as prescribed by the Japanese Geotechnical Society. The clays were mixed with 5, 10, and 20% lime or 10, 20, and 30% cement by mass of dry soil. In order to eliminate the effect of the differences in water content, distilled water was added to Clay 2 and Clay 3 to adjust the water content to 185% which is the natural water content of Clay 1. After Clay 2 and Clay 3 were mixed with the distilled water, the salt concentration of both Clay 2 and Clay 3 decreased to 12.5 and 21.2 g/l, respectively. The addition of distilled water in both clays had little effect on their salt concentrations. The remolded clays were near saturation because their water contents were quite high and their liquidity indexes were higher than one. All samples were compacted by hand vibration in three layers in the cylindrical

molds to eliminate the entrapped air. The samples consisting of 50 mm in diameter and 100 mm in height, were cured at a temperature of about 20°C and humidity of 90%. The unconfined compression tests were conducted on specimens with curing periods of 7, 14, and 28 days.

In addition, the series of oedometer tests were carried out on Clay 1 and Clay 2 specimens. The samples were remolded clays and stabilized clays with 10% and 20% lime or cement at the same initial water content of 185% and cured for 7 days.

### (3) Testing methods for SEM observation

The micrograph is an effective way to observe the microstructure of lime or cement stabilized clay. The microstructure observations were carried out using the remolded specimens of Clay 1 and Clay 2 at water content of 185%. The remolded clay samples for SEM were separated from the samples for oedometer test. The remolded clays were freeze dried after remolding. In order to investigate the microstructure of stabilized clays, the tests were set up to observe both Clay 1 and Clay 2 mixed with lime or cement. After mixing, the samples were trimmed to about 10 mm cube. All samples were wrapped in vinyl bags and cured in a curing room with constant temperature (20°C) for 7 and 28 days.

After the curing, the clay samples were dried by the freeze drying method to minimize the volume changes and the fractured surface of the samples were coated with gold in order to view the soil structure and the nature of the stabilization by-products.

### (4) Testing methods for permeability

The coefficient of permeability is one of the mechanical parameters used for analysis of the structural properties of the soil. The falling head permeability test was conducted at the end of each loading of an oedometer test. The oedometer apparatus was connected to a burette by a tube, and water was allowed to flow from the burette to the bottom of the sample. The specimen consisted of remolded clays with lime or cement stabilization after a curing time of 7 days.

### (5) Testing methods to investigate the effect of organic matter

In order to investigate the effect of organic matter, the clay specimens were treated by the alkaline extraction method to eliminate the organic matter (Clare and Sherwood<sup>2</sup>). The alkaline extraction method was done as follows. The natural clay (500 g of dry clay) was stirred into 1 liter of 0.5 N sodium hydroxide (NaOH) for 24 hours, and the

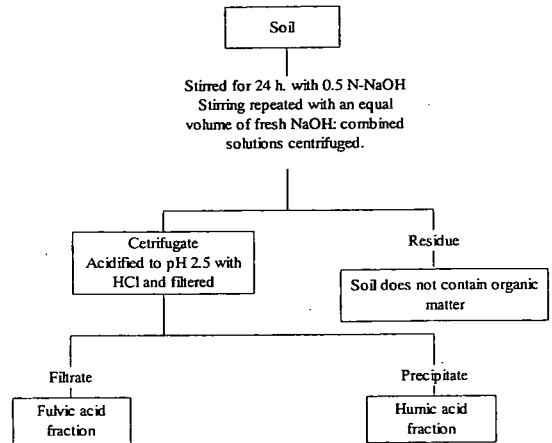


Fig.1 Extraction of fulvic and humic acids from soil (Clare and Sherwood<sup>2</sup>).

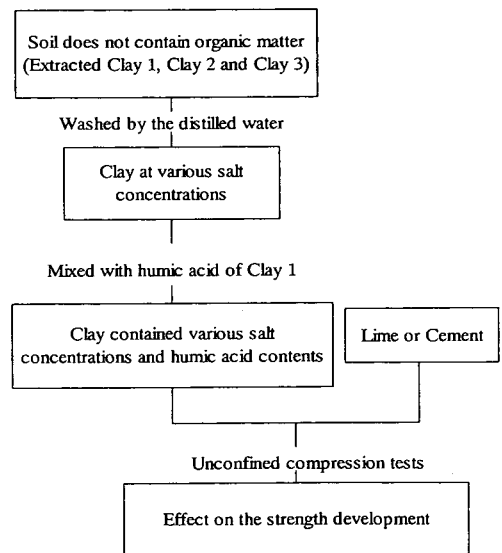


Fig.2 Testing program to investigate the effect of humic acid and salt concentration on the strength of stabilized clays.

undissolved clay was removed by decantation and centrifuging.

The procedure was repeated and the two portions of liquid were mixed. The extracted clay was washed with distilled water. The washed clay was suspended in distilled water, and the suspension was brought to the pH of the natural clay by addition of hydrochloric acid (HCl). The clay was then filtered and washed. The organic material obtained by the alkaline extraction of the natural soil can be divided into two parts, namely: (a) the humic and (b) the fulvic acids (Fig.1). The humic acid was precipitated by acidification of the extract to pH 2.5 and filtered off.

After extraction, the remaining clay (the organic matter was removed from the clay by alkaline extraction method) was used in the preparation of duplicate specimens for the unconfined compression tests, using the mixture of clay with the humic acid that was extracted from Clay 1 with 20% lime or cement. The samples were tested after curing time of 7 days.

Finally, the study also investigated the effect of salt concentration on the detrimental effect of humic acid. The extracted clays were washed to obtain the clay samples containing different salt contents by the distilled water. The clay samples were mixed with 20% lime or cement at various humic acid contents, cured, and tested after curing of 7 days (Fig.2).

### 3. RESULTS AND DISCUSSIONS

#### (1) Mechanical properties of stabilized clays

Fig.3(a) shows the strength development of lime and cement stabilized Clay 1. The unconfined compressive strength of Clay 1 which was mixed with 20% lime and cured for 28 days was very low of about 5 kN/m<sup>2</sup>. In contrast, the unconfined compressive strength of Clay 1 mixed with 20% cement at the curing time of 28 days was found to be 800 kN/m<sup>2</sup>. The results indicated that the lime failed to stabilize Clay 1. Figs.3(b) and (c) show the strength development of the lime and the cement stabilized Clay 2 and Clay 3, respectively. In this case, the strength of the lime stabilized clays is higher than the cement stabilized clays at the same admixture content. Thus, lime is more effective than the cement in terms of stabilization of Clay 2 and Clay 3. Generally, the strength of the lime and the cement stabilized clays increases with admixture contents and curing time. The unconfined compressive strength of 30% cement stabilized Clay 1, Clay 2, and Clay 3 at the curing time of 28 days were 2300, 3800, and 3200 kN/m<sup>2</sup>, respectively as shown in Figs.3(a), (b), and (c). Although the water content of all clays was the same, the strength of lime and cement stabilized Clay 1 was found to be lower than that of Clay 2 and Clay 3.

Figs.4(a) and (b) show the one-dimensional compression curves of remolded and lime or cement stabilized clays. The one-dimensional compression curves of the remolded Clay 1 and the remolded Clay 2 indicate linear relationships. The yield stresses of 10% lime and 10% cement stabilized Clay 1 were 10 and 50 kN/m<sup>2</sup>, respectively. The yield stresses of Clay 2 mixed with 10% lime and 10% cement were quite high at 1000 and 200 kN/m<sup>2</sup>,

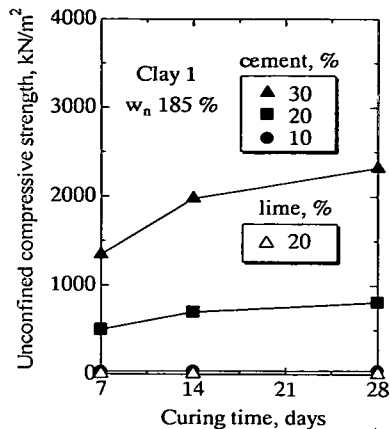


Fig-3(a)

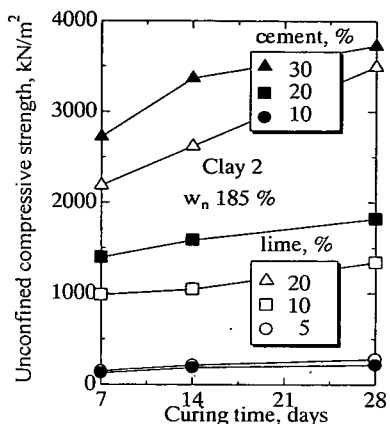


Fig-3(b)

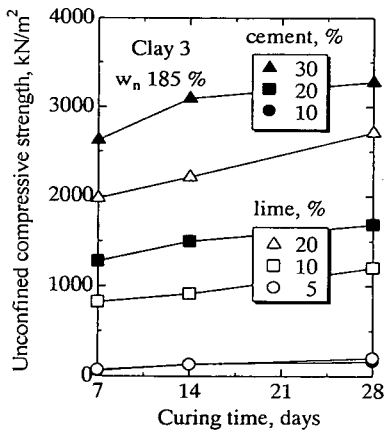


Fig-3(c)

Figs.3(a), (b), and (c) The strength development of lime and cement stabilized clays with different admixture contents.

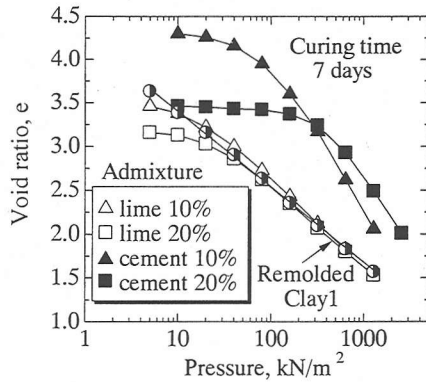


Fig.4(a) One-dimensional compression curves of the lime and cement stabilized Clay 1 at curing time 7 days.

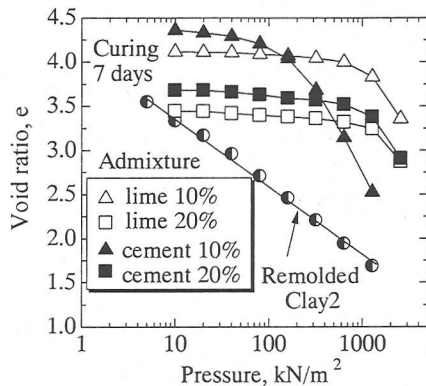


Fig.4(b) One-dimensional compression curves of the lime and cement stabilized Clay 2 at curing time 7 days.

respectively. Similar results have been obtained using 20% lime and 20% cement stabilized Clay 1 and Clay 2. Moreover, the yield stress of lime or cement stabilized Clay 1 was lower than Clay 2. Therefore, Clay 1 failed to be stabilized by lime as found from the results of the unconfined compression and the oedometer tests. In addition, the strength and the yield stress of cement stabilized Clay 1 were also low compared with both Clay 2 and Clay 3.

## (2) Microstructure feature

The term “fabric” refers to the arrangement of the particle, particle group, and pore spaces in a soil (Mitchell<sup>21</sup>). An aggregation is a grouping of particles into larger fabric units. All micrographs were taken at the magnification of 3000 times because it is easy to observe clay particles with the scale of 5  $\mu\text{m}$ . Figs.5(a) and (b) show the micrographs of remolded Clay 1 which indicated the presence of diatoms, and remolded Clay 2 at the same water content as 185%. The micrograph of

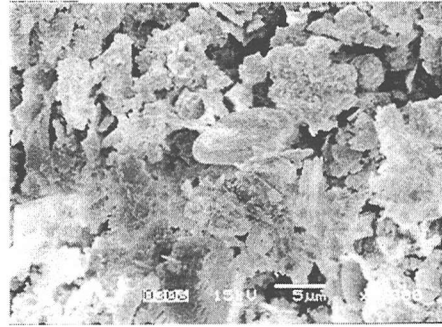


Fig.5(a) Remolded Clay 1 at water content 185%.

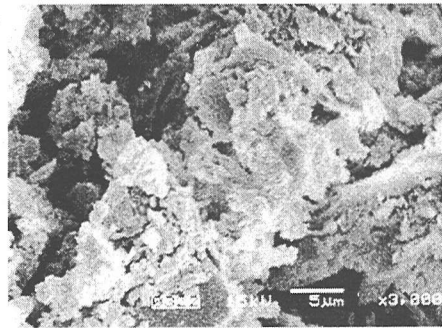


Fig.5(b) Remolded Clay 2 adjusted at water content 185%.

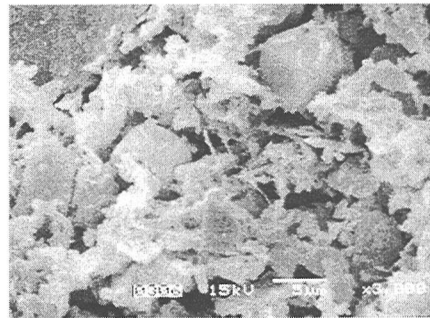


Fig.6(a) Clay 1 mixed with 10% lime at curing time 7 days.

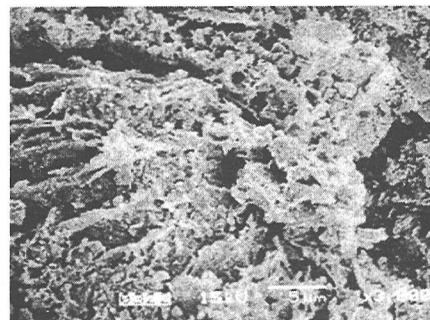
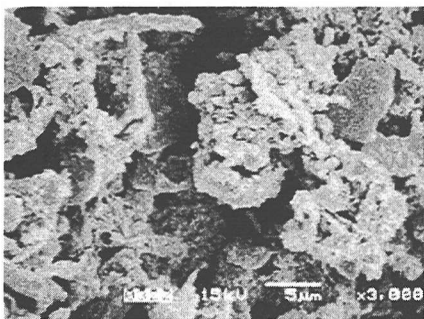


Fig.6(b) Clay 2 mixed with 10% lime at curing time 7 days.

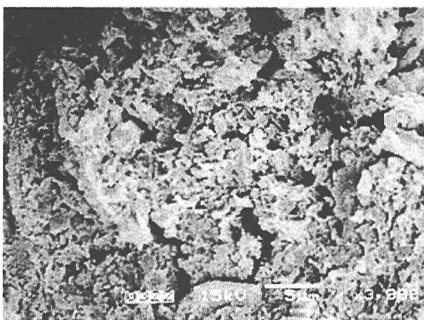
10% lime stabilized Clay 2 (**Fig.6(b)**) clearly shows the presence of cementing products in the pore spaces with the well-knit framework among the aggregations. The formation of these cementing products in lime stabilized clay was reported earlier by Kawamura and Diamond<sup>8)</sup>. The cementing products bond each aggregation together, like bridges among aggregations, called “bond bridge”.

**Fig.6(a)** shows the micrograph of 10% lime stabilized Clay 1 at a curing time of 7 days. The cementing products are not visible. In the micrograph, it can be observed that the pore spaces of the lime stabilized Clay 1 are less than remolded Clay 1 because the hydration and the cation exchange reactions induce the clay particle to lump together. **Fig.6(d)** shows the micrograph of 20% lime stabilized Clay 2 which indicates clay aggregations at several places of the micrograph. The formation of aggregations is due to the reaction of the lime on the soil particles. In the case of 20% lime stabilized Clay 1 as shown in **Fig.6(c)**, there are many pore spaces in the fabric, and the cementing products cannot be clearly observed from the micrograph.

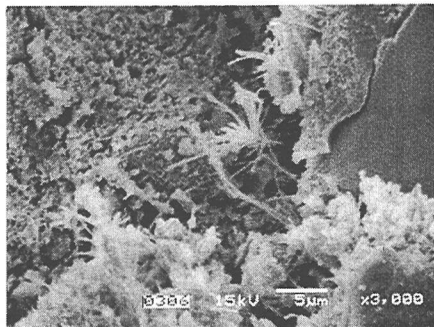
**Figs.7(a) and (b)** show the micrographs of 20% cement stabilized Clay 1 and 10% cement stabilized Clay 2 at a curing time of 7 days, respectively. The microstructure of the cement stabilized clays is different from the remolded clays. The cementing



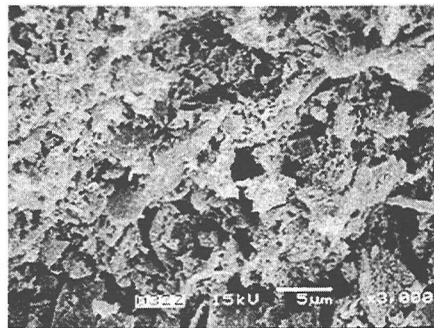
**Fig.6(c)** Clay 1 mixed with 20% lime at curing time 7 days.



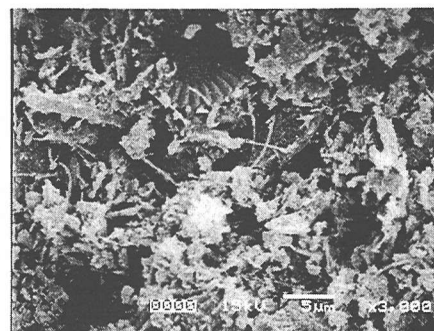
**Fig.6(d)** Clay 2 mixed with 20% lime at curing time 7 days.



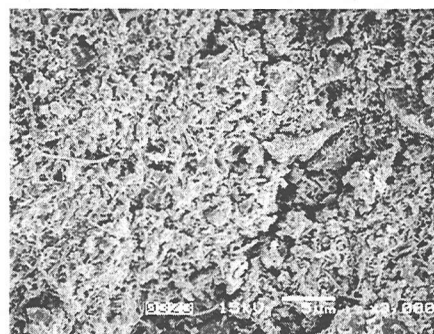
**Fig.7(a)** Clay 1 mixed with 20% cement at curing time 7 days.



**Fig.7(b)** Clay 2 mixed with 10% cement at curing time 7 days.



**Fig.8(a)** Clay 1 mixed with 20% lime at curing time 28 days.



**Fig.8(b)** Clay 2 mixed with 10% lime at curing time 28 days.

products, which are clearly visible, increased with decreasing pore spaces. The microstructure of 10% lime stabilized Clay 2 at a curing time of 28 days (Fig.8(b)) is completely different from the remolded Clay 2. The micrograph of lime stabilized Clay 2 shows the presence of the cementing products and small pore spaces. The micrograph of Clay 1 mixed with 20 % lime at the curing time of 28 days, is shown in Fig.8(a). There are many pore spaces in the fabric of the stabilized Clay 1. Furthermore, it is clearly shown that the aggregation in the soil fabric of 10% lime stabilized Clay 2 is denser than 20% lime stabilized Clay 1 at the curing time of 28 days.

The coefficients of permeability,  $k$ , of remolded Clay 1 and Clay 2, under a vertical effective stress of  $5 \text{ kN/m}^2$ , were  $2.56 \times 10^{-7}$  and  $2.09 \times 10^{-7} \text{ cm/sec}$ , respectively. Thus, the coefficients of permeability of both Clay 1 and Clay 2 were almost the same. In Fig.9(a), the permeability of remolded Clay 1, 10%, and 20% lime stabilized Clay 1 was almost the same because the microstructure did not change after being mixed with lime. Consequently, the pore spaces in fabric were the same because the cementing products were not formed.

Fig.9(c) shows the permeability of remolded Clay 2 together with 10%, and 20% lime stabilized Clay 2. The coefficient of permeability decreased with increasing lime content. The pore spaces decreased because of the formation of the cementing products as indicated in the micrograph.

Figs.9(b) and (d) show the permeability of remolded clays, 10%, and 20% cement stabilized Clay 1 and Clay 2. The permeability decreased with increasing cement content. To study the cementation effect, the microstructure of Ariake clay mixed with 5% cement and cured for 28 days was also investigated by Yamadera<sup>23</sup>. The result indicated that the microstructures of the cement stabilized clay and the remolded clay are not different. Their pore spaces are almost the same due to the low cement content. Therefore, the formation of the cementing products is not enough to affect the pore spaces. In the present study, the cement content is adequate to observe the formation of the cementing products as shown in the micrographs.

The microstructure observation agrees well with the strength development of stabilized clays in the previous section. The microstructure of the stabilized clay which is the combination of the fabric pattern and the cementation bond, relates to the strength development. The strength of lime stabilized Clay 1 is very low. Consequently, the cementing products are not obviously observed. The strength of the lime and the cement stabilized Clay 2 increase with curing time and admixture content. Subsequently, the microstructures of stabilized Clay

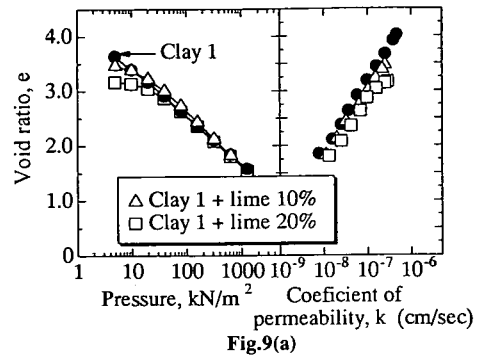


Fig.9(a)

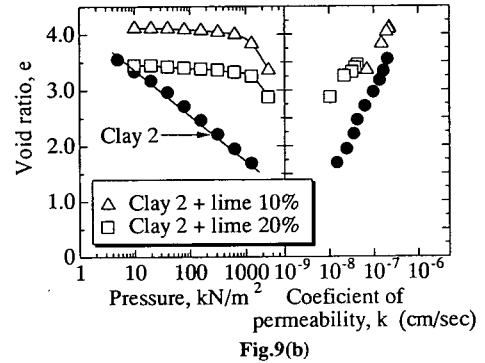


Fig.9(b)

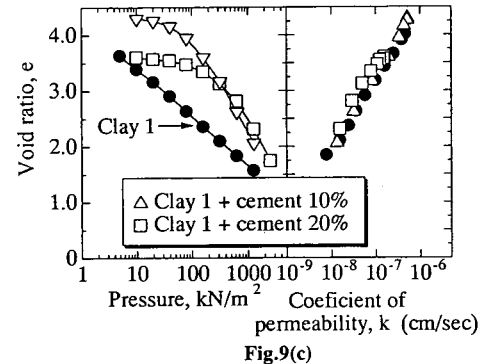


Fig.9(c)

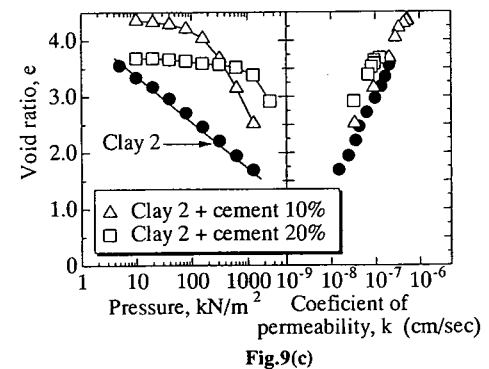


Fig.9(d)

Figs.9 (a), (b), (c), and (d) Plot of  $e-\log \alpha_v'$  and  $e-\log k$  relations in remolded and stabilized clays.

2 and remolded Clay 2 are completely different. The micrograph of stabilized Clay 2 clearly shows the presence of the cementing products.

### (3) Organic matter

The extraction of organic matter by NaOH is an effective method which can extract up to 80% of organic matter (Stevenson<sup>12</sup>). After extraction, the liquid limit of Clay 1 decreased from 142.7% to 110.5% and the specific gravity of Clay 1 increased from 2.48 to 2.55 which demonstrated the effect of organic matter in Clay 1. The unconfined compressive strengths of extracted Clay 1 mixed with 20% lime and 20% cement at a curing time of 7 days were found to be 1200 and 1500 kN/m<sup>2</sup>. These values are quite high compared with the corresponding values of 5 and 600 kN/m<sup>2</sup> obtained from similar specimens using natural Clay 1. Thus, the extraction of organic matter removed or destroyed the constituents responsible for the obstruction of hardening reactions.

The organic matter has a greater detrimental effect on the strength of the lime stabilized clay than that of the cement stabilized clay. In the case of lime stabilized clay, the organic matter prevented the formation of cementing products because it obstructed the dissolution of silica (SiO<sub>2</sub>) and alumina (Al<sub>2</sub>O<sub>3</sub>) in the clay. Thus, the organic matter has detrimental effect on the strength mobilization of lime stabilized clay by obstructing the pozzolanic reaction.

Portland cement contains tricalcium silicate (C<sub>3</sub>S), dicalcium silicate (C<sub>2</sub>S), tricalcium aluminate (C<sub>3</sub>A), and a solid solution described as tetracalcium aluminoferrite (C<sub>4</sub>A) (Lea<sup>4</sup>). These four main constituents are major strength producing compounds. When the pore water of the soil comes in contact with cement, the major cementing products are produced such as hydrated calcium silicate (CSH), hydrated calcium aluminates (CAH), and hydrated lime (Ca(OH)<sub>2</sub>). The cement stabilized clay also induces pozzolanic reaction because the hydration reaction also produces Ca(OH)<sub>2</sub>. In the cement stabilized clay, the organic matter also obstructs the hydration reaction. However, its effect is more influential in the pozzolanic reaction. The cement stabilized organic clay derives its strength from the products of hydration reaction. On the other hand, the strength of lime stabilized high organic clay is extremely low because the strength is mainly governed by the pozzolanic reaction.

The organic matter contents by the dichromate absorption method (JSF T 231-1990<sup>17</sup>) are quite low (Table 1) because this method involve little or no external heating which yields very poor recovery of organic carbon present in carbonized materials

(Nelson and Sommers<sup>10</sup>). The dichromate absorption with external heating method is also unsuitable for practical measurements because it is a quite complicated method and requires special equipment. The organic matter contents of all clays were the same showing the value of 1.1%; however, the strengths of stabilized clays were completely different. Thus, this method cannot definitely indicate the precise quantity of organic matter which has a detrimental effect on the strength of stabilized clays.

The ignition loss values of Clay 1, Clay 2, and Clay 3 were found to be 8.0, 7.3, and 10.0%, respectively, which are quite high. The determination of the change in mass of a soil sample resulting from the destruction of organic matter by ignition at high temperature causes an error. Lambe and Martin<sup>3</sup>) stated that organic matter contents determined by the ignition loss and the chemical analysis agree quite well if the non-organic portions (quartz, feldspar, etc.) of the soil do not decomposed by heat and do not contain significant amounts of adsorbed water. Consequently, the ignition loss is a very poor measure of organic matter in the dominant smectite soil because it involves large quantities of adsorbed moisture which are driven off by heat. The dominant clay mineral of Ariake clay is the low-swelling type of smectite (Ohtsubo et al.<sup>11</sup>). In Ariake clay, the ignition loss method yields an overestimate because both inorganic and organic constituents lose mass during heating. The test results showed that the ignition loss of the extracted Clay 1, Clay 2, and Clay 3 were still high at 9.5, 6.7, and 7.1%, respectively, even though the organic matter was previously removed from all clay specimens.

In order to determine the quantity of organic matter which will critically interfere with the lime and cement reaction, the ignition loss value and humus content are usually applied in practice. The humus contents of Clay 1, Clay 2, and Clay 3 were 1.94, 1.67, and 2.35, respectively, as shown in Table 1. The organic matter is usually partitioned into two main fractions as humic acid and fulvic acid. The humic acid contents of Clay 1, Clay 2, and Clay 3 were 1.60, 0.25, and 0.31%, respectively. In addition, the fulvic acid contents of Clay 1, Clay 2, and Clay 3 were 0.34, 1.42, and 2.04%, respectively. The lime and the cement were successful in stabilizing Clay 3 even though it contained high humus content because it contained low humic acid content. On the other hand, the humus content of Clay 1 was less than Clay 3 but Clay 1 failed to be stabilized by lime and cement due to its higher humic acid content. Thus, the humic acid contained in clay directly affected the strength development of



stabilized Ariake clays. Ariake clay which is low reactive with lime and cement, cannot be classified by its organic matter content because some organic compounds really have no detrimental effect on the cementing reaction. The alkaline extraction method is successful in determining accurately the quantity of the humic acid which is the major detrimental factor on the strength development of stabilized Ariake clays.

**(4) Humic acid**

Fig.10(a) shows that the strengths of the lime stabilized natural Clay 2 and Clay 3 are higher than the extracted clays. The removal of organic matter directly affected the liquid limit of the extracted clay. The lower the organic matter content is, the higher the liquidity index is, which results in the lower shear strength. The proportion of fulvic acid to humic acid in organic matter of Clay 2 and Clay 3 was about five to one. Therefore, the main composition of the organic matter in Clay 2 and Clay 3 is the fulvic acid. Thus, the fulvic acid has a low detrimental effect on the strength of stabilized clay which agreed well with the results of Clare and Sherwood<sup>2)</sup>. The addition of fulvic acid brings about some reduction in strength, but not as much as the humic acid.

Figs.10(a) and (b) show that humic acid has the detrimental effect on the strength of lime and cement stabilized Clay 1. The strength of stabilized Clay 1 decreased with increasing humic acid content. In the case of stabilized Clay 2, the humic acid has the less detrimental effect compared with Clay 1. In addition, the strength of the lime and the cement stabilized Clay 3 are almost the same, regardless of the increase in humic acid. The effect of humic acid on the stabilized clays is different, though the type and quality of the humic acid in all clays are the same. However, the detrimental effect on strength of the stabilized clays is not only controlled by the humic acid.

The salt concentration is also one of the influential factors on the strength of lime or cement stabilized Ariake clay. Miura et al.<sup>14)</sup> investigated the effect of salt concentration on the strength of stabilized Ariake clay. The higher the salt concentration is, the greater the strength of stabilized clay is mobilized. After the organic matter was eliminated from the clay by the alkaline extraction method, the salt concentrations of Clay 1, Clay 2, and Clay 3 increased to 14, 21, and 28 g/l, respectively. The salt concentration of extracted Clay 2 and Clay 3 mixed with the lime or cement as shown in Figs.10(a) and (b) were 21 and 28 g/l, respectively. In addition, the extracted Clay 1 was then mixed with lime or cement at the salt

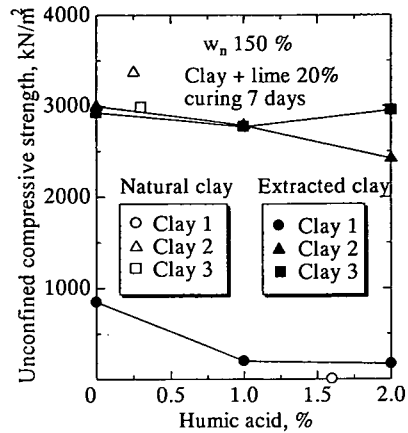


Fig.10(a) Effect of humic acid on lime stabilized extracted clays.

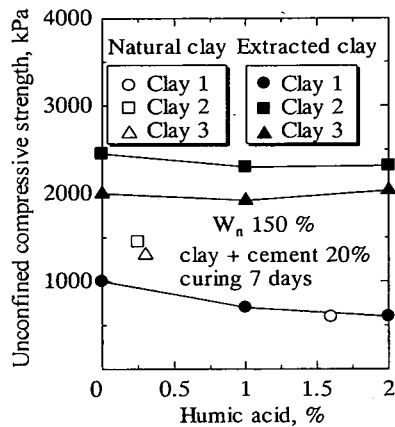


Fig.10(b) Effect of humic acid on cement stabilized extracted clays.

concentration of about 0.7 g/l to be the same as natural Clay 1 in order to eliminate the effect of salt concentration. Compared with Clay 1, the salt concentrations of Clay 2 and Clay 3 were very high.

**(5) Salt concentration**

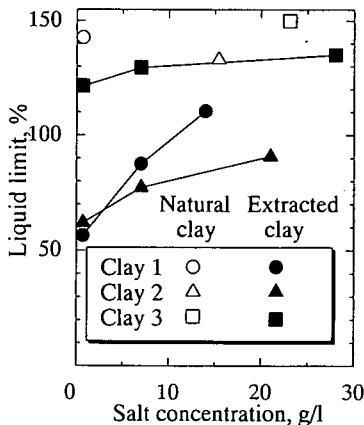
In order to investigate the effect of salt concentration, all the extracted clays were washed by distilled water to obtain different salt concentrations (Fig. 2). Table 2 shows the grain size distribution of all extracted clays with various salt concentrations. The results showed that the grain size distribution of all extracted clays did not change much with decreasing salt concentration. The change in grain size distribution has a high influence on the strength of lime or cement stabilized soil with low water content (the soil is mixed with lime or

**Table 2** Grain size distribution of extracted clays with various salt concentrations.

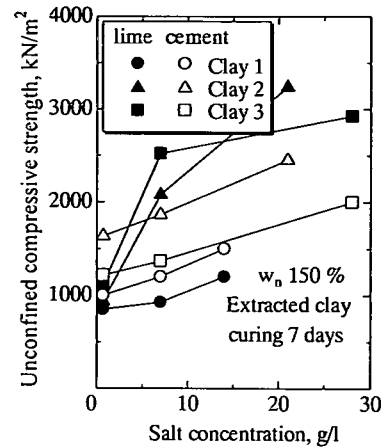
Properties Clay	Salt, g/l	Grain size distribution, %		
		Sand	Silt	Clay
Extracted Clay 1	14.0	12.0	43.0	45.0
	7.0	10.0	42.0	48.0
	0.7	7.0	43.0	50.0
Extracted Clay 2	21.0	2.0	33.0	65.0
	7.0	1.0	31.0	68.0
	0.7	1.0	29.0	70.0
Extracted Clay 3	28.0	0.0	6.6	93.4
	7.0	0.0	6.0	94.0
	0.7	0.0	4.8	95.2

cement at the optimum moisture content and compacted). If the soil has high clay content and water content, the grain size distribution is a minor factor on the strength development. However, the chemical reaction has greater influence on the strength of the high water content clay than the grain size distribution.

**Fig.11** shows the liquid limit of natural clays and extracted clays at various salt concentrations. The liquid limit of all clays decreased after the organic matter was removed. In addition, the liquid limit of all extracted clays also decreased with decreasing salt concentration which agreed well with previous research (Ohtsubo et al.<sup>11</sup>). The increase in strength of lime and cement stabilized Ariake clays as a result of high salt concentration is illustrated by the data in **Fig.12**. In the case of soils which contain salt and much clay fraction, the strength of lime



**Fig.11** Effect of salt concentration on liquid limit.



**Fig.12** Effect of salt concentration on strength of lime or cement stabilized clay.

stabilized clay was higher than cement stabilized clay.

**Figs.13(a), (b), and (c)** show the effect of the humic acid on the strength of lime or cement stabilized clays at various salt concentrations. In order to comprehend clearly its detrimental effect, the strength loss was plotted with the humic acid contents. The strength loss is defined as:

$$\text{Strength loss, \%} = \left( \frac{q_{u0} - q_u}{q_{u0}} \right) \times 100$$

where  $q_u$  is the unconfined compressive strength of stabilized clay with any humic acid content, and  $q_{u0}$  is the unconfined compressive strength of stabilized clay with humic acid content of 0%.

The results show that with lower the salt concentration, higher percentage of strength loss with the same humic acid content is obtained. The detrimental effect of the humic acid on the strength of lime and cement stabilized clays directly relates to the salt concentration. With the low salt concentration of about 0.7 g/l, the humic acid content of 1 % reduced the strength of the lime and the cement stabilized Ariake clay by up to 50% and 20%, respectively. On the other hand, the detrimental effect of humic acid on the strength of the lime or cement stabilized clay, with high salt concentration of about 21 g/l, was quite low. The strength of lime and cement stabilized clays were nearly the same, regardless of the increase in humic acid. The percentage of strength loss of the lime stabilized clays was higher than the value obtained from the cement stabilized clays with the same humic acid and salt concentration contents. Thus, the humic acid has a greater detrimental effect

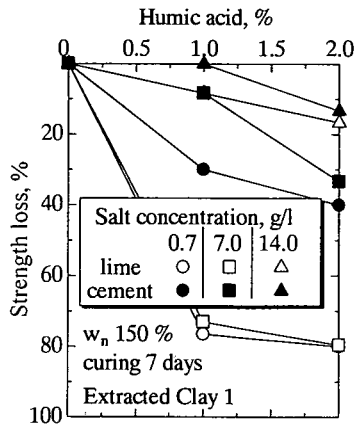


Fig.13(a)

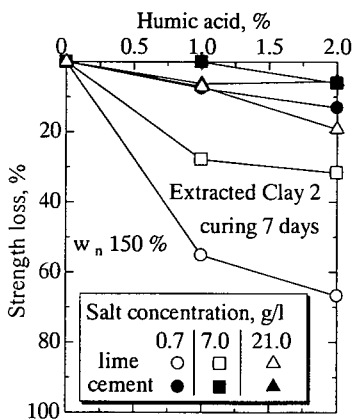


Fig.13(b)

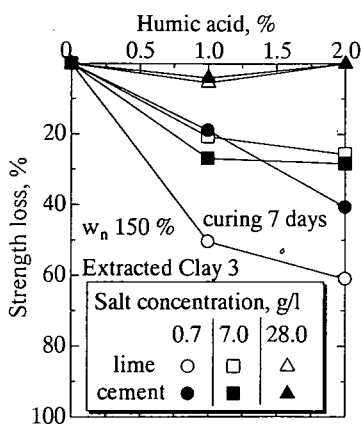


Fig.13(c)

Figs.13(a), (b), and (c) Retarding effect of humic acid on strength of stabilized clays at various salt concentration

on the strength of lime stabilized clay than the corresponding strength of cement stabilized clay.

### (6) Micromechanistic explanation

The observation on microstructure of soil is useful to appreciate the relationship between soil structure and its mechanical behavior. In the case of lime or cement stabilized clay, the study on the microstructure yields more information than natural clay. The microstructure of stabilized clay is a combination of cementation bond and fabric. The previous section showed that the addition of cementing agents directly affects the spacing among aggregations because of chemical reactions and cementing products. The study on the strength of the cement stabilized clay with the same fabric pattern of all clays at a liquid limit state was done previously by Yamadera<sup>23</sup>. With higher liquid limit, lower strength of stabilized clay with the same cement content was obtained. The strength of stabilized clay decreased with increasing spacing among aggregations. The cement content has to be increased to enhance the strength to the same level. Miura et al.<sup>25</sup> successfully integrated the parameters of the structural state of the cement stabilized soft clay by the clay-water/cement ratio,  $w/c$ . This parameter is a structural parameter reflecting the influence of both fabric of clay as reflected by its water content and cement content reflecting the level of cementation bond. Subsequently, the strength of the stabilized clays is actually controlled by two distinct factors such as the fabric of clay and the level of the cementation bond.

The salt concentration affects the fabric and the cementation bond strength. The liquidity index is reduced as a result of the higher liquid limit contributed by increasing salt concentration. With the low liquidity index, the spacing among the aggregations is small. Hence, the required cementation bond is lower in order to obtain the same level of bonding as with high liquidity index. Increasing salt concentration also increases the chemical reactions such as pozzolanic and hydration reactions. Consequently, the strength of stabilized clays increased significantly with increasing salt concentration.

Both humic acid and the salt concentration are the dominant factors that affect the level of the cementation bond and the fabric. The humic acid is a predominant factor influencing the level of cementation bond. It is further indicated that the higher the humic acid content is, the lower the cementation bond is found. The detrimental effect of humic acid on strength of stabilized Ariake clays relates to the salt concentration. With a low salt concentration, the cementation bond is delicate due

to the large spacing among aggregations and the low chemical reactions which are easily obstructed by humic acid. On the other hand, its detrimental effect is considerably less in the case of high salt concentration Ariake clay because of the decrease in pore spaces among the aggregations and the increase in the cementation bond by chemical reactions. Thus, a high level of cementation bond is induced and the detrimental effect of humic acid is reduced.

#### 4. CONCLUSIONS

Based on the investigation on the effect of organic matter on the mechanical properties and microstructure of lime or cement stabilized Ariake clays, the following conclusions can be made:

1. The strength and the yield stress of lime or cement stabilized clay increase with curing time and admixture contents. The micrographs show that the fabric of stabilized clay and remolded clay are completely different. The cementing products formed in the stabilized clay specimens can be observed by the micrographs. In the case of lime stabilized clay containing high humic acid, the strength and the yield stress are extremely low. Consequently, the cementing products are not visible on the micrographs.

2. The permeability relates to the pore spaces in the fabric. In the case of the stabilized low humic acid clay, the permeability of the stabilized clays is lower than the remolded clay because the spacing among the aggregations in the stabilized clay is decreased due to the formation of cementing products. The permeability of the remolded clay and the lime stabilized clay containing high humic acid were found to be the same. Subsequently, the spaces among the aggregations of the remolded and the stabilized clay are almost the same, demonstrating the detrimental effects of the humic acid.

3. The dichromate absorption, the ignition loss, and humus content methods cannot definitely indicate the critical quantity of organic matter in the clay samples. The organic matter has a little effect on the strength of stabilized clays because some organic matter has no negative effect on the cementing process. However, humic acid, a part of organic matter, has been identified as a major factor that hinders the strength development of stabilized Ariake clays. The alkaline extraction method has been successfully used to determine definitely the quantity of the humic acid in the clay specimens.

4. The humic acid and the salt concentration are the dominant factors affecting the cementation bond strength and the fabric. The humic acid has a greater

detrimental effect on the strength of lime stabilized clay than that of cement stabilized clay. The detrimental effect of humic acid on the strength of cement or lime stabilized clays decreased as the salt concentration increased.

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