INFLUENCE OF STORAGE CONDITIONS ON GEOTECHNICAL PROPERTIES OF ARIAKE CLAY AND ON ITS CHEMICAL STABILIZATION

by

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ABSTRACT

Influence of storage conditions on geotechnical properties of Ariake clay and on its chemical stabilization is investigated to make use of the surplus clay as construction materials. The effect of oxidation and drying during storage in various conditions on geotechnical properties of natural Ariake clay were studied. Recently, the problems of strength loss on lime and cement-treated clay during storage were reported. In order to understand the effect of oxidation and drying during storage and other factors on the gain strength of clay stabilization, the influence of organic, salts, diatom, clay minerals, oxidation and drying were examined on lime and cement-stabilized clays. Details of research are described below;

Firstly, the influence factors in lime and cement stabilization including salts, diatom and clay minerals were studied by using two groups of clays: natural clays including Ariake clay and Bangkok clay, and pure clay minerals consisting of Kaolin and Bentonite. The experiments were set up by mixing clays with various proportions of studied factors at similar water content and lime or cement content. After specified curing period, the unconfined compression test was carried out on the samples. As a result, for Bangkok clay, Kaolin and Bentonite, the factors improving the unconfined compressive strength of cement-stabilized clay are diatom content, cement content, CaCl₂ and NaCl in descending order. Conversely, Kaolin and Bentonite are detrimental factors for Bangkok clay. For Ariake clay, the positive factors are only cement content and diatom content. In case of lime stabilization, For Ariake clay, the positive factors are only lime content and 5% of NaCl. The different characteristics between Ariake and Bangkok clays after treating with various admixtures may be due to the differences in chemical properties.

Secondly, to improve the strength of surplus clay, lime and cement are normally used as admixtures. Sometimes, due to long time storage or soil containing high organic, the soil stabilized by lime or cement cannot yield high strength enough for construction. Organic matters have the tendency to coat the soil particles, causing the obstruction or delay of the pozzolanic reaction when the lime is introduced. However, the test results indicated that when sodium salt (NaCl) or calcium salt (CaCl₂) is added to the lime-organic clay mixture, the strength of mixture increases with increasing salt concentration. The strength increases by 10
times with an additional of 10% salt. Furthermore, cementing product is very visible in micrographs of lime-salt mixtures, these results were concurrent with the strength development in the stabilized soil. Comparing between the two salts mixtures, at a 10% salt concentration, the strength of clay stabilized with lime and sodium chloride is higher than clay stabilized with lime and calcium chloride. Adversely, at a 2.5% salt concentration, the strength of calcium chloride mixtures is higher. The process of lime-salt on organic clay may be as follows; salts may coagulate with the cation of organic leaving the clay particles exposed to the lime for pozzolanic reaction. In addition, salt also can flocculate soil particles and reduce pore space between soil particles, resulting in the required cementation to bridging between aggregates is relatively low. Hence, the higher strength of lime-salt stabilization could be achieved. For oxidation effect during storage on lime-stabilized clay, due to the acid produced during oxidation process, the acid reacted with lime content resulting in lime content significantly reduced and yielded the low strength in lime stabilization. In the drying process, packing more layers to form thicker domains may cause the lower strength in clay stabilization because of less surface area for lime reacting with clay. In application, the proper storage at field shall be provided by preventing the soil from these effects.

Finally, to investigate the effect of oxidation and drying on soil properties during storage, two series of laboratory testing on oxidation and drying effects were performed on Ariake clays that stored in the different conditions and periods. Tests including Atterberg’s limits, pH, oxidation reduction potential (ORP) on natural samples were carried out. The results show that after storage, the properties of all samples were changed by oxidation or drying effect. Oxidation process usually produces acids causing the dissolution of calcium carbonate, which increases the concentration of divalent cation in clay. As a result, liquid limit of clay was changed. On the other hand, during drying process, clay surfaces trend to bond more layers to form thicker domains resulting in the clay size fractions decreased and specific surface area was considerably reduced. Hence, liquid limit and plastic limit were lower.
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<td>3.8.1</td>
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Chapter 1

INTRODUCTION

1.1 GENERAL

Nowadays, the discussion in environmental impact is widespread in every field of study because the environmental problems exist in all parts of the world and become more serious in the future. Long ago, the geotechnical studies concentrated on the development of technical knowledge such as foundation, retaining structure, tunnel, ground improvement etc. Regarding to the environmental awareness, currently, the new challenge topics including the specification and characterization, modeling and numerical analysis of tailing dams and sediments, waste disposal and containment, geotechnics of waste landfill, geotechnical recycle or reuse of waste materials, remediation of contaminated ground and geo-environment regulation are recognized in geotechnical field. One of strategies to reduce environmental problems in geotechnic is to reuse waste materials from industrials or construction materials as backfill materials, subgrade, subbase, and stabilizer. Utilization of these waste materials has the twofold benefit of conserving natural resources and disposing of the waste materials. Generally, the chemical stabilization method is applied for ground improvement. The lime or cement is the effective stabilizer which is normally used in the field. In some projects also utilized the waste industrial materials such as coal fly ash, slag foamed waste glass by mixing with the lime or cement to stabilize these dredge clay.

In geotechnical engineering, soft ground problems concerning to low shear strength and high compressibility are solved by means of ground improvement. The ground improvement techniques can be divided broadly into reinforcement, admixture or grouting, compaction or densification and dewatering. In geo-environmental aspect, the application in ground improvement is generally adopted for stabilization of waste materials or surplus clay by using chemical admixtures as construction materials and for reinforcement of clay liner by using geotextile. This dissertation focuses on the chemical stabilization of surplus clays by using lime or cement.
Over four decades, researches on the mechanisms of cement and lime stabilization have been carried out with Eades et al (1962), Moh (1962), Meteos (1964), Thompson (1966), and etc. The mixing lime or cement with dredged materials has been widely used in some countries like Japan (Terashi & Tanaka, 1981). The lime or cement also has been applied to stabilize clay in the deep layer named as deep mixing method by the installation equipment. The deep mixing method also bases on the behavior and mechanism of lime or cement stabilized soft clay (Brom and Boman (1975), Okumura and Terashi (1975), Terashi et al. (1979) and Suzuki (1981). The application of waste materials with lime or cement such as cement-slag, cement-fly ash, and lime-granite soil, also has been proposed by many researchers (Kamiya et al. (1993), Omoto et al. (1993a), (1993b), Nishi et al. (1994), Yamada et al. (1995), and Yoshida et al. (1998)).

1.2 SCOPE AND OBJECTIVE OF STUDY

This dissertation aims at investigating on influence of storage condition on geotechnical properties. The influence factors including organic, clay minerals, salt, diatom, oxidation effect and drying effect on lime or cement stabilization were also studied in this research.

As to the scope of the study, the research has been undertaken with the following objectives:

1. To evaluate the effect of clay minerals, salts and diatom on lime or cement stabilized clay.

2. To understand the mechanisms and properties of lime stabilized organic clay and its solution by using salt additive.

3. To examine effect of oxidation and drying on soft clays during storage prior to stabilize with lime.
1.3 ORGANIZATION OF THE DISSERTATION

This dissertation contains six chapters, which provides two main sessions. The first part describes on the effect of clay minerals, salts, diatom and pyrite on cement-stabilized clays and the basic mechanism of salts affecting on strength of lime-stabilized organic clay. The second part explains on the oxidation and drying effects on soil properties during storage.

Chapter 1 is the introduction part describing proposes and scope of the study. Chapter 2 carried out on the literature review on properties of Ariake clay, Canadian quick clay and Bangkok clay and depositional environment.

Review on mechanisms, influence factors, development, application, etc. on lime or cement stabilized Ariake clay and the investigation on the influence of soil compositions such as clay mineral, salts and diatoms on cement and lime stabilized soft clays with results are described in Chapter 3. This chapter discusses about how these factors affect lime or cement stabilized clays. The study is carried out on Ariake and Bangkok clay by varying the proportion of considering factors mixed with lime or cement. The mechanism of factors is comprehended.

The investigations on salts effect on strength of lime stabilized organic clays are presented in Chapter 4. The laboratory test as unconfined compression, Atterberg’s limit, ignition loss, chemical analysis tests and scanning electron microscope (SEM) are conducted to find out the salt effect on strength of lime-stabilized organic clay. The mechanisms of salt stabilized organic clays were investigated. Furthermore, the microstructure of soil stabilization was examined by micrograph. The results are consistent with laboratory test, in which the amount of cement product of mixtures can be observed in the high strength mixtures.

This dissertation attempts to clarify the effect of oxidation and drying during storage prior to stabilize with lime. The series of test were performed on soil sample under different conditions and periods of storage. The results of testing are described in Chapter 5. Some chemical equations were employed to explain the phenomenon of oxidation on lime stabilized clay. Schematic diagrams in micro-scale were proposed to clarify the different mechanism of two types of clay, namely, swelling and non-swelling on liquid limit and drying effect of clays. Again, the micrograph by
SEM contributes to elucidate the dissolution of pyrite under oxidation condition.

Conclusions are drawn in each chapter and overall conclusions are summarized in Chapter 6. The flow chart illustrating the three main parts is given in Fig. 1.1:
Fig. 1.1 Flow diagram of the main part of the study
REFERENCES


Chapter 2

GEOTECHNICAL PROPERTIES

OF SOME SOFT CLAYS

2.1 GENERAL

Extensive urbanization and industrialization in low land and coastal regions of many countries have required to improving very soft ground in its shear strength and compressibility as to handle its stability and settlement problems. The ground improvement by chemical admixture such as lime or cement have been more widely used in the recent years. Stabilization with lime or cement is a ground improvement technique in which cementing agents are mixed with soft soil using mixing machine. After mixing, chemical reactions will take place between chemical admixtures and soft soil.

Recently, increase in environment awareness has resulted in emphasis on sustainability and in the particular use of waste material in construction such as dredged clay from reclamation area, and waste materials from industrials for construction materials as backfill, subgrade, subbase, and stabilizer. Utilization of these waste materials has the twofold benefit of conserving natural resources and disposing of the waste materials. Generally, the chemical stabilization method is applied for ground improvement. The lime or cement is the effective stabilizer which is normally used in the field.

Usually, the soft clay found near to the surface or the dredged sludge contains high organic content, which reduces the effectiveness of lime or cement stabilization. In addition, soils that stored for long time sometimes show the significantly low strength when stabilizing with admixtures due to change in properties during storage. Investigation on influence of some soil compositions is useful to estimation of clay strength or selection of appropriate admixtures.
The materials dealt with comprehensive literature review on the properties of Ariake clay, Canadian quick clay and Bangkok clay, which use in this research, depositional environment and sedimentary pyrite information are described in this chapter.

2.2 PROPERTIES OF ARIAKE CLAY

Ariake clay is a very soft and sensitive clay extensively distributed around Ariake Bay, northern Kyushu as shown in Fig. 2.1. Studies on properties of Ariake clay has been originated for more than four decades with Ariake Bay Research Group (1965), Fujikawa and Takayama (1980), Onitsuka (1983, 1988), and Hanzawa et al. (1990). It has been reported that Ariake clay layer can be divided into two layers, upper and lower layers from the viewpoint of the difference in environment at the time of sedimentation. The divided line is at a depth of about 10 m. Properties of Ariake clay are listed in Table 2.1. The natural water content varies from 50 to 200%. The liquid limit is 60.1-138.7% for upper layer, 53.5-111.7% for lower layer. Most of Ariake clays are classified as CH, and have the activity, A over 0.75. Particularly, the activity of the clay in the upper layer about 10 m often exceeds 1.25, belonging to an active clay.

The mechanical properties of Ariake clay are list in Table 2.2. The unconfined compressive strength, $q_u$, is 3-30 kN/m$^2$ for the upper layer of about 10 m depth and 30-100 kN/m$^2$ for the lower layer. The axial strain at failure, $\varepsilon_f$, is 2-4% for the undisturbed soil. The liquidity index of Ariake clay is normally higher than one. The sensitivity is very high because of the leaching (Egashira and Ohtsubo, 1982).

The clay minerals contained in Ariake clay are smectite, kaolinite, illite, hydrohalloysite and metahalloysite. The low-swelling type of smectite is a dominant mineral in Ariake clay (Ohtsubo et al., 1982, 1983). Diatom can be usually observed in Ariake clay form the micrograph (Onitsuka et al., 1998). Estimated quantity of diatom in Ariake clay is about 6% at depth 5 m (Shiwakoti et al., 2002).

Associated with the low shear strength and high compressibility of the soft ground are the problems of low bearing capacity, unstable embankment and excavation slopes. Thick deposits of soft clay consolidate and cause large settlements when loaded. Saturated, loose sand may liquefy under seismic loads from earthquake
occurrence.

Fig. 2.1 Locations of Saga plain and sampling points  
(redrawed from Ohtsubo et al., 1982)
### Table 2.1 Physical properties of Ariake clay
*(Fujikawa and Takayama, 1980; Onitsuka, 1988)*

<table>
<thead>
<tr>
<th>Property</th>
<th>Ariake clay</th>
<th>Marine clay in Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of soil particle, $\rho_s$ (g/cm³)</td>
<td>Clay: 2.56-2.70</td>
<td>2.76-2.75</td>
</tr>
<tr>
<td></td>
<td>Silty soil: 2.61-2.76</td>
<td></td>
</tr>
<tr>
<td>Clay content (%)</td>
<td>West shore: 25.4-78.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>East and north shore: 11.4-63.4</td>
<td></td>
</tr>
<tr>
<td>Liquid limit (%)</td>
<td>Upper layer 60.1-138.7</td>
<td>45-100</td>
</tr>
<tr>
<td>Plastic limit (%)</td>
<td>Lower layer 53.5-111.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silty soil 27.9-97.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>45-100</td>
<td></td>
</tr>
<tr>
<td>Activity, A</td>
<td>Upper layer 0.77-2.21</td>
<td>20-40</td>
</tr>
<tr>
<td></td>
<td>Lower layer 0.57-1.79</td>
<td></td>
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<tr>
<td></td>
<td>Silty soil 0.35-2.13</td>
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<td></td>
<td>&gt;1.25</td>
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</tbody>
</table>

### Table 2.2 Mechanical properties of Ariake clay
*(Fujikawa and Takayama, 1980; Onitsuka, 1988)*

<table>
<thead>
<tr>
<th>Property</th>
<th>Upper layer</th>
<th>Lower layer</th>
<th>Silty soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive index, $c_c$</td>
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<td></td>
</tr>
<tr>
<td>Coefficient of volume compressibility, $m_v$ (1/ kN/m²)</td>
<td></td>
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<td></td>
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<tr>
<td>Coefficient of consolidation $c_v$ (cm²/d)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unconfined compressive strength, $q_u$ (kN/m²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strain at failure, $\varepsilon_f$ (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constants $a$ and $b$ ($q_u = a + bz$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate of strength increase, $c_u/p$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity ratio, $S_t$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$$c_c = 0.49(e_n - 0.41)$$
$$c_c = 0.013(w_n - 10)$$

Consolidation pressure

<table>
<thead>
<tr>
<th>$p&lt;200$ kN/m²</th>
<th>$p&gt;200$ kN/m²</th>
<th>$p=p_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^3$</td>
<td>$10^4$</td>
<td>$10^3$</td>
</tr>
</tbody>
</table>

Coefficient of consolidation $c_v$ (cm²/d)

$$3.5 \times 10^1 - 1.5 \times 10^3$$

Unconfined compressive strength, $q_u$ (kN/m²)

<table>
<thead>
<tr>
<th>Upper layer</th>
<th>Lower layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-30</td>
<td>30-100</td>
</tr>
</tbody>
</table>

Strain at failure, $\varepsilon_f$ (%) 2-4

Constants $a$ and $b$ ($q_u = a + bz$)

$$a = 10-160$$
$$b = 14-36$$

Rate of strength increase, $c_u/p$ 1/3

Sensitivity ratio, $S_t$ $>8$, $>16$ (most of Ariake clay)
2.3 PROPERTIES OF CANADIAN QUICK CLAY

Canadian soft soils are a product of sedimentation in proglacial and postglacial lake basin that existed between 18,000 and 6,000 years BP. (Before present). They consist of both freshwater and marine clays which usually behave quite differently, due to dispersion of the marine clay following postglacial crustal rebound that elevated all clay deposits.

The sedimentology shows clearly that varved clay are normally features of bottom, heavy-density turbidity current origin, probably in very cold, ice-contact lakes, warmer postglacial lakes were probably characterized by low-density overflows, and thinly laminated clay deposits developed rather than varved clay sequences (Quingly, 1980). Marine deposits also developed from low-density freshwater overflowed followed by flocculation, organic agglomeration and sedimentation.

The available data of Canadian quick clay from Lissard and Mitchell (1985) are as tabulated in Table 2.3.

Table 2.3 Physical properties of Canadian quick clay
(Data from Lissard and Mitchell, 1985)

<table>
<thead>
<tr>
<th></th>
<th>Canadian quick clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of soil particle, $\rho_s$ (g/cm$^3$)</td>
<td>2.75-2.78</td>
</tr>
<tr>
<td>Clay content (%)</td>
<td>40-60</td>
</tr>
<tr>
<td>Liquid limit (%)</td>
<td>20.0-26.5</td>
</tr>
<tr>
<td>Plastic limit (%)</td>
<td>15.2-23.2</td>
</tr>
<tr>
<td>Activity, $A$</td>
<td>0.08-0.14</td>
</tr>
</tbody>
</table>
2.4 PROPERTIES OF BANGKOK CLAY

The Bangkok clay was mainly formed by the Chao Phraya delta in sedimentary process with the influence of sea level fluctuations. The change of sea level caused the repetition of aggradation and erosion of sediments, which brought fine particles to deposit on the top layer. According to Muktabhant et al. (1966), factors involved in creating the depression of the Chao Phraya basin was considered the results of the Late Tertiary structural movements of the earth crust and as a sequence of alluviation cycle.

In general, the subsoil condition is relatively uniform consisting of four different layers namely: weathered crust, very soft to soft clay (Bangkok Clay), medium stiff clay and stiff clay within the depth of 20 m. The changes of physical properties with depth are associated with the increasing silt or fine sand content and decreasing clay fractions. The general soil properties obtained from laboratory tests, field vane shear tests, at New Bangkok International Airport are summarized below and illustrated in Figures 2.2 (TMSUM, 2002).

**Weathered Crust**

The brownish grey weathered crust is the uppermost hard clay material formed by cyclic wetting process together with natural cementation with total thickness of 1 to 2 m. The average natural water content, total unit weight and undrained field vane shear strength is about 85%, 1.5 t/m³ and 2.3 t/m², respectively.

**Very Soft to Soft Clay**

The greenish grey soft clay material with total thickness of 8 to 10m, as called “Bangkok Clay”, is found beneath the weathered crust. In general, this layer can be divided into two parts:

- Very soft clay up to 8 m below the original ground with over 100% nature water content and less than 2 t/m² of undrained vane shear strength;

- Soft clay from 8 to 11 m below the original ground with average natural water content, total unit weight and undrained field vane shear strength of 85%, 1.4t/m³ and 2.2 t/m², respectively.
This soft and highly compressible “Bangkok Clay” is the major concern for soft ground problems.

*Medium Stiff to Stiff Clay*

The light grey medium stiff to stiff clay lies between 11 to 15 m below the original ground with average natural water content, total unit weight and undrained field vane shear strength of 65%, 1.65 t/m³ and 2.7 t/m², respectively.

*Stiff Clay*

The light grey to light brown stiff clay is generally found below the depth of 15 m with average natural water content, total unit weight and undrained field vane shear strength of 40%, 1.8 t/m³ and 5 t/m², respectively.
Geotechnical properties of some soft clays

Fig. 2.2 Soil profile at New Bangkok International Airport (TMSUM, 2002)
2.5 DEPOSITIONAL ENVIRONMENT

The environment of deposition determines the complex of physical, chemical, and biological conditions under which a sediment accumulates and consolidates. The three general geographical depositional environments are continental, mixed continental and marine, and marine (Mitchell, 1993). Continental deposits are located above the tidal reach and include terrestrial, paludal (swamp) and lacustrine (lake) sediments. Mixed continental and marine deposits include littoral (between tides), deltaic and estuarine sediments. Marine deposits are located below the tidal reach and consist of continental shelf (neritic), continental slope and rise (bathyal), and deep ocean (abyssal) sediments. Characteristic soil types and properties associated with these depositional environment are briefly in the following sections.

2.5.1 Terrestrial Deposits

**Aeolian Deposits**

Of the various transportation agents, wind is the only one that can move sediment uphill. Wind is most easily able to move sand. The load suspended by the wind, which is composed primarily of silt-size particles, is carried high above the ground and may be transported for great distance. Deposition from wind occurs with reduction in wind velocity. Consequently, accumulations are found in the lee of desert areas.

**Glacial Deposits**

Depositions from ice results from melting and a variety of deposits may form. Glacial deposits are dropped directly from the melting ice; the bottom of moraine is an example. Glaciofluvial deposits are transported from the melting point by flowing melt water. Glacial lake deposits are quiet water sediments that are usually composed of fine-grained materials. Varved clay is an example.

The characteristics of glacial deposits depend on the type and erodability of the parent material, type and distance of transportation, gradients, and pressures. For example, bottom moraines are usually finer grained and more consolidated than lateral or end moraines. Finely ground (silt and clay size) rock flour is produced by the grinding action of the ice and may be a major constituent of post glacial marine
and lake clays found in Canada and Scandinavia.

**Alluvial Deposits**

Alluvial deposits result from pluvial (high rain area) and fluvial (river) deposition and are generally characterized by laterally discontinuous, lenticular bed which are oriented downstream and have different particle size characteristics. Gravels are often in contact with sand and silt.

Deposition from stream results from a decrease in slope, increased resistance to flow, a decrease in stream discharge, or discharge into the more quiet water of oceans and lakes. As the slope flattens the stream loses energy and all particles larger than a certain size are dumped in a jumble of large and small particles. The flow then slips to one side following the steepest slope. The channel may subsequently fill, and the flow shifts again. When this process occurs at the base of a slope, the result is an alluvial fan, a temporary feature that is a symmetrical pile of material spread out radially from the point of slope change.

**Lacustrine and Paludal Deposits**

Lacustrine, or lake, deposition may occur under fresh water or saline conditions. Gravity settling of sediments discharged into saline lakes may be accelerated by flocculation of clay particles. Saline deposition can result in the precipitation of salt beds, or evaporite deposits. Fresh water lacustrine deposits are generally fine grained, quiet water deposits, except narrow shore zones of sand.

Paludal, or swamp deposits usually consist of plastic silts, muds, and clays with high water content and organic matter. Difficult problems may be associated with these deposits because of their low strength and high compressibility and from the formation of marsh gas.

**2.5.2 Mixed Continental and Marine Deposits**

**Littoral Deposits**

Littoral deposits form in the tidal zone and consist of tidal lagoon, tidal flat, and beach sediments. Lagoon sediments include fine-grained sands and silts in the channel and organic-rich silt and clay in the quiet areas. Organic matter and carbonates may be abundant. Tidal flat deposit consists of fine-grained dark muds,
with lenses or stringers of sand and gravel, and are free of intermediate size sediments. Beach deposits consist of fine-to-coarse-grained sand with occasional stringers of gravel.

**Estuarine Deposits**

Estuarine are semienclosed coastal bodies of water that have a free connection with the sea. They consist of channel muds, silts, and sands deposited in response to seasonal river processes and tidal rhythms. Estuarine sediments typically grade seaward into fine-grained tidal deposits and landward into coarser-grained river (alluvial) deposits. Estuaries are often fringed by fine-grained tidal flats with salt marshes.

**Deltalic Deposits**

Deltas form at the mouth of a river where it enters the sea. They build up where there is no tidal or current action capable of removing the sediments as fast as they are deposited. Deltas build forward from the coastline in a complex process that leads to the formation of a number of separate channels, isolated lagoon, levees, marshy ground, and small streams. As a result, delta may consist of coarse and fine material, organic matter and marl. There are alternations between coarse and fine material owing to the continual shifting of the stream. Suspended silt and clay in the main stream is flocculated by salts in the sea water to form marine mud in the seaward delta face, which is later covered by alluvial, lacustrine, and beach deposits as the delta grows.

**2.5.3 Marine deposits**

An average profile through the marine environment is shown in Fig. 2.3. The continental shelf extends from low tide to a water depth of about 400 ft. The steeper continental slope (average of 4°) leads down to the more gently sloping continental rise. The average water depth in the deep ocean is more than 11,500 ft.

There are three main types of marine sediments: lithogenous (derived from terrestrial, volcanic, or cosmic source); biogenous (remains of marine organisms); and hydrogenous (precipitates out of the sea water or interstitial water).
Biogenous sediments, formed from the remains of marine plants and animal, cover about half of the continental shelves, more than half of the deep sea abyssal plains, and parts of the continental slopes and rises. They are abundant as coarse grained bioclastic sediments in shallow water of the coastal zone in tropical regions.

Fig. 2.3 Idealized profile of the continental margin, with vertical exaggeration (after Heselton, 1969 from Mitchell, 1993)
2.6 SEDIMENTARY PYRITE FORMATION

As reported by Berner (1984), sedimentary pyrite formation during early diagenesis is a major process for controlling the oxygen level of atmosphere and the sulfate concentration in seawater over geologic time. The amount of pyrite that may form in a sediment is limited by the rates of supply of decomposable organic matter, dissolved sulfate, and reactive detrital iron minerals. Organic matter appears to be the major control on pyrite formation in normal (non-euxinic) terrigenous marine sediments where dissolved sulfate and iron minerals are abundant. By contrast, pyrite formation in non-marine, freshwater sediments is severely limited by low concentrations of sulfate and this characteristic can be used to distinguish ancient organic-rich fresh water shales from marine shales. Under marine euxinic conditions sufficient H$_2$S is produced that the dominant control on pyrite formation is the availability of reactive iron minerals. **Fig. 2.4** shows diagrammatic representation of the overall process of sedimentary pyrite formation.

**Fig. 2.4** Diagrammatic representation of the overall process of sedimentary pyrite formation (after Berner, 1972)

Pyrite forms during shallow burial via the reaction of detrital iron minerals with H$_2$S. The H$_2$S, in turn, is produced by the reduction of interstitial dissolved sulfate by bacteria using sedimentary organic matter as a reducing agent and energy
source. The initial product of this reaction is not, in fact, pyrite but rather a series of metastable iron monosulfides which during early diagenesis readily transform to pyrite under most conditions, (but by a process that is rather poorly understood). This is all illustrated in Fig. 2.4. Note in Fig. 2.4 that the major factors controlling how much pyrite can form in a sediment are the amounts of organic matter and reactive iron minerals deposited in a sediment, and the availability of dissolved sulfate.

2.7 CONCLUSIONS

Geotechnical properties of some soft clay are described in this chapter. The following concluding remarks are summarized.

1. Soft clay deposits such as Ariake clay and Bangkok clay are caused the problems on stability and settlement because of their low shear strength and high compressibility. Thus, the ground improvement by chemical admixtures is introduced to solve these problems.

2. The environment of deposition can be divided by the complex of physical, chemical, and biological conditions into three general depositional environments, which are continental, mixed continental and marine, and marine.

3. The amount of pyrite that may form in a sediment is limited by the rates of supply of decomposable organic matter, dissolved sulfate, and reactive detrital iron minerals. However, pyrite formation in non-marine sediment is severely limited by low concentrations of sulfate and this characteristic can be used to distinguish ancient organic-rich fresh water shales from marine shales.
REFERENCES

Ariake Bay Research Group (1965) Quaternary system of the Ariake clay and shiranui Bay Areas, with the special reference to Ariake clay soft clay, *Association for Geological Collaboration in Japan*.


Chapter 3

SOME INFLUENCE FACTORS ON CHEMICAL STABILIZATION FOR SOFT CLAYS

3.1 INTRODUCTION

Cement and lime stabilizations are usually applied for ground improvement on soft clays. Key factors influencing the success of cement stabilized soil can be divided into two parts. One is the properties of soil and the other is quality control at field construction. This chapter focuses on part of soil compositions that affect on cement and lime stabilized soil.

The development of ground improvement in Ariake plain, the engineering behavior and influence factors of the lime and cement stabilized soils, and microstructure of soil were reviewed in this chapter.

To examine influence of soil compositions including clay minerals, salts and diatom, these contents were mixed in various proportions on four types of clays: Ariake clay, Bangkok clay, Bentonite and Kaolin. After that, the mixtures were stabilized with cement and performed unconfined compression test at specified curing time. In addition, the microstructures of some samples were observed by scanning electron microscope (SEM).

The results indicate how the factors influence to the cement-stabilized soil. Hence, the predict strength of stabilized soil may be estimated from these soil compositions. Also, the appropriate admixtures can be selected to the particular type of soil as considering from its compositions. The details of testing and results are described in following sections.
3.2 STABILIZATION OF ARIAKE CLAY

Stabilization of Ariake clay was actually started decades ago. Most of the stabilization has been aimed to improvement of the ground in order to support structures such as building and road embankment. Both shallow and deep foundations of Ariake clay are treated. This study focuses on the stabilization by chemical admixture method.

Nanri (1997) studied the fundamental properties of stabilized Ariake clay with quicklime and other pozzolanic materials. The water content reduced with increase of quicklime content is also associated closely with the increase in strength. About 85% of the water reduction occurred within 1 hour after mixing because of hydration. Consequently, the strength of stabilized Ariake clay increased with quicklime content. It is suggested that the quicklime, which can reduce much of the water of the Ariake clay, is better stabilizer than cement.

Nishida (1995) reported that in Ariake clay, quicklime is a better stabilizer than cement with regard to the strength increase due to the good water absorption and high temperature. The admixture of 8% quicklime and 20% cement can successful to stabilized Ariake clay for the construction materials.

It was illustrated that the effectiveness of Ariake clay stabilization is affected by the content of organic substance contained in the Ariake clay, the salt concentration in the clay, the bacteria and microorganism which can balance alkali, and the composition of the clay particles. Cement stabilizer is more effective than quicklime to improve high organic Ariake clay. Most of Ariake clay deposited around Ariake Bay contains diatom consisting of more than 80% silica that are easy to dissolve at high pH. The pozzolanic reaction is prompted to occur, thus the strength of stabilized Ariake clay increase. The strength increase of the stabilized Ariake clay at early stage is remarkable and by far larger than that observed for Bangkok clay.

3.3 THE STRENGTH OF LIME AND CEMENT STABILIZED ARIAKE CLAY

The bond strength is governed by many factors such as clay minerals, organic matter, pH and so on. The strength of lime and cement stabilized clays is mainly
obtained from the chemical reaction. There are many factors affecting the chemical reaction in order to clearly understand these factors and their influencing, it is merit to comprehend the mechanism of lime and cement stabilized clays.

### 3.4 MECHANISM OF LIME STABILIZED CLAY

The major strength grain of lime treated clay is mainly derived from three reactions namely: hydration of soil, ion exchange, and pozzolanic reaction. Other mechanisms such as carbonation cause minor strength increase and can be neglected. Short term reaction includes hydration (for quicklime) and flocculation (cation exchange). Longer term reactions are cementation and carbonation. The use of lime as a stabilizing additive is mainly due to its well-known effects when mixed with soils. The natural stabilizing agent for cohesive soils is calcium hydroxide, hydrated lime, or slaked lime. Calcium hydroxide is not itself a binder, but will produce a binder (consisting of calcium silicate hydrates) by slow chemical reactions principally with the silicates in the clay mineral of cohesive soils.

#### 3.4.1 Hydration

A large amount of heat is released when quicklime (CaO) is mixed with soil. This is due to the hydration of quicklime with the pore water in the soil. The increase in the temperature can, at times, be so high that the pore water starts to boil as shown in equation 3.1 (Broms, 1984). An immediate reduction of natural water contents occurs when quicklime is mixed with cohesive soil, as water is consumed in the hydration process.

\[
\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 + \text{HEAT (280 Cal/gm of CaO)} \quad (3.1)
\]

The calcium hydroxide, \( \text{Ca(OH)}_2 \), from the hydration of quicklime or when using calcium hydroxide as stabilizer, dissociates in the water, increasing the electrolytic concentration and the pH of the pore water, and dissolving the \( \text{SiO}_2 \) and \( \text{Al}_2\text{O}_3 \) from the clay particles.

\[
\text{Ca(OH)}_2 \rightarrow \text{Ca}^{2+} + 2\text{(OH)}^- \text{ (ionization of calcium hydroxide; pH rises to 12.4)(3.2)}
\]

These processes will result in ion exchange, flocculation, and pozzolalnic reactions.
3.4.2 Cation Exchange and Flocculation

The general order of replace ability of the common cation associated with soils is given by the lytropic series (Grim, 1953), Na⁺ < K⁺ < Ca²⁺ < Mg²⁺. Any cation will tend to replace the cations to the left of it and monovalent cations are usually replaceable by multivalent cations. The addition of lime to soil supplies an excess of Ca²⁺ as shown in equation 3.2 and cation exchange will occur with Ca²⁺ replacing dissimilar cations from the exchange complex of the soil.

The addition of lime to a fine grain soil causes flocculation and aggregation of the clay fraction. These reactions result in an apparent change in texture—the clay particles “clumping” together into larger sized “aggregates”. According to Herzong and Mitchell (1963), the flocculation is affected by the increased electrolyte content in the pore water and also as a result of ion exchange by the clay to the calcium form. The influence of cation exchange, flocculation, and aggregation are primarily responsible for changes in plasticity, shrinkage and workability characteristics of lime-soil mixtures (Thompson, 1966). These beneficial changes were noted for all soils studied and relatively small percentages of lime were required to achieve the change. Figure 3.1 illustrates the change in texture due to the phenomenon of cation exchange followed by flocculation. Fig. 3.1a shows low strength clay soil where particles are separated by large water layer. The addition of lime shrinks the water layer (Fig. 3.1b) allowing the plate-like particles to flocculate.
(a) Parallel arrangement of clay particles with hydrated water layers

(b) Edge-to-face attraction induced by thin water layer, which allows attractive forces to dominate

Fig. 3.1 The texture change due to cation exchange (Little, 1987)
3.4.3 Pozzolanic Reaction

The shear strength of the stabilized soil gradually increases with time mainly due to pozzolanic reaction. Pozzolan is defined as “a siliceous or siliceous and aluminous material which in itself, possesses little or no cementitious value but will, in finely-divided form and in the presence of moisture, react chemically with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties” (ASTM, 1955). Some components of natural soils, notably clay minerals, are natural pozzolanas and have the ability to react with any lime added to the soil to produce cementitious products. The highly alkaline environment (pH 12.4) produced by the addition of lime promotes the dissolution of clay as shown in Fig 3.2. Calcium hydroxide in the soil water reacts with the silicates and aluminates to form cementing materials or binders, consisting of calcium silicates and/or aluminate hydrates (Diamond and Kinter, 1965). The dissolved dissociated Ca\(^{2+}\) ions react with the dissolved SiO\(_2\) and Al\(_2\)O\(_3\) from the clay particle’s surface and form hydrated gels, resulting in the combination of the soil particles as shown in equation 3.3 and 3.4.

\[
\text{Ca}^{2+} + 2\text{OH}^- + \text{SiO}_2 \rightarrow \text{CSH} \quad (3.3)
\]

\[
\text{Ca}^{2+} + 2\text{OH}^- + \text{Al}_2\text{O}_3 \rightarrow \text{CAH} \quad (3.4)
\]

The main part of reaction does not start until a couple days after the mixing of lime. As a rule, it is not finished until one to five years later. The solubility of pozzolans and thus their inclination to react with lime depends on the pH of soil water. The rate of reaction also increases with increased soil temperature (Broms, 1984).

3.4.4 Lime Carbonation

Lime reacts with carbon dioxide (CO\(_2\)) to form the relatively weak cementing agents calcium and magnesium carbonate, depending on the type of lime used (Davidson and Handy, 1960). The calcium carbonate (CaCO\(_3\)) can be formed in the case of lime stabilized soils were laboratory cured in the open air. The field conditions were 2.5% of CaCO\(_3\) formed because of the carbonation reaction (Eades et al., 1962).
3.5 MECHANISM OF CEMENT STABILIZED CLAY

Portland cement contains tricalcium silicate (C₃S), dicalcium silicate (C₂S), tricalcium aluminate (C₃A), and a solid solution described as tetracalcium alumino-ferrite (C₄A) (Lea, 1956). These four main constituents are major strength producing compounds. When the pore water of the soil encounters with the cement, the major cemented products are C₂SHₓ, C₃S₂Hₓ, C₃AHₓ, C₄AHₓ and hydrated lime Ca(OH)₂, occurs. The cement-stabilized clay also induced pozzolanic reaction because the Ca(OH)₂ is produced after hydration. The compounds in the Portland cement are transformed on the addition of water as follows:

---

**Fig. 3.2 Solubility of soil minerals at various pH (after Loughnan, 1969)**

---
Some influence factors on chemical stabilization for soft clays

\[
2(3\text{CaO}.\text{SiO}_2) + 6\text{H}_2\text{O} \rightarrow 3\text{CaO}.2\text{SiO}_2.3\text{H}_2\text{O} + 3\text{Ca(OH)}_2 \quad (3.5)
\]
(tricalcium silicate) (water) (tobermorite gel) (calcium hydroxide)

\[
2(2\text{CaO}.\text{SiO}_2) + 4\text{H}_2\text{O} \rightarrow 3\text{CaO}.2\text{SiO}_2.3\text{H}_2\text{O} + \text{Ca(ОН)}_2 \quad (3.6)
\]
(bicalcium silicate) (water) (tobermorite gel) (calcium hydroxide)

\[
4\text{CaO}.\text{Al}_2\text{O}_3.\text{Fe}_2\text{O}_3 + 10\text{H}_2\text{O} + 2\text{Ca(ОН)}_2 \rightarrow 6\text{CaO}.\text{Al}_2\text{O}_3.\text{Fe}_2\text{O}_3.12\text{H}_2\text{O} \quad (3.7)
\]
(tetracalciumaluminoferrite) (calcium aluminoferrite hydrate)

\[
3\text{CaO}.\text{Al}_2\text{O}_3 + 12\text{H}_2\text{O} + \text{Ca(ОН)}_2 \rightarrow 3\text{CaO}.\text{Al}_2\text{O}_3.\text{Ca(ОН)}_2.12\text{H}_2\text{O} \quad (3.8)
\]
(tricalcium aluminate) (tetracalcium aluminate hydrate)

\[
3\text{CaO}.\text{Al}_2\text{O}_3 + 10\text{H}_2 + \text{CaSO}_4.\text{H}_2\text{O} \rightarrow 3\text{CaO}.\text{Al}_2\text{O}_3.\text{CaSO}_4.12\text{H}_2\text{O} \quad (3.9)
\]
(tricalcium aluminate) (gypsum) (calcium monosulfoaluminate)

The equations 3.5 and 3.6, whose materials constitute 75% of Portland cement, show that the hydration of the two calcium silicate types produces new compounds lime and tobermorite gel, with latter playing the leading role with regards to strength, since bondage, strength, and volume variations are mainly governed by them. The reactions, which take place in soil cement stabilization, can be represented in the equation given below. The reactions given here are for tricalcium silicate (C₃S) only, because they are the most important constituents of Portland cement:

\[
\text{C}_3\text{S} + \text{H}_2\text{O} \rightarrow \text{C}_3\text{S}_2\text{H}_x \text{(hydrated gel)} + \text{Ca(ОН)}_2 \quad (3.10)
\]
(Primary cementitious products)

\[
\text{Ca(ОН)}_2 \rightarrow \text{Ca}^{2+} + 2\text{(OH)}^- \quad (3.11)
\]

\[
\text{Ca}^{2+} + 2\text{(OH)}^- + \text{SiO}_2\text{(soil silica)} \rightarrow \text{CSH} \text{ (secondary cementitious product)}
\]

\[
\text{Ca}^{2+} + 2\text{(OH)}^- + \text{Al}_2\text{O}_3\text{(soil alumina)} \rightarrow \text{CAH} \text{ (secondary cementitious product)} \quad (3.12)
\]

In order to have additional bonding forces produced in the cement-clay mixture, the silicates and aluminates in the material must be soluble. In the above equations, the cementation strength of the primary cementitious products is much stronger than that of the secondary ones.
3.6 PREDOMINANT FACTORS THAT CONTROL STRENGTH OF LIME STABILIZED CLAY

There are many factors that control the strength development of lime stabilized clay. The main factors have investigated by the previous research such as water content, clay mineral, type of soil, organic matter, sulfide, diatom, curing time, curing temperature, type and content of lime, soil pH etc.

3.6.1 Water Content

In the case of low water content clay, the water content is not the main influence because it is applied at approximately optimum moisture content. On the other hand, the water content is a predominant factor on strength of lime stabilized high water content clay. The relationships between shear strength and water content; at any quicklime content follow a power law (Locat et al., 1990 and Shen, 2000).

3.6.2 Clay Mineral

Clay mineral has been found to be a major factor in soil-lime stabilization. Montmorillonite and kaolinite clay respond better to lime than illitic and chloritic clay. The dominant halloysite clay attains lower strengths than any other type. Representative strength of lime stabilized soils that contain different clay minerals types are shown in Table 3.1.

3.6.3 Type of Soil and Organic Matter

For lime treatment to be successful, the clay content of the soil should not be less than 20% and the sum of the silt and clay fractions should preferably exceed 35%, which is normally the case when the plasticity index of the soil is larger than 10 (Broms, 1984). The shear strength increase of the stabilized soil is highly dependent on pozzolanic reaction, i.e., the reactions of lime with silicates and aluminates in the soil.

The increase in strength with time is in general highest for normally consolidated silty clays, with low plasticity index and low water content. The
strength increase in lime treated organic soils is often very low; even a relatively small amount of organic material can have a large effect on the strength increase (Brom, 1984). Generally, the effect of lime decreases with increasing water content (Miura et al., 1988).

Table 3.1 Representative immersed unconfined compressive strengths of lime stabilized soils \(^a\) (Thompson, 1966)

<table>
<thead>
<tr>
<th>Type soil</th>
<th>Curing Time (^b)</th>
<th>Type of lime</th>
<th>Optimum lime content %</th>
<th>Strength kN/m(^2)</th>
<th>Optimum lime content %</th>
<th>Strength kN/m(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Calcitic hydrated Ca(OH)(_2)</td>
<td></td>
<td></td>
<td>Dolomitic monohydrate Ca(OH)(_2)+MgO</td>
<td></td>
</tr>
<tr>
<td>Montmorillonite</td>
<td>7</td>
<td>2-8</td>
<td>414-827</td>
<td>8-12</td>
<td>690-1379</td>
<td></td>
</tr>
<tr>
<td>Kaolinite-rich</td>
<td>28</td>
<td>2-8</td>
<td>1034-1724</td>
<td>8-14</td>
<td>1724-2758</td>
<td></td>
</tr>
<tr>
<td>Illite and Chlorite-rich</td>
<td>28</td>
<td>4-6</td>
<td>896-1172</td>
<td>4-8</td>
<td>1379-1724</td>
<td></td>
</tr>
<tr>
<td>Halloysite-rich</td>
<td>7</td>
<td>4-8</td>
<td>345-690</td>
<td>4-8</td>
<td>345-690</td>
<td></td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>4-8</td>
<td>517-862</td>
<td>6-14</td>
<td>1034-1379</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) 5 cm. high by 5 cm. diameter samples molded near standard Proctor maximum density and immersed one day prior to testing.

\(^b\) Cured at 70 °F and 90% or higher relative humidity.

Soil organic matter has been defined as the organic fraction of soil, including plant, animal, and microbial residues, fresh and at all stages of decomposition, and the relatively resistant soil humus.

The great influence of organic matter on lime reactivity can logically be attributed to the retardation of the strength producing lime-soil pozzolanic reaction by some mechanism, the organic matter either prevents the dissolution of soil silica and/or alumina or combines with the lime added to the soil. Cooper (1952) and Iler (1955) suggested that the presence of organic complexes on silica surfaces prevents dissolution. In an analogous manner, the “masking effect” of the organic cations may prevent the clay from yielding silica or alumina or both, for reaction with the lime. The soil was treated by hydrogen peroxide (H\(_2\)O\(_2\)) to remove their organic matter and then was mixed with lime. The treated soils displayed considerably greater strengths, from 841 kN/m\(^2\) to 2082 kN/m\(^2\) larger, than the natural soil. The removal of the soil
(a) Influence of organic carbon on lime reactivity* (Thompson, 1966)

*Lime reactivity is the difference between the maximum compressive strength of the lime-soil mixture and the compressive strength of the natural.

(b) Unconfined compressive strength of quicklime and cement stabilized Ariake clay versus admixture contents at various organic matter contents (Miura et al., 1988)

Fig. 3.3 Effect of organic matter on lime and cement stabilized clays
organic matter evidently eliminated the “masking effect” on the clay surface (Thompson, 1966). The detrimental influence of organic carbon on lime-stabilized soil is shown in Fig. 3.3(a).

Miura et al. (1988) in a related study reported that the lime fails to stabilize Ariake clay that contains organic matter more than six percent as shown in Fig. 3.3(b).

Recently Onitsuka et al. (2003) studied on the effect of organic matter stabilized by quick lime and Portland cement on Ariake clays. Three samples from various locations with different organic compounds are stabilized with quick lime and Portland cement. The properties of samples are tabulated in Table 3.2.

The result shows that the clay containing higher humic acid (Clay 1) failed to be stabilized with quick lime, while strength values obtained from Clay 2 and Clay 3 are much greater as illustrated in Figure 3.4. Consequently, the humic acid was extracted from the clay samples using NaOH (Clare and Sherwood, 1956), then adding again humic acid and salt in different contents to the samples. As showed in Figure 3.5, the result indicates that at the same humic acid content, strength loss is less in higher salt concentration sample. The study concludes that the humic acid has adverse effect to strength of stabilized clay however the effect can be mitigated by the increase of salt concentration.

Trembley et al. (2002) studied the effect of the organic compounds on soil stabilization with cement. Thirteen organic compounds usually found in soil were mixed separately with weight of 10% dry soil sample to two different soils and treated with 10% of Portland cement or Geolite 10 (enriched sulfate cement developed by Onoda Chemico Co., Ltd.). The research summarized that some compounds strongly affected the cementing process by inhibiting the hydration reactions however others had no affect on the cementing process or delay the setting time to attain the final strength.

Kuno et al. (1989) investigated the effectiveness of various binders on soils having different humic acid contents and natural water contents. Thirty-five very soft cohesive soils throughout Japan were stabilized with 5 binders. Finally, Guideline for stabilizing soils containing humic was introduced as demonstrated in Figure 3.6 and
Table 3.3. The research concluded that in high humic acid and water content soil, adding gypsum to Portland cement or slaked lime is more effective for stabilization than Portland cement or slaked lime alone.

Table 3.2 Properties of Soil samples (Onitsuka et al., 2003)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Clay 1</th>
<th>Clay 2</th>
<th>Clay 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Okawa</td>
<td>Ashikari</td>
<td>Isahaya</td>
</tr>
<tr>
<td>Depth, m</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Water Content (%)</td>
<td>185</td>
<td>150</td>
<td>170</td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
<td>143</td>
<td>133</td>
<td>150</td>
</tr>
<tr>
<td>Plastic Limit (%)</td>
<td>53</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td>Plastic index</td>
<td>90</td>
<td>71</td>
<td>88</td>
</tr>
<tr>
<td>pH</td>
<td>6.0</td>
<td>7.6</td>
<td>8.0</td>
</tr>
<tr>
<td>Salt Content (g/l)</td>
<td>0.7</td>
<td>15.4</td>
<td>23.1</td>
</tr>
<tr>
<td>Particle size distribution (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand (2.000-0.075 mm)</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Silt (0.075-0.005 mm)</td>
<td>52</td>
<td>44</td>
<td>19</td>
</tr>
<tr>
<td>Clay (&lt; 0.005 mm)</td>
<td>45</td>
<td>55</td>
<td>81</td>
</tr>
<tr>
<td>Organic Matter (%)</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Ignition Loss, (%)</td>
<td>8.0</td>
<td>7.3</td>
<td>10.0</td>
</tr>
<tr>
<td>Humus Content (%)</td>
<td>1.9</td>
<td>1.7</td>
<td>2.4</td>
</tr>
<tr>
<td>Humic Acid (%)</td>
<td>1.6</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Fulvic Acid (%)</td>
<td>0.3</td>
<td>1.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Fig. 3.4 Strength development of lime and cement stabilized clays

(Onitsuka et al., 2003)
Notes:
1. At Wn = 150%, Curing 7 days, Extracted Clay 1 and 20% Lime/Cement
2. Strength loss, % = \((q_u - q_{u0}) \times 100 / q_{u0}\)

Where \(q_u\) is the strength at any humic acid content, and 
\(q_{u0}\) is the strength at humic acid content at 0%.

Fig. 3.5 Retarding effect of humic acid on strength at various salt concentration 
(Onitsuka et al., 2003)
Fig. 3.6 Soil classification zones based upon the water content and humic acid content (Kuno et al., 1989)

Table 3.3 Guideline for selecting binders on the basis of soil classification shown in Fig. 3.6 (Kuno et al., 1989)

<table>
<thead>
<tr>
<th>Soil Classification</th>
<th>Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slaked Lime</td>
</tr>
<tr>
<td>Zone A</td>
<td>●</td>
</tr>
<tr>
<td>Zone B</td>
<td>○</td>
</tr>
<tr>
<td>Zone C</td>
<td>X</td>
</tr>
<tr>
<td>Zone D</td>
<td>X</td>
</tr>
<tr>
<td>Zone E</td>
<td>X</td>
</tr>
<tr>
<td>Zone F</td>
<td>X</td>
</tr>
</tbody>
</table>

Notes:
1. ● denotes the short-term strength increase is excellent,
2. ○ denotes the short-term strength increase is not so good,
3. X denotes even in a long term the strength does not manifest itself.
3.6.4 Sulfide

The oxidization of sulfide minerals such as pyrite results in the transfer of sulfates to other sites through ground water movement (Sherwood, 1962). The presence of acid dissolved sulfates, carbonates and pyrites in soils, and their stability with the environmental changes should be considered before the application of lime or cement stabilization techniques in the field.

The reaction mechanisms involved in the formation of ettringite and related effects in lime treated soils are similar to cement treated system. Ettringite induced swelling in cement or concrete materials was reported by Mehta (1973). Also, the sulfate enriched minerals induced swelling in lime treated soils (Hawkins and Pinches, 1987). Mehta (1983) mentioned that the adsorption of sulphate on CSH surfaces result in the reduction of strength due to the decrease in cementation ability.

The pozzolanic reactions involved in the formation of ettringite compounds, and strongly associated with the heavy metal immobilization. This reaction further results in swelling. A simplified geochemical reaction reported by Hunter (1988) for lime induced heave reactions can be summarized as follows:

\[
\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 + \text{HEAT (280 Cal/gm of CaO)} \quad (3.1)
\]

\[
\text{Ca(OH)}_2 \rightarrow \text{Ca}^{2+} + 2(\text{OH})^- \quad \text{(ionization of calcium hydroxide; pH rises to 12.4)} \quad (3.2)
\]

\[
6 \text{Ca}^{2+} + 2\text{Al(OH)}_4^- + 4\text{OH}^- + 3(\text{SO}_4)^{2-} + 26\text{H}_2\text{O} \rightarrow \\
\text{Ca}_6[\text{Al(OH)}_6]_2.(\text{SO}_4)_3.26\text{H}_2\text{O (Formation of ettringite)} \quad (3.13)
\]

\[
\text{Ca}_6[\text{Al(OH)}_6]_2.(\text{SO}_4)_3.26\text{H}_2\text{O} + 2\text{H}_2\text{SiO}_4^{2-} + 2\text{CO}_3^{2-} + \text{O}_2 \rightarrow \\
\text{Ca}[\text{Si(OH)}_6]_2.(\text{SO}_4)_3.(\text{CO}_3)_2.24\text{H}_2\text{O} + 2\text{Al(OH)}_4^- + \text{SO}_4^{2-} + 4\text{OH}^- + 2\text{H}_2\text{O} \quad (3.14)
\]

(Isostructural substitution as ettringite changes to thaumasite)

Sherwood (1993) explained that the presence of sulphate in soils induces detrimental effects to materials strength due to the swelling.
Dredging marine sediments or reclamation of bay areas containing heavy metals results in ground water contamination due to oxidation of pyrite. The pyrite oxidation reactions in marine clays result in the production of iron hydroxide and sulphate ions as per the following equations (Ohtsubo et al., 1991)

\[
4\text{FeS}_2 + 15\text{O}_2 + 14\text{H}_2\text{O} \rightarrow 14\text{Fe(OH)}_3 + 16\text{H}^+ + 8\text{SO}_4^{2-} \quad (3.15)
\]

\[
\text{CaCO}_3 + 2\text{H}^+ + \text{SO}_4^{2-} + \text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + \text{CO}_2 \quad (3.16)
\]

Also leaching of \text{SO}_4^{2-} and reduction of sulphate results in the production of gypsum (\text{CaSO}_4 \cdot 2\text{H}_2\text{O}), and calcite (\text{CaCO}_3), which is quite common in marine clays (Kawasaki, 1988). The above research findings indicate the release of adsorbed zinc from marine clays into soluble phase due to the exposure of soil surface to atmosphere. In the presence of excess water, sulfates induce negative effects in the cement stabilized soils. Besides sulfates, sulfides can also be present in the form of pyrites and thus the release of sulfate attacks stabilized soils.

### 3.6.5 Diatom

Recently studies on marine sediments like Ariake clay proved that chemical and microstructural aspects of soil particles play a dominant role in determining the mechanical behavior of sediments (Tanaka et al., 2001; Rajasekaran, 2006). Sediments contain high concentrations of diatoms yielding diatomite deposit and low concentration resulting in diatomaceous soil. Diatomaceous soil is composed of the siliceous skeletons of microorganism. It is pozzolanic, which can be as sources providing silica or alumina in pozzolanic reaction. The addition of pozzolana to lime or cement adding can therefore be beneficial by reacting with the calcium hydroxide released by the lime or cement to produce further cementitious material (Sherwood, 1993).

### 3.6.6 Curing Time

The shear strength of lime stabilized soil gradually increase with time through pozzolanic reactions when lime reacts with the silicates and aluminates in the soil (Broms, 1984). Fig. 3.7 shows a typical plot of the strength versus time for various types of soils. The shear strength of lime stabilized clay is higher than that of
undisturbed clay about 1-2 hours after mixing. The rate of shear strength is generally rapid at early stage; thereafter the rate of increase decreases with time.

Fig. 3.7 Increase of shear strength with time (Bergado et al., 1996)

Fig. 3.8 shows the relationship between shear strength and time that is proposed by Locat et al. (1990). It shows that the strength development of low water content clay is faster than high water content clay. Locat et al. (1990) has been discussed that in Fig. 3.8 with regards to two different soil-lime mixes: (1) low water content (LWC) mix that can be compacted and (2) high water content (HWC) mix that cannot be compacted. Obviously, intermediate cases are possible. The model proposed by Perret (1977) for silty soils is also presented in Fig. 3.8 (identified by the letter P). Low water content soils are initially distinguished by a significant shear strength resulting from successful compaction of the sample. This model assumes that strength increase results chiefly from particle bridging by the pozzolanic reaction products (CASH and CSH minerals), for as long as reactants are available. Strength development can be subdivided into three phases with time. Because precipitates have finite dimensions, the greater the initial void ratio (or water content), the more time needed to create significant bridges (or contacts) between soil particles. Fig. 3.8 is a dimensional, both HWC and LWC soils tending to reach their ultimate strength with time.
Phase I corresponds to the initial period when bridging is not mechanically felt, even if the chemical reactions are highly active and cements are formed. This is mostly observed for HWC soils in a few cases only, this phase is observed for compacted or (LWC) soil, but with a much shorter duration.

Phase II is a period of efficient bridging development, when the pozzolanic reactions are mechanically felt as a sharp increase in strength. During that period, more and more efficient particle or aggregate bonds are created by the neoformed minerals. According to Perry (1977), LWC silty soils may present two phases of strong strength increase (curve P in Fig. 3.8). Reasons for this are not very clear.

Phase III is characterized by a reduction in the rate of increase of shear strength, or even a leveling. Phase III could take place for at least three reason: (1) completion of pozzolanic reactions due to exhaustion of lime, (2) reactions are still going on but with greater difficult for solutes to diffuse within the soil-cements matrix, or (3) reaction products are still produced in abundance but their effects on strength are not as pronounced as in phase II, since the soil has already a new, more

Fig. 3.8 Mechanical conceptual model of shear strength development with time for high water content (HWC) and low water content (LWC) lime stabilized clayey soil (Locat et al., 1990).
rigid structure. Precipitation of neoformed minerals may continue to fill the pore space.

3.6.7 Curing Temperature

Effect of temperature on the strength development of the lime-stabilized soil is very marked. **Figure 3.9** which is typical, shows that in the range 0°-30° C the relation between strength and temperature is approximately linear but that above 30°C there is a large increase in strength for each degree C rise in temperature. The effect of high temperatures generally produces accelerated hardening of soil-lime mixtures (Sherwood, 1993).

![Graph showing the relation between strength and curing temperature of heavy clay stabilized with 5% lime (Sherwood, 1993)](image-url)

**Fig. 3.9** Relation between strength and curing temperature of heavy clay stabilized with 5% of lime (Sherwood, 1993)
3.6.8 Type and Content of Lime

The efficiency of lime stabilization depends in part on the type and content of lime material used. Quicklime is generally more effective than hydrated lime because it contains approximately 25 percent more available lime and faster drying action on wet soils due to amounts of heat released (Sherwood, 1993).

The lime fixation point is defined as the point at which the percentage of lime is such that additional increments of lime produce no appreciable increase in the plastic limit. Lime contents equal to the lime fixation point for a soil will generally contribute to the improvement in soil workability, but may not result in sufficient strength increases (Hilt and Davidson, 1960).

Methods of determining the optimum lime requirement for stabilization have been proposed by Eades and Grim (1966). This method suggested that the amount of lime consumed by a soil after one hour affords a quick method of determining the percentage of lime required for stabilization, i.e., the lowest percentage of lime required to maintain a pH of 12.6 is the percentage required to stabilize the soil. However, a strength test is still necessary to show the percentage of strength increase. McDowell (1959) pointed out that short-time or quick tests probably will not identify optimum lime contents, but are essential in checking against the use of non-reactive soils for treatment of lime.

3.6.9 Soil pH

Lime addition will increase the pH of water content in the soil, and give rise to increased solubility. The base exchange is low when the pH value less than 7. The long-term chemical reactions in lime stabilized soils are favored by a high pH-value (pH > 12) since the reactions are accelerated due to the increased solubility of the silicates and aluminates present in the clays (Broms, 1984). A minimum pH of approximately 10.5 is necessary for pozzolanic reaction to take place as shown in Fig. 3.2 (Loughnan, 1969).
3.7 PREDOMINANT FACTORS OF STRENGTH OF CEMENT STABILIZED CLAY

The hardening characteristics of cement treated soil mixtures are developed by a number of factors. Owing to the large number of alternatives and combinations, it is impossible to tabulate the various mechanical properties as functions of these factors, so the experimental determination is indispensable in most cases. There are, nevertheless, some predominant factors presented below, but they only provide information outlining order of dominance value, and illustrating the effect of these factors on the strength and stiffness of the cement stabilized clay.

3.7.1 Water Content

Water content is one of the main factors in cement stabilized clay. The strength of cement stabilized clay decreases with the increasing in water content. The strength of cement stabilized clay at liquid limit can draw as straight line (Nagaraj et al., 1998). The cement content and the water content can be applied to predict the strength of cement stabilized clay as proposed by Horpibulsuk et al. (2000).

3.7.2 Organic Matter

Many soils, particularly those near the surface, contain organic matter and this can react with the Portland cement and prevent the soil-cement mixture from hardening. This is a serious handicap since a particularly economical method of processing (the mix in place method) can often be employed if cement will harden satisfactorily when mixed with soil from near the surface. Investigation on the nature of the organic compounds in soil affecting the hardening of Portland cement was done by Clare et al. (1956) as shown in Table 3.4. The strength of cement stabilized clay on organic soils is often very low. However, cement is more effective than lime in the stabilization of organic soils (Miura et al., 1988).
Table 3.4 Effect of fractions of organic matter on the hardening of cement  
(Clare et al., 1956)

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Composition</th>
<th>Added to soil (%)</th>
<th>Compressive strength reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Amino-acids, sugars and other low-molecular-weight compound</td>
<td>0.2</td>
<td>20</td>
</tr>
<tr>
<td>B</td>
<td>Phenylglycosides</td>
<td>0.1</td>
<td>10</td>
</tr>
<tr>
<td>C</td>
<td>Polyuronic acids</td>
<td>0.05</td>
<td>15</td>
</tr>
<tr>
<td>D</td>
<td>Compounds rich in nitrogen and phosphorus</td>
<td>0.4</td>
<td>20</td>
</tr>
<tr>
<td>E</td>
<td>Fats and waxes</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>Co-precipitated fulvic acid</td>
<td>0.15</td>
<td>20</td>
</tr>
<tr>
<td>G</td>
<td>Lignin-enriched humic acid</td>
<td>1.0</td>
<td>95</td>
</tr>
<tr>
<td>H</td>
<td>Carbohydrate-enriched humic acid</td>
<td>0.9</td>
<td>0</td>
</tr>
<tr>
<td>I</td>
<td>Hydrolyzed tannins and resins</td>
<td>0.05</td>
<td>10</td>
</tr>
<tr>
<td>J</td>
<td>Humic acid free from co-precipitated material</td>
<td>0.6</td>
<td>30</td>
</tr>
</tbody>
</table>

3.7.3 Salt Concentration

The salt concentration is one of the influential factors in the strength of stabilized Ariake clay. Miura et al. (1988) investigated the effect of salt concentration on the strength of stabilized Ariake clay as shown in Figs. 3.10(a) and (b). They stated that the higher the salt concentration, the greater the lime-clay or the cement-clay reaction in Ariake clay. The addition of salt acts as a catalyzer according to Ariizumi (1977) and the ion Cl⁻, Na⁺, Mg²⁺ accelerate the pozzolanic reaction.
(a) Effect of sea and fresh water on strength of cement or lime stabilized clay

(b) Effect of NaCl on strength of lime stabilized clay

Fig. 3.10 Relationship between unconfined compressive strength and admixture content (after Miura et al., 1988)
3.7.4 Cement Content

In general, it has been found that the greater the cement content, the greater the strength of the cement stabilized clay (Broms, 1984). Zonal demarcation showing the effectiveness of cement stabilization has been shown in Fig. 3.11. The strength of cement stabilized clay was sub-divided into 3 zone on the basis of gradient.

![Influence of cement content on unconfined compressive strength](image)

**Fig. 3.11 Influence of cement content on unconfined compressive strength**

*(Kamaluddin, 1995)*

3.8 MICROSTRUCTURAL STUDY OF SOIL

The observation on microstructure of soil is useful to appreciate the relation between soil structure and its mechanical behavior. In lime and cement stabilized clays, it also merits to consider in their structures. From the previous investigations, Kawamura and Dimond (1975), Kamon and Nontananandh (1991), and Rajasekaran et al. (1997) investigated the formation of cementing products (CaO-SiO₂-H₂O, CaO-Al₂O₃-H₂O) by x-ray diffraction and scanning electron microscope (SEM). It evidently demonstrated that the strength of lime or cement stabilized clay is primarily governed by the formation of cementing products.
It is generally regarded that a soil particle does not exist as a single unit, and soil structure invariably consists of enclosed pores and structural units which are made up of groups of particles. A group of soil particles is called a domain, cluster, ped, aggregate, assemblage, etc. Matsuo and Kamon (1979) proposed that soil structure can be expressed by ped and pore, and determined their magnitude as the basic unit in the analysis of soil structure. Fig. 3.12 shows the soil structure model expressed by Collins and McGown (1974). The soil structure is explained by the connectors, which exist between silts, sand and aggregates, and different types of pores.

In order to study soil structure of Ariake clay in its undisturbed, remolded and reconstituted states, Onitsuka and Negami (1998) and Onitsuka et al. (1998) used pore size distribution measurement and scanning electron microscopy. They stated that the structure of Ariake clay has been formed by aggregations which contain diatoms and broken pieces of diatoms along with other minerals, and the pores are mainly distributed around 10 mm. In the remolded and the reconstituted samples, a part of the linkage is broken. Hence, the pore size distribution shows two peaks at the equivalent exterior-aggregate pore and inter aggregate pore. During the compression processes, the linkage of undisturbed specimens is cut off and broken with an increase in consolidation pressure, and the pores decrease with a re-distribution of the aggregation.
3.8.1 Microstructure of Lime and Cement Stabilized Clays

The comparison between low and high water content of soil stabilization has been pointed out by Locat et al. (1996). For a soil with high water content (low density), the lower strength development observed could be partly associated with fewer lime particles per unit volume. On the other hand, the higher the water content, the easier the mixing and the better the dispersion should be. As detailed hereafter, the slower strength increase observed at higher water contents is mostly attributed to the fact that more cementing products must be produced between the more distant soil particles before there is any significant strength increase.

Fig. 3.12 Soil structure model expressed by Collins and McGown (1974)
A schematic model describing the physicochemical process initially proposed by Ingles and Metcalf (1973) and later modified by Choquette (1988) to take into account the results for high water content soils is presented in Fig. 3.13. This model illustrates how the reaction products are disseminates within the soil matrix, creating bridges (or coating) between or on soil particles. This cementation process is responsible for the increase in strength and acts primarily on the cohesion component of the shear strength parameters of the soil. On the long term, a high water content soil may even perform better than a soil with a low water content soil, likely because movement of solutes is eased within the porous space (Fig. 3.13).

Fig. 3.13 Physical conceptual model proposed for lime stabilization of sensitive clays (Locat et al., 1990)
Some influence factors on chemical stabilization for soft clays

The analysis of Fig. 3.13 and mercury porosimetry measurement made by Choquette et al. (1987) and Choquette (1988) provide an opportunity to speculate on the effects of lime stabilization on permeability. It is known that the initial flocculation occurring immediately after lime addition tends to produce aggregates (or apparent coarser particles), thus likely increasing the permeability of the soil. If one assumes that the model of Fig. 3.13 is valid, permeability should decrease as reaction products gradually fill the pore space.

Nanri (1997) proposed the chemical reaction of soil, quicklime, and waste material by products by the schematic diagrams in three stages (Fig. 3.14). It was proposed that the chemical reactions between soil and quick lime could be divides in three stages depending on the curing time. The first stage is the reaction between water in clay and calcium hydroxide as hydration, the second stage is the cation exchange of Ca²⁺ in clay mineral, and the last is the pozzolanic reaction as the reaction between alumina and/or silica in clay minerals with the calcium hydroxide. The diagram also showed that the addition of waste materials by product induces two chemical reactions as hydration at first stage by free lime (CaO) and pozzolanic reaction at third stage by silica and alumina in waste materials.

![Schematic diagram of chemical reactions among soil, quicklime, and waste materials](image)

**Fig. 3.14 Schematic diagram of chemical reactions among soil, quicklime, and waste materials (Nanri, 1997)**
Saitoh et al. (1985) proposed the conditions of hardening with the schematic diagrams of the condition immediately after mixing a cohesive soil and hardening agent slurry (Fig. 3.15). It is considered that even if the cohesive soil and hardening slurry are thoroughly mixed, clay particles will form a cluster, which will be surrounded by the slurry. Fig. 3.15(b) shows the condition of cohesive soil and hardening agent slurry that have formed a hardened body. Here the hardening agent slurry shown in Fig. 3.15(a) produces hydrated calcium silicates, hydrated calcium aluminates, Ca(OH)$_2$, etc., and forms hardened cement bodies. The pozzolanic reaction between the clay and Ca(OH)$_2$ produced by the cement hydration reaction produces hardened soil bodies. It is considered as shown in Fig. 3.15 that the strength of the improved soil depends upon the strength characteristics of both types of hardened bodies.

![Diagram of improved soil](image)

**Fig. 3.15 Schematic illustrations of improved soil (Saitoh et al., 1985)**

Saitoh et al. (1985) identified the following reactions between soil, cement, and slag diagrammatically in Fig. 3.16.

a) Hydration of ordinary portland cement producing Ca(OH)$_2$ (the calcium hydroxide generated equals up to 25% of weight of the cement).
b) Absorption of Ca(OH)$_2$ by the clay.
c) If and when the clay is saturated with Ca(OH)$_2$, a pozzolanic reaction between these two components occurs.

The success of deep mixing varies with the type of soil being treated, more specifically on their calcium hydroxide absorption capacity and their pozzolanic reactivity. Saitoh et al. (1985) also concluded that from the point of view of its wide applicability with respect to soil types, deep mixing with ordinary portland cement, blended with blast furnace slag is more advantageous.
Fig. 3.16  Chemical reaction between soil and hardening agents
(Saitoh et al., 1985)

3.9 UTILIZATION OF SURPLUS SOFT CLAY

Research on recycling and utilization of waste materials has been documented for decades in Japan (Kamon, 1997). The waste materials recycled and utilized for pavement materials include the surplus soils from excavation of any constructions such as road, building, tunnel, pipe, and piles as well, Institute of Civil Engineering (1982), Kamiya et al. (1993). Some of industrial wastes, such as fly ash, steel slag, have been also reused, Omoto et al. (1993a), (1993b), Nishi et al. (1994), Yamada et al.(1995), (1996), and Yoshida et al. (1998).

Tang et al. (2001) pointed out the handicaps on the reuse of dredging as following. One weak point to be mentioned is the cost for this recycled geomaterial. Another is the disagreement between supply and demand in time and territory.
Like other activities of recycling resources, the reuse of dredging will cost more than conventional geomaterials. However, it is not reasonable to compare recycled and natural geomaterial directly by construction cost. Excavating hills for landfill or disposing the dredging to the open sea may cause environment disputes. Establishing embankments to form a space to discharge dredging needs a large construction expense. The price of recycling dredging should be estimated by taking into account various social factors.

The disagreement between supply and demand in time and territory is also an important reason that obstructs the reuse of dredging. In general, different agencies with different purposes at different time manage dredging works and projects’ potential reuse of dredging. To eliminate such disagreements, a temporary stoking space becomes necessary, but this means that additional cost will be involved. It seems important to regulate the period both for dredging work and for the projects’ potential reuse of dredging trade is desirable, when the treated dredging is offered and accepted as a recycled geomaterial.

Kamiya et al. (1993) has proposed the recycling system for excavated soil from construction road in Sapporo. The utilization of excavated base or subbase, and subgrade soils is recycled by two separate wastes to get materials with different grain sizes. The subbase and base materials contain big size particle such as stone and sand while the subgrade mainly consists of fine size particles such as clay and sandy clay. Excavated base and subbase materials are transported from the site to plant first, and then washed and sieved by vibration. Coarser materials such as stone and sand can be thus collected. The engineering properties of the coarser material are improved in both strength and durability by a proper gradation design with the stone and sand. They can be used as road materials. The water washed residue, called dewatered cake, is in the shape of cakes with water content less than 40% after dewatering in sediment in a pit. The excavated subgrade soils are moved to the stockyard of the plant, and then piled up with different classification. Mixture is formed by mixing the subgrade soil with the dewatered cake from excavated base and subbase. The grain size distribution of the mixtures is made to determine the suitability as construction materials.
As reported, Ninomiya et al. (1996), some soil stabilization methods are applied to surplus soil utilization. The most spreading method is by using chemical additives such as cement, lime and hygroscopic polymer and surface activator. Another widely used is the aging method where surplus soils are stored in a stockyard in long term and sometimes mixed with up to be improved naturally. Recently some methods to increase the value of soil materials have been developed. Light weight soil stabilization method, where surplus soil are mixed with light weight materials such as EPS or foamed cement, has been expected to be utilized for embankment and backfill. The soil mixture by this method has similar characteristics as general soil materials, deferring from the use of EPS only. Fiber mixing method, where soil or stabilized soil are mixed with fiber (0.02-0.1) mm of thickness and 3 cm of length, can produce the persistent and durable soil materials against erosion or crack. Geotextile reinforced soil method is available for embankment construction by reclaiming surplus soil with high water content. Bagged soil method, where the non-woven fabric bags are filled with surplus soil, is being studied in order to construct underwater embankment or flexible bulkhead.

The importance of environmental geotechnology within the discipline of geotechnical focuses on (1) the creation of better environment, (2) prevention of environment risks due to human activities, and (3) the prevention of danger to human life caused by natural hazards. Kamon (1997) proposed “NICE” criteria, which stands for Non-hazardous Improvable Compatible and Economical treatment to utilize the waste as the construction materials which falls into the second category. Utilization of wastes from various industries, e.g., electric power generation companies etc. has been well documented. However, there is a need to utilize the wastes that have been generated from various construction sites.

A utilization system of waste slurry which consists of two treatment methods are dehydration and solidification. In dehydration method, it is proposed that the waste slurry with Carbonate Aluminate Salts (CAS) and Fluidized Bed Combustion Coal Ash (FA) as flocculent should be dehydrated with the object of volume reduction. The addition of FA and CAS are helpful for the sedimentation and volume reduction of the slurry. When the slurry for the sites reaches the standard required as not being dehydration, then solidification is carried out for the slurry. The slurry was
solidified by mixing with the additives such as FA and CAS. It was proved that the addition of these additives are effective in strength increase and durability improve and mixing workability.

Sogabe et al. (1996) have developed a high pressure dewatering method of cement-mixed soft soil for increasing strength and decreasing volume of soft cohesive soil, together with mud and slurry derived from urban construction works. Soft clay with high water content is thus dewatered and as a result, volume is decreased. The treated soft clay is made as a granular material. It was proved that the crushed cakes of classified small-grain size by a crusher could be used as a material for roadbed.

3.10 SOIL SAMPLE AND METHOD OF INVESTIGATION

3.10.1 Soil Sample

Natural clays including Ariake clay (Okawa area) and Bangkok clay (KMIT-NB campus), and pure clay minerals consisting of Bentonite and Kaolin were used in this study. Properties of these clays are shown in Table 3.5. Properties and composition of mixing diatom remain which is used as one of admixture are tabulated in Tables 3.5 and 3.6.

Ariake clay is very high sensitive clay, which deposited around the coast of Ariake Bay in Kyushu Island, Japan. Bangkok clay is usually high sensitive clay formed by the Chao Phraya delta in sedimentary process with the influence of sea level fluctuations. The mineral and chemistry of two marine alluvial deposits are different parent materials, Ariake clay was derived from pyroclastic origin while Bangkok clay derived from non-pyroclastic origin (Ohtsubo et al., 2000). Both clays contain Smectite as major mineral, but Smectite of Ariake clay is non-swelling type, while Bangkok clay is swelling type. Ariake clay has abundant of fossil remains, mostly derived from diatoms while microfossils in Bangkok clay are rare (Tanaka et al., 2001). Their natural water contents vary from 50 to 200%. The liquidity index of these clays are generally equal or larger than 1.
Table 3.5 Properties of soil samples and diatom

<table>
<thead>
<tr>
<th>Soil</th>
<th>Ariake Clay (AC, Marine Clay)</th>
<th>Bangkok Clay (BC, Marine Clay)</th>
<th>Bentonite (B)</th>
<th>Kaolin (K)</th>
<th>Mixing Diatom*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>2.0-2.5</td>
<td>3.0-3.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Water content, w_d (%)</td>
<td>90</td>
<td>60</td>
<td>-</td>
<td>-</td>
<td>137~169</td>
</tr>
<tr>
<td>Liquid limit, w_L (%)</td>
<td>80</td>
<td>61</td>
<td>388</td>
<td>49</td>
<td>NP</td>
</tr>
<tr>
<td>Plastic limit, w_P (%)</td>
<td>42</td>
<td>36</td>
<td>288</td>
<td>16</td>
<td>NP</td>
</tr>
<tr>
<td>Plastic index, PI</td>
<td>38</td>
<td>25</td>
<td>100</td>
<td>33</td>
<td>NP</td>
</tr>
<tr>
<td>Particle size distribution, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand (2.000-0.075 mm)</td>
<td>17</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0~16</td>
</tr>
<tr>
<td>Silt (0.075-0.005 mm)</td>
<td>48</td>
<td>34</td>
<td>8</td>
<td>31</td>
<td>65~68</td>
</tr>
<tr>
<td>Clay (&lt;0.005 mm)</td>
<td>35</td>
<td>65</td>
<td>90</td>
<td>68</td>
<td>20~32</td>
</tr>
<tr>
<td>NaCl (g/l)</td>
<td>0.5</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ignition loss (%)</td>
<td>6.4</td>
<td>4.0</td>
<td>-</td>
<td>-</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Note: * Diatom from Kusu-Gun, Oita prefecture and data from Tateishi (1997)

Table 3.6 Compositions of diatom *

<table>
<thead>
<tr>
<th>Type of Soil</th>
<th>Chemical Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO₂</td>
</tr>
<tr>
<td>Diatom</td>
<td>87.60</td>
</tr>
<tr>
<td>Ariake Clay</td>
<td>53.62</td>
</tr>
</tbody>
</table>

Note: * Data from Tateishi (1997)

3.10.2 Program of Investigation

Clays with various proportions of considering factors were mixed with 10% cement or lime and conducted the unconfined compression test at curing periods of 7 and 28 days. Effect of cement or lime was also investigated by using various cement or lime contents at 10%, 15% and 20% for Ariake and Bangkok clays. During testing, the water content of clays before cement stabilization is regularly kept at 90% for Ariake clay mixtures and at 60% for Bangkok clay mixtures, Bentonite and Kaolin. Testing program for unconfined compression test is shown in Tables 3.7 and 3.8 for cement and lime stabilization, respectively. It is noted that clay minerals used in Ariake clay mixture are different from other patterns having liquid and plastic limits of 65% and 24% for Bentonite, and 53% and 34% for Kaolin, respectively.
Table 3.7 Testing program for cement stabilization

<table>
<thead>
<tr>
<th>Factors</th>
<th>Clays</th>
<th>Admixtures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>Ariake clay &amp; Bangkok clay</td>
<td>Cement 10%, 15% and 20%</td>
</tr>
<tr>
<td>Salt</td>
<td>Ariake clay, Bangkok clay, Bentonite &amp; Kaolin</td>
<td>NaCl or CaCl₂ at 5 % or 10% with cement 10%</td>
</tr>
<tr>
<td>Diatom</td>
<td>Ariake clay, Bangkok clay, Bentonite &amp; Kaolin</td>
<td>Diatom content at 3%, 5% and 10% with cement 10%</td>
</tr>
<tr>
<td>Clay minerals</td>
<td>Mixing Ariake clay or Bangkok clay with Bentonite or Kaolin in the ratio of 25:75, 50:50, 75:25 (AC or BC: B or K)</td>
<td>Cement 10%</td>
</tr>
</tbody>
</table>

Table 3.8 Testing program for lime stabilization

<table>
<thead>
<tr>
<th>Factors</th>
<th>Clays</th>
<th>Admixtures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lime</td>
<td>Ariake clay</td>
<td>Lime 10%, 15% and 20%</td>
</tr>
<tr>
<td>Salt</td>
<td>Ariake clay</td>
<td>NaCl or CaCl₂ at 5 % or 10% with cement 10%</td>
</tr>
<tr>
<td>Diatom</td>
<td>Ariake clay</td>
<td>Diatom content at 3%, 5% and 10% with lime 10%</td>
</tr>
<tr>
<td>Clay minerals</td>
<td>Mixing Ariake clay with Bentonite or Kaolin in the ratio of 25:75, and 75:25 (AC: B or K)</td>
<td>Lime 10%</td>
</tr>
</tbody>
</table>

3.10.3 Physical Properties

Physical property tests including Atterberg’s limits, natural water content, specific gravity, ignition lost and particle size distribution were carried out. Atterberg’s limits followed the JIS-A1205; natural water content test followed JIS-A1203; ignition lost test followed JIS-A1226; and particle size distribution test followed JIS-A1204.

3.10.4 Unconfined Compression Test

The samples were mixed with content of admixtures by mass of dry soil. 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 strain rate of 1% per minute at curing periods of 7 and 28 days according to the procedure of JIS-A1216.

3.10.5 Scanning Electron Microscope (SEM)

In order to study the microstructure of samples, the stabilized samples at 28 day curing period or natural samples were prepared for SEM. A small piece of sample was cut with an iron wire before drying by a freeze-dry method to minimize the volume change. The fractured surfaces of samples were coated with gold before scanning by the JSM-5800 JEOL microscope.

3.11 RESULTS AND DISCUSSIONS ON CEMENT STABILIZATION

3.11.1 Effect of Clay Minerals

Figures 3.17 and 3.18 show the unconfined compressive strength of Ariake and Bangkok clays mixing with Bentonite or Kaolin and stabilizing with cement 10%. The results clearly indicate that when increasing Bentonite or Kaolin, the strength of mixtures will decrease. In order to comparison the clay mineral effect with other effects, the graph plotted in term of percentage of difference in strength as calculated by equation (3.17).

\[ Dq_u (\%) = \frac{q_{uf} - q_{u0}}{q_{u0}} \times 100 \]  \hspace{1cm} (3.17)

Where,
Dq_u is change in strength comparing with 10% cement or lime-clay mixture (%),
q_{uf} is the strength in considering mixture (kN/m²) and
q_{u0} is the strength in 10% cement or lime-clay mixture (kN/m²).
Fig. 3.17  Unconfined compressive strength of stabilized Ariake clay at various contents of Kaolin and Bentonite

Fig. 3.18  Unconfined compressive strength of stabilized Bangkok clay at various contents of Kaolin and Bentonite
Figure 3.19 shows the influence of clay mineral on unconfined compressive strength of cement stabilized Ariake and Bangkok clays. The results indicate that the strength of mixtures trend to decrease when Bentonite or Kaolin increases. Therefore, the Dq₄ yields negative value except the mixtures of both clays with 25% Kaolin.

![Figure 3.19 Influence of clay minerals on the change in strength of cement stabilized clays](image)

3.11.2 Effect of Salts

Figures 3.20 and 3.21 illustrates the strength and the change in strength in term of different percentage after adding NaCl in cement stabilizing Ariake clay, Bangkok clay, Bentonite and Kaolin. Figures 3.22 and 3.23 illustrates the strength and the change in strength in term of different percentage after adding CaCl₂ in cement stabilizing Ariake clay, Bangkok clay, Bentonite and Kaolin. The results show that the strength increases with salt content for Bangkok clay, Bentonite and Kaolin, while strength of Ariake clay decreases with increasing salt. However, increase in strength with salt content in cement-treated Ariake clay has been reported by Miura et al. (1988) and Onitsuka et al. (2004). Salts have been well known to accelerate the setting and hardening of Portland cement reaction (Taylor, 1997). The reason of scattered results in Ariake clay is not clearly known yet.
Fig. 3.20 Influence of NaCl on strength of cement stabilized clays

Fig. 3.21 Influence of NaCl on the change in strength of cement stabilized clays
Some influence factors on chemical stabilization for soft clays

Fig. 3.22 Influence of CaCl₂ on strength of cement stabilized clays

- Ariake clay
- Bangkok clay
- Kaolin
- Bentoinite

Cement 10% curing 28 days

Unconfined compressive strength, kN/m²

CaCl₂ content, %

0.0 2.5 5.0 7.5 10.0

0 500 1000 1500 2000

Fig. 3.23 Influence of CaCl₂ on the change in strength of cement stabilized clays

- Ariake clay
- Bangkok clay
- Kaolin
- Bentoinite

Cement 10% curing 28 days

Change in strength, %

CaCl₂ content, %

0 2.5 5.0 7.5 10.0

0 20 40 60

-60 -40 -20 0 20 40 60
3.11.3 Effect of Diatom

Figures 3.24 and 3.25 show the strength and the different percentage of strength with diatom content. The strength increases with diatom content for all clays. Diatom acted as silica source provides silica to the system and helped in water absorption.
3.11.4 Combination of Effects

Change in strength due to various factors in cement stabilized Ariake and Bangkok clays are plotted in Figures 3.26 and 3.27. The positive factors for Bangkok clay can be arranged from greater influences as diatom, cement content, CaCl$_2$ and NaCl. The negative factors for Bangkok clay are Kaolin, Bentonite and pyrite. However in Ariake clay, only cement content and diatom content are positive factors.

![Diagram showing change in strength due to various factors on cement stabilized Ariake clay](image-url)
Fig. 3.27 Change in strength in percentage due to various factors on cement stabilized Bangkok clay
3.11.5 Microstructure

**Figure 3.28** shows micrograph of diatom in natural Bangkok clay having porous structure. Micrograph diatom with cement are illustrated in **Fig. 3.29** indicating that porous of diatom is filled by cement products. Diatom acted as silica source provides silica to the system and also plays a role in water absorption.

**Figure 3.30** shows the micrograph of Bangkok clay stabilizing with cement 10% at 28 day curing period. Fine tubular shapes that probably CSH gel, a precocious form of cement hydration products can be seen in the micrograph (Tremblay et al. 2002).

**Figures 3.31 and 3.32** illustrate the micrograph of Kaolin and Bentonite stabilizing with cement 10% at 28 day curing period, respectively. In the micrographs of Kaolinite-cement, cement products are existed on the particle surface. In the micrograph of Bentonite-cement, cement products connecting between clay particles can be also clearly observed. Because of lower liquidity index in Bentonite, cement product can be distributed more efficiently resulting in higher strength.

**Figure 3.33** shows micrograph of natural Ariake clay containing diatoms and pyrite. Ettringite in needle-like form can also be observed in the micrograph of Ariake clay mixing with cement 10% as shown in **Figure 3.34. Figure 3.35** illustrates the micrograph of diatom and Ariake clay mixing with cement 10%. From **Figure 3.35**, the voids between the clay aggregates or diatom of the mixture are filled with cement products resulting in higher strength, which is consistency with result of unconfined compression test. As seen from the figures, the micrographs contribute to explain the mechanism of soil-cement stabilization more clearly.
Fig. 3.28 Micrograph of natural Bangkok clay

Fig. 3.29 Micrograph of diatom mixture with cement at 28 day curing period
Some influence factors on chemical stabilization for soft clays

Fig. 3.30  Micrograph of Bangkok clay stabilizing with cement at 28 day curing period (the arrow points at cement product)

Fig. 3.31  Micrograph of Kaolin stabilizing with cement at 28 day curing period
Fig. 3.32  Micrograph of Bentonite stabilizing with cement at 28 day curing period

Fig. 3.33  Micrograph of natural Ariake clay
Some influence factors on chemical stabilization for soft clays

Fig. 3.34  Micrograph of Ariake clay stabilizing with cement at 28 day curing period (the arrow points at cement product)

Fig. 3.35  Micrograph of 10% diatom and Ariake clay mixture with cement at 28 day curing period
3.12 RESULTS AND DISCUSSIONS ON LIME STABILIZATION

3.12.1 Combination of Effects

Change in strength due to various factors in lime stabilized Ariake clay are plotted in Figure 3.36 and 3.37. The positive factors for Ariake clay can be arranged from greater influences as lime and NaCl at 5%. The negative factors for Ariake clay are Kaolin, Bentonite, diatom CaCl$_2$ and NaCl at 10%.

![Graph showing change in strength due to various factors on lime stabilized Ariake clay](image)

Fig. 3.36 Change in strength due to various factors on lime stabilized Ariake clay
Some influence factors on chemical stabilization for soft clays

Fig. 3.37 Change of strength in percentage due to various factors on lime stabilized Ariake clay
3.13 CONCLUSIONS

This chapter concentrates on previous research regarding development of ground improvement in Ariake plain, the engineering behavior and influence factors of the lime and cement stabilized soils, and microstructure of soil, and investigation on some influence on chemical stabilization of Ariake clay and Bangkok clay. The reviews and results are summarized as follows:

1. The surplus wastes such as soft clay, slurry from construction sites is increasing. The utilization of waste materials can answer an urgent and important society problem such that environment impacts are reduced and natural resources are saved. Technical method of stabilization by a process of dewatering with pressure and solidifying with stabilizers has been documented for soft clay. Improvement of soft ground of Ariake clay has been applied to decrease the high water content and increase the strength decades ago.

2. The strength of lime stabilized clay is governed by pozzolanic and hydration reactions. In the case of cement stabilized clay, the hydration is the main reaction to impart the strength to the cement stabilized materials. Quicklime is a better stabilizer than cement for Ariake clay stabilization because of potential water reduction resulted from hydration and high temperature. However, in clay contain high organic the cement stabilization is more efficient. The treated Ariake clay is more brittle and easy to produce.

3. There are many factors affecting the strength of lime and cement stabilized clays such as water content, clay mineral, admixture content, pH, organic matter, sulfate etc.

4. The microstructure of lime and cement stabilized clays can be clearly observed by micrograph. The strength of lime and cement stabilized clays is mainly obtained by the formation of the cementing products.
5. In cement stabilization of Bangkok clay, Kaolin and Bentonite, the positive factors (strength increasing after adding these materials) in descending order are diatom content, cement content, CaCl₂ and NaCl. The negative factors (strength decreasing after adding these materials) of Bangkok clay are Kaolin and Bentonite, in descending order.

6. In cement stabilization of Ariake clay, the positive factors are only cement content and diatom content, respectively. The negative factors are CaCl₂, NaCl, Kaolin and Bentonite, in descending order. However, increase in strength with salt content in cement-treated Ariake clay has been reported by Miura et al. (1988) and Onitsuka et al. (2004).

7. In lime stabilization of Ariake clay, the positive factors are only lime content and NaCl at 5%, respectively. The negative factors are Diatom, CaCl₂, Bentonite and Kaolin, in descending order.

8. The different characteristics of two clays after treating with various admixtures may be due to the differences in chemical properties. In addition, the micrograph is useful to explain the mechanism and behaviors of stabilized soils more clearly.
REFERENCES


Some influence factors on chemical stabilization for soft clays


Some influence factors on chemical stabilization for soft clays


Chapter 4

INFLUENCE OF SALT ON LIME STABILIZATION FOR ORGANIC CLAY

4.1 INTRODUCTION

Soil stabilization by lime and cement is a common improvement method used for stabilizing the soft clay and the dredged sludge. The soft clay found near to the surface and the dredged sludge usually contain high organic content, which reduces the effectiveness of lime or cement stabilization.

The influence of the organic matter has significant effect on the strength gain of lime and cement stabilization due to the obstruction of pozzolanic reaction. Thompson (1966) suggested that the pozzolanic reaction was obstructed in organic soil because soil particles, which are a primary source of silica and/or alumina used in stabilization process, were coated by organic cations. This “masking effect” prevented the silica and/or alumina dissolution, resulting in an absence of silica and/or alumina in pozzolanic reaction.

However, not all of the organic compounds have a negative effect (Tremblay et al., 2002). Many experiments were carried out to investigate the possibilities of using various binders including gypsum (Kuno et al., 1989), carbonated-aluminate-salt (Kamon et al., 1989), pulverized fuel ash, and blast furnace slag (Hebib and Farrell, 2003) to stabilize organic soils. Not only the types of binders, but also the salt concentration plays an important role in stabilization of organic soil (Onitsuka et al., 2003). It was reported that the adverse effect of organic matter on strength of stabilized soil can be mitigated in soil having high salt concentration (Onitsuka et al., 2003). To extend this finding in an application, binders of lime with addition of sodium chloride (NaCl) and calcium chloride (CaCl₂) were examined for organic soil stabilization. Lime was selected as main binder in this chapter because lime was more sensitive with organic than cement (Onitsuka et al., 2003) and recently cement stabilization was found to cause water and soil pollutions by leaching of hexavalent chromium (Tsuneoka et al., 2003).
In order to identify the mechanism of stabilization and chemical reaction during the cementing development, the dissolved elements in solution were observed by chemical composition analysis. The main objective of this chapter is to evaluate the effectiveness of salt-lime-organic clay mixtures in comparison with lime-organic clay mixture. The strength and cementing products of mixtures were monitored by unconfined compression tests and scanning electron microscope (SEM).

4.2 SOIL SAMPLE AND METHODOLOGY OF TESTING

4.2.1 Soil Sample

Soft clay from Rokkaku Kawa bank in Ariake area, Japan at depth 0.5 m was used in this study. The location map and photographs of site are shown in Figures 2.1 and 4.1, respectively. The clay has a high plasticity with liquid limit of 142% and a plastic limit of 54%. The organic matter by ignition loss method and humic acid are quite high, with value of 12.8% and 1.2%, respectively. The clay fraction (< 0.005 mm) is 67%. Humic acid is known as one of factors retarding the ability of soil to react with binders and decrease the soil improvement effect (Kuno et al., 1989; Tremblay et al., 2002; Onitsuka et al., 2003). Soil cannot be improved effectively by quicklime if that soil containing humic acid more than 1% and water content higher than 100% (Kuno et al., 1989).

Furthermore, the clay was treated by sodium hydroxide (NaOH) to extract the organic content. Procedures of organic extraction are described in the next section. Some properties of clay were changed because of organic removal process. Liquid and plastic limits were lower to about 122% and 49%, respectively and specific gravity was increased from 2.52 to 2.56. The clay fraction of treated clay was decreased from 67% to 46%. Properties of natural and treated clays are summarized in Table 4.1.

4.2.2 Physical Properties

Physical properties included natural water content (\(w_n\)), liquid limit (\(w_L\)) and plastic limit (\(w_P\)), specific gravity (\(G_s\)), and grain size distribution. Tests were made according to the procedure given in the test standard JIS (1999), in which \(w_n\) followed the JIS-A1203-1999; \(w_L\), and \(w_P\) followed the JIS A 1205-1999; \(G_s\)
followed the JIS A 1202; and the particle size distribution followed the JIS A 1204-2000.

Fig. 4.1 Photographs of sampling point under Rokkaku Kawa bridge

(a) View at sampling point

(b) View from outside
Table 4.1 Properties of Rokkaku Kawa clay before and after organic extraction by NaOH

<table>
<thead>
<tr>
<th>Properties</th>
<th>Rokkaku River Clay</th>
<th>Treated Clay (Extracting organic matter by NaOH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>0.5-1.0</td>
<td>-</td>
</tr>
<tr>
<td>Water content, (w_n) (%)</td>
<td>123.2</td>
<td>-</td>
</tr>
<tr>
<td>Liquid limit, (w_L) (%)</td>
<td>141.6</td>
<td>121.9</td>
</tr>
<tr>
<td>Plastic limit, (w_p) (%)</td>
<td>54.1</td>
<td>48.5</td>
</tr>
<tr>
<td>Plastic index, (I_p)</td>
<td>87.5</td>
<td>73.4</td>
</tr>
<tr>
<td>Specific gravity, (G_s)</td>
<td>2.52</td>
<td>2.56</td>
</tr>
<tr>
<td>Particle size distribution (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand (2.000-0.075 mm)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Silt (0.075-0.005 mm)</td>
<td>31</td>
<td>52</td>
</tr>
<tr>
<td>Clay (&lt; 0.005 mm)</td>
<td>67</td>
<td>46</td>
</tr>
<tr>
<td>Color</td>
<td>Gray</td>
<td>Gray</td>
</tr>
<tr>
<td>NaCl (g/l)</td>
<td>4.4</td>
<td>15</td>
</tr>
<tr>
<td>Ignition loss (%)</td>
<td>12.8</td>
<td>12.8</td>
</tr>
<tr>
<td>Humic acid (%)</td>
<td>1.2</td>
<td>-</td>
</tr>
<tr>
<td>Unit weight (kN/m³)</td>
<td>14.2</td>
<td>-</td>
</tr>
<tr>
<td>pH</td>
<td>7.6</td>
<td>7.6</td>
</tr>
</tbody>
</table>

4.2.3 Unconfined Compression Test

Various binders, including quicklime, normal Portland cement, salt, and gypsum were chosen for the stabilization. All samples were compacted by hand-vibration to reduce the entrapped air. The specimens, 50 mm in diameter and 100 mm in height, were cured at temperatures of 20°C and a humidity of 90%. In general, the unconfined compression tests were performed on the treated samples at curing periods of 7, 14 and 28 days, but for some samples treated with lime and lime salts, the tests were also conducted at curing periods of 1, 3, and 5 days.

In order to investigate the influence of organic matter, the organic matter was extracted by the alkaline extraction method by method suggested by Clare and Sherwood (1956). The extraction method shown in Figure 4.2 is as follows:
(1) Natural clay (500 g of dry clay) was stirred with 1 liter of 0.5 mol sodium hydroxide (NaOH) for 24 hours by a mechanical shaker.

(2) The undissolved clay was removed by centrifuging and decantation.

(3) The process was repeated and the two portions of liquid were combined to find the humic acid later.

(4) The treated clay was then washed with distilled water, and the suspension was brought to a pH of about 7.6 by adding hydrochloric acid (HCl) to a normal level for natural clay.

(5) The clay was separated again by centrifuging and decantation.

The material obtained by the alkaline extraction can be divided into two parts, which are humic acid and fulvic acid. The humic acid was precipitated by acidification of the extracted liquid to a pH of 2.5 by using HCl and filtration. After extraction, the treated clay (with organic matter removed in the alkaline extraction process), was used for the unconfined compression test by mixing with 10% of lime at curing periods of 7, 14 and 28 days.

Fig. 4.2 Extraction process of fulvic and humic acids from soil (Clare and Sherwood, 1956)
4.2.4 Chemical Composition Analysis

The chemical composition analysis was conducted on tested samples after performing unconfined compression tests. The preparation procedure is as follows:

1. The samples were crushed by a pestle and mortar into particles under 2 mm diameter.
2. The samples were mixed with distilled water at a ratio of 1: 20 (solid: liquid).
3. The slurry was stirred for 24 hours by a mechanical shaker.
4. A centrifugation for a period of 30 minutes at 3000 rpm was performed before filtration to separate the solids from the liquid.
5. The concentrations of specific chemicals in the liquid along with its pH value were determined.

The concentrations of cations, such as Ca, Na, Mg and Fe, were determined by the atomic absorption spectrometer (Shimazu AA-6650, Figure 4.3), the concentration of Si was analyzed with a spectrophotometer (Hach DR/2400, Figure 4.4), The Al concentration was measured by the inductively coupled argon plasma spectrometer (Shimazu ICPS-8100, Figure 4.5), by which the pH value was determined from the H$_3$O$^+$ (aq) and OH$^-$ (aq) ions.

4.2.5 Scanning Electron Microscope (SEM)

In order to study the microstructure of stabilized samples, samples stabilized with lime and lime-salt of the unconfined compression tests with curing period of 28 days were prepared for SEM. A small piece of sample was cut with an iron wire before by using freeze-drying equipment (Figure 4.6) to minimize the volume change. The fractured surfaces of samples were coated with gold before scanning by the JSM-5800 JEOL microscope (Figure 4.7).
Fig. 4.3 Atomic absorption spectrometer (Shimazu AA-6650)

Fig. 4.4 Spectrophotometer (Hach DR/2400)
Fig. 4.5 Inductively coupled argon plasma spectrometer (Shimazu ICPS-8100)

Fig. 4.6 Freeze drying equipment
Fig. 4.7 SEM apparatus (JSM-5800 JEOL microscope)
4.3 RESULTS AND DISCUSSIONS

4.3.1 Strength Development

Figure 4.8 shows the unconfined compressive strength of clay stabilization with various binders. In general, the strength increases with the time, indicating a continuous pozzolanic reaction from the additives. The strengths of clay with 10% and 20% quicklime at curing period of 28 days were 100 kN/m$^2$ and 199 kN/m$^2$, which are relatively low compared to other binders. The strength values of clay with 10% cement; 5% quicklime and 5% gypsum; 10% quicklime with 10% NaCl; and 10% quicklime with 10% CaCl$_2$ at curing period of 28 days were 644 kN/m$^2$, 579 kN/m$^2$, 1,295 kN/m$^2$ and 1,039 kN/m$^2$, respectively.

Notes: 1. L, Na, Ca, Tc, Ce, G denotes quicklime, NaCl, CaCl$_2$, Treated clay, normal Portland cement and gypsum, respectively.
2. 10L+10Na denotes 10% of lime and 10% of NaCl.
3. % denotes % of dry soil weight.

Fig. 4.8 Unconfined compressive strength of clay stabilization with various binders
Influence of salt on lime stabilization for organic clay

To examine the influence of organic, the organic content of clay was removed through addition of sodium hydroxide (caustic soda, NaOH). The results indicated that the strength of treated clay-lime increased to 1,060 kN/m² at a 28 day curing period.

Among these binders, lime with NaCl and lime with CaCl₂ were the two most effective binders for this clay. **Figures 4.9 and 4.10** show stress-strain curves of clay, one stabilized with lime and sodium chloride (NaCl), and the other stabilized with lime and calcium chloride (CaCl₂) in various proportions. The figures indicate that stiffness of organic clay stabilized with lime has improved with addition of salts. The salt may contribute by two folds, one is to coagulate with the organic cation, leaving the clay particles exposed to lime for pozzolanic reaction and the other is to cause flocculation of the soil.

![Stress-strain curve of unconfined compression test on clay stabilized with 10% lime and various contents of sodium chloride (NaCl) at a 28 day curing period](image)

**Fig. 4.9** Stress-strain curve of unconfined compression test on clay stabilized with 10% lime and various contents of sodium chloride (NaCl) at a 28 day curing period
Fig. 4.10  Stress-strain curve of unconfined compression test on clay stabilized with 10% lime and various contents of calcium chloride (CaCl$_2$) at a 28 day curing period

4.3.2 Organic Extraction

The extraction of organic matter by NaOH is an effective method that can remove the organic content up to 80% (Stevenson, 1994). After extraction, the liquid limit decreased from 142% to 122%, specific gravity increased from 2.52 to 2.55 and strength increased from 100 kN/m$^2$ to 1,060 kN/m$^2$ at 28 day curing period with 10% lime stabilization, despite of no changes in ignition loss. These clearly showed the effect of organic matter in the clay. Decreasing in clay fraction from 63% to 46%, may be resulted from flocculation by increasing of salt concentration after organic extraction.
The ignition loss value of clay before and after organic extraction was quite high about 12.8%. The determination of the change in mass of a soil sample resulting from destruction of organic matter by ignition at high temperature is subject to error. Lambe and Martin (1956) reported that the organic matter determined by the ignition loss and the chemical analysis agreed well if non-organic portion (quartz, feldspar, etc.) of the soil are not decomposed by heat and do not contain significant amounts of adsorbed water. The ignition loss is a very poor measure of organic matter in soils, which have minerals, such as montmorillonites, that have large quantities of adsorbed moisture, and which are driven off by heat. The dominant clay mineral of Ariake clay is the low swelling type of smectite (Ohsubo et al., 1982). In Ariake clay, the ignition loss method overestimates the organic content because both inorganic and organic constituents lose mass during heating. The ignition loss value of the treated clay was still high even though the organic matter has been removed.

### 4.3.3 Chemical Composition Analysis

Prior to analysis, the lime-clay reaction mechanisms are briefly described as follows. When lime (CaO) is added to soil, hydration reaction occurs and forms Ca(OH)₂, releasing about 17x10⁹ J of heat per kg of CaO (s) added (Boardman et al., 2001). Some water evaporates due to the increase in the temperature by this reaction. The creation of calcium hydroxide increases in the pH of the pore water. The presence of additional Ca²⁺ may result in an increase in flocculation of particles, modifying its plasticity.

Solidification, referring to the long-term strength gain of soil, occurs as a result of a pozzolanic reaction involving the formation of cementitious compounds within the clay structure. The compounds are formed by the availability of calcium, while the alumina and silica oxides dissolve from the clay structure at such high alkali environment. The component reacts to form calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), cementitious products tend to bond the clay particles. The degree of cementation depends greatly on the available lime, clay minerals and overall environment. Strength gain can continue for several months or even years under suitable condition (Little, 1996).

The results illustrate the changes in the pH value (Figure 4.11) and the elemental analysis of the solution from chemical analysis at varying curing periods.
for the different mixtures. The pH value of the Rokkaku River clay was about 7.6, which is close to neutrality. After the addition of lime, the pH value increases significantly after 1 day as expected. There is a clear drop in the pH value after 3 days, except for solution containing a 10% lime with slight decrease as a proportion of the strength increase. However, the pH of each mixture was maintained to a sufficient level to allow mineral dissolution. It should be noted that the solubility of $\text{Al}_2\text{O}_3$ and $\text{SiO}_2$ is pH dependent as illustrated in Figure 3.2.

---

Notes: 1. L, Na, Ca, Tc, Ce, G denotes lime, NaCl, CaCl$_2$, Treated clay, cement and gypsum, respectively.
2. 10L+10Na denotes 10% of lime and 10% of NaCl.
3. % denotes % of dry soil weight.

**Fig. 4.11 pH of clay stabilization with various binders**
Figures 4.12 through 4.15 indicate the development of ions concentration including Ca, Na, Si, Al and Mg for the 10% lime, the 10% lime with 10% NaCl, the 10% lime with CaCl$_2$, and 10% lime with treated clay, respectively. It should be noted that Fe ions were not detected in any solution and Mg concentration was relatively low compared with other ions.

The Ca ions decreased with time in all mixtures due to the progress of reaction. As expected, mixtures of lime with CaCl$_2$ gave high concentration of Ca ions due to the addition of CaCl$_2$. In the same manner, with NaCl, Na ion was highest in the lime with sodium-salt mixture.

![Graph showing chemical composition analysis of clay stabilized with 10% lime solution](image)

**Fig. 4.12** Chemical composition analysis of clay stabilized with 10% lime solution (24h, 30 rev/min, 1:20 Solid/Liquid)
Fig. 4.13  Chemical composition analysis of natural clay stabilized with 10% Lime + 10% NaCl solution (24h, 30 rev/min, 1:20 Solid/Liquid)

Fig. 4.14  Chemical composition analysis of natural clay stabilized with 10% lime + 10% CaCl₂ solution (24h, 30 rev/min, 1:20 Solid/Liquid)
Based on lime-clay reaction, the strength of mixture depends on the quantity of cementing agent which includes CSH and CAH. Calcium (Ca\(^{2+}\)) and hydroxyl (OH\(^-\)) were in excess for the reaction as indicated in Figures 4.12 through 4.15. Therefore, the Si and Al concentrations govern the production rate of the reaction.

However, the dissolved silica concentration is much greater than alumina for lime and lime-salts stabilization on untreated clay as illustrated in Figures 4.12 through 4.14. In Figures 4.15 and 4.16, comparing between the untreated clay and treated clay stabilized with 10% lime, it can be seen that the dissolved silica and alumina concentration of treated clay mixture was higher than that of untreated clay. This may be resulted from the removal of organic matters through masking effect, producing higher strength.

In case of salt-lime mixtures, the silica concentration depends on type of salt rather than the content. In the lime-sodium chloride mixtures, the silica concentration was much higher than that in the untreated clay which was observed in previous research by Iler (1955). It was reported that the sodium chloride (NaCl) greatly
accelerates the formation of soluble silica. Soil silica dissolution process in lime-clay reaction may be catalyzed by presence of sodium ions. In lime-calcium chloride mixtures, the silica concentration was slightly lower than that in the lime-sodium chloride mixtures, but higher than that in untreated clay mixture.

By comparing between the two salts mixtures at 10% of salt content, the strength of clay stabilized with lime and sodium chloride is higher than clay stabilized with lime and calcium chloride. However, at 2.5% of salt content, the strength of calcium chloride mixture is higher. Stevenson (1994) reported that organic colloid can be coagulated by electrolytes such as salt solution. Salt may coagulate with the cation of organic, leaving the clay particles exposed to the lime for pozzolanic reaction. As investigated by SEM and soil properties, Onituka et al.(2003) also stated that salt solution can flocculate the soil particles then reducing the pore space, therefore, the required cementation to bridging between aggregates to grain the strength is relatively low. Consequently, by these two actions, the lime-salt mixtures can yield a higher strength. It may conclude that not only dissolved silica can affect on strength of lime stabilization, but also, salt may contribute to coagulate with organic cation and reduce pore space between soil particles.
Fig. 4.16 Average values of dissolved silica in solution at different mixtures and unconfined compressive strength at a 28 day curing period

Influence of salt on lime stabilization for organic clay
Figure 4.17 illustrates the proposed schematic of organic clay particles before and after adding salts in the mixture in accordance to assumption that salts may coagulate with the cation of organic leaving the clay particles exposed to the lime for pozzolanic reaction and pore spaces are reduced due to flocculation. However, it is noted that in economical and environmental aspects, additive salt may be costly and if utilizing with the large quantity, it will be harmful to environment (Ariizumi, 1977). Therefore, using of additive salt in lime stabilization shall be performed with cautions.

4.3.4 Microstructure

Scanning electron microscope observations were done on the same stabilized samples after performing unconfined compression tests at 28 day curing period. For the clay stabilized with lime 10% shown in Figure 4.18, a flocculating structure is visible. On the other hand, for the clay stabilized with 10% lime and NaCl, with lime 10% and CaCl2 10%, and treated clay with 10% lime (Figures 4.19 through 4.21), cementation can be observed. The cementing products with a thin plate-form create an arch-like structure on and between the aggregates, which are mainly calcium silicate hydrates (CSH - the main cementing product responsible for cement setting, Choquette et al., 1987). Comparing with Figure 4.18, the soil particles are not as distinct since they are covered with reaction products, and the voids between soil particles are also less distinct. In summary, the results were in agreement with strength development in the stabilized soil.
Influence of salt on lime stabilization for organic clay

Fig. 4.17 Purposed schematic of organic clay particles before and after adding salt
(a) Normal scale (10 μm)

(b) Enlarge scale (5 μm)

Fig. 4.18  Micrograph of clay with 10% lime at a 28 day curing period
Fig. 4.19  Micrograph of clay with 10% lime + 10% NaCl at a 28 day curing period
Fig. 4.20  Micrograph of clay with 10% lime + 10% CaCl₂ at a 28 day curing period
Influence of salt on lime stabilization for organic clay

Fig. 4.21 Micrograph of treated clay with 10% lime at a 28 day curing period
4.4 CONCLUSIONS

This chapter concentrates on the effectiveness and mechanism of organic soil stabilized by lime and additional salts. Based on the results, the following conclusions are made:

1. Lime stabilization with additional sodium or calcium salt on organic soil yields relatively high strength compared to that of lime stabilization without any salt.

2. The process of lime-salt on organic clay may be as follows; salts may coagulate with the cation of organic leaving the clay particles exposed to the lime for pozzolanic reaction. In addition, salt can flocculate the soil particles reducing pore space, then the required cementation to bridging between aggregates is relatively low. Hence, higher strength could be achieved.

3. Comparing between the two salts at 10% of salt content, the strength of clay stabilized with lime and sodium chloride is higher than clay stabilized with lime and calcium chloride. However, at 2.5% of salt content, the strength of calcium chloride mixture is higher.
REFERENCES


Chapter 5

INFLUENCE OF OXIDATION AND DRYING DURING STORAGE ON ARIAKE CLAY

5.1 INTRODUCTION

The disposal of surplus Ariake clays from the construction sites has become a serious problem because of its very high water content and low shear strength. **Figure 5.1** and **Figure 5.2** shows the Ariake clay mud at Kubota dike that contains reddish brown color at surface and gray color at inside due to oxidize with oxygen at surface area. The common used method is chemical improvement by stabilizer such as lime or cement (Onitsuka and Shen, 1998). The surplus soils sometimes have to be stored at stockyard prior to utilize in other areas. There is a question that after stored for months in the stockyard the properties of soil are changed or not. The strength of lime stabilization on Ariake clay reduced significantly due to property change during storage has been also reported (Negami, T., 2004, by verbal discussions).

Not only in engineering aspect, but also in agriculture, soil degradation by oxidation phenomenon in the coastal lowland of Southeast Asia has been reported (Kazutake, 2003). Mangrove mud contains sulfidic materials, mainly in the form of pyrite. Acid sulfate soils are formed as a result of the oxidation of pyrite. This happens when the sediments are exposed to the atmosphere, in the course of natural land accretion or in the process of artificial land reclamation. The major fertility problems of acid sulfate soils are a low pH and high level of exchangeable Al, and low level of phosphorus and silica. The proportion of peat in insular Southeast Asia is very high. Southeast Asia has a land area which is only 5% of the world’s total tropical land, but it has some 20 million ha or two-third of the total tropical peat area.

The clay samples are usually altered in color after storage. As illustrated in **Figure 5.3**, Ashikari sample after 3 month storage, the color of soil changes from gray to reddish brown. **Figure 5.4** also shows the change in color of Rokkauka Kawa clay after storage in the bucket for 1 year. Many cases have been reported significant changes in sensitivity, Atterberg limits, and pore water chemistry occurred during
storage. Torrance (1976) reported the effects on the pore water chemistry under a wide variety of conditions after 3 month storage. The soft Champlain clay with a low salinity and a sensitivity of 10-20 was used in testing. The salinity and the percentage of divalent cations in the pore water had increased. The increase in the concentration of calcium and magnesium in the pore water during storage is probably related to attack on carbonates present in soil.

![Image](image1.jpg)

**Fig. 5.1** Clay mud at Kubota dike

![Image](image2.jpg)

**Fig. 5.2** Kubota clay mud showing reddish brown color at first 2 cm at outer surface
Fig. 5.3 Ashikari 1 sample after 3 months storage

(a) Initial condition          (b) After one year storage

Fig. 5.4 Rokkaku Kawa sample before and after one year storage in plastic bucket.
Lessard and Mitchell (1985) also investigated the changes of soft Champlain quick clay over 1 year to evaluate the effect of various storages. Regardless of storage procedure, the remolded strength, plastic limit, and liquid limit increased with time, whereas the sensitivity, the liquidity index and the pH decreased. The water content, plastic limit and undisturbed strength are remained unchanged. Soil properties of Champlain quick clay before and after 14 months under air tight plastic
container are tabulated in Table 5.1. The pore water concentrations of calcium, magnesium, and sulfate were increased by several folds.

Ohtsubo et al. (1991) studied the role of iron oxide on properties of illite. The iron oxide in soil can be observed by the red color on soil surface. They concluded that additional of irons oxide increases the yield stress over a pH range of 3 to 10. The yield stress decreases with increasing pH for lower iron oxide contents. Changes in the yield stress of illite by addition of iron oxide are different depending on whether or not the iron oxide particles in the complex are associated with illite surface.

Comparing with Ariake clay, the Champlain quick clay has lower water content and Atterberg’s limits (Lessard and Mitchell, 1985). The major minerals of Champlain clay are rock-flours mineral such as feldspar, quart, amphibole and calcite while that of Ariake clay are smectite, vermiculite, mica and kaolinite, respectively (Ohtsubo et al., 2000). Thus, the activity of Champlain clay is lower than that of Ariake clay.

Recently, regarding to the problem on oxidized clay, the leak of cannel dike at Rokkaku River was believed that cause from strength reduction of lime-stabilized soil due to oxidation of pyrite at surface clay (Hara and Du, 2006, midterm presentation). Figures 5.1 and 5.2 show the leaking points of dike indicating that the soil color in that area becomes red of iron oxide. However, this case is now under investigation.

There are only few researches regarding to storage effects of Ariake clay and the soil properties of Ariake and Champlain clays are quite different. In order to understand the changes in properties occurring on Ariake clay during storage and their effects on lime stabilization, the testing program was carried out.
Table 5.1 Properties of Champlain and Rokkaku Kawa clays

<table>
<thead>
<tr>
<th>Locations</th>
<th>Champlain quick clay*</th>
<th>Rokkaku Kawa</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditions</td>
<td>Initial</td>
<td>After 14 month storage</td>
<td>Initial</td>
</tr>
<tr>
<td>Water content, $w_n$ (%)</td>
<td>45.0</td>
<td>45.0</td>
<td>123.2</td>
</tr>
<tr>
<td>Liquid limit, $w_L$ (%)</td>
<td>25</td>
<td>40</td>
<td>142</td>
</tr>
<tr>
<td>Plastic limit, $w_P$ (%)</td>
<td>20</td>
<td>20</td>
<td>54</td>
</tr>
<tr>
<td>Specific gravity, $G_s$</td>
<td>2.75</td>
<td>-</td>
<td>2.52</td>
</tr>
<tr>
<td>Particle size distribution (%)</td>
<td>-</td>
<td>-</td>
<td>Gray</td>
</tr>
<tr>
<td>Sand (2.000-0.075 mm)</td>
<td>0</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Silt (0.075-0.005 mm)</td>
<td>48</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>Clay (&lt;0.005 mm)</td>
<td>52</td>
<td>-</td>
<td>68</td>
</tr>
<tr>
<td>Color</td>
<td>-</td>
<td>-</td>
<td>Gray</td>
</tr>
<tr>
<td>NaCl (g/l)</td>
<td>-</td>
<td>-</td>
<td>4.4</td>
</tr>
<tr>
<td>Ignition loss (%)</td>
<td>0.6</td>
<td>-</td>
<td>12.8</td>
</tr>
<tr>
<td>pH</td>
<td>9.5</td>
<td>8.5</td>
<td>7.6</td>
</tr>
<tr>
<td>ORP 3 min</td>
<td>-</td>
<td>-</td>
<td>-128</td>
</tr>
<tr>
<td>ORP 5 min</td>
<td>-</td>
<td>-</td>
<td>-153</td>
</tr>
<tr>
<td>UC test at 28 day on 10% lime stabilized clay, kN/m²</td>
<td>-</td>
<td>-</td>
<td>107</td>
</tr>
</tbody>
</table>

Note: * Data from Lessard and Mitchell (1985).
5.2 SOIL SAMPLE AND METHOD OF INVESTIGATION

5.2.1 Soil Sample

The soft Ariake clay samples used in the testing program consisting of samples from Ashikari and Rokkaku Kawa, Saga prefecture, and Okawa, Fukuoka prefecture. Location map is shown in Figure 2.1. Figure 5.7 shows the site condition at Okawa.

The properties of Ariake clay samples are shown in Tables 5.1 through 5.4. Ariake clay is a very high sensitive clay, which deposited around the coast of Ariake Bay in Kyushu Island, Japan. Its natural water content varies from 50 to 200%. The liquidity index of the Ariake clay is usually larger than 1.

Table 5.2 Properties of Ashikari 1 clay

<table>
<thead>
<tr>
<th>Locations</th>
<th>Ashikari 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditions</td>
<td>Initial</td>
</tr>
<tr>
<td>Water content, ( w_n ) (%)</td>
<td>146.1</td>
</tr>
<tr>
<td>Liquid limit, ( w_L ) (%)</td>
<td>122</td>
</tr>
<tr>
<td>Plastic limit, ( w_P ) (%)</td>
<td>57</td>
</tr>
<tr>
<td>Specific gravity, ( G_s )</td>
<td>2.58</td>
</tr>
<tr>
<td>Particle size distribution (%)</td>
<td></td>
</tr>
<tr>
<td>Sand (2.000-0.075 mm)</td>
<td>2</td>
</tr>
<tr>
<td>Silt (0.075-0.005 mm)</td>
<td>28</td>
</tr>
<tr>
<td>Clay (&lt;0.005 mm)</td>
<td>70</td>
</tr>
<tr>
<td>Color</td>
<td>Gray</td>
</tr>
<tr>
<td>NaCl (g/l)</td>
<td>3.0</td>
</tr>
<tr>
<td>Ignition loss (%)</td>
<td>7.2</td>
</tr>
<tr>
<td>pH</td>
<td>-</td>
</tr>
<tr>
<td>ORP 3 min</td>
<td>-</td>
</tr>
<tr>
<td>ORP 5 min</td>
<td>-</td>
</tr>
</tbody>
</table>
### Table 5.3 Properties of Okawa clay

<table>
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<tr>
<th>Conditions</th>
<th>Initial</th>
<th>Outside</th>
<th>Outside with blue-sheet</th>
<th>In lab.</th>
<th>Oven-drying</th>
<th>Treated by H₂O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage time</td>
<td>-</td>
<td>6 mth.</td>
<td>6 mth</td>
<td>6 mth</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Water content, wₐ (%)</td>
<td>103.1</td>
<td>46.7</td>
<td>100.1</td>
<td>4.6</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td>Liquid limit, wₐ (%)</td>
<td>85</td>
<td>63</td>
<td>97</td>
<td>69</td>
<td>60</td>
<td>71</td>
</tr>
<tr>
<td>Plastic limit, wₚ (%)</td>
<td>41</td>
<td>40</td>
<td>41</td>
<td>39</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Specific gravity, Gₛ</td>
<td>2.56</td>
<td>2.56</td>
<td>2.54</td>
<td>2.54</td>
<td>2.57</td>
<td>2.59</td>
</tr>
<tr>
<td>Particle size distribution (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand (2.000-0.075 mm)</td>
<td>13</td>
<td>8</td>
<td>9</td>
<td>18</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>Silt (0.075-0.005 mm)</td>
<td>43</td>
<td>75</td>
<td>44</td>
<td>52</td>
<td>58</td>
<td>43</td>
</tr>
<tr>
<td>Clay (&lt;0.005 mm)</td>
<td>44</td>
<td>17</td>
<td>47</td>
<td>30</td>
<td>31</td>
<td>44</td>
</tr>
<tr>
<td>NaCl (g/l)</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ignition loss (%)</td>
<td>7.2</td>
<td>7.7</td>
<td>7.7</td>
<td>8.0</td>
<td>7.0</td>
<td>6.1</td>
</tr>
<tr>
<td>pH</td>
<td>8.0</td>
<td>3.3</td>
<td>4.9</td>
<td>7.2</td>
<td>6.7</td>
<td>4.6</td>
</tr>
<tr>
<td>ORP 3 min</td>
<td>-2</td>
<td>372</td>
<td>292</td>
<td>175</td>
<td>280</td>
<td>209</td>
</tr>
<tr>
<td>ORP 5 min</td>
<td>-13</td>
<td>373</td>
<td>288</td>
<td>172</td>
<td>280</td>
<td>210</td>
</tr>
<tr>
<td>Unconfined compression test at 28 day on 10% lime stabilized clay (kN/m²)</td>
<td>2,551</td>
<td>921</td>
<td>1,788</td>
<td>726</td>
<td>833</td>
<td>257</td>
</tr>
</tbody>
</table>

### Table 5.4 Properties of Ashikari 2 clay

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Initial</th>
<th>Outside</th>
<th>Outside with blue-sheet</th>
<th>In lab.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage time</td>
<td>-</td>
<td>1.5 mth</td>
<td>1.5 mth</td>
<td>1.5 mth</td>
</tr>
<tr>
<td>Water content, wₐ (%)</td>
<td>128.2</td>
<td>64.4</td>
<td>97.7</td>
<td>4.4</td>
</tr>
<tr>
<td>Liquid limit, wₐ (%)</td>
<td>97</td>
<td>71</td>
<td>89</td>
<td>71</td>
</tr>
<tr>
<td>Plastic limit, wₚ (%)</td>
<td>37</td>
<td>32</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>Specific gravity, Gₛ</td>
<td>2.57</td>
<td>2.51</td>
<td>2.52</td>
<td>2.52</td>
</tr>
<tr>
<td>Particle size distribution (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand (2.000-0.075 mm)</td>
<td>13</td>
<td>8</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>Silt (0.075-0.005 mm)</td>
<td>29</td>
<td>33</td>
<td>35</td>
<td>54</td>
</tr>
<tr>
<td>Clay (&lt;0.005 mm)</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>33</td>
</tr>
<tr>
<td>NaCl (g/l)</td>
<td>4.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ignition loss (%)</td>
<td>8.7</td>
<td>7.0</td>
<td>6.8</td>
<td>7.4</td>
</tr>
<tr>
<td>pH</td>
<td>8.9</td>
<td>8.7</td>
<td>8.3</td>
<td>9.1</td>
</tr>
<tr>
<td>ORP 3 min</td>
<td>-63</td>
<td>212</td>
<td>185</td>
<td>128</td>
</tr>
<tr>
<td>ORP 5 min</td>
<td>-72</td>
<td>215</td>
<td>188</td>
<td>132</td>
</tr>
</tbody>
</table>
Chapter 5

5.2.2 Investigation Program on Oxidation Process

Samples from Ashikari were used for physical property test immediately after transportation. Then, the samples were wrapped by plastic sheet and stored in the laboratory for 3 months. Color of samples was changed from gray to reddish brown due to oxidation at the surface, however the inside color was still gray as shown in Figure 5.3. The sample was carefully cut into two portions by color. Testing including Atterberg’s limits, oxidation reduction potential (ORP), scanning electron microscope (SEM), pore size distribution and pH were performed.

Secondly, laboratory testing including Atterberg’s limits, ORP, SEM, pH on natural sample and unconfined compression test on lime stabilized sample were performed before and after one year storage on Rokkaku Kawa soil. The sample was stored in plastic bucket, after storage, the color also changed from gray to red as shown in Figure 5.4.

Lastly, samples from Okawa were treated by 6% Hydrogen peroxide ($H_2O_2$) according to pretreatment method of hydrometer analysis for high plasticity soil to simulate the highly oxidized condition. After that, testing was carried out to compare with initial condition. Hydrogen peroxide was chosen as a strong laboratory oxidant for rapid emulation of the relatively slower oxidation in a field environment by $H_2O$ and $O_2$. The potential for improved accuracy in prediction of potential acidity in pyrite through the use of $H_2O_2$ oxidation methodologies has previously been demonstrated by O’shay (1990). Hydrogen peroxide provided $H_2O$ and $O_2$ to soil according to equation 5.1. pH of treated soil was down to 4.6.

\[
2 \text{H}_2\text{O}_2 \rightarrow 2 \text{H}_2\text{O} + \text{O}_2 \quad (5.1)
\]
5.2.3 Investigation Program on Drying Effect

Samples from Okawa and Ashikari 2 were stored in three various conditions including at outside, at outside with covering by blue-sheet and in the laboratory as illustrated in Figure 5.8.

Testing including Atterberg’s limits, ORP, pH, specific gravity, ignition loss and grain size analysis were carried out on both soils. In addition, unconfined compression test on 10% lime stabilized samples conducted on the Okawa soil. The soil samples were performed the testing periodically at the beginning, every week until six weeks and the 3rd month for Okawa soil, and at the beginning, 2nd week, 4th week and 6th week for Ashikari 2 soil. Moreover, additional conditions by oven-drying were carried out on Okawa soil.
a) Outside and outside with blue sheet.

b) In the laboratory

Fig. 5.8 Various conditions of storage
5.2.4 Physical Properties

Physical properties included water content ($w$), liquid limit ($w_L$) and plastic limit ($w_P$), specific gravity (Gs), and grain size distribution. Tests were made according to the procedure given in the test standard JIS (1999), in which $w$ followed the JIS-A1203-1999; $w_L$, and $w_P$ followed the JIS A 1205-1999; Gs followed the JIS A 1202; and the particle size distribution followed the JIS A 1204: 2000.

5.2.5 Oxidation Reduction Potential (ORP)

ORP is the quantitative measurement of electron availability in redox reactions indicating whether the redox couples are in oxidized or reduced state. The ORP was measured directly in soil sample and recorded values at 3 and 5 min. after pushing the electrode probe into the soil.

5.2.6 Unconfined Compression Test of Stabilized Clay

The samples were mixed with 10% of quicklime by mass of dry soil. 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 strain rate of 1% per minute at curing periods of 7, 14 and 28 days according to the procedure of JIS-A1216. Clay 1 and Clay 2 were mixed with 5, 10, 15, 20, and 30% lime, and then Atterberg limit tests were conducted immediately after being mixed to investigate the effect of lime addition on the consistency limits. The tests were also carried out on 10% lime stabilized clays at the curing periods of 7, 14, and 28 days.

5.2.7 Scanning Electron Microscope (SEM)

In order to study the microstructure, samples were prepared as follows. A small piece of natural sample was cut with an iron wire or placed in the bottle cap before by a freeze-dry method to minimize the volume change. The fractured surfaces of samples were coated with gold before scanning by the JSM-5800 JEOL microscope.
5.2.8 Pore Size Distribution

The samples were prepared in the same procedure as SEM by freezing dry method. Then, the samples were measured by mercury intrusion porosimeter.

5.2.9 Consolidation Test

The sample was set in a stainless steel ring with a diameter of 6 cm and height of 2 cm, following the test method for one-dimensional consolidation properties of soils using incremental loading standard of JIS A 1217-2000.

5.3 RESULTS AND DISCUSSIONS

5.3.1 Oxidation Process

Based on Lessard and Mitchell (1985), two major oxidation processes take place in the Champlain quick clay during storage: the organic matter and pyrite oxidations.

5.3.1.1 Organic matter oxidation

The oxidation of carbohydrates or organic matter (for example formaldehyde CH₂O) produces CO₂ according to the reaction

\[ \text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} \] \hspace{1cm} (5.2)

The increase in pressure of CO₂ results in the formation of a weak acid, H₂CO₃, which decreases the pH and increases the concentration of calcium and bicarbonate by dissolving calcium carbonate.

5.3.1.2 Pyrite oxidations

Figure 5.9 shows the various steps involved in the pyrite oxidation. First, pyrite is directly oxidized by oxygen according to the equation

\[ 4\text{FeS}_2(s) + 14\text{O}_2 + 4\text{H}_2\text{O} \rightarrow 4\text{Fe}^{2+} + 8\text{H}^+ + 8\text{SO}_4^{2-} \] \hspace{1cm} (5.3)
Ferrous iron is then oxidized to ferric iron by the reaction

$$4 \text{Fe}^{2+} + 4 \text{H}^+ + \text{O}_2 \rightarrow 4 \text{Fe}^{3+} + 2\text{H}_2\text{O} \quad (5.4)$$

The reaction in (5.4) occurs extremely slowly at low pH unless it is catalyzed by bacterial. The ferric iron formed by the reaction in [5.3] may either participate as $\text{Fe(OH)}_3$ according to the reaction

$$4 \text{Fe}^{3+} + 12\text{H}_2\text{O} \rightarrow 4 \text{Fe(OH)}_3(\text{s}) + 12\text{H}^+ \quad (5.5)$$

or be available to oxidize more $\text{FeS}_2$ to $\text{Fe}^{2+}$ by the reaction

$$4\text{FeS}_2(\text{s}) + 14\text{Fe}^{3+} + 8\text{H}_2\text{O} \rightarrow 15\text{Fe}^{2+} + 2\text{SO}_4^{2-} + 16\text{H}^+ \quad (5.6)$$

In neutral or slightly acid waters, $\text{Fe(OH)}_3$ is insoluble, and the formation of sulfuric acid will be increased which causes a decrease in pH. Sulfuric acid results in dissolution of calcium carbonate in sample. Therefore, the total salinity will be increased resulting in a decrease of interparticle forces and leads to an increase in remolded strength and liquid limit of quick clay.

![Fig. 5.9 Mechanism of pyrite oxidation (Lessard and Mitchell, 1985)](image-url)
5.3.2 Storage Methods

The samples were stored in various conditions to simulate the conditions as stockyard in the field. The various conditions generally made difference in water contents of soil. The plot of water content versus storage time is shown in Figure 5.10. Figures 5.11 through 5.13 illustrates the photos of soil conditions at different periods during storage in outside, outside with cover sheet and laboratory, respectively.

Clays stored in the laboratory yielded the lowest water of about 5% after 3 weeks storage. For the clays stored at outside, the water content was not much low because of occasionally raining and snowing during 3 month storage in the winter season, the water content was about 65% to 75%. The clays stored at outside under cover sheet provided the relatively constant water content which is about 100% to 115% and 65% to 98% for Okawa and Ashikari2 clays, respectively.

Clay under oven-drying produced the dried soil condition having water content 0%.

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**Fig. 5.10 Water content versus storage time at various conditions for Okawa and Ashikari 2 clays**
Fig. 5.11 Okawa clay after storage at outside with different periods
Fig. 5.12 Okawa clay after storage at outside with cover at different periods
Influence of oxidation and drying during storage on Ariake clay

Fig. 5.13 Okawa clay after storage in laboratory at different periods
5.3.3 Atterberg’s Limits

Atterberg’s limits of Ariake clays and Champlain quick clay (data from Lessard and Mitchell, 1985) after storage for various periods and storage conditions, are shown in Figure 5.12. Liquid limits of Ashikari1, Rokkaku Kawa and Okawa clays decreased whiles liquid limit of Champlain quick clay increased. Figures 5.13 and 5.14 show the second series of test indicating Atterberg’s changes during 3 months storage for Okawa and Ashikari 2 clays, respectively.

![Graph showing Atterberg's limits changes](image)

Fig. 5.14 Oxidation effect on Atterberg’s limits of Ariake clays and Champlain quick clay
Influence of oxidation and drying during storage on Ariake clay

Fig. 5.15 Atterberg’s limits of Okawa clay during storage in various conditions (Ohtani et al., 2006)

Fig. 5.16 Atterberg’s limits of Ashikari 2 clay during storage in various conditions (Ohtani et al., 2006)
5.3.4 pH

pH values of Rokkaku Kawa decreased from 7.6 to 5.9 during one year storage. pH of Ashikari clay is showed in Tables 1. pH of Okawa clay treated by H₂O₂ decreased from 8.0 to 4.6. In all clays, pH trends to decrease during storage which is due to acid from oxidation process. Although the declined rates of pH are different in various clays because of difference in organic content, pyrite content and storage conditions. Figure 5.17 illustrates pH value of Okawa and Ashikari 2 clay during storage in various conditions. The result from Okawa clay also states that the rate of decrease in pH is much faster in the higher temperature in summer.

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**Fig. 5.17 pH of Okawa and Ashikari 2 clays during storage in various conditions**
5.3.5 Oxidation Reduction Potential (ORP)

ORP of Rokkaku Kawa clay increased from -153 to 311 mV. ORP of Ashikari clay is shown in Table 1. ORP of Okawa clay treated by H$_2$O$_2$ increased from -13 to 210 mV. **Figure 5.18** shows ORP value of Okawa and Ashikari 2 clay during storage in various conditions. In all clays, ORP trends to increase during storage of first 4-5 weeks and no significant change after that.

![Figure 5.18 ORP of Okawa and Ashikari 2 clays during storage in various conditions](image_url)
5.3.6 Particle Size Analysis

Particle size of Rokkaku Kawa clay was unchanged during one year storage as tabulated in Table 5.1. On the other hand, as shown in Figures 5.19 and 5.20, the particle size of Okawa clay and Ashikari 2 clays decreased in clay-size particle after storage in the laboratory. Clay-content of Okawa clay after oven-drying also decreased from 43% to 31%. Decrease in clay-size content in both cases may be caused from drying effect. However, for other conditions, the clay-size content only slightly changed.

Fig. 5.19 Grain size distribution curves of Okawa during storage in various conditions
Fig. 5.20 Grain size distribution curves of Ashikari 2 during storage in various conditions
5.3.7 Unconfined Compressive Strength of Stabilized Clay

Strength at 28 days curing period of Okawa stabilized clay during 3 month storage in various condition are shown in Figure 5.19. The results show that the sample stored in the laboratory yielded the lowest strength following by the sample at outside and at outside under cover showed the highest strength. The decrease in strength of the stabilized samples is mainly due to effect of drying.

Unconfined compressive strength at 28 days curing period of Rokkaku Kawa stabilized clay decreased from 107 kN/m$^2$ to 42 kN/m$^2$. It is noted that the low in strength of stabilized Rokkaku Kawa soil is because the soil contains high organic content. The strength of stabilized Okawa clay treated by hydrogen peroxide decreased from 2,551 kN/m$^2$ to 257 kN/m$^2$. The reduction in strength is because of oxidation effect as observed by low pH value after storage or treating with H$_2$O$_2$.

From the oxidation process during storage, the process will increase carbonic acid (H$_2$CO$_3$) and sulfuric acid (H$_2$SO$_4$) to the system as shown in equations (5.2) and (5.3). Thus the carbonic acid and sulfuric acid will react with Ca(OH)$_2$ (hydrated lime) derived from quicklime in equation (5.7) to form CaCO$_3$ (Calcium carbonate) and CaSO$_4$ (Gypsum) as shown in equations (5.8) and (5.9), respectively.

$$\text{CaO + H}_2\text{O} \rightarrow \text{Ca(OH)}_2 + \text{heat} \quad (5.7)$$

(Quick lime) (Hydrated lime)

$$\text{Ca(OH)}_2 + \text{H}_2\text{CO}_3 \rightarrow \text{CaCO}_3 + 2\text{H}_2\text{O} \quad (5.8)$$

(Calcium carbonate)

$$\text{Ca(OH)}_2 + \text{H}_2\text{SO}_4 \rightarrow \text{CaSO}_4 + 2\text{H}_2\text{O} \quad (5.9)$$

(Gypsum)

Once content of hydrate lime decreases due to reaction with carbonic and sulfuric acids, then cement product and strength of lime stabilized clay will be decreased.
Fig. 5.21  Unconfined compressive strength of Okawa stabilized with quicklime 10% during storage in various conditions (Ohtani et al., 2006)

5.3.8 Microstructure

The micrographs of red and gray portions of Ashikari clay are illustrated in Figure 5.22. In the gray portion, as typical Ariake clay, diatoms and pyrite (i.e. the small sphere in the middle of the photo) can be observed as illustrated in Figure 5.22a (Tanaka et al., 2001). In the other hand, in the red portion in Figure 5.22b, diatoms and pyrite cannot be clearly observed due to oxidizing. In addition, Figure 5.23 shows micrographs of Rokkaku Kawa clay before and after storage for 1 year. Pyrite and diatom can be easily observed in original sample (Figure 5.23a) and in the 1 year storage sample, pyrite and diatom are difficult to identify as expected (Figure 5.23b). The existing of diatoms and pyrite is shown that soil environment is rather reductive condition (Hino, 2001).
(a) Micrograph of gray portion (10µm) denotes pyrite

(b) Micrograph of red portion (10µm)

Fig. 5.22 Micrograph of Ashikari 1 clay (Kuroiwa et al., 2005)
Influence of oxidation and drying during storage on Ariake clay

(a) Micrograph in initial condition (10µm)

(b) Micrograph after 1 year storage (15µm)

Fig. 5.23 Micrograph of Rokkaku Kawa clay
5.3.9 Pore Size Distribution

Figure 5.24 shows the pore size distribution of red (oxidized) and gray (reduced) portions of Ashikari clay. The red portion has one peak at 4 µm pore diameter while reduce sample has two peaks at about 4 and 10 µm pore diameter. This result is consistent with micrograph that is shown slightly smaller size of void in red portion than gray portion.

Fig. 5.24 Pore size distribution of Ashikari 1 clay (Ifuku et al., 2005)
5.3.10 Compression curve

Compression curves on red and gray portions of Ashikari 1 soil are illustrated in Figure 5.25. The result indicates that the preconsolidation pressure of red potion was less than the gray portion sample about 19 kN/m², however the compression and recompression index of two curves were almost equal. The lower of preconsolidation value in red portion may be due to the sample disturbance by oxidation reaction.

Fig. 5.25  Compression curves of Ashikari 1 clay (Ifuku et al., 2005)
5.3.11 Effect of Oxidation on Liquid Limit

After oxidation, liquid limit of Champlain quick clay increased, while liquid limit of Ariake clays decreased. The explanation for this contradiction follows. Oxidation process increases the formation of Ca\(^{2+}\) because of dissolution of calcium carbonate by acids. Effect of cation exchange on liquid limit is generally different between the expansive and non-expansive clays.

Table 5.5 Atterberg’s limits of two smectite with different exchangeable cations (adopted from, Zhang et al., 2004)

<table>
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<th>Sample</th>
<th>Exchangeable cation</th>
<th>w_L (%)</th>
<th>w_p (%)</th>
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<td>54</td>
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<tr>
<td></td>
<td>K(^+)</td>
<td>660</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>Ca(^{2+})</td>
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<td>Na(^+)</td>
<td>360</td>
<td>51</td>
</tr>
<tr>
<td></td>
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<td>45</td>
</tr>
<tr>
<td></td>
<td>Al(^{3+})</td>
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</tr>
<tr>
<td></td>
<td>Fe(^{3+})</td>
<td>133</td>
<td>79</td>
</tr>
</tbody>
</table>

Notes:
1) Data from Table 3.4 in Lambe and Whitman (1969)
2) Data from Rao et al. (1989): clay treated to become homo-ionic.

For expansive clay like smectite, liquid limit value is strongly influenced by type of cation. Atterberg’s limits of two smectite with different exchangeable cations are tabulated in Table 5.5. Clearly, the Na\(^+\) form has the highest w_L because Na-smectite particles can exist as single 2:1 layers (i.e. two silica tetrahedral sheets and one alumina octahedral sheet; Fig. 5.26) and thus they have a lot of external surface area compared with smectite having other exchange cations as shown in Figure 5.27. Conversely, higher valence cations (e.g. Ca\(^{2+}\), Fe\(^{3+}\)) tend to bond several 2:1 layers to form thicker particles (domains), which result in a significant reduction in the external surface area (Zhang et al., 2004). This is why smectite with higher valence cations have a much smaller w_L than Na-smectite.

For non-expansive clay like kaolinite, liquid limit value is dominated by soil structure. Yong and Waken tin (1966) observed that saturation of kaolinite with
divalent and trivalent cations favors electrostatic attraction between positive edges and negative face leading to flocculated particle arrangement resulting in a higher $w_L$ because of greater amount of water entrapment in soil structure as shown in Figs 5.28 and 5.29. The more acidic a soil (low pH), the greater available of $H^+$ ions for interaction with edge hydroxyl groups and hence the higher the edge positive charge and the degree of positive edge negative face flocculation yielding higher $w_L$ (Sridharan, 1988).

It is possible that the Rokkaku Kawa, Ashikari and Okawa clays are dominated by expansive clay because liquid limit of these clays decreased during storage due to Ca$^{2+}$. 
Chapter 5

Fig. 5.26 Sketch of structure and location of hydrated divalent cations for kaolinite and smectite domains (redrawn from Zhang et al, 2004)
Fig. 5.27 Difference between Na-smectite with thick interacting double layers and Ca-smectite domain with thin double layers (adopted from Zhang et al., 2004)
Fig. 5.28 Positive face and negative edge of clay particles

Fig. 5.29 High valent cation attached or low pH leading to form more flocculated structure in Kaolinite
5.3.12 Effect of Drying

The processes that occur during soil drying can be broadly subdivided into three different mechanisms: mechanical, physio-chemical and chemical (Zhang et al., 2004).

**Mechanical.** The loss of pore water during drying causes a very high matrix suction, which increases the effective stress applied to the soil skeleton. The resultant soil compression (i.e. shrinking) breaks interparticle cementation bonds and reduces the size and strength of the aggregates. This process is similar to remoulding and makes an aggregated soil more easily dispersed.

**Physico-chemical.** This mechanism involves the loss of diffuse double layer, adsorbed and absorbed water. The two latter forms of water involve dehydration of the surface exchangeable cations and the interlayer cations of clay minerals respectively (Fig. 5.27). Oven-drying will totally remove the water associated with hydrated cations, whereas air-drying will partially remove such water. The dehydrated exchangeable cations (e.g. Ca$^{2+}$, Fe$^{3+}$, but not Na$^+$) associated with clay surfaces tend to bond more 2:1 layers to form thicker domains. In case of monovalent cation, the Na$^+$ promotes strong interparticle repulsion and large particle separation while in di- and trivalent cations promote strong inter-particle attraction and small particle separations (Rao et al., 1989). That is why drying on Na$^+$ smectite is not formed thicker domain. Although thicker domains may not change the clay size fraction, they will result in a considerable reduction in the effective external surface area. Furthermore, completely dehydrated interlayer cations can bond adjacent layers so as to prevent rehydration when the soil is rewetted. Hence oven-drying reduces the effect of absorbed water on the measured Atterberg limits.

**Chemical.** Two chemical reactions occur during drying:

Soluble salts are precipitated from the pore water solution. If the pore water contains a high concentration of soluble salts, the precipitates usually form ate particle contacts and can act as cementation that bonds particles together. If some newly form precipitates are insoluble in water, this process is irreversible, that is, the precipitate will trend to increase the particle size and decrease the plasticity.
It has been recognized that partially dried clay surface possess high acidity (Moore and Reynolds, 1997). During drying, the adsorbed water layer on clay surfaces become increasingly thin, and the remaining water molecules dissociate more than free water, generating a very low pH. This strong surface acidity is responsible for dissolution of cementation, and consequently the weaker aggregates can be more readily broken down to produce a more dispersed soil.

Based on the above discussion, the effect of drying on the grain size distribution of Okawa and Ashikari 2 clays (Figs 5.19 and 5.20) can be interpreted. During drying, all mechanisms take place except the precipitation of soluble salts, because this soil has a very low concentration of salts (Tables 5.3 and 5.4).

The effect of drying on Okawa and Ashikari 2 clays results in decrease in both $w_L$ and $w_p$ (Figs 5.15 and 5.16). The presence of smectite with higher valence cations (e.g. $Ca^{2+}$, $Fe^{3+}$), whose $w_L$ and $w_p$ decrease with drying. With abundant rainfall, $Na^+$ is usually leached out by pore water flow. Thus, this soil’s $w_L$ and $w_p$ could be expected to be reduced by oven-drying which probably is caused by the physico-chemical mechanisms discussed above.

During drying, the water between clay particles is removed and dehydrated exchangeable cations associated with clay surfaces tend to bond more layers to form thicker domains. As a result, the clay-size fractions decrease and specific surface area is considerably reduced. Thus the surface area for dissolving silica or alumina is decrease resulting in reduction of strength in lime stabilized clay.
5.4 CONCLUSIONS

This chapter concentrated on oxidation process influencing on soil properties and strength of soil stabilization. Based on results the following conclusions are made:

1. The oxidation process plays important role on soil properties during storage. The process begins from the oxidation of pyrite, which results in producing of sulfuric acid. The acid causes the dissolution of calcium carbonate, which increases the concentration of divalent cation in clay, thus altering in soil properties.

2. As the increase in calcium ion in oxidation process, liquid limit of clay was changed. For kaolinite dominate clay, liquid limit will increase because soil structure attraction between positive edges and negative face leading to flocculated particle arrangement when di- or trivalent cation attached, resulting in greater mount of water entrapment, thus higher liquid limit. On the other hand, in smectite dominate clay like Ariake clay, liquid limit will decrease because its value is strongly influenced by type of cation. The Na$^+$ form has the highest liquid limit. Conversely, higher valence cations (e.g. Ca$^{2+}$, Fe$^{3+}$) tend to bond several 2:1 layers to form thicker particles (domains), which result in lower liquid limit.

3. The effect of oxidation also influences on the strength of lime stabilized clay. As oxidation process generating carbonic acid and sulfuric acid, these acids will react with hydrated lime affecting in reduction in amount of lime, which will be used in pozzolanic reaction to produce cement products. Hence, the strength of lime stabilized clay will be decreased.

4. In addition, ORP increasing indicates the change of environment to oxidation. The micrographs show that after storage, pyrites are disappeared because of oxidation.

5. The effect of drying on Okawa and Ashikari clays results in decrease in both Atterberg limits and the strength in lime stabilized clay. The presence of smectite with higher valence cations (e.g. Ca$^{2+}$, Fe$^{3+}$), whose $w_L$ and $w_p$ decrease because the dehydrated exchangeable cations associated with clay surfaces tend to bond more 2:1 layers to form thicker domains. As a result, the clay-size fractions
decrease and specific surface area is considerably reduced. Thus the liquid and plastic limits, and strength in lime stabilized clay decrease.

6. In application, the proper storage at field shall be provided by preventing the soil from oxidation and drying, which can cause the low strength in lime stabilized soil. pH is good indicator in order to monitor the oxidation effect during storage.
REFERENCES


Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

This dissertation focuses on the influence of storage conditions on geotechnical properties and chemical stabilization for soft clays. In order to investigate the mechanism, the laboratory tests as unconfined compression, SEM, organic matter, salt concentration, pH, chemical composition analysis, pore size distribution, and Atterberg limits tests were carried out. The study explained about the effect of various factors including salts, clay minerals and diatom on strength of cement and lime stabilized clays. The mechanism of lime stabilized organic clay and improving strength by salt additive were pointed out. The mechanism of oxidation and drying effects during storage before treated by lime were also investigated and recommended the suitable method for storage at site. In addition, the microstructure of soil was carried out to explain the mechanisms of those mentioned.

6.1 CONCLUSIONS

The results and discussions pointed out the effects of various factors on chemical stabilized clays and the influence of salt on lime stabilized organic clay were demonstrated in Chapter 3 and Chapter 4. Chapter 5 pointed out the influence of oxidation and drying effects during storage. The following conclusions can be made:

1. Chapter 3 focuses on the effect of various factors including salts, diatom and clay mineral on cement and lime-treated clays. The results are summarized as below:

   (1) For cement stabilization of Bangkok clay, Kaolin and Bentonite, the positive factors (strength increasing after adding these materials) in descending order are diatom content, cement content, CaCl$_2$ and NaCl. The negative factors (strength decreasing after adding these materials) of Bangkok clay are pyrite, Kaolin and Bentonite, in descending order.
(2) For cement stabilization of Ariake clay, the positive factors are only cement content and diatom content, respectively. The negative factors are CaCl$_2$, NaCl, Kaolin and Bentonite, in descending order.

(3) For lime stabilization of Ariake clay, the positive factors are only lime content and NaCl at 5%, respectively. The negative factors are Diatom, CaCl$_2$, Bentonite and Kaolin, in descending order.

(4) The different characteristics of two clays after treating with various admixtures may be due to the differences in chemical properties. Furthermore, the micrograph is useful to explain the mechanism and behaviors of stabilized soils more clearly.

2. Addition of salts contributes to significantly increase in strength of lime-stabilized organic clay. The mechanism of this process investigated in Chapter 4 can be summarized as following.

(1) Lime stabilization with additional sodium or calcium salt on organic soil yields relatively high strength compared to that of lime stabilization without any salt.

(2) The process of lime-salt on organic clay may be as follows; salts may coagulate with the cation of organic leaving the clay particles exposed to the lime for pozzolanic reaction. In addition, salt can flocculate the soil particles reducing pore space, then the required cementation to bridging between aggregates is relatively low. Hence, higher strength could be achieved.

(3) Comparing between the two salts at 10% of salt content, the strength of clay stabilized with lime and sodium chloride is higher than clay stabilized with lime and calcium chloride. However at 2.5% of salt content, the strength of calcium chloride mixture is higher.

3. Chapter 5 focuses on the mechanism of oxidation and drying effects during storage before treated by lime. Based on results the following conclusions are made:

(1) The oxidation process plays important role on soil properties during storage.
The process begins from the oxidation of pyrite, which results in producing of sulfuric acid. The acid causes the dissolution of calcium carbonate, which increases the concentration of divalent cation in clay, thus altering in soil properties.

(2) As the increase in calcium ion in oxidation process, liquid limit of clay was changed. For kaolinite dominate clay, liquid limit will increase because soil structure attraction between positive edges and negative face leading to flocculated particle arrangement when di- or trivalent cation attached, resulting in greater mount of water entrapment, thus higher liquid limit. On the other hand, in smectite dominate clay like Ariake clay, liquid limit will decrease because its value is strongly influenced by type of cation. The Na⁺ form has the highest liquid limit. Conversely, higher valence cations (e.g. Ca²⁺, Fe³⁺) tend to bond several 2:1 layers to form thicker particles (domains), which result in lower liquid limit.

(3) The effect of oxidation also influences on the strength of lime stabilized clay. As oxidation process generating carbonic acid and sulfuric acid, these acids will react with hydrated lime affecting in reduction in amount of lime, which will be used in pozzolanic reaction to produce cement products. Hence, the strength of lime stabilized clay will be decreased.

(4) In addition, ORP increasing indicates the change of environment to oxidation. The micrographs show that after storage, pyrites are disappeared because of oxidation.

(5) The effect of drying on Okawa and Ashikari clays results in decrease in both liquid and plastic limits and the strength in lime stabilized clay. The presence of smectite with higher valence cations (e.g. Ca²⁺, Fe³⁺), whose w_L and w_p decrease because the dehydrated exchangeable cations associated with clay surfaces tend to bond more 2:1 layers to form thicker domains. As a result, the clay-size fractions decrease and specific surface area is considerably reduced. Thus the liquid and plastic limits, and strength in lime stabilized clay decrease.
6.2 RECOMMENDATIONS

1. In application, the proper storage at field shall be provided by preventing the soil from oxidation and drying, which can cause the low strength in lime stabilized soil. pH is good indicator in order to monitor the oxidation effect during storage.

2. This study concerns only the factors on the properties of clay. The influence factors such as the curing condition in the field, the homogeneous of mixing, method of mixing, and time of mixing from field construction is also very interesting to investigate. The full scale shall be constructed and compared to the laboratory data for finding out the safety factor.

3. Not only discuss about the most effective admixture, the engineering behavior and the economic, but also the environmental assessment is one of the main aspects to select the suitable stabilizer in this century. The study shall be pointed out on the leaching of chemical in lime or cement on the surrounding improvement area. In order to investigate on the leachate of lime-stabilized clay, the column leaching test shall be carried out and compared to the standard criteria. For another the environmental aspect, the lime or cement stabilized clay can be applied to be the clay liner because of its low permeability. The centrifuge machine is applied for this investigation.

4. The investigation by chemical test such as X-ray test, homoionic clays, pyrite contents and sulfuric content shall be performed to verify the conclusions.

5. Sea water used instead of additional salt in lime stabilized organic clay shall be investigated to reduce the cost of construction in the field.
# NOTATIONS

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<td>$\varepsilon$</td>
<td>Axial stain</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>Density of soil particle (g/cm$^3$)</td>
</tr>
</tbody>
</table>
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