Doctoral Thesis

Comprehensive Research on Improvement and Evaluation Method of Clay with High Water Content under Low Environmental Loading

低環境負荷における高含水比粘土の改良及び評価方法に関する研究

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2. ABSTRACT

A large amount of waste dredged clay (WDC) was produced during the reconstruction of Kumamoto Ohkirihata Reservoir. Due to its extremely high-water content, the WDC even makes transportation a challenge. Experiments show that WDC with a natural water content of 1.1-1.3 times the liquid limit (1.1-1.3w_L) under the condition that no matter what form of solidifying agent is difficult to effectively improve is necessary to reduce the natural water content before improvement. This paper proposes a low-cost and low-energy improvement method for on-site high-water content WDC treatment. Firstly, synthetic materials were used to dehydrate WDC in its natural state. After one month of dehydration, the initial water content of WDC decreased from 1.5 w_L to 0.9 w_L. Then, the curing agent was added to achieve high strength improvement under a low mixing amount.

In addition, clays with high water content are normally treated by cement or cement-based solidifying agent for utilization as geomaterial in the construction of soil structures. Selection of geomaterials is based on mechanical properties such as strength and stiffness. The mechanical properties of clay improvement greatly depends on the water content and content of solidifying agent. It is important to evaluate accurately the improvement effect of clay with different physical or chemical properties for making high-quality improved clay at a low cost. In order to assess the performance of high-water-content clayey sediments at different liquid limits as the clays are treated with cement-based solidifying materials. Three clay samples are obtained from different locations in the Kumamoto Reservoir. Two types of cement-based solidifying agents, namely, Ordinary Portland Cement and a cement-fly ash binder, are used. Using the initial water content of clay and the mixing amount of the solidifying agent as experimental variables, a cone penetration test is performed on the solidifying-agent-stabilized clays to obtain the cone index (q_c). The results showed that when the water content to cementitious content ratio (w/A_w) was used as a parameter for evaluating the improvement of solidifying agent-stabilized clay, different forms of improvements were observed when different water and solidifying agent contents were used. This implies that the parameter w/A_w is not suitable for evaluating the improvement of such clay. A new parameter, K, representing the content of solidifying agent, is introduced to account for the water content. For all sampled clays, the correlation coefficients for the K–ln q_c relationship exceed 0.9. Considering the effect of the liquid limit of the samples, the modified content of the solidifying agent, K_L, is introduced to evaluate the cone index of the stabilized soils. It is discovered that the proposed equation unifies the assessment of the improvement of the three samples of Kumamoto clayey sediments owing to the new parameter K_L.

In order to judge the improvement effect of clay from the physical properties of clay, two types of solidifying agents, namely ordinary Portland cement (OPC) and fly ash-containing solidifying agent (DF), were used for five kinds of clays with different liquid limits (w_L) and ignition loss. A cone penetration test was performed on the improved clays to obtain cone index. A new parameter, K_L, for representing an effect of content of solidifying agent was introduced by considering liquid limit. An empirical equation of the cone index (q_c) with the modified content of solidifying agent (K_L) was proposed based on the experimental results.

It was clear that parameters on the q_c-K_L empirical equation relate to liquid limit, ignition loss, and type of solidifying agent.

The accumulation of a large amount of cow dung and oyster shells and the production of cement and other solidifying agents have led to serious environmental problems. In order to solve this problem, this study proposes a clay improvement case using calcined oyster shells (COS) and carbonized cow dung compost (CC) as substitutes for cement to stabilize clay with high-water content. In this study, the solidifying agent/water ratio, $C/(w/100)$, was introduced as an important parameter to evaluate the improvement effect of COS stabilized clay. Compared with ordinary Portland cement (OPC), the amount of COS required for effective improvement is significantly reduced ($\approx$ 43%–46%). In addition, the incorporation of more environmentally friendly carbonation materials improves the improvement effect of COS stabilized clay. A comparison with commercial wood charcoal proved that CC with better adsorption capacity improved high-water-content clay. The test results of energy-dispersive X-ray spectrometry (EDS) and scanning electron microscope (SEM) show that with an increase in COS content, the reaction product hydrated calcium silicate is formed, and the improvement effect of stabilized clay is enhanced. In addition, the incorporation of water-absorbent materials reduced the void space in the clay structure, which is conducive to stabilizing the internal cementation of clay. SEM evidenced the change of microstructure of the stabilized clay owing to the solidifying materials.

Keywords: Waste dredged clay, Solidifying agent, Reutilization, Liquid limit, Cone index, Stabilized clay, Evaluate method, High water content, clayey sediment, Cement, Fly ash, Soft clay, Solidifying agent, Calcined oyster shell, improvement effect, carbide

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1. Introduction

1.1 Background

1.1.1 Production and utilization status of high-water content dredged clay

With the construction and renovation of infrastructures such as reservoirs and swamps, a large amount of dredged clay at the bottom of the reservoir needs to be treated. According to the ministry of the environmental survey in Japan, the reservoir and artificial lakes of above 10 million cubic meters exceed 100,000 (MOE). From 1978 to 2010, with the decline of the water level line, the sediment accumulation of reservoirs has increased year by year (Sumi., 2013). Due to the construction and renovation of infrastructures such as reservoirs and swamps, about $2*10^7$ m^3 of dredged soils is produced yearly (JCMA, 2015). Fine-grained clay accounts for about 2/3 of the total. On the one hand, the high-water content liquid dredged clay unearthed is difficult to be improved, and the transportation cost is high. On the other hand, finding suitable land to treat waste dredged clay is difficult. In coastal areas, the area of landfillable public waters is decreasing year by year. Inland areas, the long-distance treatment of land and the high cost of treatment and transportation have become extremely obvious, and the reuse of dredged clay has become an urgent problem to be solved. Dredged clay has high water and organic content, resulting in poor engineering properties. Therefore, the mechanical properties of the clay must be improved before it is used for construction.

One necessary treatment is dewatering slurry sediment before use as landfilling material or dumping at the disposal site. According to Flemmy et al., (2019) and Zhang et al., (2019), dewatering of slurry clay before adding admixture will reduce the amount admixing agents (lime, cement or fly ash) needed for improving the strength of dredged clay. There are numerous techniques for dewatering high‑water content clay. However, a choice of dewatering method will be made by considering a treatment cost, period of construction, efficiency of the technique, and environmental impact. The dewatering of soft clay by preloading or surcharge method has been used widely in place of traditional sun drying method which takes 2 to 4 months to satisfactorily remove water from slurry clay/dredged sediment. However, dewatering by preloading without vertical drain is not spontaneous. During the dewatering process using preloading method, fine particles shift into the void pores of the soil. When this happens, the dewatering rate will be reduced. Generally, preloading method is not suitable for treating highly sensitive clay. According to Ali A. et al., (2019), vertical drains (sand, paper or PVD) are used to accelerate slurry clay dewatering rate.

Cement has been widely used to improve soft clay. At the initial stage of mixing the clay cement, the natural bonds inside the clay matrices are destroyed, whereas new bonds are created owing to the

effect by cement. A small portion of the dredged clay improved using cement-based solidifying agents has been extensively used in port construction in many countries, such as Japan and Thailand (Satoh, 2003; Satoh et al., 2001; Jamnongpipatkul et al., 2009). In addition, fly ash (FA) is one of the materials extracted from the flue gases of a furnace fried with coal from an electric power plant. Its generation is significantly greater than its utilization. In fact, researchers have attempted to use fly ash from industries to reduce cement input (Chindaprasirt et al., 2004; Singh et al., 2008; Yoobanpot et al., 2017; Xiao et al., 2018; Yu et al., 2018). As a partial substitute for cement, fly ash has a positive effect on improving soil environmental problems.

The Mw 6.2 foreshock and Mw 7.0 mainshock of the 2016 Kumamoto earthquakes occurred at 21:26 JST on April 14 and at 01:25 JST on April 16, respectively. The earthquake sequence damaged significantly buildings and infrastructure around the Kumamoto City (Goda et al., 2016). During the Kumamoto earthquake, violent shaking also occurred around the Ohkirihata reservoir. As shown in Fig.1.1, the Ohkirihata reservoir diversion facilities are damaged, and a large amount of water leakage leads to a serious decline in water level. During the investigation after the Kumamoto earthquake, a fault was found directly below the Ohkirihata reservoir. According to the Kumamoto Restoration and Rehabilitation 4-Year Strategy issued by the Kumamoto Prefecture of Japan in December 2016, it was decided to build a new reservoir 237 meters upstream of the original Kumamoto Reservoir. The resulting large amount of waste dredged clay needs to be treated. For waste dredged clay with high water content from Kumamoto Ohkirihata Reservoir, to obtain high strength stabilized clay by adding

(a) Water diversion equipment damaged

(b) leakage positions

(c) Damage to surrounding roads

Fig. 1.1. The disaster situation of Ohkirihata reservoir after Kumamoto earthquake in 2016. （https://haradaoffice.biz/ohkirihata-dam/.）

a large amount of cement-based curing agent, which is neither environmentally friendly nor economical. In addition, liquid clay's dehydration methods usually include mechanical and natural dehydration. Mechanical dehydration costs are high, and the additional power consumption causes greenhouse gas CO_2 emissions. Natural dehydration requires transportation and storage, bringing environmental problems and increasing management costs. A more environmentally and cost-effective and easy-to-use recycling method for waste dredged clay is still in high demand.

1.1.2 Stabilization using cement

One of the common methods of chemical stabilization is to mix soil with cement to form a product named as soil–cement (Croft, 1967). Soil–cement can be defined as a mixture of soil and measured amounts of Portland cement and water and compacted to the desired density. Soil–cement has been used as a base material as an adoption of improved measure in many projects, such as slope protection of dams and embankments, pavement of highways, building pads, terminals for rail and truck, composting facilities, cheap base for streets, parking lots, channels and reservoir linings, mass soil–cement placement for dikes, foundation stabilization etc. It serves to amend the mechanical and the engineering properties of the soil. The new performance depends on the ability of the additives to react with the mixing soil. There are four main properties of soil; strength, permeability, volume stability, and durability that can be enhanced with additives (Estabragh, et al., 2013; Anggraini, et al., 2014). The choice of a specific additive depends on the type of soil, service that is required to serve and the surrounding environment. When water is mixed with cement, hydration occurs, meaning cementing compounds of calcium–silicate–hydrate (C–S–H) and calcium–aluminate–hydrate (C–A–H) are formed and excess calcium hydroxide $(CaOH)_2$ is released, approximately 31% by weight (Parsons and Milburn, 2003). Formation of C–S–H and C–A–H occurs when crystals begin forming a few hours after the water and cement are mixed; crystals will continue to form as long as unreacted cement particles and free water remain within the mixture (Khan, et al., 2015).

The other significant effects of soil–cement stabilization is reduction in shrinkage and swell potential, increase in strength, elastic modulus, and resistance against the effect of moisture, freeze, and thaw. Cement treated soils show a brittle behavior compare of non-treated soils (Jones and Jefferson, 2012; Al-Rawas, et al., 2005). Cement can be applied to stabilize any type of soil, except soils with organic content greater than 2% or having pH lower than 5.3 (ACI 230.1R-90, 1990). There are many factors contributing to the length of curing time required for strength gain in soil–cement samples. These include ambient air temperature, relative humidity, type of cement used, and concentration of cement used.

1.1.3 Stabilization using lime

Limestone is broken down at elevated temperatures to form lime (Chittoori, 2008). As a result, three forms of lime are produced: quicklime (calcium oxide–CaO), hydrated lime (calcium hydroxide–$Ca(OH)_2$), and hydrated lime slurry; all of which can be used to treat soils. Quicklime is manufactured by chemically transforming calcium carbonate (limestone–$CaCO_3$) into calcium oxide. Furthermore, hydrated lime is created when quicklime chemically reacts with water. When hydrated lime is mixed with clay particles, it permanently forms strong cementitious bonds (Bell,1996; Tedesco, 2006; Louafi, et al., 2015). Lime has been known to reduce the swelling potential, liquid limit, plasticity index and maximum dry density of the soil, and increases its optimum water content, shrinkage limit and strength (Croft, 1967; Pei, et al., 2015). It improves the workability and compact ability of subgrade soils (Jung and Bobet, 2008).

If quicklime is used, it immediately hydrates (i.e., chemically combines with water) and releases heat. Soils are dried, because water present in the soil participates in this reaction, and because the heat generated can evaporate additional moisture. The hydrated lime produced by these initial reactions will subsequently react with clay particles. These subsequent reactions will slowly produce additional drying because they reduce the soil's moisture holding capacity. If hydrated lime or hydrated lime slurry is used instead of quicklime, drying occurs only through the chemical changes in the soil that reduce its capacity to hold water and increase its stability. After initial mixing, the calcium ions (Ca^{2+}) from hydrated lime migrate to the surface of the clay particles and displace water and other ions. The soil becomes friable and granular, making it easier to work and compact. At this stage the Plasticity Index of the soil decreases dramatically, as does its tendency to swell and shrink. The process, which is called "flocculation and agglomeration" generally occurs in a matter of hours.

1.1.4 Stabilization using fly ash

For sustainable development purpose, the use of local soil, waste and industrial byproduct are encouraged to supply earthwork and earthen structure (Furlan, et al., 2018; Siham, et al., 2008; Phetchuay, et al., 2016). Two well-known industrial byproducts are often cited: bottom ash and fly ash. The benefits of use of bottom ash for road construction was been recently studied by different authors (Hung-Le, et al., 2018; Thuy Minh Nguyen, et al., 2018; Yoobanpot, et al., 2020). On the other hand, the use of fly ash still requires further investigation because different mechanisms of interaction need to be clarified. Researches in concrete technology has demonstrated that fly ash (FA) improves mechanical properties of concrete, reduces the costs of production and is ecologically beneficial. FA addition may enhance durability of the matrix and reduces the loss of heat energy during cement hydration (Yin, et al., 2018; Lee, et al., 2003). FA is a waste from coal-fired electrical power plants

that is being studied as admixture in soil stabilization (Furlan, et al., 2018; Horpibulsuk, et al., 2009; Phetchuay, et al., 2016). Commonly, FA is composed by calcium, silicon and aluminium. The main oxides are CaO, SiO_2 and Al_2O_3. Class C Fly ash contains about 20% of CaO which might induce cation exchanges, flocculation and pozzolanic reactions, resulting in strength gain. Aluminum rich composition of FA might promote a specific cementitious compounds formation, such as C-A-H and C-A-S-H (Solanki and Zaman, 2012; Chew, et al., 2004; Fernandez, et al., 2016).

In concrete, FA addition stimulates reaction rate of cement hydration, promotes nucleation and growth of cementitious compounds. The effects of FA action on soils are then physical and chemical. At physical point of view, finer particles of FA would fill voids of soil particles. Chemically, pozzolanic products induced by FA presence would fill pores. Both effects reduce porosity so that microstructure becomes denser. As results, strength and stiffness are increased and compressibility is reduced (Kang, et al., 2015).

1.2 Objective and thesis structure

This study proposed a method for improving and evaluating clay with a high-water content ratio based on the clay field reconstruction project in the Kumamoto Ohkirihata reservoir. The purpose is to effectively improve high water content clay with low environmental load and cost.

Chapter 1 gives a brief introduction of the background, the objective and the structure of this thesis.

In Chapter 2, the field investigation of the original Kumamoto Ohkirihata Reservoir was carried out, and the accumulation of the abandoned dredged clay was obtained. An improved scheme is proposed for the characteristics of high-water content and high organic matter content of waste-dredged clay.

In Chapter 3, three clay samples were obtained from different locations of the Kumamoto Ohkirihata Reservoir. Two types of cement-based solidifying agents, namely, Ordinary Portland cement and a cement-fly ash binder, are used. Using the initial water content of clay and the mixing amount of the solidifying agent as experimental variables, a cone penetration test is performed on the solidifying-agent-stabilized clays to obtain the cone index (q_c). The proposed equation unifies the evaluation of the improvement of three samples of Kumamoto clay sediments.

In Chapter 4, two types of solidifying agents, namely Ordinary Portland cement (OPC) and fly ash-containing solidifying agent (DF), were used for five kinds of clays with different liquid limits (w_L) and ignition loss. A cone penetration test was performed on the improved clays to obtain the cone index. A new parameter, K_L, for representing an effect of the content of solidifying agent was introduced by considering the liquid limit. An empirical equation of the cone index (q_c) with the modified content of solidifying agent (K_L) was proposed based on the experimental results.

Chapter 5 introduces several methods of stabilizing high-water content clay under low environmental load. The effect of calcined oyster shells (COS) on the mechanical properties of clay was investigated. In addition, biochar (BC) was considered in the study to reduce the incorporation of the solidifying agent in COS-stabilized soil. SEM, EDS and cone penetration tests were carried out to study stabilized clay's microstructure and mechanical properties.

Chapter 6 summarizes the major conclusions obtained from the studies of this thesis.

Comprehensive Research on Improvement and Evaluation Method of Clay with High Water Content under Low Environmental

Chapter 1: Introductions

Chapter 2: Investigation on dehydration and improvement effect of waste dredged clay with high water content.

Part 1: Taking Kumamoto Ohkirihata reservoir clay as a case, the improvement method of high-water content clay is discussed.

Chapter 3: Evaluation on improvement effect of Kumamoto waste dredged clay.

Chapter 4: Unified evaluation of the improvement effect of different clay types based on the physical properties of clay.

Part 2: Discussion on the empirical formula for evaluating improvement effect of high-water content clay.

Chapter 5: Investigation on improving method of high-water content clay under low environmental load.

Part 3: To reduce the environmental load, a new composite material was proposed to stabilize high-water content clay.
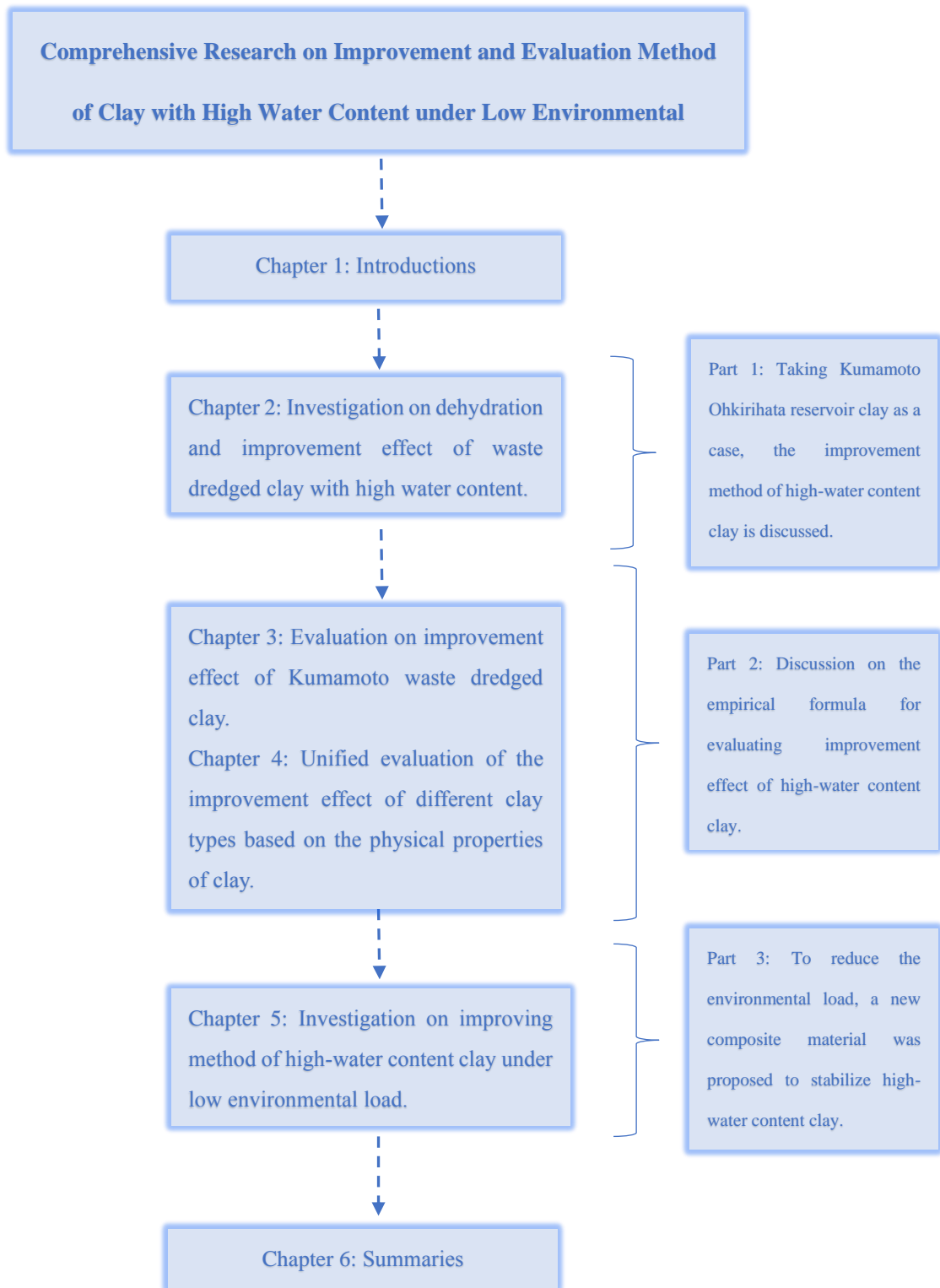
Chapter 6: Summaries

Fig. 1.2. The structure of this thesis.

References

Ali A, Mohammed S, and Ameer A (2019), Evaluation of vertical drain with different materials. International Conference on Civil Engineering, 584. 1012011.Doi.10.1088/1757.

Al-Rawas AA, Hago AW, Al-Sarmi H (2005), Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman. Build Environ 40(5):681–687. https://doi.org/10.1016/j.buildenv.2004.08.028.

Anggraini V, Huat BBK, Asadi A, Nahazanan H (2014), Effect of coir fibre and lime on geotechnical properties of marine clay soil. In: 7th International congress on environmental geotechnics: iceg2014, engineers, Australia. pp1430.

Bell FG (1996), Lime stabilization of clay minerals and soils. Eng Geol 42(4):223–237. https://doi.org/10.1016/0013-7952(96)00028-2.

Chew SH, Kamruzzaman AHM, Lee FH (2004), Physicochemical and engineering behavior of cement treated clays. J. Geotech. Eng., 130 (7), pp. 696-706. 10.1061/(ASCE)1090-024130:7(696).

Chindaprasirt P, Homwuttiwong S, Sirivivatnanon V (2004), Influence of fly ash fineness on strength, drying shrinkage and sulfate resistance of blended cement mortar. Cement Concrete Res. 34 (7), 1087-l092. https://doi.org/10.1016/j.cemconres.2003.11.021.

Chittoori BCS (2008), Clay mineralogy effects on long-term performance of chemically treated expansive clays, Doctoral dissertation, The University of Texas at Arlington.

Croft JB (1967), The influence of soil mineralogical composition on cement stabilization. Geotechnique 17(2):119–135. https://doi.org/10.1680/geot.1967.17.2.119.

Estabragh AR, Bordbar AT, Javadi AA (2013), A study on the mechanical behavior of a fiber-clay composite with natural fiber. Geotech Geol Eng 31(2):501–510. https://doi.org/10.1007/s10706-012-9602-6.

Fernandez R, Ruiz AI, Cuevas J (2016), Formation of C-A-S-H phases from the interaction between concrete or cement and bentonite. Clay Miner., 51, pp. 223-235. 10.1180/claymin.2016.051.2.09.

Flemmy SO, Omine K, and Zicheng Z (2019), Soft clay improvement technique by dewatering and mixing sand soil. International Journal of Geomate, 17 (63): 9-16. DOI: 10.1007/978-981-16-0077-7_3.

Furlan AP, Razakamanantsoa A, Ranaivomanana H, Levacher D, Katsumi T (2018), Shear strength performance of marine sediments stabilized using cement, lime and fly ash, 184:454–463. DOI: 10.1016/j.conbuildmat.2018.06.231.

Goda, K, et al (2016), The 2016 Kumamoto earthquakes: cascading geological hazards and compounding risks. Frontiers in built environment, 2016, 2: 19. https://doi.org/10.3389/fbuil.2016.00019.

Horpibulsuk S, Rachan R, Raksachon Y (2009), Role of fly ash on strength and microstructure development in blended cement stabilized silty clay. Soils Found., 48 (1), pp. 85-98. 10.3208/sandf.49.85.

Hung-Le N, Razakamanantsoa A, Nguyen M, Phan VT, Dao P, Nguyen DH (2018), Evaluation of physicochemical and hydromechanical properties of MSWI bottom ash for road construction, 80:168-174. DOI: 10.1016/j.wasman.2018.09.007.

Jamnongpipatkul P, Dechasakulsom M, Sukolrat J (2009), Application of air-foam stabilized soil for bridge-embankment transition zone in Thailand. In GeoHuman International Conference 2009, Changsha, China, August 3-6 2009. https://doi.org/10.1061/41042(349)24.

Japan Construction Machinery and Construction Association (JCMA) (2015) Separation, classification, effective use of dredged soil and tsunami deposits, and disposal volume reduction (in Japanese). https://jcmanet.or.jp/bunken/kikanshi/2015/01/015.pdf

Jones LD, Jefferson I (2012), Expansive soils. ICE Publishing, London, pp 413–441.

Jung C, Bobet A (2008), Post-construction evaluation of lime-treated soils. https://doi.org/10.5703/1288284313443.

Kang X, Kang GC, Chang KT, Ge L (2015), Chemically stabilized soft clays for road-base construction. J. Mater. Civil. Eng. ASCE 27 (7) (2015) ASCE4 (ASCE) MT.1943-5533.0001156.

Khan TA, Taha MR, Firoozi AA, Firoozi AA (2015), Strength tests of enzyme-treated illite and black soil mixtures. In: Proceedings of the institution of civil engineers-engineering sustainability, vol. 169, no. 5. Thomas Telford Ltd, Westminster. pp 214–222.

Lee CY, Lee HK, Lee KM (2003), Strength and microstructural characteristics of chemically activated fly ash–cement systems. Cem. Concr. Res., 33, pp. 425-431. 10.1016/S0008- 8846(02)00973-0.

Louafi B, Hadef B, Bahar R (2015), Improvement of geotechnical characteristics of clay soils using lime. In: Advanced materials research, vol 1105. Trans Tech Publications, Zürich. pp 315–319.

MOE (Ministry of the Environment of Japan). Available online: https://www.env.go.jp/council/09water/y092-05/mat04-1.pdf. (Accessed on 10 October 2022).

Parsons R, Milburn J (2003), Engineering behavior of stabilized soils. Transp Res Rec J Transp Res Board 1837:20–29. https://doi.org/10.3141/1837-03.

Pei X, Zhang F, Wu W, Liang S (2015), Physicochemical and index properties of loess stabilized with lime and fly ash piles. Appl Clay Sci 114:77–84. https://doi.org/10.1016/j.clay.2015.05.007.

Phetchuay C, Horpibulsuk S, Arulrajah A, Suksiripattanapong C, Udomchai A (2016), Strength development in soft marine clay stabilized by fly ash and calcium carbide residue based geopolymer Appl. Clay Sci., 127–128, pp. 134-142. 10.1016/j.clay.2016.04.005.

Satoh T (2003), Application of pneumatic flow mixing method Central Japan International Airport construction. Journal of Japan Society of Civil Engineers, 749:33–47 (in Japanese). https://doi.org/10.2208/jscej.2003.749_33.

Satoh T, Tsuchida T, Mitsukuri K, Hong Z (2001), Field placing test of lightweight treated soil under seawater in Kumamoto port. Soils Found, 2001, 41:145-154. https://doi.org/10.3208/sandf.41.5_145.

Siham K, Fabrice B, Edine AN, Degrugilliers P (2008), Marine dredged sediments as new materials resource for road construction. Waste Manage., 28 (5), pp. 919-928. 10.1016/j.wasman.2007.03.027.

Singh SP, Tripathy DP, Ranjith PG (2008), Performance evaluation of cement stabilized fly ash–GBFS mixes as a highway construction material. Waste Manage. 28 (8), 1331-1337. https://doi.org/10.1016/j.wasman.2007.09.017.

Solanki P, Zaman M (2012), Microstructural and mineralogical characterization of clay stabilized using calcium-based stabilizers Intech. pp. 772-798. 10.5772/34176.

Sumi T (2013), Selection of dam sediment database and appropriate reservoir sediment management measures in Japan. In ICOLD 2013 International Symposium, Seattle, USA, August 12-16 2013.

Tedesco DV (2006), Hydro-mechanical behaviour of lime-stabilised soils, Doctoral dissertation, Ph.D. thesis, Universitã degli Studi di Cassino Facoltã di Ingegneria.

Thuy Minh Nguyen T, Rabbanifar S, Brake AN, Qian Q, Kibodeaux K, Crochet HE, Oruji S, Whitt R, Farrow J, Belaire B, Bernazzani B, Jao M (2018), Stabilization of silty clayey dredged material. J. Mater. Civ. Eng., 30 (9). 10.1061/ASCEMT.1943-5533.0002391.

Xiao D, Jiang GL, Liao D, Hu YF, Liu XF (2018), Influence of cement-fly ash-gravel pile-supported approach embankment on abutment piles in soft ground. J. Rock Mech. Geotech. Eng. 10 (5), 977-985. https://doi.org/10.1016/j.jrmge.2018.06.001.

Yin B, Kang T, Kang J, Chen Y, Wu L, Du M (2018), Investigation of the hydration kinetics and microstructure formation mechanism of fresh fly ash cemented filling materials based on hydration heat and volume resistivity characteristics. Appl. Clay Sci., 166, pp. 146-158. 10.1016/j.clay.2018.09.019.

Yoobanpot N, Jamsawang P, Horpibulsuk S (2017), Strength behavior and microstructural characteristics of soft clay stabilized with cement kiln dust and fly ash residue. Appl. Clay Sci. 141, 146-156. https://doi.org/10.1016/j.clay.2017.02.028.

Yoobanpot N, Jamsawang P, Poorahong H, Jongpradist P, Likitlersuang S (2020), Multiscale laboratory investigation of the mechanical and microstructural properties of dredged sediments stabilized with cement and fly ash. Eng. Geol., 267. 10.1016/j.enggeo.2020.105491.

Yu J, Mishra DK, Wu C, Leung CK (2018), Very high volume fly ash green concrete for applications in India. Waste Management & Research, 36(6), 520-526. https://doi.org/10.1177/0734242X18770241.

Zhang Z., Omine K., and Flemmy, S.O (2019), Effect of Solidification Agent Addition and Water Content on Improvement Effect of Reservoir Clay and Simple Dehydration method, Proc. of Technical Forum on Mitigation of Geo-disasters in Asia.

2. Investigation on dehydration and improvement effect of waste dredged clay with high water content

2.1 Introduction

In Japan, the annual amount of waste dredged clay (WDC) produced by dredging projects is about 2×10^7 m³ (JCMA, 2015). Nowadays, as land demand sharply increases, finding land to stack the waste clays from dredging activities becomes more and more difficult. Several environmentally friendly disposal methods for WDC have been identified. It mainly includes: used in agriculture, forestry, and aquaculture, dumped on the coast for shoreline stability, aggregate manufacturing and building materials (Siham et al., 2008). Solidifying agents such as cement and fly ash to stabilize WDC have achieved the most promising results and has been widely used in infrastructure construction in many countries (Satoh, 2003; Satoh et al., 2001; Jamnongpipatkul et al., 2009; Ifediniru and Ekeocha 2022). WDC usually has the characteristics of natural water content higher than its liquid limit and high organic content, so the engineering performance is poor. As the most common soil stabilizers, Portland cement and lime have been widely used to improve WDC. At the initial stage of mixing the clay cement, the natural bonds inside the clay matrices are destroyed, whereas new bonds are created owing to the effect by cement. In addition, fly ash is one of the materials extracted from the flue gases of a furnace fried with coal from an electric power plant. Its generation is significantly greater than its utilization. In fact, researchers have attempted to use fly ash from industries to reduce cement input (Chindaprasirt et al., 2004; Singh et al., 2008; Yoobanpot et al., 2017; Xiao et al., 2018; Yu et al., 2018). As a partial substitute for cement, fly ash has a positive effect on improving soil environmental problems.

The Mw 6.2 foreshock and Mw 7.0 mainshock of the 2016 Kumamoto earthquakes occurred at 21:26 JST on April 14 and at 01:25 JST on April 16, respectively. The earthquake sequence damaged significantly buildings and infrastructure around the Kumamoto City (Goda et al., 2016). During the Kumamoto earthquake, the Ohkirihata Reservoir diversion facilities were damaged, and the water level was seriously reduced due to a large amount of water leakage. During the investigation after the Kumamoto earthquake, a fault was found directly below the Ohkirihata Reservoir. According to the "Kumamoto Restoration and Rehabilitation 4-Year Strategy issued" by the Kumamoto Prefecture of Japan in December 2016, it was decided to build a new reservoir 237 meters upstream of the original Kumamoto Ohkirihata Reservoir. This process produces generates considerable amounts of dredged sediments, which are classified as waste (Frihy et al., 2016). Since the straight-line distance between the reservoir and Kumamoto crater is only about 15 km, volcanic ash may be mixed into the sediments.

During the field investigation, WDC showed a high liquid limit different from other clays, and the natural water content was higher than its liquid limit.

Several research studies have been carried out on the evaluation methods of fly ash-stabilized clay in recent years. The clay-water/cement ratio (w/C), which is the ratio of the initial water content of the clay to the cement content, is a standard parameter for investigating the engineering behavior of soft clay stabilized with cement-based stabilizer (Miura et al., 2001; Horpibulsuk et al., 2005). In many studies on the stabilization of clay with different properties by cement-based solidifying agents, the same conclusion is obtained; there is an inverse relationship between the w/C and the strength of clay (Lorenzo and Bergado 2004; Horpibulsuk et al., 2003; Horpibulsuk et al., 2011b). Therefore, increasing the solidifying agent's content is an effective way to improve the strength of stable clay from Kumamoto Ohkirihata Reservoir. For WDC with high water content from Kumamoto Ohkirihata Reservoir, to obtain high strength stabilized clay by adding a large amount of cement-based solidifying agent, which is neither environmentally friendly nor economical. The demand for vast amounts of cement-based solidifying agents will cause environmental problems such as excessive greenhouse gas emissions. In order to reduce the environmental load and improve the economic benefit, the dredged clay should be dehydrated before mixing with the solidifying agent. Liquid clay's dehydration methods usually include mechanical and natural dehydration. Mechanical dehydration costs are high, and the additional power consumption causes greenhouse gas CO_2 emissions. Natural dehydration requires transportation and storage, bringing environmental problems and increasing management costs. For WDC with special properties, there is still a high demand for more environmentally friendly, cost-effective, and simple recovery methods.

This study takes the treatment of waste dredged clay from the Kumamoto Ohkirihata Reservoir in Japan as an example to introduce the recycling scheme of WDC. It aims to improve mechanical properties while achieving a low-carbon environmental protection economy. The accumulation of waste dredged clay to be treated in the Ohkirihata Reservoir was determined through field tests. Kumamoto clay was obtained from three locations in the Kumamoto reservoir, cement and fly ash were used for the improvement. A cone penetration test was performed on stabilized clays to obtain the cone index. According to the research results, an on-site dehydration method is proposed to realize the evaporation of water in the clay with low energy consumption by inserting a circulating dewatering material into the on-site dredged clay. This treatment method has the advantages of low CO_2 emission and low cost and has reference value for recycling WDC.

2.2 Test Procedure

2.2.1 Characterization of the Clayey Sediment

As shown in the reservoir plan presented in Figure 2.1, to confirm the depth of the clay sediment in the Kumamoto Ohkirihata Reservoir, a dynamic cone penetration test (JIS A 1230, 2018) was performed in areas № 1 to 11. The driving hammer with a mass of 5 kg was freely dropped from a height of 0.5 m, and the cone penetrometer had an initial angle of 60° and a diameter of 25 mm and the number of blows per penetration depth of 0.1 m (N_d) required to penetrate 0.1–0.5 m cone was measured. To determine the linear relationship between N_d and water content, the water content was measured for soil samples at a depth of 0.1–0.5 m. A loss-on-ignition test was performed at 750 °C (JIS A 1226, 2020) on the clays obtained from three locations to determine the organic matter content. The loss-on-ignition (LOI) test results of № 1 to 11 are shown in Table 2.1.

Two types of cement-based solidifying agents were used. One was type 1 OPC, and the other was a cement–fly ash binder (DF). DF comprises OPC (30%), coal fly ash (58%), and a heavy metal dissolution inhibitor (12%). Heavy metal dissolution inhibitors are composed of inorganic metals and chemicals. By mixing with heavy metal dissolution inhibitors, the effect of inhibiting the dissolution of natural heavy metals in soil was achieved. To clarify the effect of the physical properties of clayey sediment on the improvement, three different locations (in Figure 2.1) were selected to obtain clay
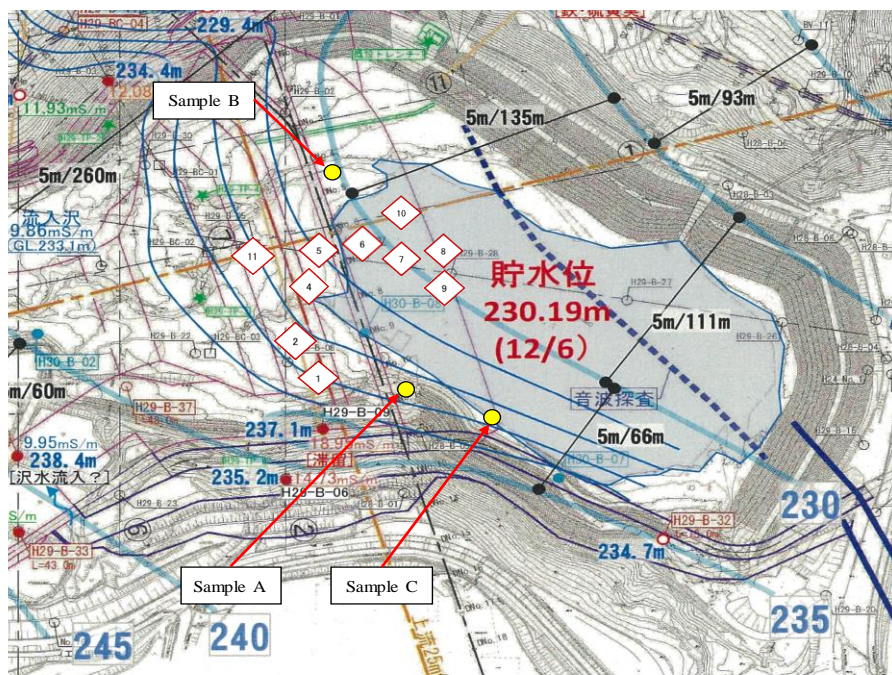

Fig. 2.1. Locations where dynamic cone penetration test and water content measurement was performed; sampling position of Kumamoto clay

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samples (samples A, B, and C). The physical properties of clayey sediment are listed in Table 2.2. The grain size distribution of clayey sediment obtained from the particle size test (JIS A 1204, 2020) is shown in Figure 2.2. The test results show that the fine particle content of all the samples constituted more than 60% of the clay. The water content of the three types of samples in the natural state was 160% in sample A, 152% in sample B, and 208% in sample C. Based on the experimental results of the liquid and plastic limit of each sediment sample (JIS A 1205, 2020), the water content of the three samples in the natural state is 10% to 50% higher than the liquid limit. Based on the results of the loss-on-ignition (LOI) test performed at 750 °C, the range of LOI in the sediments was between 17% and 24%. A uniaxial compression test (JIS A 1216, 2020) was performed on an undisturbed sample obtained from the location where sample C was acquired. In addition, the sample was kneaded after the uniaxial compression test, and a uniaxial compression test was performed to obtain the sensitivity ratio.

Table 2.1 Measurement results of organic matter (OM) content in № 1 to 11 area

No.	1	2	3	4	5	6	7	8	9	10	11
LOI (%)	26.15	22.98	28.24	30.23	28.68	23.46	35.61	29.07	17.60	35.80	30.10

Table 2.2 Measurement Physical properties of Kumamoto clay

Clay type	Fine particle content Fc^* (%)	Liquid limit w_L (%)	Plastic limit w_p (%)	Plasticity index I_p	Ignition loss LOI (%)	Density ρ_s (g/cm³)	Natural water content w_n (%)
Sample A	64.77	121.98	82.12	39.86	23.4	2.32	160
Sample B	65.05	142.00	93.68	48.32	19.2	2.27	156
Sample C	67.46	158.00	96.92	61.08	17.3	2.55	208

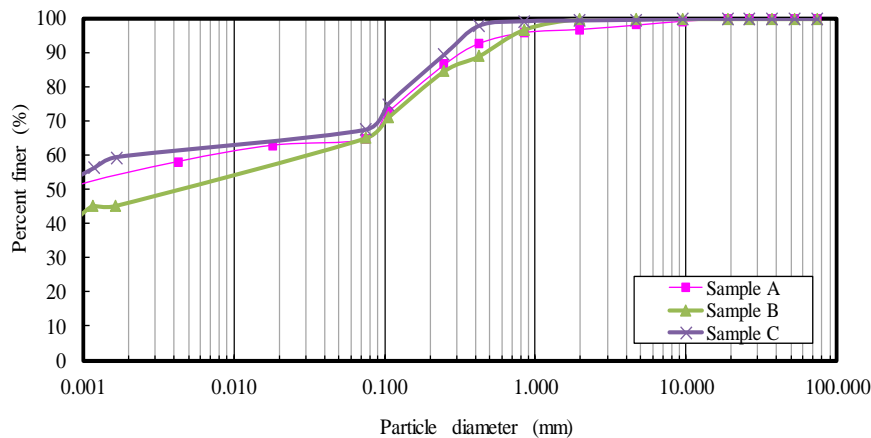*Fine particle content Fc : The maximum particle size is 0.075 mm

Fig. 2.2 Grain size distribution of Kumamoto clay

2.2.2 Sample Preparation

All the clay was passed through a 4.75 mm sieve to remove the coarser particles. In the water content adjustment experiments, the water content value was derived from a water content test (JIS A 1203, 2020). The water content of the clay was adjusted by adding free water and placing it in the natural air-drying location at the ventilating place, and the water content of all the experimental clays was equal to the target water content. During specimen preparation, the target clay was first mixed uniformly with a mortar mixer. Then, the solidifying agent was added to the clay and fully mixed until the whole sample attained form consistency. In order to prevent evaporation and absorption of moisture in the test sample, the test sample was sealed with macromolecular polyethylene, and then the sealed test sample was placed under constant temperature (25 ± 3 °C) and humidity (90 ± 3%). Sample preparation was based on the standard of the Japanese Geotechnical Society's method of preparing samples by 'Practice for making and curing compacted stabilized soil specimens using a rammer' (JGS 0811, 2020). Table 2.3 shows the cone penetration test conditions. After 28 days of storage, the sample was compacted in a mold with a height of 127 mm and a diameter of 100 mm using a hammer with a mass of 2.5 kg and a drop height of 300 mm. A compaction layer was set at

Table 2.3 Compaction and cone penetration test conditions

Clay	Kumamoto clay (Sample A, Sample B, Sample C)
Type of solidifying agent	OPC and DF
Mold	Inner diameter is 100mm, and the capacity is about $0.001m^3$
Rammer	The weight of the heavy hammer is 2.5kg, the falling height is 300mm, and the falling method is free fall
Solidification time	28days (Cone index test after 28 days of mixing)
Cone penetrometer	Tip angle 30°, bottom area 320 mm^2
Penetration Rate	1cm/s
Measuring method	The penetration resistance force at the distance of penetration of 50, 75, 100 mm is measured, and the value obtained by dividing the average value by the cone bottom area is defined as the cone index.
Product type of load measurement	RZTA-1000N produced by IMADA

about 40 mm intervals to press the sample into the mold three times, and each layer had 25 compaction cycles (JIS A 1210 A-c method: compaction energy about 550 kJ/m^3). Then, a cone penetration test was immediately performed.

2.2.3 Cone Index Determination

A cone penetration test was performed on the solidifying agent-stabilized clays to determine the cone index (JIS A 1228, 2020). Table 2.4 summarizes the experimental conditions for the improved clay. Two series of experiments were conducted in this study using different solidifying agent contents(C) and initial water contents (w). In the first series of experiments, the initial water content of the clay was constant, i.e., the initial water content of samples A and B was 160%, and that of sample C was 200% because of the higher liquid limit. Different contents of solidifying agents DF and OPC were used: 100, 200, 300, and 400 kg/m^3. The objective of series 1 was to investigate the effect of the solidifying agent content on the cone index of the improved clays. For series 2, the content of the solidifying agent was constant, i.e., 100 kg/m^3 for all the samples. The initial water content of the clay was different for each clay. The aim of series 2 was to investigate the effect of the initial water content on the improved clays. The penetration resistance of the test sample at 50, 75, and 100 mm was measured, and the average value divided by the cone bottom area was defined as the cone index. For each clay type, solidifying agent type, and combination of water content and cement content, at least three samples were tested under the same conditions to check for test consistency. In most cases, the results under the same testing condition were reproducible.

Table 2.4 List of experimental programs

Series	Sample	Water content (%)	Content of solidifying agent (kg/m³)	Type of solidifying agent
	A	160	100, 200, 300, 400	OPC, DF
1	B	160	100, 200, 300, 400	OPC, DF
	C	200	100, 200, 300, 400	OPC, DF
	A	100, 120, 140, 160	100	OPC, DF
2	B	100, 115, 135, 160	100	OPC, DF
	C	120, 140, 160, 200	100	OPC, DF

2.3 Dehydration test

2.3.1 Dehydration of waste dredged clay

The maximum value of the water content of a clay soil in the range of plastic consistency is defined as the liquid limit (w_L). As a physical property for keeping free water in the soil, liquid limit (w_L) is proved to have an important role in assessing the engineering properties of remolded and natural clay (Horpibulsuk et al., 2011c). In addition, Zhang et al. (2022) proved that reducing the water content below the liquid limit can be a noticeable improvement for the stable Kumamoto dredged clay with high water content. In order to realize the effective utilization of dredged clay with high water content under the low solidifying agents mixing amount, the water content of dredged clay should be reduced to below its liquid limit by a dehydration test.

(a) Composite string polyester (diameter 9mm)   (b) Nonwoven geotextile (thick 0.6mm)

Fig. 2.3 Drainage materials

2.3.2 Methodology

Two drainage materials were used to accelerate the dewatering rate of the dredged sediment by inserting them in the slurry clay. As shown in Figure 2.3, the drainage materials include string (composite polyester) and non-woven cloth (geotextile materials). The drainage materials were installed in the slurry clay in each case of the test condition at specific distance in order to accelerate the dewatering rate of the slurry clay. For the field dewatering conditional, the drainage materials in Fig. 2.3 (a) and (b) were installed in the slurry clay at 100 mm pitch.
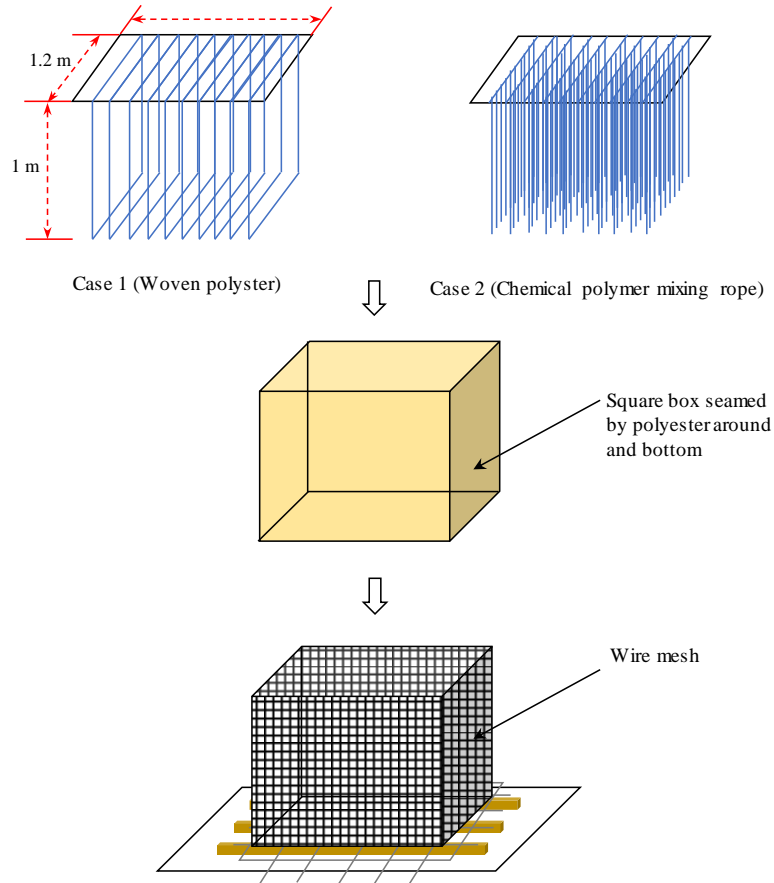
2.3.3 Field dewatering test

It has been proved in previous dehydration tests that chemical polymer mixing rope and woven polyester are excellent drainage materials, and the vertical placement of dehydrated materials significantly improves the dehydration efficiency (Flemmy et al., 2019; Flemmy et al., 2020; Flemmy et al., 2022). The field dewatering test of waste dredged clay was conducted under two dewatering conditions. The test conditions using simple vertical drains were designated as Case 1 and 2 with the installation of vertical drainage material. Woven polyester is used as the vertical drainage material for Cases 1, while for Case 2, chemical polymer mixture rope is used as the vertical drainage material. The thickness of the woven polyester is 0.60 mm, and the diameter of the chemical polymer mixing rope is 8.80 mm. For Case 1, the vertical drainage material with a size of 1.2 m * 1 m was connected to the steel rod with a transverse spacing of 100 mm. For case 2, a vertical drainage rope with a length of 1 m was selected and connected to the steel rod with a transverse-longitudinal spacing of 100 mm. The steel rod was set at the upper end of the square woven polyester bag, and the surrounding was fixed with a wire mesh, as shown in Fig. 2.4 (a). The field test photos of Cases 1 and 2 are shown in Fig. 2.4 (b). Finally, the wire meshes and the stands having the drainage materials at definite spacing are incorporated to the sunshine dewatering method of NCPWT to form the simple vertical drain method under field dewatering conditions.

The clay used in the field dewatering test is the clay near the Sample A sampling site in Fig.2.1. The clay was used as excavated from the pond without adjusting its natural water content. Then, the soft clay was poured into two dehydration boxes with different vertical drainage materials. The dewatering of waste dredged clay under field conditions after a while is shown in Fig. 2.5. As shown in Fig. 2.5 (a) and (b), the degree of saturation of clay is high and presents a high wet state in the initial stage after dumping. In Fig. 2.5 (c) and (d), the clay surface has begun to show a dry state after one week of dehydration. In Fig.2.5 (c), it can be observed that the area where the dehydrated material is embedded in the clay has an obvious dehydration gap due to the faster evaporation of water. After one month of clay dehydration, the surface clay shows an extremely dry state, as shown in Figs. 2.5 (e) and (f).

In order to determine the change in clay water content, three sampling points are set for each measurement. Sampling was carried out in the depth range of 0.05m-0.6m at each sampling point. Ensure that the experimental average water content comes from at least eight clay samples at different locations or depths. The average water content was calculated according to the water content of all samples. Figures.2.6 (a) and (b) show the experimental results of water content distribution with depth in case 1 and case 2, respectively. The initial average water content after adding clay is 145 %. The average water content after 7 days was 108 % in Case 1 and 110 % in Case 2. The average water content after 1 month was 84.3 % in Case 1 and 83.9 % in Case 2. The clay with initial moisture

content of about 145 % decreased to about 110 % in one week and less than 90 % in one month. The suction measured by pF sensor showed that a large negative pressure of 20-30 kPa appeared after one month.

1.2 m

1 m

Case 1 (Woven polyster)

Case 2 (Chemical polymer mixing rope)

Square box seamed by polyester around and bottom

Wire mesh

(a) Illustration of field dewatering test with simple vertical materials

(b) Photograph of the field dewarering test, the left is Case 1 ; the right is Case 2.

Fig.2.4 Setup of field dewatering test of waste dredged clay.

As shown Fig. 2.7, the field pF value simultaneously increases as void ratio of the clay decreases. The increase of the suction pF and the reduction of the void ratio is aided by the daily dissipation of water from the soil through the drainage material installed in the slurry clay.

(a) Case 1

(b) Case 2

(c) Case 1 (7-days)

(d) Case 2 (7-days)

(e) Case 1 (1 month)

(f) Case 2 (1 month)

Fig.2.5 Dewatering situations of waste dredged clay under field conditions
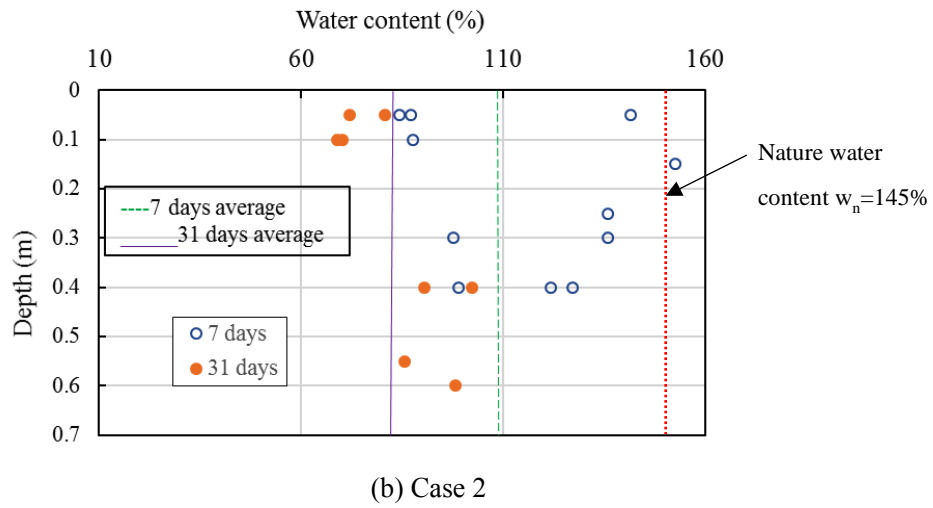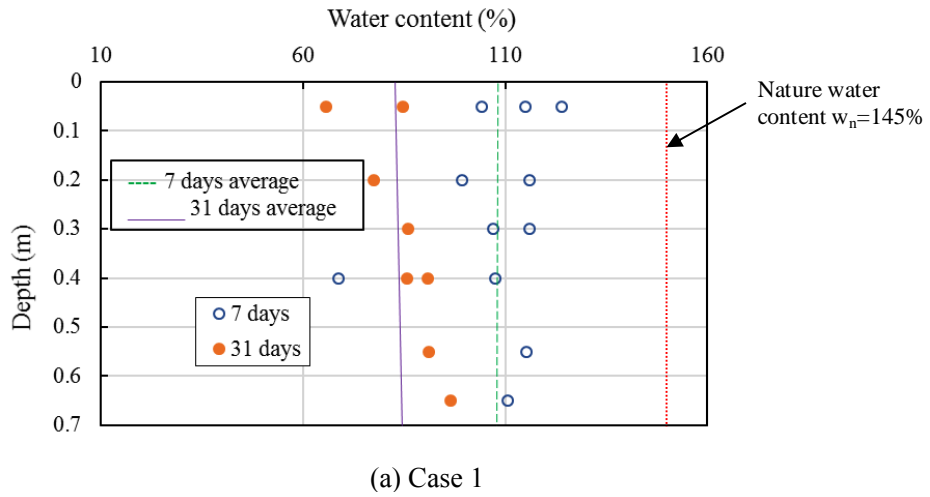
(a) Case 1

(b) Case 2

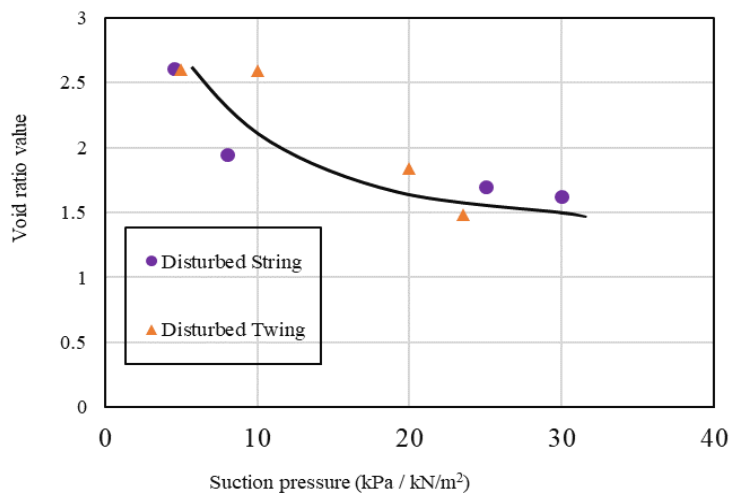**Fig.2.6** Evaluation of dewatering effect of waste dredged clay

Fig.2.7 Relationship between void ratio of field test and consolidation pressure

2.4 Results

2.4.1 On-Site Sediment Characterization

The uniaxial compression test results for the undisturbed and remolded clays of sample C are shown in Figure 2.8. The sensitivity ratio (S_t) is defined as the compressive strength (q_{u1}) of undisturbed clays relative to the compressive strength (q_{u2}) of remolded clays.

$$St = q_{u1} / q_{u2} \tag{2.1}$$

Clays with a value of St exceeding 10 were classified as super-sensitive clay. The test results indicated an $S_t = 11$; therefore, Kumamoto sediment was regarded as a super-sensitive clay. This means that although the Kumamoto sediment exhibited 30 kPa of unconfined compressive strength, its strength would become very low, less than 3 kPa, once disturbed.

When burned at high temperatures, the organic matter (OM) in clay begins to ignite at about 200 °C and will be completely depleted at about 550 °C (Santisteban et al., 2004). Loss-on-ignition (LOI) is a parameter that represents the organic matter content (Nielsen and Stefanakis., 2020). Generally, clays with an LOI of more than 20% are regarded as highly organic clay (Aitkenhead et al., 2004). The LOI test was carried out on the sediments from areas № 1 to № 11. The LOI test was performed on the sediments from areas № 1 to № 11, and the results are shown in Table 2.1. In addition to the LOI = 17.6 % in area № 9, the LOI of all other areas is higher than 20 %. In areas № 4, № 7, № 10 and № 11, the LOI is even more than 30 %. Combined with the LOI test results of samples A–C in Table 2.2, the sediment was classified as high-organic clay. This indicates that the sediments of
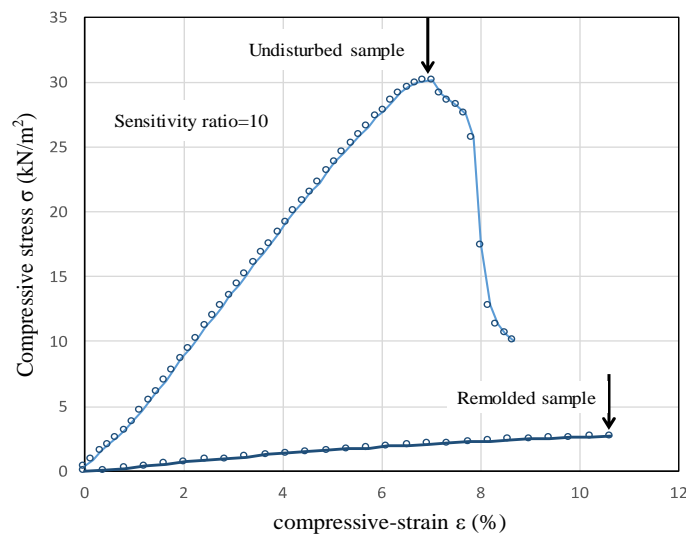

Fig. 2.8 Locations where dynamic cone penetration test and water content measurement was performed; sampling position of Kumamoto clay
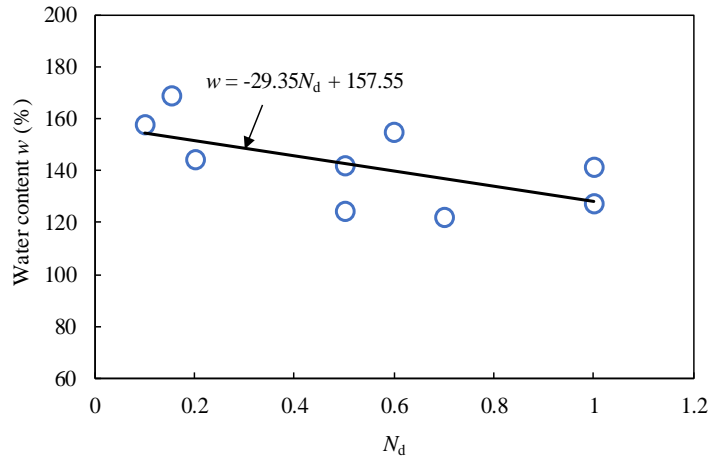
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Fig. 2.9 Locations where dynamic cone penetration test and water content measurement was performed; sampling position of Kumamoto clay

Kumamoto Reservoir not only have extremely high natural water content but also contain high organic components mixed in the clay.

Figure 2.9 shows the relationship between the water content and the number of blows per penetration depth of 0.1 m (N_d) determined by the dynamic cone penetration test. Usually, in the case of a very soft foundation, the penetration depth in 1 blow or several blows will be more than 10 cm. At this time, the respective unit penetration depth (d) is calculated according to the cumulative penetration depth (Unit penetration depth = cumulative penetration depth − depth before penetration). The number of blows per penetration of 10 cm is calculated according to the formula:

$$N_d = (N / d) \times 10 \tag{2.2}$$

N : Number of blows (times)

d : Unit penetration depth (cm)

N / d : Number of blows per penetration depth of 1cm (times /cm)

The N_d value is usually used to correspond to the depth of the site to reflect the difficulty of each 10 cm penetration in the surface depth of the site. In order to understand the state of the site foundation. The sediment samples for measuring the water content were obtained from a depth range of 0.1 to 0.5 m from the surface of the Kumamoto reservoir. Based on the results of all samples, the following correlations were derived:

$$w \, (\%) = 157.55 - 29.35 N_d \tag{2.3}$$

As shown in Equation (2.3), the water content in the depth direction can be calculated using N_d. Figure 2.10 shows the distribution of converted water content with depth in the areas № 1–11 calculated from N_d. The purpose of measuring the actual water content is to correct the distribution curve. This figure shows the distribution of natural water content in the sediments of the Kumamoto reservoir. It was discovered that clay with a high water content (exceeding 100%) was deposited at a depth of 1 to 2 m.
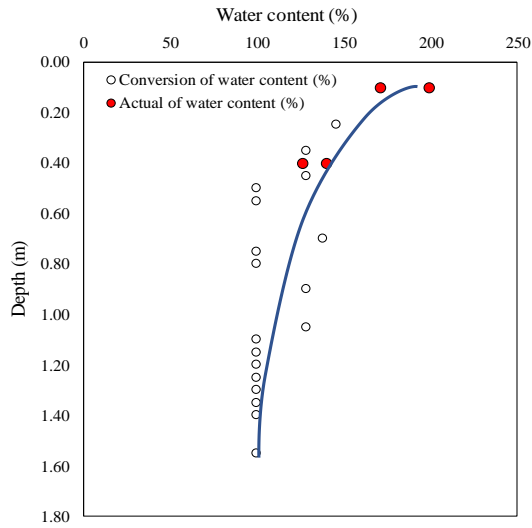
(a) Area No.1
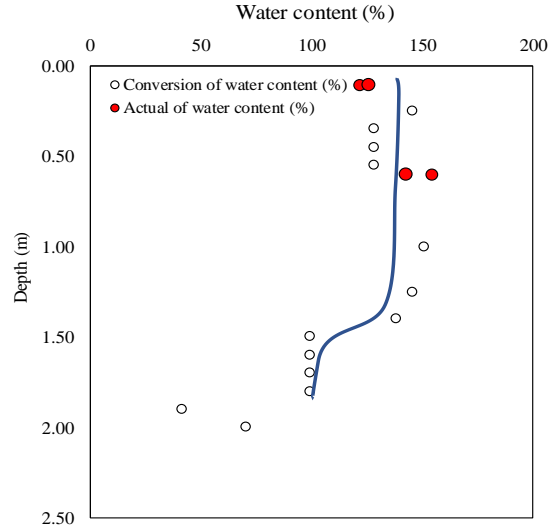
(b) Area No.2
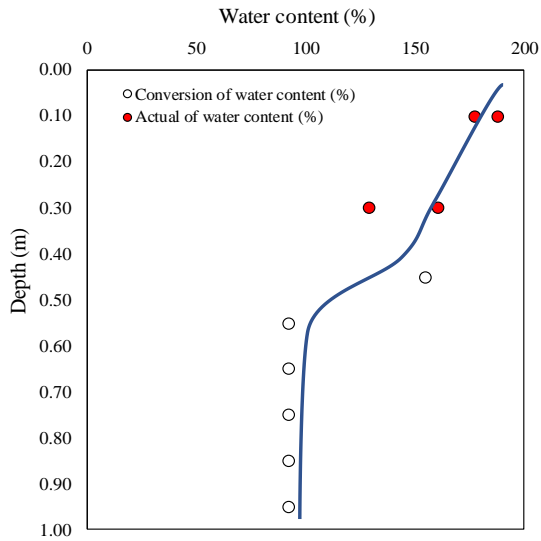
(b) Area No.3

(d) Area No.4
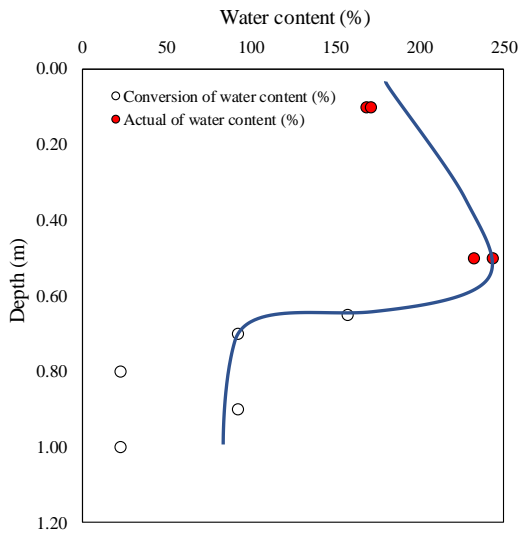
(e) Area No.5
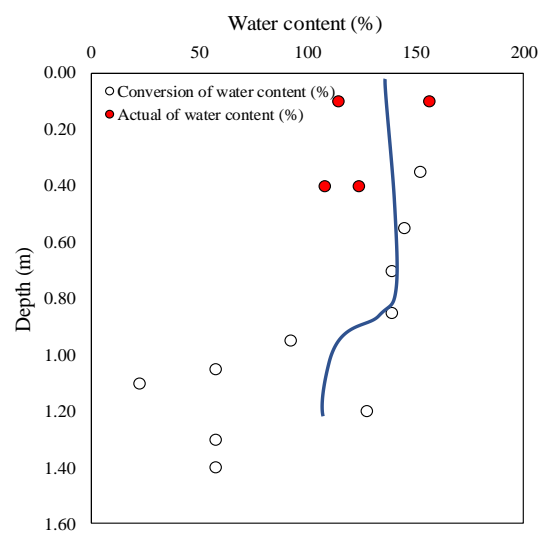
(f) Area No.6
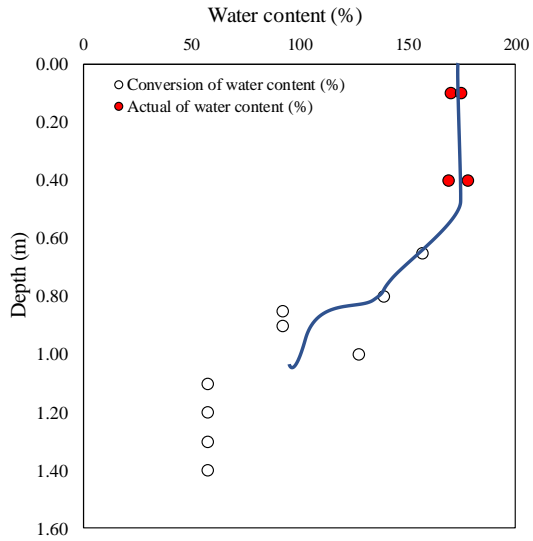
(g) Area No.7
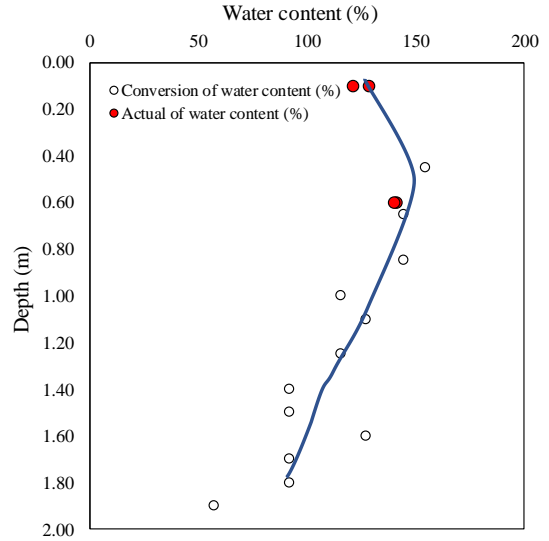
(h) Area No.8
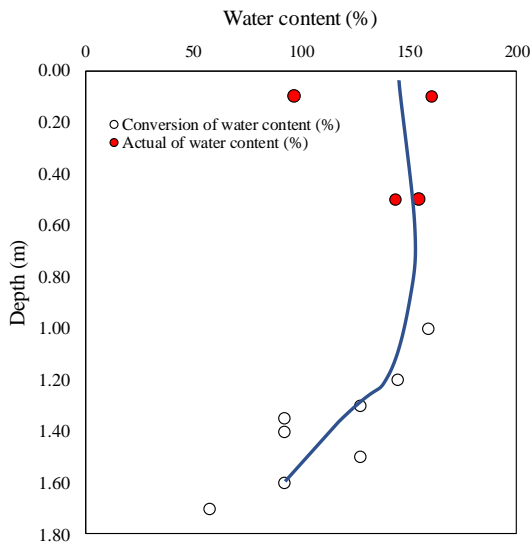
(i) Area No.9
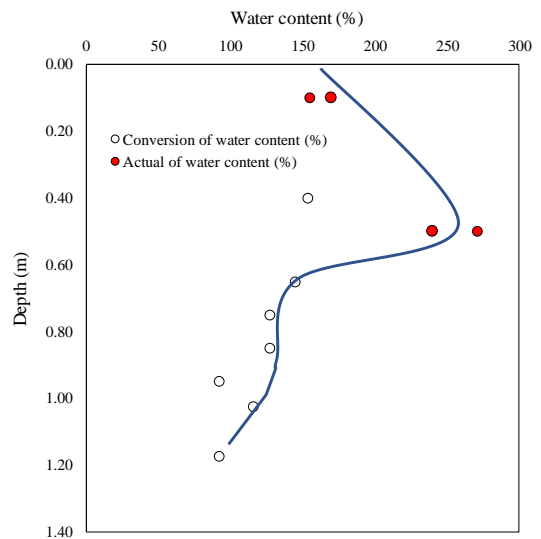
(j) Area No.10
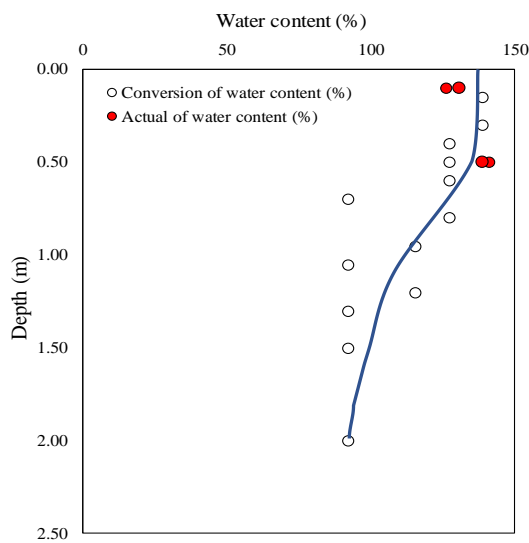
(k) Area No.11

Fig. 2.10 Change in water content based on depth in areas of Nos. 1−11

2.4.2 Effect of OPC and Cement–Fly Ash Binder on the Clayey Sediment Improvement

In soil stabilization by cement, cement hydration provided calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), resulting in increased improvement at a curing period of 28 days (Ghosh and Subba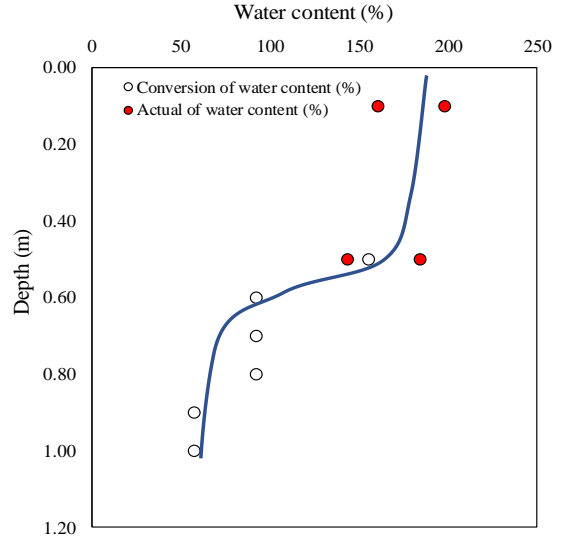rao., 2007). Similar to OPC, DF indicated increased strength owing to the reaction of calcium hydroxide with siliceous and aluminous materials to produce CSH and CAH (Horpibulsuk et al., 2010). The original water content in the clay promoted hydration and pozzolanic reactions, which rapidly generated ettringite. The hydration products of the cement were observed in the pores of the microstructure, and the amount of cementitious products increased significantly. The

(**a**)

(**b**)
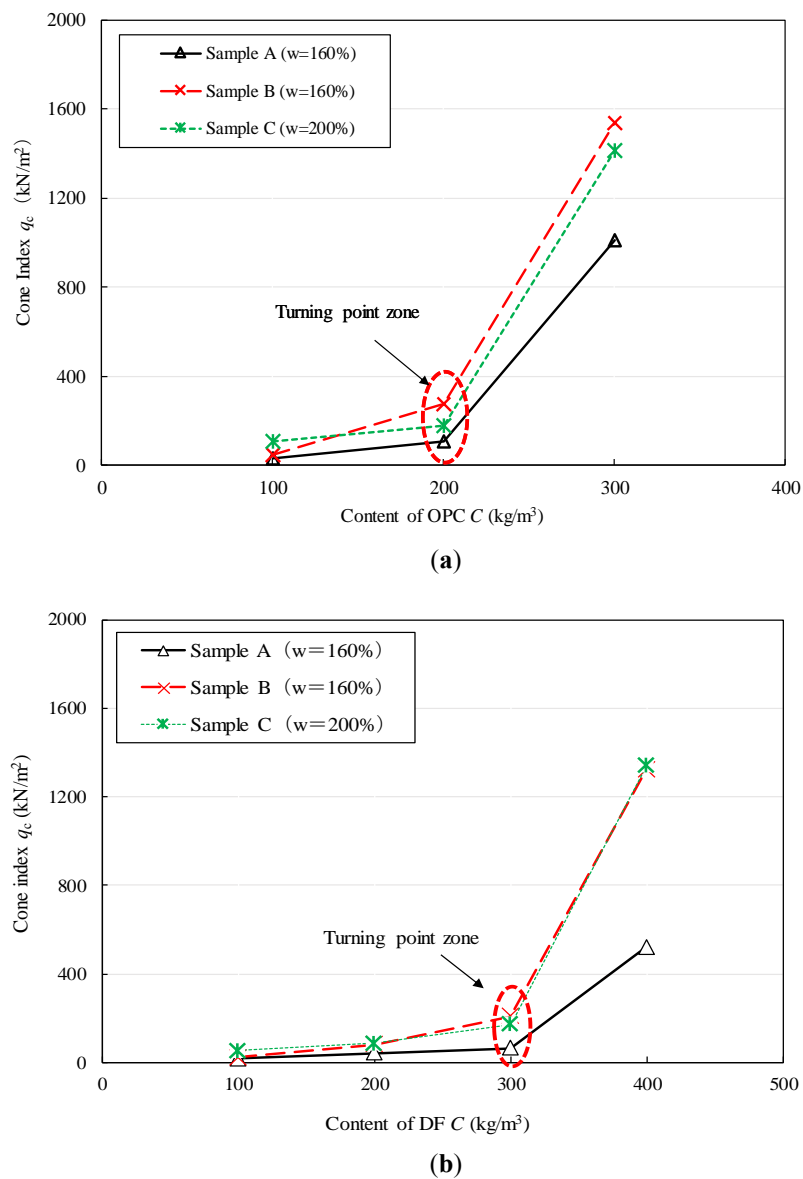
Fig. 2.11 Relationship between cone index of stabilized clay and content of solidifying agents. (**a**) Stabilized clay by OPC, (**b**) Stabilized clay by DF

cementitious products not only enhanced the inter-cluster bonding strength, but also filled the pore space. The volume of pores smaller than 0.1 μm reduced significantly, thereby reducing the total pore volume. Consequently, the strength increased significantly (Wang et al., 2013). The fly ash particles were discovered to be beneficial for reducing voids in the clay structure and making the microstructure denser, resulting in improved clay strength after curing (Furlan et al., 2021; Silitonga et al., 2010).

In series 1 under the constant water content condition (samples A and B: w = 160%; sample C: w = 200%), the relationship between the content of the solidifying agent and the cone index is shown in Figure 2.11(a) and (b). As shown in Figure 2.11(a), the OPC reached the improved 'turning point zone'
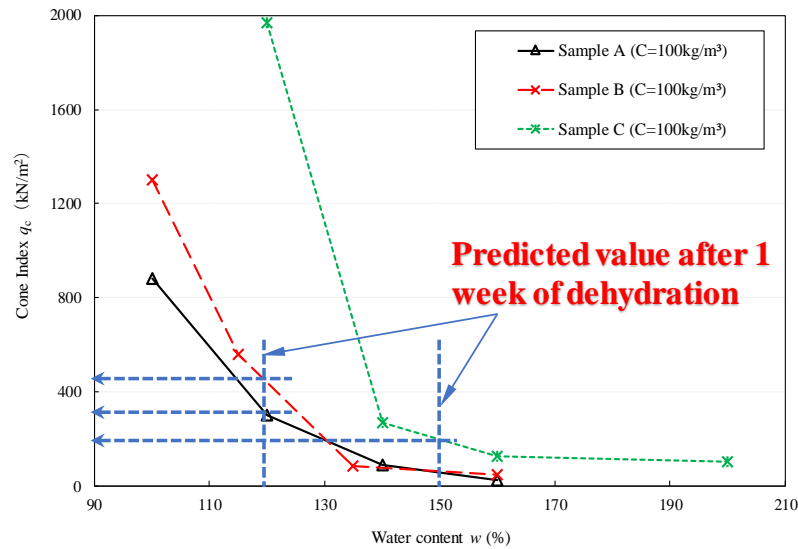
(a)
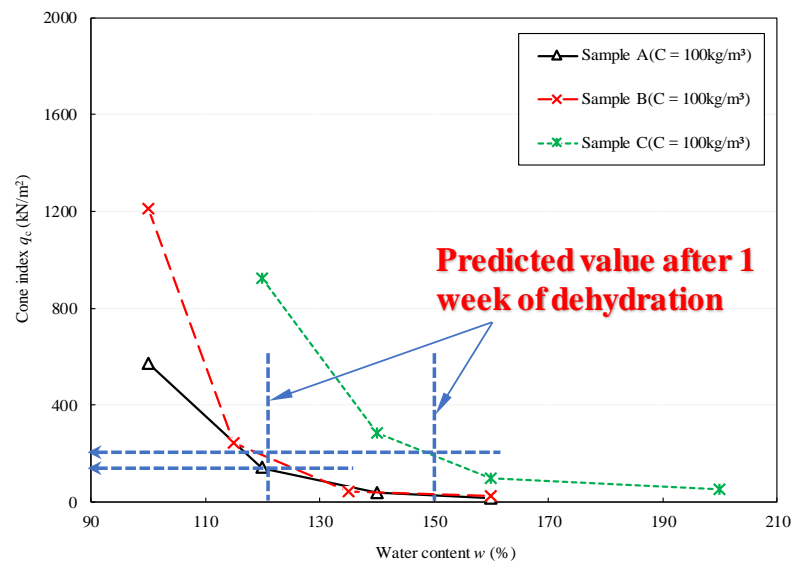
(b)

Fig. 2.12 Relationship between cone index and water content at constant content of solidifying agent (100 kg/m^3) (**a**) Stabilized clay by OPC, (**b**) Stabilized clay by DF

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when the content reached 200 kg/m^3. This means that more than 200 kg/m^3 of stable clay had been significantly improved. Meanwhile, the cone index of the soil stabilized by DF increased rapidly when the content of DF exceeded 300 kg/m^3, as shown in Figure 2.11(b). When using cement–fly ash binder containing 30% cement to stabilize sediment with high water content, a certain amount of hydration products must be produced to facilitate the embedding of fly ash particles into the gap of gel materials. Therefore, the DF needs more mixing quantity to reach the 'turning point zone' in the improved Figure 2.11(b). It was assumed that DF was applicable for improving Kumamoto clay, although the required content of DF was much higher than that of OPC. Since the OPC content in DF was only 30%, it afforded low CO$_2$ emission in comparison with OPC.

2.4.3 Effect of Reducing Water Content of Clayey Sediment

For the test results of series 2, Figure 2.12(a)(b) shows the relationships between the cone index and the initial water content of the three types of Kumamoto clay under a constant content of the solidifying material (100 kg/m^3). The cone index of the soils stabilized by the solidifying agents significantly decreased as the initial water content increased. This is because the sample with a higher clay water contents is easy to break up the cementation bond under the influence of higher void ratios, which affects the hardening rate (Miura et al., 2001). Consequently, the improvement became less prominent as the water content increased. By contrast, the decrease in the water content of the clay reduced the distance between the particles or cluster of particles, and the amount of hydration products increased. Under the same improvement conditions, the degree of improvement depended on the OM content of the sediment. The higher the OM content, the more difficult it was to effectively improve. Based on the results of the field composite string polyester and nonwoven geotextile dehydration test, the water content of clay decreased by about 25 % after one week, and the water content of clay decreased by about 38 % after one month. Corresponding to the experimental results in Fig.2.12, the strength of 100 kg/m^3 OPC stabilized three sample clays after one week of dehydration is 200 ~ 400 kN/m^2, and the strength of 100 kg/m^3 DF stabilized three sample clays is about 200 kN/m^2. In addition, both 100 kg/m^3 OPC and DF were effectively improved after one month of dehydration.

2.5 Conclusions

This study investigated the feasibility of improving dredged clay with high water content by dewatering and adding a solidifying agent. Through the confirmation of the accumulation of dredged

clay on site, as well as the study of the effect of the on-site dehydration test and the mechanical properties of the samples mixed with the solidifying agent, a set of schemes for treating dredged clay with high water content was summarized. The specific conclusions are as follows:

1. The field test results of Kumamoto Ohkirihata reservoir indicated the presence of mass sediments of clay with high water and high organic matter within 1–2 m of the reservoir sediment.

2. The dehydration effects of two kinds of composite materials on high water-content dredged clay are similar. That is, after one week the water content of clay was below the liquid limit, and after one month the water content decreased by about 40 %.

3. DF was applicable to the improvement of Kumamoto clay, although the required content was much larger than that of OPC. DF is a recycling material composed primarily of fly ash; hence, it affords less environmental pollution owing to its low CO_2 emission.

4. After the high water content dredged clay is simply dehydrated by inserting the composite material, the improvement of the high water content dredged clay under the low solidifying agent mixing amount can be realized.

References

Aitkenhead MJ, Donnelly D, Sutherland L, Miller DG, Coull MC, Black HIJ, 2015, Predicting Scottish topsoil organic matter content from colour and environmental factors. *Eur J Soil Sci*, 66.1: 112-120. https://doi.org/10.1111/ejss.12199.

Chindaprasirt P, Homwuttiwong S, Sirivivatnanon V, (2004), Influence of fly ash fineness on strength, drying shrinkage and sulfate resistance of blended cement mortar. *Cement Concrete Res*. 34 (7), 1087-l092. https://doi.org/10.1016/j.cemconres.2003.11.021.

Flemmy S, Omine K, Zhang Z, (2020), Effect of Installed Geotextile/Polyester and Biodegradable Materials for Dewatering Soft Clay. In: *Advances in Sustainable Construction and Resource Management*, pp. 23-31. DOI: 10.1007/978-981-16-0077-7_3.

Flemmy S, Omine K., Zhang Z, (2019), Soft clay improvement technique by dewatering and dewatering sandy soil. *Int. J. GEOMATE*. 17 (63), 9-16. DOI: 10.21660/2019.63.03627.

Flemmy SO, Omine K, Zhang Z, (2022), Simple dehydration technique using drainage string to treat drinking water sludge for utilization as geomaterial. *J Mater Cycles Waste Manag*. https://doi.org/10.1007/s10163-022-01420-x.

Frihy O, Moufaddal W, Deabes E, Helmy EED, (2016), Economic evaluation of using marine dredged material for erosion control along the northeast coast of the Nile Delta, *Egypt. Arab J Geosci*, 9(14) 1-19. https://doi.org/10.1007/s12517-016-2660-y.

Furlan AP, Razakamanantsoa A, Ranaivomanana H, Amiri O, Levacher D, Deneele D, (2021), Effect of Fly Ash on micro-structural and resistance characteristics of dredged sediment stabilized with lime and cement. *Constr. Build. Mater*. 272, 121637. https://doi.org/10.1016/j.conbuildmat.2020.121637.

Ghosh A, Subbarao C, (2007), Strength Characteristics of Class F Fly Ash Modified with Lime and Gypsum. Geotech. *Geoenvironmental Eng*, 133, 757–766. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:7(757).

Goda K et al, (2016), The 2016 Kumamoto earthquakes: cascading geological hazards and compounding risks. *Frontiers in built environment*, 2: 19. https://doi.org/10.3389/fbuil.2016.00019.

Horpibulsuk S, Liu MD, Liyanapathirana DS, Suebsuk J, (2010), Behavior of cemented clay simulated via the theoretical framework of the Structured Cam Clay model. *Comput. Geotech*. 37, 1–9. https://doi.org/10.1016/j.compgeo.2009.06.007.

Horpibulsuk S, Miura N, Nagaraj TS, (2003), Assessment of strength development in cement-admixed high water content clays with Abrams' law as a basis. *Geotechnique*. 53 (4), 439-444. https://doi.org/10.1680/geot.2003.53.4.439.

Horpibulsuk S, Miura N, Nagaraj TS, (2005), Clay–water/cement ratio identity for cement admixed soft clays. *J Geotech Geoenviron*,131(2) 187-192. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:2(187).

Horpibulsuk S, Rachan R, Suddeepong A, Chinkulkijniwat A, (2011), Strength development in cement admixed Bangkok clay: laboratory and field investigations. *Soils Found*. 51 (2), 239-251. https://doi.org/10.3208/sandf.51.239.

Horpibulsuk S, Yangsukkaseam N, Chinkulkijniwat A, Du YJ, (2011c), Compressibility and permeability of Bangkok clay compared with kaolinite and bentonite. *Appl. Clay Sci*. 52 (1-2), 150-159. https://doi.org/10.1016/j.clay.2011.02.014.

Ifediniru C, Ekeocha NE, (2022), Performance of cement-stabilized weak subgrade for highway embankment construction in Southeast Nigeria. *Int J Geo-eng*, 13:1-16. https://doi.org/10.1186/s40703-021-00166-z.

Jamnongpipatkul P, Dechasakulsom M, Sukolrat J, (2009), Application of air-foam stabilized soil for bridge-embankment transition zone in Thailand. In: *GeoHuman International Conference* 2009, Geotechnical Special Publication. China, Changsha, pp. 181-193. https://doi.org/10.1061/41042(349)24.

Japan Construction Machinery and Construction Association (JCMA) (2015), Separation, classification, effective use of dredged soil and tsunami deposits, and disposal volume reduction (in Japanese). https://jcmanet.or.jp/bunken/kikanshi/2015/01/015.pdf.

JGS 0811, 2020, Practice for Making and Curing Compacted Stabilized Soil Specimens Using a Rammer. Japanese Industrial Standard Association, The Japanese Geotechnical Society, Tokyo, Japan (in Japanese).

JIS A 1203, 2020, Test Method for Water Content of Soils. Japanese Industrial Standard Association, The Japanese Geotechnical Society, Tokyo, Japan (in Japanese).

JIS A 1204, 2020, Test method for particle size distribution of soils. Japanese Industrial Standard Association, The Japanese Geotechnical Society, Tokyo, Japan (in Japanese).

JIS A 1205, 2020, Test method for liquid limit and plastic limit of soils. Japanese Industrial Standard Association, The Japanese Geotechnical Society, Tokyo, Japan (in Japanese).

JIS A 1210, 2020, Test method for Soil Compaction Using a Rammer. Japanese Industrial Standard Association, The Japanese Geotechnical Society, Tokyo, Japan (in Japanese).

JIS A 1216, 2020, Method for unconfined compression test of soils. Japanese Industrial Standard Association, The Japanese Geotechnical Society, Tokyo, Japan (in Japanese).

JIS A 1226, 2020, Test method for ignition loss of soils. Japanese Industrial Standard Association, The Japanese Geotechnical Society, Tokyo, Japan (in Japanese).

JIS A 1228, 2020, Test Method for Cone Index of Compacted Soils. Japanese Industrial Standard Association, The Japanese Geotechnical Society, Tokyo, Japan (in Japanese).

JIS A 1230, 2018, Method for dynamic cone penetration test. Japanese Industrial Standard Association, The Japanese Geotechnical Society, Tokyo, Japan (in Japanese).

Lorenzo GA, Bergado DT, (2004), Fundamental parameters of cement-admixed clay—New approach. *J. Geotech. Geoenviron.* 130 (10), 1042–1050. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:10(1042).

Miura N, Horpibulsuk S, Nagaraj TS, (2001), Engineering behavior of cement stabilized clay at high water content. *Soils Found*. 41 (5), 33-45. https://doi.org/10.3208/sandf.41.5_33.

Nielsen S, Stefanakis AI, 2020, Sustainable dewatering of industrial sludges in sludge treatment reed beds: Experiences from pilot and full-scale studies under different climates. *Applied Sciences*, 10.21: 7446. https://doi.org/10.3390/app10217446.

Santisteban JI, Mediavilla R, Lopez-Pamo E, Dabrio CJ, Zapata M, Garcia M, Castano S, 2004, Martínez-Alfaro P.E. Loss on ignition: a qualitative or quantitative method for organic matter and carbonate mineral content in sediments. *J. Paleolimnol*, 32:287-299. https://doi.org/10.1023/B:JOPL.0000042999.30131.5b.

Satoh T, (2003), Application of pneumatic flow mixing method Central Japan International Airport construction. In: *Journal of Japan Society of Civil Engineers*, 749, 33–47 (in Japanese). https://doi.org/10.2208/jscej.2003.749_33.

Satoh T, Tsuchida T, Mitsukuri K, Hong Z, (2001), Field placing test of lightweight treated soil under seawater in Kumamoto port. *Soils Found*. 41 (5), 145-154. https://doi.org/10.3208/sandf.41.5_145.

Siham K, Fabrice B, Edine AN, Patrick D, (2008), Marine dredged sediments as new materials resource for road construction. *Waste Manage*, 28(5), 919-928. https://doi.org/10.1016/j.wasman.2007.03.027.

Silitonga E, Levacher D, Mezazigh S, (2010), Utilization of fly ash for stabilization of marine dredged sediment. *Eur. J. Environ. Civ. Eng*. 14, 253–265. https://doi.org/10.1080/19648189.2010.9693216.

Singh SP, Tripathy DP, Ranjith PG, (2008), Performance evaluation of cement stabilized fly ash–GBFS mixes as a highway construction material. *Waste Manage*. 28 (8), 1331-1337. https://doi.org/10.1016/j.wasman.2007.09.017.

Wang DX, Edine AN, Rachid Z, (2013), Strength and deformation properties of Dunkirk marine sediments solidified with cement, lime and fly ash. *Eng. Geol*. 166, 90–99. https://doi.org/10.1016/j.enggeo.2013.09.007.

Xiao D, Jiang GL, Liao D, Hu Y.F, Liu XF, (2018), Influence of cement-fly ash-gravel pile-supported approach embankment on abutment piles in soft ground. *J. Rock Mech. Geotech. Eng*. 10 (5), 977-985. https://doi.org/10.1016/j.jrmge.2018.06.001.

Yoobanpot N, Jamsawang P, Horpibulsuk S, (2017), Strength behavior and microstructural characteristics of soft clay stabilized with cement kiln dust and fly ash residue. *Appl. Clay Sci*. 141, 146-156. https://doi.org/10.1016/j.clay.2017.02.028.

Yu J, Mishra DK, Wu C, Leung CK, (2018), Very high volume fly ash green concrete for applications in India. *Waste Management & Research*, 36(6), 520-526. https://doi.org/10.1177/0734242X18770241.

Zhang Z, Omine K, Flemmy SO, Li C, (2022), The Liquid Limit as a Factor in Assessing the Improvement of Stabilized Cement-Based Highwater Content Clayey Sediments. *Materials*. 15(20):7240. https://doi.org/10.3390/ma15207240.

3. Evaluation on improvement effect of Kumamoto waste dredged clay

3.1 Introduction

It is important to predict the improvement of stabilized clays for preliminary design and cost analysis. A simple method has been established for soft clay admixed with cement to estimate the unconfined compressive strength q_u of cement-treated soils while considering cement and water contents (Tang et al., 2001). The clay-water/cement ratio (*w/c*), which is the ratio of the initial water content of the clay to the cement content, is a standard parameter for investigating the engineering behavior of cement-stabilized clays at high water contents (Miura et al., 2001). The generalized strength equation based on Abrams' law (1919) can be realized as the target strength and the desired levels of strength and compressibility obtained in laboratory tests (Horpibulsuk et al., 2005). It was demonstrated that $(C/W)_{total}$, which is the ratio of cement to the total volume of water in a mass, is an effective parameter for predicting the improvement of cement-stabilized clays (Sakka et al., 2002). The cement content required to stabilize roof tile waste-silt soil can be estimated using strength equations involving the unconfined compressive strength and porosity/volumetric cement content ratio (Moreira et al., 2019). Many studies have focused on the behavior of cemented clay. However, the improvement afforded by cement-based solidifying materials is significantly affected by the unique physical properties of the clay, such as its particle size composition, organic matter content, clay minerals, and pH (Babasaki et al., 1996; Mitsui et al., 2001; Hussan et al., 2022). Therefore, for reservoir clay with high organic matter content and high natural water content, the applicability of the evaluation behavior should be considered.

Reservoir clays typically exhibit high water and organic matter contents, which vary widely based on region. Therefore, the improvement by solidifying agents should be assessed under different mixing conditions. In this study, Kumamoto clay was obtained from three locations in the Kumamoto reservoir, and two types of cement-based solidifying agents were used for the improvement. The improvement of the three types of Kumamoto clays with high water content was expounded in terms the solidifying agent and water contents. A cone penetration test was performed on cement-stabilized clays to obtain the cone index. An empirical equation for assessing the improvement of Kumamoto clays mixed with cement-based solidifying agents is discussed herein based on laboratory test results and a new parameter, which is the modified content of the solidifying agent.

3.2 Description of the evaluation method

3.2.1 The w/A_w Ratio as a Factor for Assessing the Improvement of Stabilized Clayey Sediment

It is important to predict the improvement of stabilized clays for preliminary design and cost analysis. In previous studies, the contents of stabilization binders and water have been proven to be the main factors affecting improvement (Horpibulsuk et al., 2006; Horpibulsuk et al., 2003b; Horpibulsuk et al., 2011a). Some researchers de-fined the content of stabilized binder (A_w) as the ratio of stabilization binder weight to the dry weight of clay and used the ratio of water content (w) to Aw as a controlled parameter to study the behavior of stabilized clay. The results show that w/A_w described well the mechanical properties of stabilized clay, and the correlation coefficient R^2 reached 0.953 (Lorenzo and Bergado, 2004; Jongpradist et al., 2010). In this section, an assessment of the improvement by the solidifying agents is pro-vided while considering the effect of w/A_w.

Figure 3.1 shows the relationship between the cone index (q_c) and w/A_w on the clay stabilized by OPC in the three types of Kumamoto clay. The results indicate different trends under constant water and solidification agent contents. The difference in qc became more evident as w/A_w decreased. This is due to the different effects of water content and curing agent addition on the improvement effect. It can be found from Fig.3.1 that when the water content is constant, the amount of solidifying agents added is the only variable in w/A_w. The greater the amount of solidifying agents added, the more obvious the improvement effect. In addition, when the amount of solidifying agents is constant, the water content is the only variable in w/A_w. The greater the water content, the more difficult to be
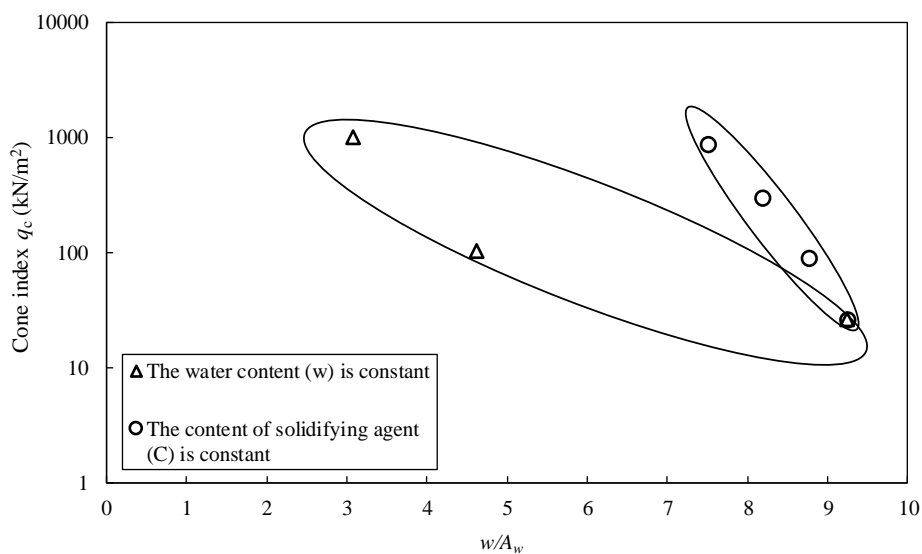
(a) Sample A
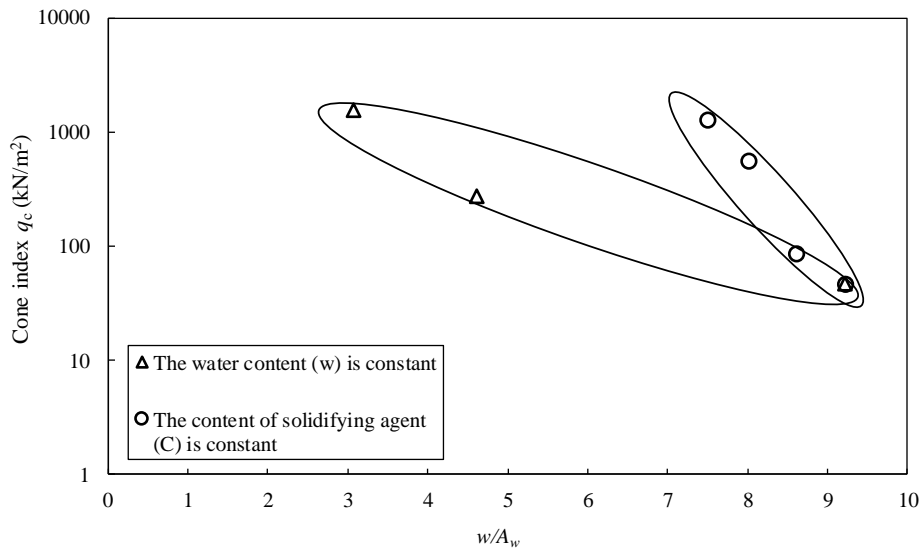
(b) Sample B
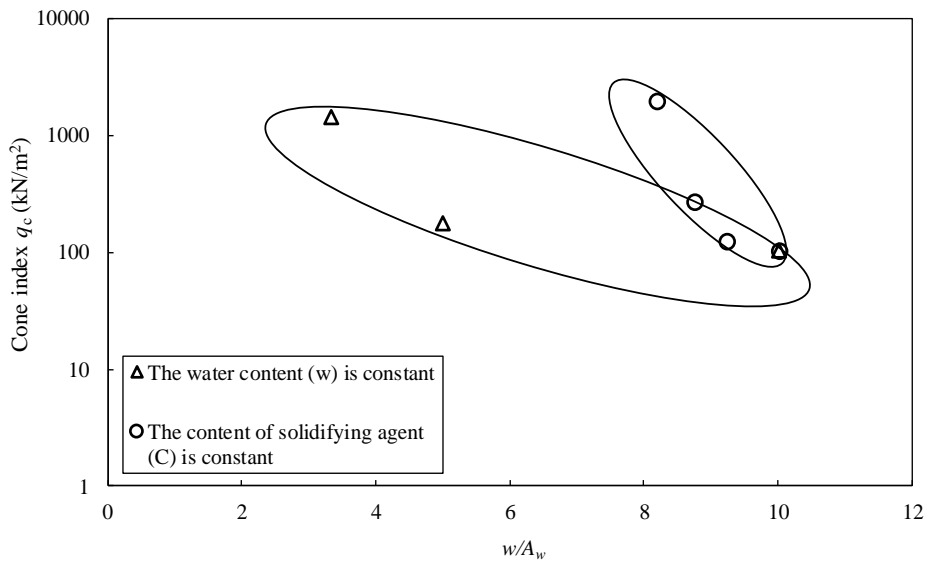
(c) Sample C

Fig. 3.1 Cone index q_c vs. w/A_w ratio of clays stabilized by OPC in three types of Kumamoto clay

effectively improved. Comparing the development trend of the improvement effect under the influence of the two variables, it can be concluded that the effect of water content on the improvement effect is greater than that of solidifying agents addition for Kumamoto clay. A similar trend was observed for the clay stabilized by DF, as shown in Figure 3.2. All q_c–w/A_w relations did not show a unique line; therefore, it was concluded that the previous evaluation method was not suitable for Kumamoto clay with high water and organic matter contents.
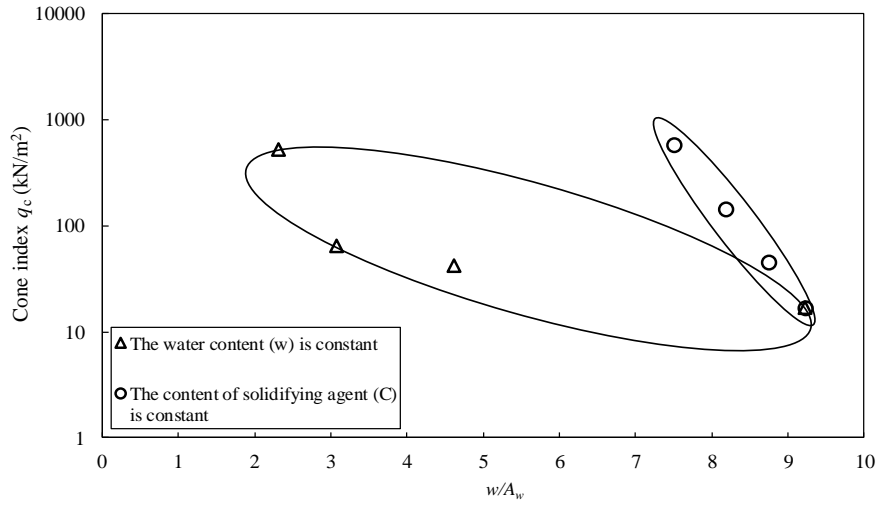
(a) Sample A
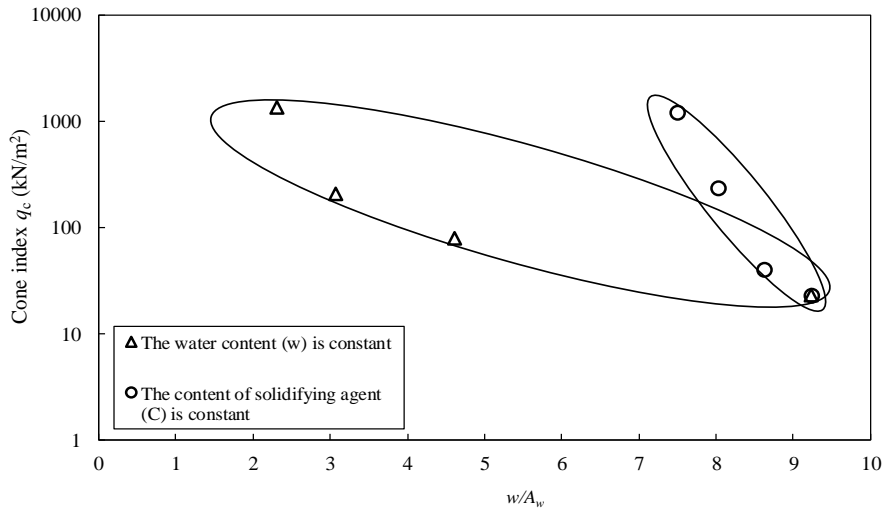
(b) Sample B
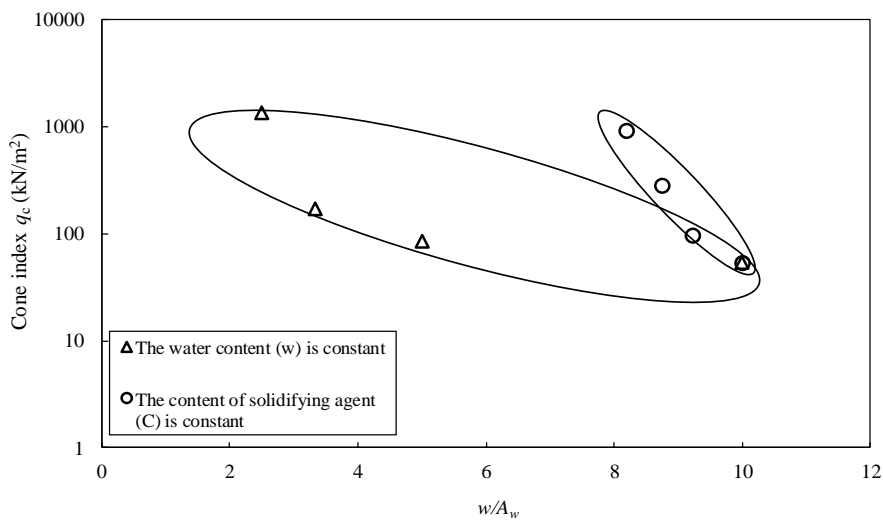
(c) Sample C

Fig. 3.1 Cone index q_c vs. w/A_w ratio on the stabilized clays by DF in three types of Kumamoto clay

3.2.2 The K Parameter as a New Factor for Assessing the Improvement of Stabilized Clayey Sediment

Highly organic soil contains bitumen, fulvic acid, and other humic acids with different degrees of organic matter decomposition. Substances in the humic acid dissolved in acidic methanol hydrochloride affect the solidified strength (Uchida et al., 1985). In addition, the inhibition of cement
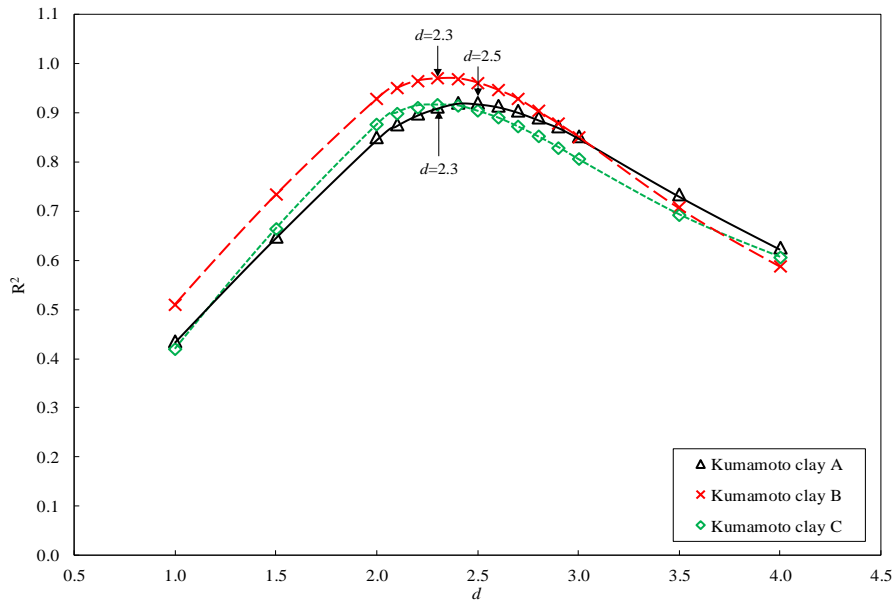
(a) OPC
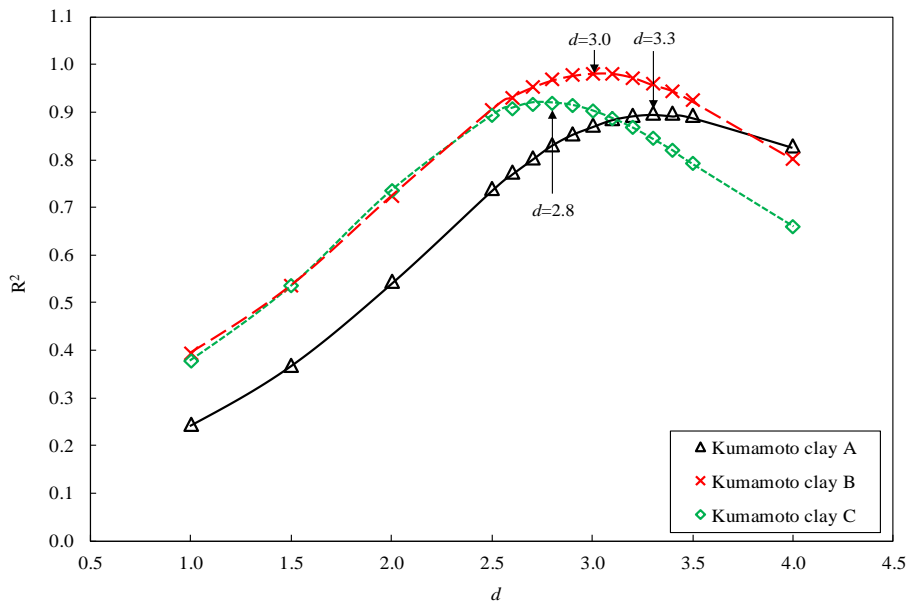
(b) DF

Fig. 3.3 Cone index q_c vs. w/A_w ratio on the stabilized clays by DF in three types of Kumamoto clay clay stabilized by OPC or DF

hydration by humic acid occurs when eluted Ca^{2+} reacts with humic acid. Its calcium salt is deposited on the surface of unhydrated cement particles or forms a complex. Humic acid inhibits cement hydration and delays the reaction (Okabayashi et al., 2004). Therefore, for clays with high liquid limits and organic matter contents, a parameter to replace w/A_w should be considered. Considering the effect of the water content on q_c, a new parameter, K (kg/m^3), was introduced, as shown in equation (2):

$$K = C/(w/100)^d \qquad (3.1)$$
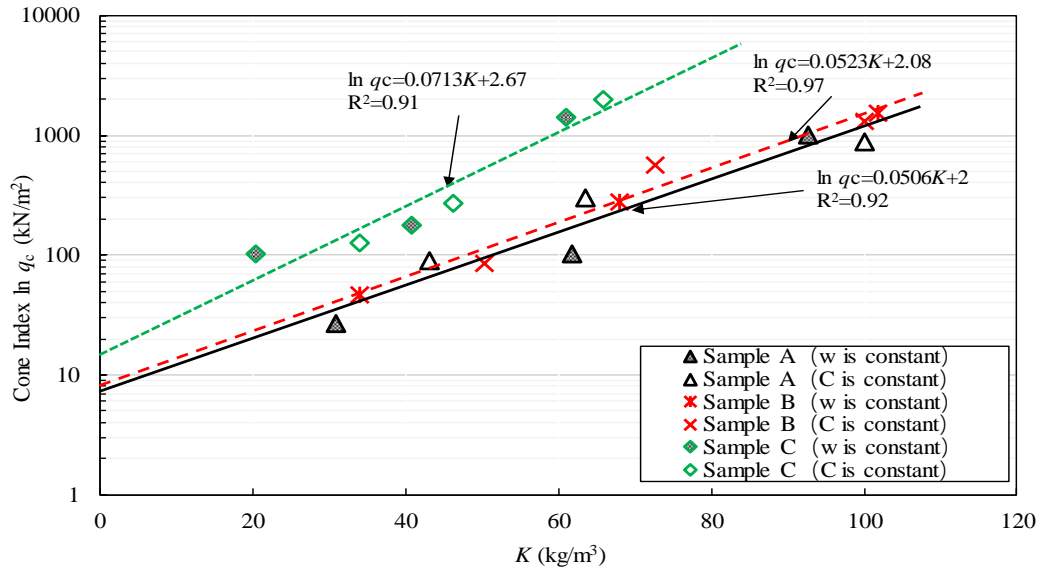
(a) OPC
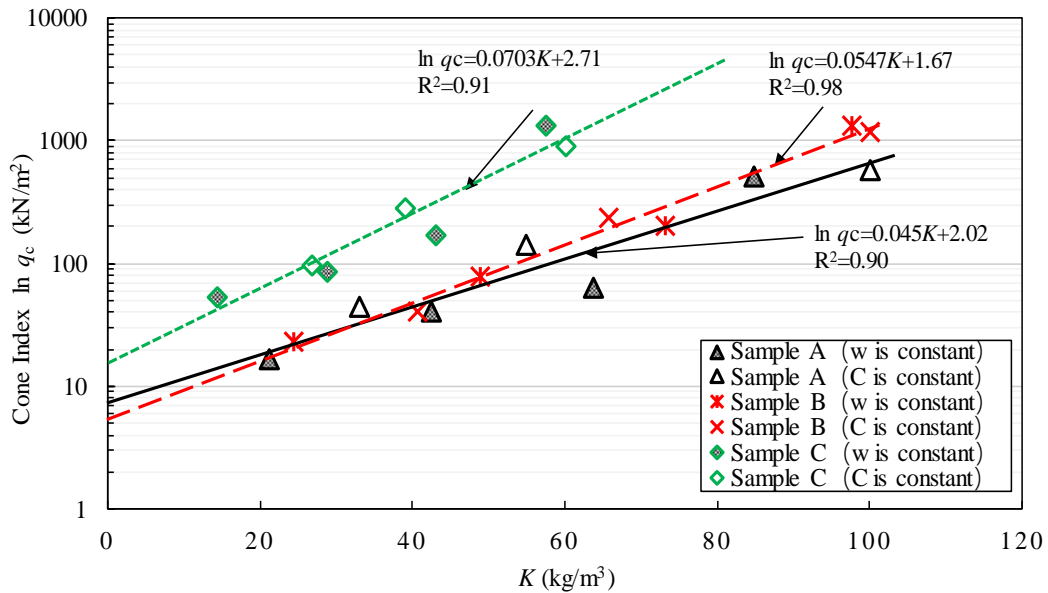
(b) DF

Fig. 3.4 Relationship between ln q_c and K for clay stabilized by OPC or DF

where d is a parameter representing the effect of the water content, C (kg/m³) is the cement content, and w is the initial water content of the clay. In this study, the following equation correlating q_c and K is used:

$$q_c = A\exp(BK) \tag{3.2}$$

where A (kN/m²) and B (m³/kg) are constants. Eq. (3.2) can be converted into Eq. (3.3), which shows a linear relationship between $\ln q_c$ and K.

$$\ln q_c = \ln A + BK \tag{3.3}$$

Figures 3.3 (a) and (b) show the changes in the correlation coefficient R^2 of Eq. (3.2) for different d values of the clay stabilized by OPC or DF, respectively. It was discovered that R^2 indicated a peak value above 0.9 in all stabilized clays. In the clay stabilized by OPC, when R^2 reached its peak, the corresponding d ranged from 2.3 to 2.5. In the clay stabilized by DF, the correlation coefficient R^2 reached its peak when d was 2.8–3.3. The value of d corresponding to the highest R^2 was applied for each stabilized clay.

Figures 3.4 (a) and (b) show the relationship between q_c and K obtained from the test results. The relationship between $\ln q_c$ and K can be represented by a straight line with an R^2 exceeding 0.9 for all samples of Kumamoto clay. The constant A in Eq. (3.3) represents the intercept of this line and corresponds to the value of q_c at $K = 0$, namely, the q_c of the clay without a solidifying agent. The constant B represents the inclination of the straight line. It is assumed that B and d are affected by the physical properties, such as the liquid limit and organic matter content of the clays. Table 3.1 summarizes the parameters A, B, and d for the stabilized clay obtained from Figs.3.4 (a) and (b). The improvement of each sample was assessed based on Eq. (3.3). In other words, the proposed equation is crucial for calculating the required content of solidifying agents in an arbitrary water content in the clay to obtain the target cone index.

Table 3.1 Parameters A, B, and d of Eq. (3.2) for stabilized clay

Sample	Solidifying agent	d	A (kN/m²)	B (m³/kg)	R^2
Sample A	DF	3.3	7.52	0.045	0.90
	OPC	2.5	7.36	0.0506	0.92
Sample B	DF	3.0	5.33	0.0547	0.98
	OPC	2.3	7.97	0.0523	0.97
Sample C	DF	2.8	14.96	0.0703	0.92
	OPC	2.3	14.41	0.0713	0.91

3.2.3 A Liquid Limit-Based Parameter as a Unified Factor for Assessing the Improvement of Stabilized Clayey Sediment

Although the expression shown in Eq. (3.3) can estimate the cone index of each stabilized clay effectively, the effect of the physical properties of clay must be considered when assessing the improvement in a unified manner. Hence, a unified estimation formula must be devised to describe the improvement of all samples of Kumamoto clay. The w/w_L ratio is an important parameter for
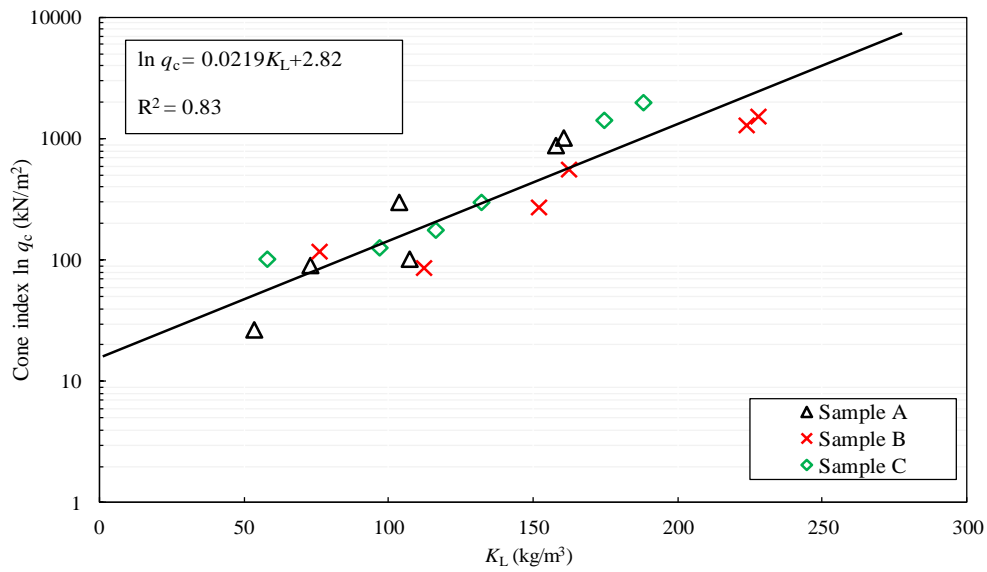
(a) OPC
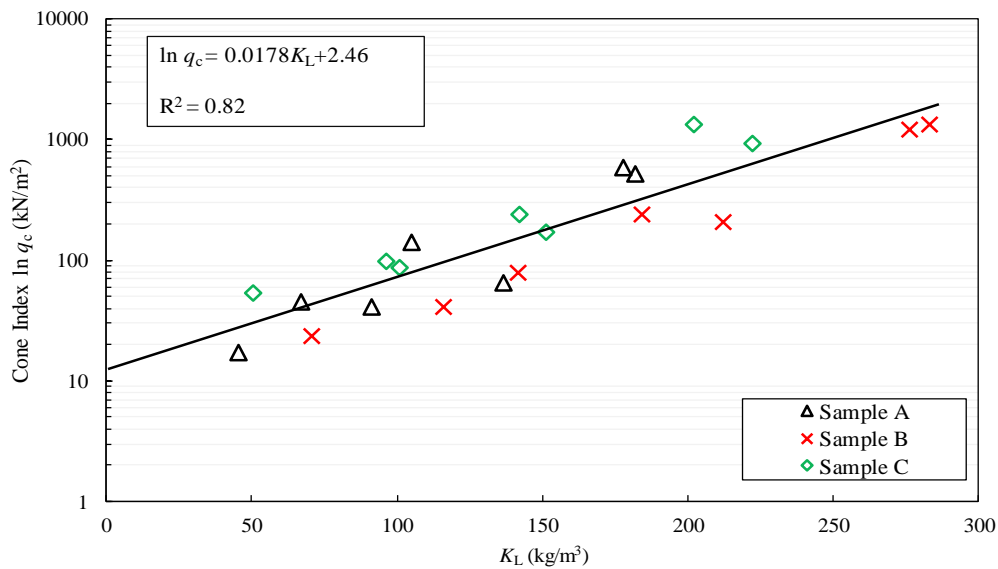
(b) DF

Fig. 3.5 Relationship between $\ln q_c$ and K_L of clay stabilized by OPC or DF

assessing the engineering properties of remolded and natural clays, where w is the water content of clay, and w_L is the liquid limit (Horpibulsuk et al., 2011b). Considering the effect of the liquid limit of the samples, the content of the solidifying agent (as indicated in Eq. (3.1)), K (kg/m^3), changes to the modified content of the solidifying agent K_L (kg/m^3), as follows:

$$K_L = C/(w/w_L)^{d_L} \tag{3.4}$$

where d_L is a coefficient representing the effect of the water content based on the liquid limit. By introducing the new parameter K_L, Eqs. (3.2) and (3.3) can be redefined as follows:

$$q_c = A_L \exp(B_L K_L) \tag{3.5}$$

$$\ln q_c = \ln A_L + B_L K_L \tag{3.6}$$

where A_L (kN/m^2) and B_L (m^3/kg) are constants.

Figures 3.5 (a) and (b) show the relationship between q_c and K_L for the clays stabilized by OPC or DF. A straight line representing Eq. (3.6) is presented in the figure in addition with the measured cone index of all the stabilized clays. It was observed that Eq. (3.6) unifies the assessment of the improvement of Kumamoto clay using K_L. Table 3.2 summarizes the coefficient d_L and the corresponding parameters A_L and B_L, based on the highest correlation coefficient R^2. The R^2 of Eq. (3.6) for the clays stabilized by OPC and DF were 0.83 and 0.82, respectively, which indicated good correlations and satisfies the number of data required for the significance level of 5%. As listed in Table 3.2, the value of d_L of the clay stabilized by DF was larger than that stabilized by OPC. This indicates that the improvement of the clay stabilized by DF was more sensitive to the water content compared with that by OPC. However, this suggests that the cone index of the stabilized clay with a higher value of d_L can be effectively increased by reducing the water content to less than the liquid limit. Based on this result, the authors attempted to reduce the water content of Kumamoto clay to less than the liquid limit using a simple dehydration method (Flemmy et al., 2019; Flemmy et al., 2020).

Table 3.2 Parameters of A_L, B_L, and dL in Eq. (3.5) for stabilized clay

Solidifying agents	Sample size	d_L	A_L (kN/m^2)	B_L (m^3/kg)	Correlation coefficient R^2
DF	21	2.9	11.7	0.0178	0.82[*]
OPC	18	2.3	16.71	0.0219	0.83[*]

[*]Significant level: 5%

3.2.4 Evaluation of Estimate Methods

In the case of DF and OPC, the comparison results of estimated value and actual value of cone index value of the three sample clays are shown in Figs. 3.6 (a) and (b). The estimated values respectively in the diagram are from Eq. (3.1) ~ (3.3). The actual values are the experimental results of the cone index of three
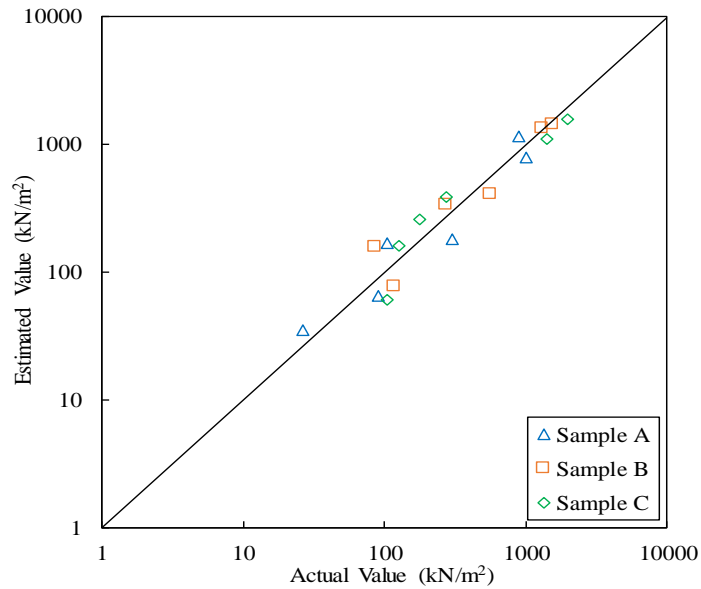
(a) OPC
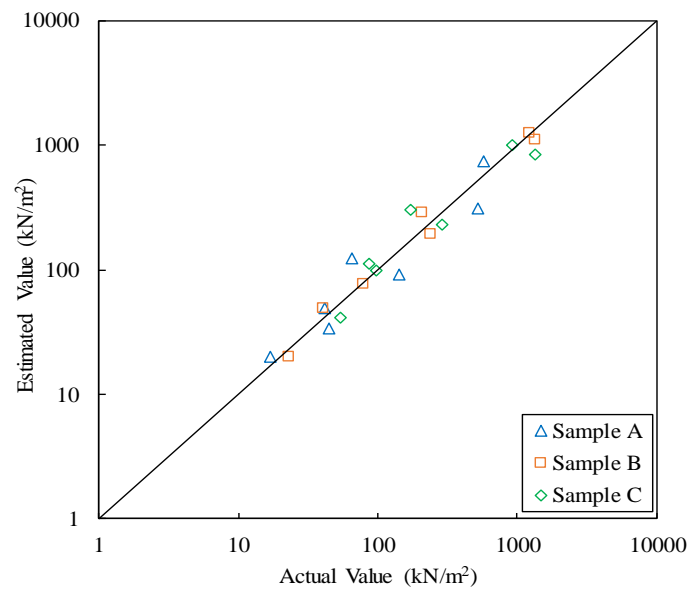
(b) DF

Fig. 3.6 Comparison of actual value and estimated values of three kinds of clay in solidifying agent improvement

kinds of clay mixed with solidifying materials after 28 days. Comparing Figs. 3.6 (a) and (b), it can be seen that both at DF improvement and OPC improvement, the measured and estimated values for the three clays are relatively evenly distributed, and all of the correlation coefficients R^2 are generally larger than 0.9, indicating that the estimating formula is somewhat accurate.

The results are shown in Figs. 3.7 (a) and (b) after comparing the estimated and actual values of cone index of all Kumamoto clays. The estimated values respectively in the diagram are from Eq. (3.4) ~
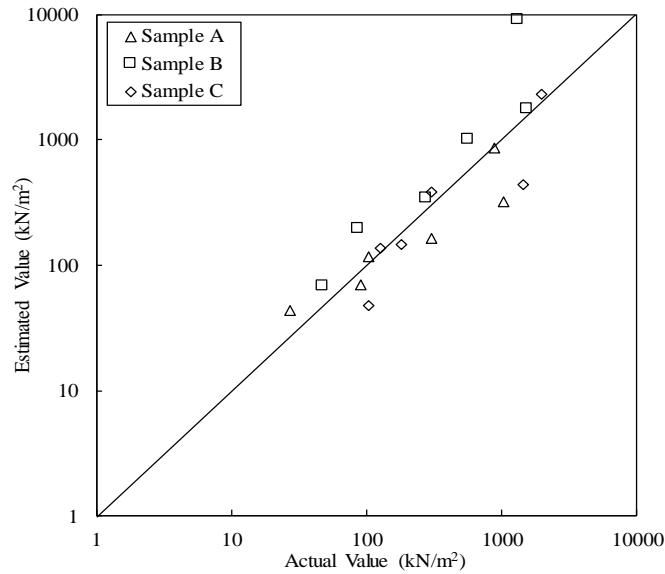
(a) OPC
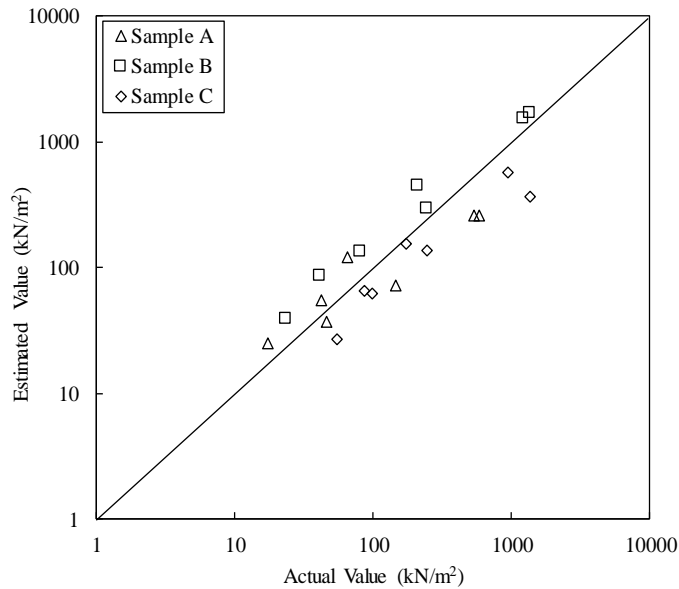
(b) DF

Fig. 3.7 Comparison of actual value and estimated values of all Kumamoto of clay in solidifying agent improvement

(3.6). Due to the huge amount of clay sediment in the field, there is a certain distance between the three acquisition points. Therefore, with the increase of clay sample type in Figs. 3.7 (a) and (b), the correlation coefficient is slightly lower than the three separate estimates（The correlation R^2 of OPC improvement decreased from 0.91~0.97 to 0.84, while the correlation R^2 in DF improvement decreased from 0.90~0.98 to 0.82）. Similar to Figs. 3.7 (a) and (b), when qc is low, the estimated value is closer to the actual value. And Figs. 3.4~3.5 show that there is a positive correlation between K (or K_L) and qc. Therefore, it can be said that the lower the value of K (or K_L) the higher the estimate accuracy of the related derivation formula.

3.3 Conclusions

In this study, sediments from the Kumamoto reservoir were investigated via a field test. The experimental results indicated the presence of mass sediments of clay with high water and high organic matters within 1–2 m of the reservoir sediment. Two types of cement-based solidifying agents, i.e., OPC and DF, were added to three samples obtained from different locations, and a cone penetration test was performed. The following conclusions were obtained:

(1) The w/A_w was not applicable to Kumamoto clay with high water and organic contents as a parameter for evaluating the improvement of clay stabilized by OPC or DF.

(2) A new parameter representing the content of the solidifying agent, K, was introduced by considering the effect of water content. The relationship between ln qc and K can be represented by a straight line with R^2 exceeding 0.9 for each sample of Kumamoto clay.

(3) Considering the effect of the liquid limit of the samples, the modified content of the solidifying agent, K_L, was introduced to evaluate the cone index of the stabilized soils. It was discovered that the proposed equation unified the assessment of the improvement of the three Kumamoto clay samples in a unified manner owing to the new parameter K_L.

References

Tang YX, Miyazaki Y, Tsuchida T, (2001), Practice of reused dredgings by cement treatment. *Soils Found*, 2001, 41:129–143. https://doi.org/10.3208/sandf.41.5_129.

Miura N, Horpibulsuk S, Nagaraj TS, (2001), Engineering behavior of cement stabilized clay at high water content. *Soils Found*, 2001, 41:33-45. https://doi.org/10.3208/sandf.41.5_33.

Abrams, DA, (1919), Design of concrete mixtures. Structural Materials Research Laboratory, Lewis Institute. Chicago, USA.

Horpibulsuk S, Miura N, Nagaraj TS, (2005), Clay–water/cement ratio identity of cement admixed soft clay. *J. Geotech Geoenviron*, 131:187-192. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:2(187).

Sakka H, Ochiai H, Yasufuku N, Omine K, (2002), Evaluation of deformation-strength properties of cement-stabilized soils by falling weight deformation measurement apparatus. *Journal of Japan Society of Civil Engineers*, 58:283-292 (in Japanses). https://doi.org/10.2208/jscej.2002.701_283.

Moreira EB, Baldovino JA, Rose JL, Izzo RLS, (2019), Effects of porosity, dry unit weight, cement content and void/cement ratio on unconfined compressive strength of roof tile waste-silty soil mixtures. *J. Rock Mech. Geotech. Eng*, 11:369-378. https://doi.org/10.1016/j.jrmge.2018.04.015.

Mitsui T, Yoshikawa T, Ikeda A, Aoyama K, Nakagawa K, (2001), A Basic Study of Improved Soils with Different Fine Grain Contents by Laboratory Mixing Tests. *Journal of Japan Society of Civil Engineers*, 693:117–129 (in Japanese). https://doi.org/10.2208/jscej.2001.693_117.

Hussan A, Levacher D, Mezazigh S, Jardin L, (2022) Valorization of a Highly Organic Sediment: From Conventional Binders to a Geopolymer Approach. *J Compos Sci*, 6:147. https://doi.org/10.3390/jcs6050147.

Babasaki R, Terashi M, Suzuki T, Maekawa J, Kawamura M, Fukazawa E, (1996), Influencing Factors on Strength of Stabilized Soil. In: *Proceedings of the Symposium on Cement Stabilized Soil*, Geotechnical Engineering Society. Japan, Tokyo, pp. 20-41. (in Japanese).

Horpibulsuk S, Katkan W, Sirilerdwattana W, Rachan R, (2006), Strength Development in Cement Stabilized Low Plasticity and Coarse Grained Soils: Laboratory and Field Study. *Soils Found*, 46:351-366. https://doi.org/10.3208/sandf.46.351.

Horpibulsuk S, Miura N, Nagaraj TS, (2003), Assessment of strength development in cement-admixed high water content clays with Abrams' law as a basis. *Geotechnique*, 53:439-444. https://doi.org/10.1680/geot.2003.53.4.439.

Horpibulsuk S, Rachan R, Suddeepong A, Chinkulkijniwat A, (2011), Strength development in cement admixed Bangkok clay: laboratory and field investigations. *Soils Found*, 51:239-251. https://doi.org/10.3208/sandf.51.239.

Lorenzo GA, Bergado DT, (2004), Fundamental parameters of cement-admixed clay—New approach. *J. Geotech. Geoenviron,* 130:1042–1050. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:10(1042).

Jongpradist P, Jumlongrach N, Youwai S, Chucheepsakul S, (2010), Influence of Fly Ash on Unconfined Compressive Strength of Cement-Admixed Clay at High Water Content. *J. Mater. Civil Eng*, 22:49-58. https://doi.org/10.1061/(ASCE)0899-1561(2010)22:1(49).

Uchida K., Fukubayashi Y., Yamashita J. Effect of Humic Acid in Soil on Hydration of Irwin Cement. The annual report of Cement and Concrete Engineering, 1985, 39:486-489 (in Japanese). DOI: 10.11501/2308567.

Okabayashi S, Omori H, Yanagihara H, Takahashi S, (2004), Principles and applications of soil hardening: 2. Cement and cement-based solidifying material chemistry. Soil mechanics and foundation engineering, 2004, 52:47-54 (in Japanese).

Horpibulsuk S, Yangsukkaseam N, Chinkulkijniwat A, Du Y.J, (2011), Compressibility and permeability of Bangkok clay compared with kaolinite and bentonite. *Appl. Clay Sci*, 52:150-159. https://doi.org/10.1016/j.clay.2011.02.014.

Flemmy SO, Omine K, Zhang Z, (2020), Effect of Installed Geotextile/Polyester and Biodegradable Materials for Dewatering Soft Clay. Advances in Sustainable Construction and Resource Management, pp. 23-31. DOI: 10.1007/978-981-16-0077-7_3.

Flemmy SO, Omine K, Zhang Z, (2019), Soft clay improvement technique by dewatering and dewatering sandy soil. Int. *J. GE-OMATE*, 17:9-16. DOI: 10.21660/2019.63.03627.

4. Unified Evaluation of the Improvement Effect of Different Clay Types Based on the Physical Properties of Clay

4.1 Introduction

Along with the construction of river bays and reservoirs, a large number of river bed dredged clays have been produced. It has become a social problem to find an economical and environmentally friendly solution to deal with and eventually recycle these clays. The undesirable properties of soft clay, namely low shear strength and high compressibility, can improve clay strength by mixing cement-based solidifying material (Frioozi et al., 2017). The mechanism of strength development in clay stabilized with cement can be explained by chemical reactions. When cement and water are mixed with clay, primary and secondary reaction products from the hydration reaction are formed and improve the clay properties. The primary products are comprised of calcium silicates hydrates (CSH), calcium aluminates hydrates (CAH) and lime. The secondary products resulting from the pozzolanic reaction between lime and clay minerals, clay silica and clay alumina were continuously formed as CSH and CAH after a curing period (Japan Cement Association, 2012). As a result of both reaction products, the clay became denser, stronger and harder, which resulted in an increase in the treated clay strength after curing (Chang et al., 2007). In Japan, cement-based solidifying material modified clay as ground materials has been widely used in highway and port construction (Sato et al., 2003; Watabe and Noguchi., 2011).

Considering the cost of clay improvement and potential environmental impacts, many studies have focused on the development of new cementitious materials to replace ordinary portland cement (OPC) as a soil solidifying agent. Fly ash (FA) has long been understood as an industrial by-product with pozzolanic material properties in a concrete field. Fly ash is usually used to add to the cement solidifying agent, as a part of the cement substitute to improve the microstructure (fabric and cementation bond) of cement stabilized clay, resulting in the improvement of engineering properties (strength compressibility, permeability, and durability) (Horpibulsuk et al., 2009). Studies have shown that the mixing of cement-clay mixture and air foam as two "lightweight cemented clays" has been widely used (Jamnongpipatkul et al., 2009; Kikuchi et al., 2011). A few studies revealed that the use of the cement kiln dust (CKD) as a potential clay stabilizer is comparable to that of the OPC, and it can be used to increase clay strength, reduce the permeability of the clay (Peethamparan et al., 2009; Amadi., 2014; Safari et al., 2017). Red ceramic waste (RCW) as supplementary cementitious materials in structural concrete to maintain mechanical properties while reducing carbon dioxide emissions to achieve a circular economy (Pavesi et al., 2021). Although this new solidifying agent has many advantages and has been proved to be applicable in geotechnical engineering to improve the strength

of clay and increase the bearing capacity, it is still necessary to consider the appropriate additional amount before use. Therefore, it is very important to correctly evaluate the relationship between the amount of solidifying agent and the improvement effect before construction.

For soft clay admixed with cement, a simple method has been established to estimate the unconfined compressive strength q_u of cement-treated soils by taking into account the cement content and water content, a good correlation between empirical and measured values in the range of 0~3000 kN/m² (Tang et al., 2001). Clay–water/cement ratio (w_c/c) which is the ratio of the initial water content of the clay (%) to the cement content (%) and void/cement ratio(v/c) was proved as a standard parameter for investigating the engineering behavior of cement-stabilized clay at high water content (Mitsui et al., 2001; Horpibulsuk., 2012). The generalized strength equation based on Abrams' law (1919) can be realized the target strength and obtains the compressibility level at the target strength in the test (Horpibulsuk et al., 2005). At the same time, other studies have summarized the influence of cement-fly ash ratios on the unconfined compressive strength of admixed clay, and successfully predicted the strength of the mixture through the empirical equation of cement-fly ash ratio (Jongpradist et al., 2010). However, many factors will affect the improvement effect of high organic clay, including several internal factors of the clay itself, such as pH value, particle size composition and mineral composition (Babasaki et al., 1996). In this study, a modified content of solidifying agent K_L considering a liquid limit is introduced to evaluate the effects of the content of solidifying agent and water content of clay. Based on the test results of five kinds of clays, the relationship between the physical properties of clay and the parameters in the empirical formula is discussed.

4.2 Materials and methods

4.2.1 Soil samples

In this study, five kinds of clays with different physical properties were used, namely Kaolin clay, Kibushi clay and three kinds of clays from the Kumamoto reservoir (Kumamoto clay A, Kumamoto clay B and Kumamoto clay C) in Japan. Kaolin and Kibushi clay were obtained by commercial products, while Kumamoto clays were obtained by field sampling. Sampling was performed from the depth of 1 to 2 m in the clay layer. The physical properties of all clays were summarized in Table 4.1. The higher organic content in Kumamoto clay leads to the lower density of three types of Kumamoto clay. Based on the Unified Soil Classification System (USCS), the Kaolin clay was classified as inorganic clay of low plasticity (CL) and the Kibushi clay was classified as inorganic clay high plasticity (CH). The X-ray diffraction (XRD) results of the two clays show that the kaolin clay consists

mainly of kaolinite and subordinate illite; and the Kibushi clay consists are quartz and kaolinite, and trace feldspar, montmorillonite and illite (Takehisa et al., 1986). The clay of Kumamoto was classified as organic clay of high plasticity (OH) based on the USCS. The particle size curves of the clays are shown in Fig. 4.1.

The composition of fly ash varies considerably depending on the nature of the coal burned and the power plant operational characteristics but grinding does not have much effect on chemical composition (Erdogdu and Turker, 1998). Ground fly ashes might be partially replacing cement to produce low-cost environmentally friendly cement-based solidifying agents. Type 1 Ordinary Portland Cement (OPC) similar to ASTM C150, a recycled material (DF) consisting of cement (30% of the total), fly ash (60% of the total) and a mixture of heavy metal insoluble agents were used in this study.
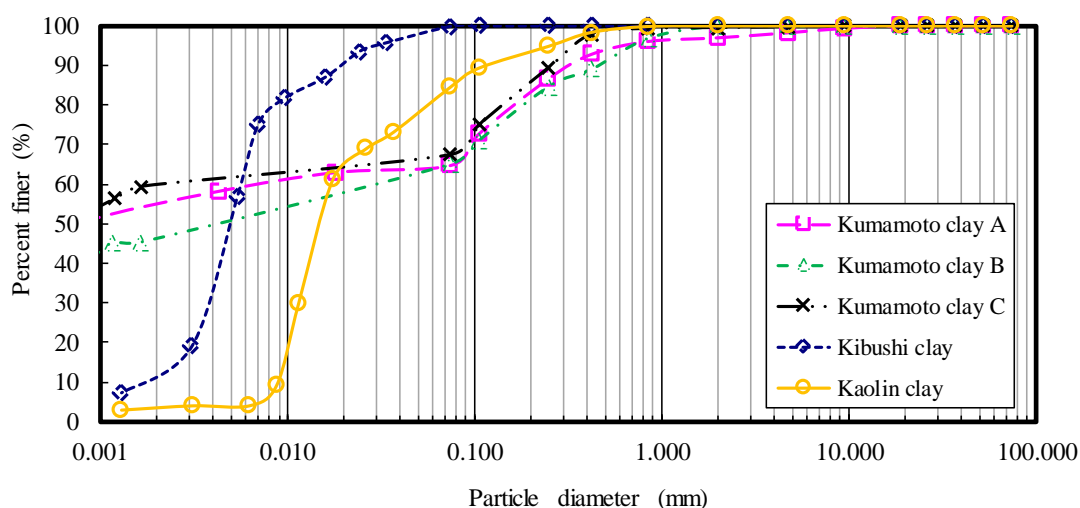
Fig.4.1 Grain size distribution curves of Kumamoto clay, Kaolin clay and Kibushi clay

Table 4.1 Physical properties of clays

Properties	Kumamoto clay A	Kumamoto clay B	Kumamoto clay C	Kibushi clay	Kaolin clay
Liquid Limit, w_L (%)	121.98	142.00	158.00	71.95	44.40
Plastic limit, w_p (%)	82.12	93.68	96.92	54.24	24.28
Plasticity index, I_p	39.86	48.32	61.08	17.71	20.12
Density, ρ_s (g/cm^3)	2.32	2.27	2.55	2.58	2.62
Ignition loss, L_i (%)	23.40	19.20	17.30	13.00	11.82
Natural water content, w_n (%)	185.0	152.0	208.0	-	-
Fine particle content, Fc (%)	64.77	65.05	67.46	99.92	84.60

50

4.2.2 Methodology

All the clay was passed through a 4.75mm sieve to remove the coarser particles. In the water content adjustment experiments, the actual water content was derived from the water content experiment (JIS A 1203 2020). The water content of clay was adjusted by adding free water and placing it in the natural air drying at the ventilating place, and the actual water content of all experimental clays was within the target water content of ±2%. In the mixing experiment, samples of the clay (Kumamoto clay, Kibushi clay, and Kaolin clay) were

prepared by mixing them uniformly with the solidified agent for 5 minutes using a stirrer. According to different water content, the unit mass of clay samples ranges from 1.4×10^3 kg/m^3 to 1.5×10^3 kg/m^3. After uniform mixing, to prevent the evaporation and absorption of moisture in the test sample, the test sample is sealed with macromolecular polyethylene, and then the sealed test sample is placed under constant temperature (25 ± 3 °C) and humidity (90 ± 3 %). The mold height is 126.94mm, and the inner diameter is 99.66mm. A compaction layer is set at about 40 mm intervals to press the sample into the mold three times, and each layer has 25 compaction cycles (JIS A 1210 A-c method: compaction energy about 550 kJ/m^3) (JIS A 1210 2020). The number of setting compaction cycles may be appropriately changed according to the strength of the stabilized clay specimen. Table 2.3 shows the cone penetration test conditions. After 28 days of storage, cone penetration tests will be conducted according to the standard sample size (JIS A 1228 2020).

Table 4.3 summarizes the test conditions for making the stabilized clays. In this study, in order to achieve the evaluation of the improvement effect by the content of solidifying agent (*C*) and water content, the experiment is divided into two series, namely, series 1 experiment with the added amount of solidifying agent as the variable and series 2 experiment with the initial water content as the variable. In the first series of experiments, the initial water content of the clay is constant, and the content of the 2 types solidifying agents (DF and OPC) was used as a variation for the experiment. w/w_L has been considered as an essential parameter for evaluating specific clay void ratios (Horpibulsuk et al., 2007). Therefore, w/w_L is used as an important basis for the setting range of water ratio in the test. In the test, the values (w/w_L) of Kumamoto clay and Kibushi clay are in the range of 0.7-1.4. But for low swelling clay (Kaolin clay), the particles are associated with each other in an edge-to-face manner (Olphen, 1963); i.e. the clay exhibits an open flocculated fabric with greater shear strength. Even at the same state (w/w_L), more water should be added to kaolin to have the same viscosity (Horpibulsuk et al., 2012). Therefore, the value (w/w_L) of Kaolin clay is set in the range of 1-2. The objective of Series 1 is to investigate the effect of the amount of solidifying agent added when the water content remains constant. In Series 2 for investigating the effect of initial water content, samples were prepared with

the constant content of solidifying agent. The cone index of all stabilized clays was obtained by JIS A 1228 (2020). For each clay type, solidifying agent type and combination of water content and cement content, at least three samples were tested under the same conditions to check for test consistency. In most cases, the results under the same testing condition were reproducible.

Table 4.3 Compositions of the specimens for making the stabilized clays

Series	Sample	Water content （%）	Content of solidifying agent （kg/m³）	Solidifying agent
1	Kumamoto clay A	160	100,200,300,400	OPC,DF
	Kumamoto clay B	160	100,200,300,400	OPC,DF
	Kumamoto clay C	200	100,200,300,400	OPC,DF
	Kibushi clay	100	15,25,50,75,100	OPC,DF
	Kaolin clay	44	20,40,60,80	OPC,DF
2	Kumamoto clay A	100,120,140	100	OPC,DF
	Kumamoto clay B	100,115,135	100	OPC,DF
	Kumamoto clay C	100,140,160	100	OPC,DF
	Kibushi clay	60,70,80,90,100	100	OPC,DF
	Kaolin clay	60,70,80,90	100	OPC,DF

4.3 Results

4.3.1 Effect of solidifying agents content on clay improvement effect

In the relationship between unconfined compressive strength and cement content, it can be considered that the range with high improvement effect of cement content is defined as the active zone (Zhang et al., 2013; Horpibulsuk et al., 2003). In terms of microstructure in the active zone, hydration products are seen in the pores and the cementitious products significantly increase with the increase

of cement content. The cementitious products not only enhance the inter-cluster bonding strength but also fill the pore space, the volume of pores smaller than 0.1μm is significantly reduced with cement, thus, the reduction in total pore volume. As a result, the strength significantly increases with cement (Horpibulsuk et al., 2010). Similar to OPC hydration, CSH (calcium silicates hydrates) is the main hydration product in the process of DF stabilizing clay. It is found that FA particles are beneficial to reduce the voids in clay structure, resulting in the improvement of clay strength after curing (Wang et
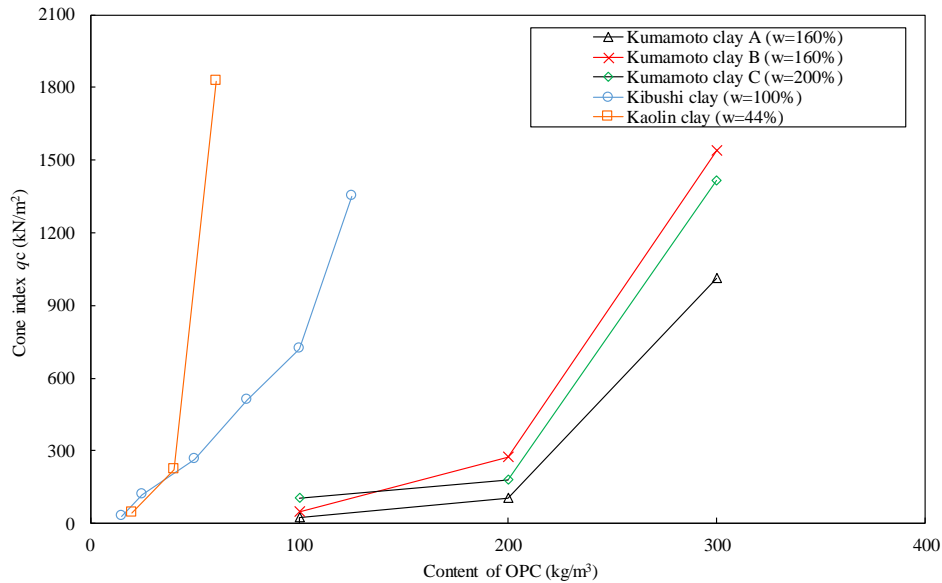
(a) Solidifying agent of OPC
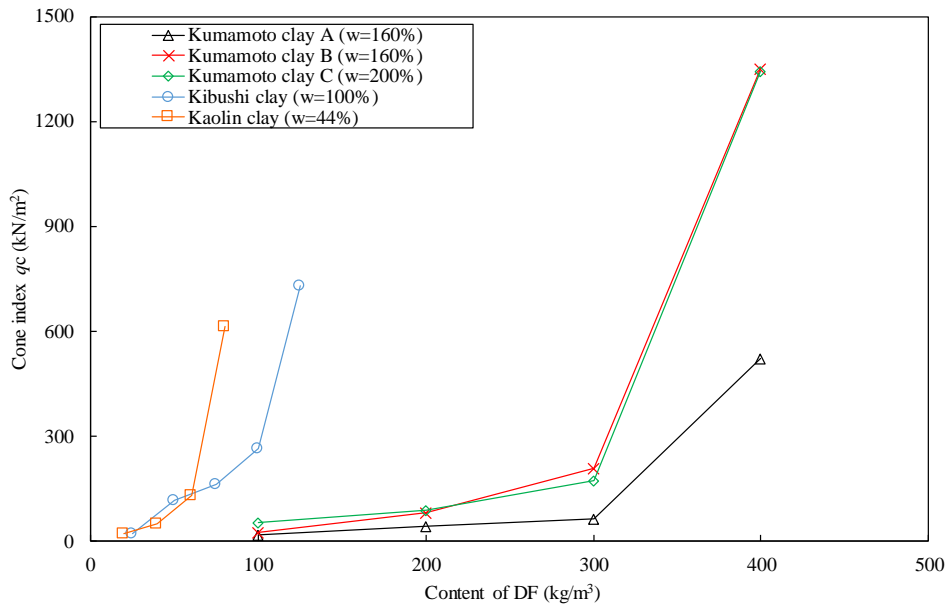
(b) Solidifying agent of DF

Fig. 4.2 Relationship between cone index of stabilized clay and content of OPC and DF

al., 2013). This CSH fabric along with FA particles embedded in the clay structure (Yoobanpot et al., 2013). FA particles filled the gap in the clay will result in the improvement effect.

Figure 4.2 (a) and (b) are the results of series 1, showing the relationship between the cone index of the stabilized clay and the content of solidifying agent. As shown in Fig. 4.2 (a), cone index of the stabilized clays increases considerably beyond a certain range of content of OPC. This trend depends on type of clays. Although DF solidifying agent contains small amount of cement (30 %) and 60 % of fly ash, a trend of increasing cone index on the stabilized clays by DF is similar to that of the stabilized clays by OPC and the improvement effect is smaller than that of OPC. The reason can be considered as the result of the initial inadequate calcium hydroxide products from the hydration process for pozzolanic reaction and hydration products increased with the addition of DF with fly ash. In addition, the mineral composition and pH of clay and the content of organic matter in clay are external factors affecting water and reaction (Aoyama et al., 2002; Babasaki., 1996; Uchida et al., 1985). However, compared with the abundant CSH fabric produced in the OPC hydration reaction process, the hydration reaction process of DF is more affected by the physical properties of clay.

4.3.2 Effect of water content in clay on the improvement effect

The experimental results of series 2 are shown in Fig.4.3 (a) and (b). When the content of solidifying agent was constant, the improvement effect decreased with the increase of water content in clay. The reason is that excess water from the hydration process caused the increase in distance of particle spacing, the decrease of hydration products which affect drop of strength (Miura et al., 2001). Water content influences not only the hydration products but also the pore volume, with the increase of porosity, the improvement effect also showed a downward trend. By comparing the improvement effects of OPC and DF, it can be found that when the same improvement effect is achieved, the water content in the stabilized clay by DF is lower than that of OPC. This is because there is not enough cement hydration reaction in the improvement process, namely FA particles cannot play its filling function, and the improvement effect becomes low. In addition, the difference in improvement effect between clays may be caused by the difference in excess moisture content in clay (Nagaraj et al., 2006). The liquid limit has been used as the main control factor to describe the water state of clay in previous studies. Actually, the improvement effect is not only affected by external conditions such as water content and amount of solidifying agent but also controlled by the physical properties of the clay itself. For evaluating the improvement effect of various types of clays, it is important to consider a difference of consistency property such as the liquid limit in each clay.
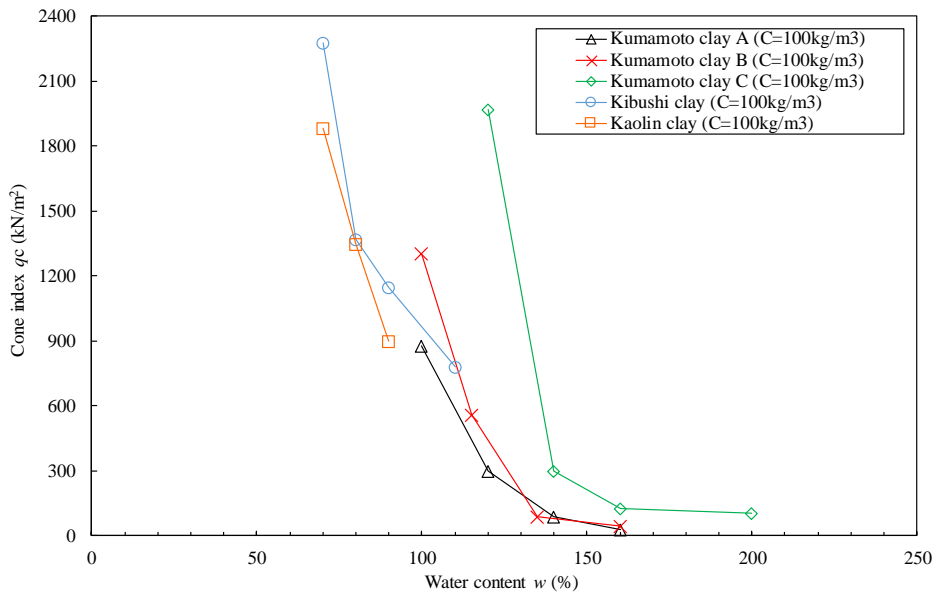
(a) Solidifying agent of OPC
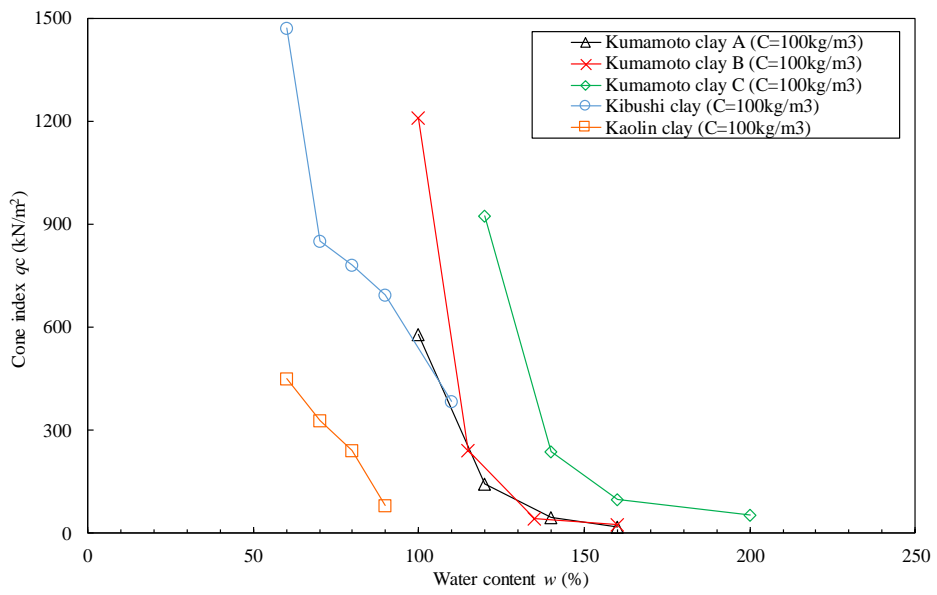
(b) Solidifying agent of DF

Fig.4.3 Relationship between the cone index and water content

4.4 Discussion

4.4.1 Evaluation of Improvement Effect by Modified Content of Solidifying Agent

The improvement effect of ordinary clays has been evaluated by cement-water ratio *C/W* (Sakka et al., 2002; Kalim et al., 2017; Tsuchida et al., 2013; Omine et al., 1999; Kaneshiro et al., 2004).
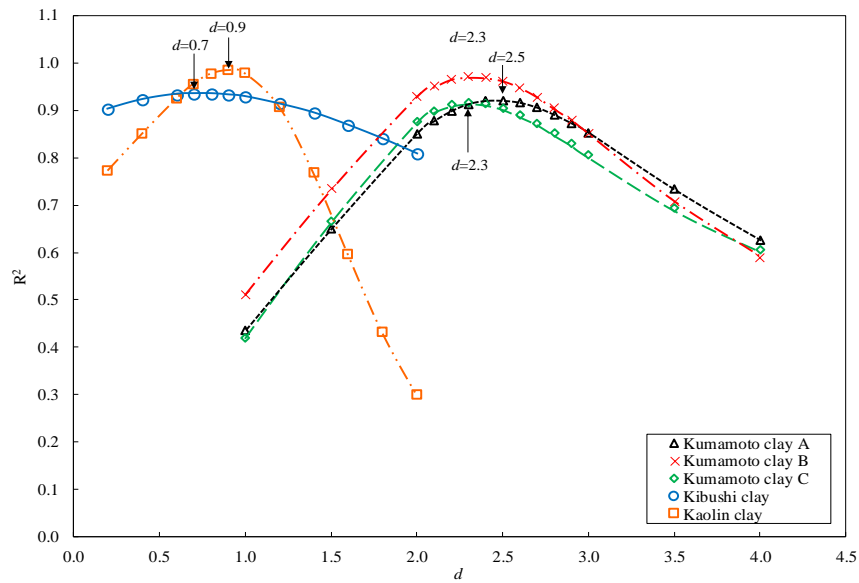
(a) Solidifying agent of OPC
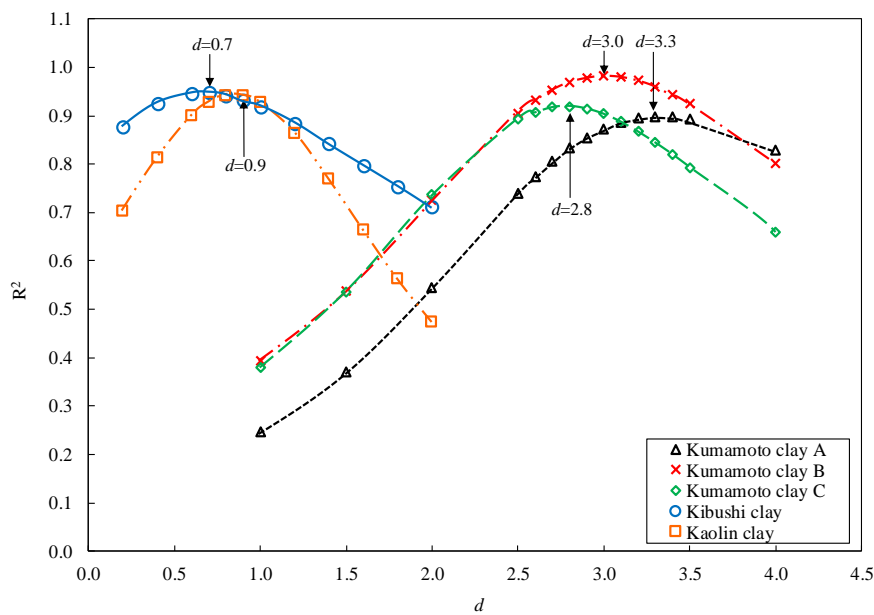
(b) Solidifying agent of DF

Fig. 4.4 A change of correlation coefficient R^2 in Eq. (3) in different value of *d*

However, it became clear that the cement-water ratio is not suitable for high organic clay and another evaluation method should be considered. As a physical property for keeping free water in the soil, liquid limit (w_L) is proved to have an important role in assessing the engineering properties of remolded and natural clay (Horpibulsuk et al., 2011b). The following new parameter, a modified content of solidifying agent K_L (kg/m^3), for representing an effect of content of solidifying agent was introduced by considering liquid limit.

$$K_L=C/(w/w_L)^d \tag{4.1}$$

Where C (kg/m^3) is the content of the solidifying agent, w and w_L are the water content and liquid limit of the clay, respectively, and d is a coefficient for representing the influence of water content. In this study, the following relationship between the cone index q_c and the modified content of solidifying agent K_L is proposed.

$$q_c=A\exp(B_LK_L) \tag{4.2}$$

Where A (kN/m^2) and B_L (m^3/kg) are constants of this equation, q_c (kN/m^2) is the cone index obtained from the cone penetration test. Eq. (4.2) can be converted to Eq. (4.3) with a linear relationship between $\ln q_c$ and K_L.

$$\ln q_c=\ln A+B_LK_L \tag{4.3}$$

Table 4.4 Summary of the parameters in the empirical equation

Sample	Solidifying agent	A (kN/m^2)	B_L (m^3/kg)	d	R^2
Kumamoto clay A	OPC	7.39	0.0308	2.5	0.92
	DF	8.00	0.023	3.3	0.90
Kumamoto clay B	OPC	8.00	0.0234	3.0	0.97
	DF	5.31	0.0191	2.3	0.98
Kumamoto clay C	OPC	14.59	0.0249	2.8	0.92
	DF	14.59	0.0195	2.3	0.91
Kibushi clay	OPC	37.71	0.0396	0.7	0.94
	DF	14.44	0.0417	0.7	0.95
Kaolin clay	OPC	7.69	0.0876	0.9	0.99
	DF	5.75	0.0576	0.9	0.94

Figure 4.4 (a) and (b) shows a change of correlation coefficient R^2 in Eq.(4.3) with different d on the stabilized clay by OPC or DF, respectively. It is found that R^2 has an obvious peak value above 0.9 in all stabilized clays. A value of d at the maximum value of R^2 is selected in this study. As shown in Fig.4.4, the value of d on low plasticity clay such as Kaolin clay and Kibushi clay is approximately
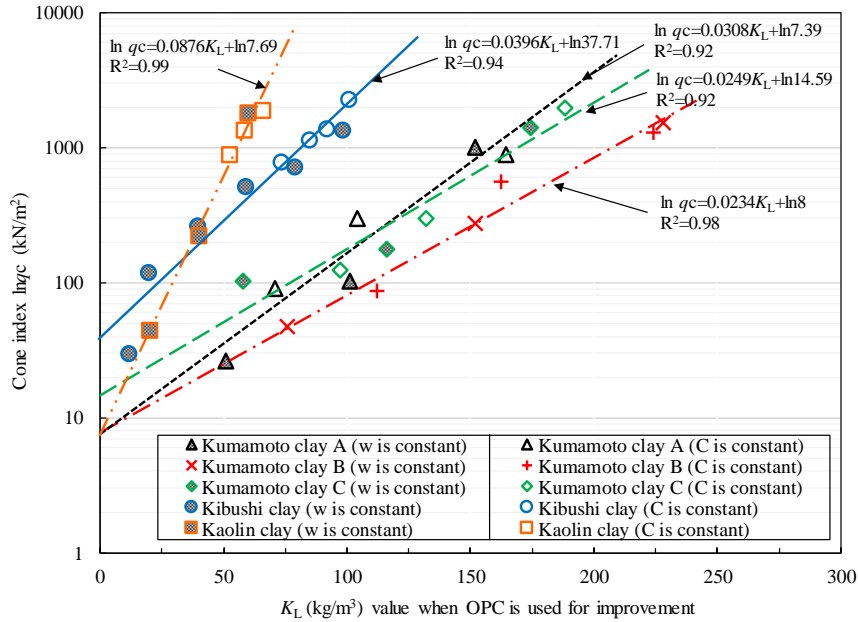
(a)
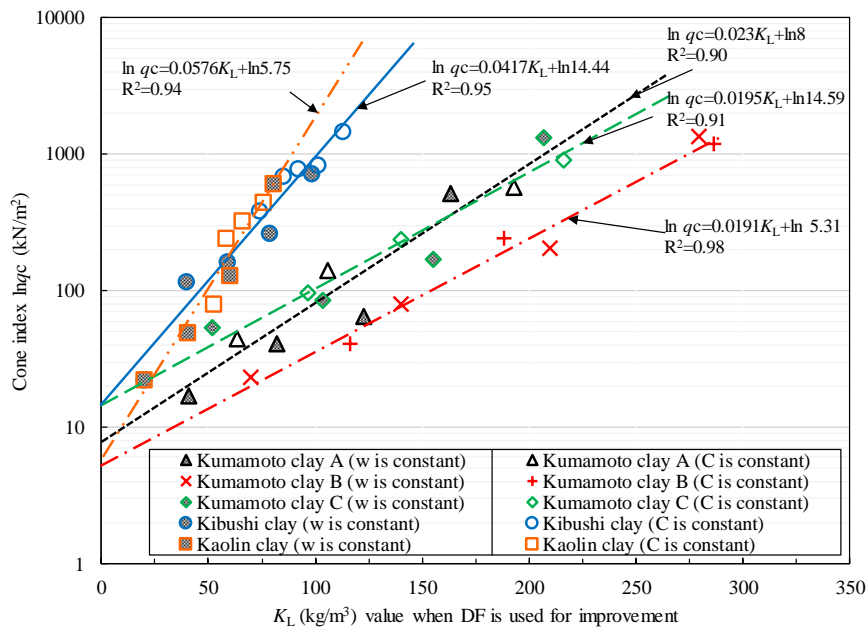
(b)

Fig.4.5 Comparison between test results and the empirical equation of Eq. (3) for the stabilized clays

0.7-0.9 and it is close to 1. On the other hand, the value of d on high organic clay such as Kumamoto clays is greater than 2.

Figure 4.5 (a) and (b) shows the relationships between q_c and K_L obtained from the test results and by the empirical equation of Eq.(4.3) on the stabilized clay by OPC or DF, respectively. As shown in Fig.4.5, the relationship between q_c and K_L can be represented by an approximation of a straight line in spite of a wide range of water content and content of solidifying agent for all stabilized clays. The meaning of parameters A and B_L is that A is an intercept of the line between q_c and K_L (at K_L=0) and B_L represents an inclination of the line. Table 4.4 shows the summary of the parameters (A, B_L and d) in the empirical equation in Fig.4.5 (a) and (b). According to the empirical equation, the improvement effect of the target clay can be evaluated when the values of C and w/w_L are known, and all empirical formulas have a certain correlation. In addition, this proposed equation has a guiding role in determining the required content of solidifying agents at changing the water content of clay in practice.

4.4.2 Relationship between Physical Properties and Parameters

A value of A in Eq.(4.3) corresponds to the cone index at K_L=0, namely q_c on the clay without solidifying agent. Based on the corresponding A value of each clay in Table 4.4, the A value is similar in most cases when the same type of clay is improved. At this time, the A value represents the cone penetration index of the target clay without adding a solidifying agent under the condition of the initial water content setting. In this study, when the target clay is improved, the set value of water content is almost near or higher than the liquid limit, and the A value under this water content is minimal and can be considered to be roughly constant in this range. Therefore, for any clay improvement, A value can be determined by the cone index obtained under the initial water content state.

In Eq. (4.1), when $w=w_L$, K_L is equal to C independent of d. It is therefore that B_L in Eq (4.2) can be regarded as an important coefficient for representing the improvement effect of the stabilized clay at the same water condition such as the liquid limit. Figure 4.6 shows the relationship between B_L and w_L on the stabilized clays. The value of B_L decreases with the increase of liquid limit for both stabilized clays of two solidifying agents. The value of B_L on the stabilized clays by OPC for low liquid limit is larger than that of DF. On the other hand, the values in the condition of high liquid limit become almost the same independent of the solidifying agents of OPC and DF.

In Eq (4.1), d is regarded as an important parameter for representing the influence of water content. Highly organic soil contains humic acid, bitumen, and fulvic acid. The inhibition of humic acid on cement hydration is due to the reaction between dissolved Ca^{2+} and humic acid, which makes calcium salts deposit on the surface of unhydrated cement particles or form chelates, thereby reducing the

concentration of Ca^{2+} significantly delaying the subsequent hydration reaction (Uchida et al., 1985; Okabayashi et al., 2004). This characteristic more easily occurs in high water content clay with a large gap ratio. Therefore, the reason for the d value difference can be explained by clay organic matter content. Figure 4.7 shows the relationship between d and ignition loss L_i of the clays. When L_i is less than 13%, it is usually considered as clay with low organic content and the value of d is close to 1 independent of the type of solidifying agent. When L_i is more than 17 %, it is usually regarded as clay with high organic content and the value of d indicates above 2 depending on L_i and type of solidifying agent. Compared with the clay of the low organic matter content zone, the improvement effect of clay in this zone is more easily affected by the change in water content.

The ignition loss is one of the parameters for representing the content of organic matter. The test result shows that the value of d depends on the ignition loss L_i. In the high organic content zone, the value d the stabilized clay by DF is larger than that of the stabilized clay by OPC. It indicates that the stabilized clay by DF is influenced by water content more sensitively. This is because even if the organic content is the same, the OPC hydration reaction with higher cement content is more complete, and the hydration product CSH fabric is far more than DF. The relationship between K_L/C and w/w_L obtained from Eq. (4.1) is shown in Fig.4.8. The value of K_L/C means an influence degree on the content of solidifying agent. When $w=w_L$, K_L/C is equal to 1. In the condition of $w>w_L$, K_L/C reduces with increase in the value of d. On the contrary, in the condition of $w<w_L$, K_L/C increases largely with increase in the value of d. This is important for high organic clays with high water content. Because it suggests that a large improvement effect can be obtained for the stabilized clay with a high value of d by reducing the water content less than the liquid limit. In Fig. 4.3, when the water content of the target clay gradually drops below the liquid limit, the growth rate of q_c of Kumamoto three clays with higher
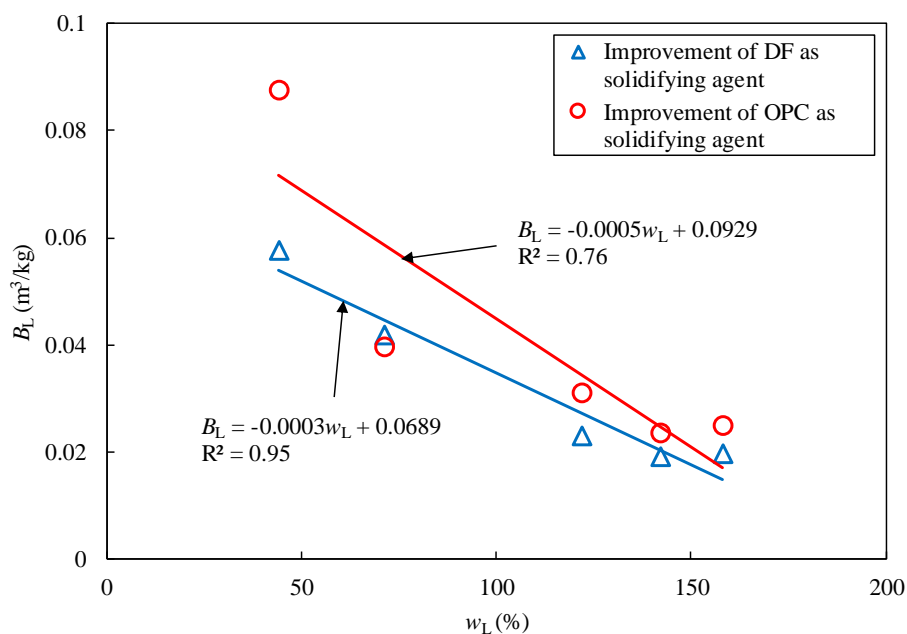
Fig.4.6 Relationship between B_L and liquid limit w_L on the stabilized clays
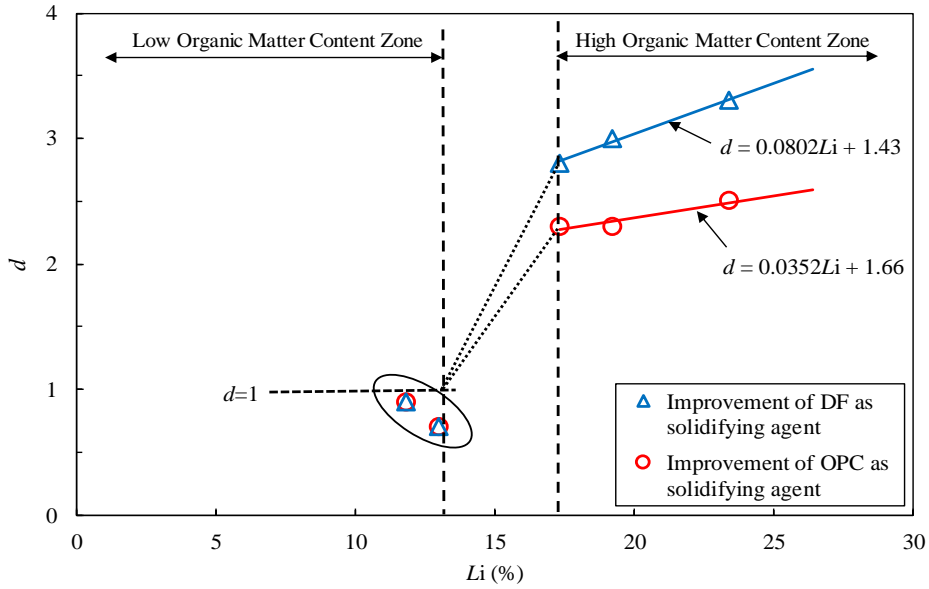
Fig.4.7 Relationship between d representing the influence of water content and the ignition loss L_i
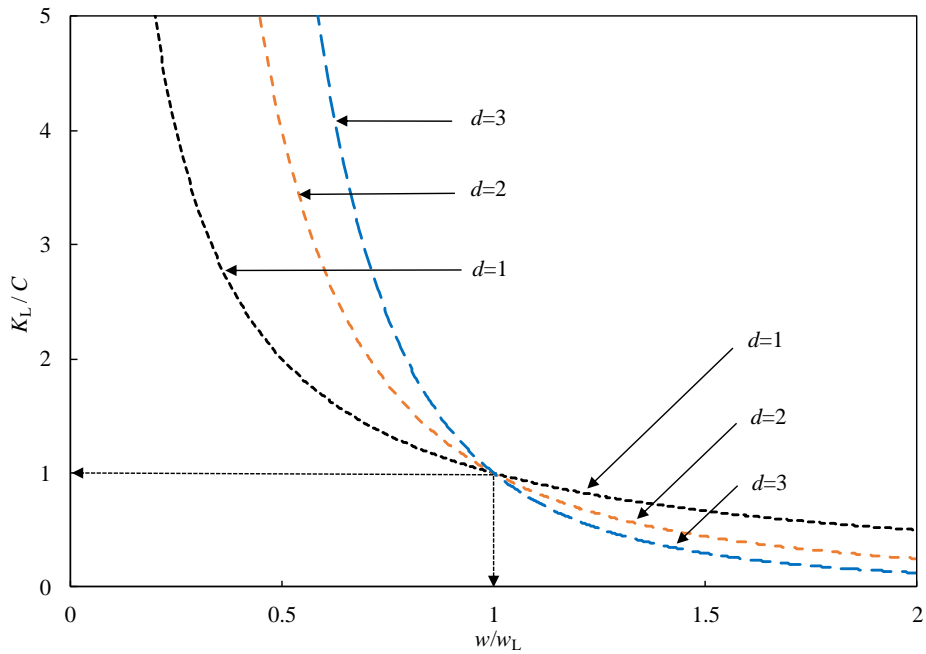
Fig.4.8 Relationship between K_L/C and w/w_L obtained from Eq. (1)

d value is generally higher than that of Kaolin clay and Kibushi clay, so this trend is also verified in Fig. 4.3. Based on this result, the authors attempted to reduce the water content of Kumamoto clay less than the liquid limit by a simple dehydration method at the field (Flemmy et al., 2019; Flemmy et al., 2022).

4.5 Conclusions

In this study, the improvement effect of cement-stabilized clays with different solidifying agent addition and water content was investigated based on the test results of cone index using five kinds of clays. Two types of solidifying agents, namely ordinary portland cement (OPC) and fly ash-containing solidifying agent (DF), were used. The conclusion obtained from this study can be drawn as follows:

1. A new parameter, K_L, for representing a modified content of solidifying agent was introduced by considering the liquid limit. An empirical equation of the cone index (q_c) with the modified content of solidifying agent (K_L) was proposed based on the experimental results. The validity of the proposed equation was confirmed for all the stabilized clays with different water content and two types of solidifying agents.

2. It was clarified that the parameters on the q_c-K_L empirical equation in different types of clays relate to liquid limit, ignition loss and type of solidifying agent.

3. The proposed empirical equation has a guiding role in determining the required content of solidifying agent in different water content of clay. The proposed formula mentioned in this paper has guiding significance for specific clay in the range of L_i = 11 ~24 %, w/w_L = 0.7 ~2.

References

Frioozi AA, Olgun CG, Firoozi AA, Baghini MS, (2017), Fundamentals of soil stabilization. *International Journal of Geo-Engineering* 8:26. https://doi.org/10.1186/s40703-017-0064-9.

Japan Cement Association (2012) Manual for Ground Improvement with Cement-Based Solidifying Material (in Japanese). Gihodoshuppan. Tokyo, Japan.

Chang TP, Shih JY, Yang KM, Hsiao TC, (2007), Material properties of Portland cement paste with nano-montmorillonite. *Journal of Materials Science.* 42:7478-7487. https://doi.org/10.1007/s10853-006-1462-0.

Sato T, (2003), Application of pneumatic flow mixing method Central Japan International Airport construction (in Japanese). *Japan Society of Civil Engineers.* 749:33–47. https://doi.org/10.2208/jscej.2003.749_33.

Watabe Y, Noguchi T, (2011), Site-Investigation and Geotechnical Design of D-Runway Construction in Tokyo Haneda Airport. *Soils and Foundations.* 51(6):1003-1018. https://doi.org/10.3208/sandf.51.1003.

Horpibulsuk S, Rachan R, Raksachon Y, (2009), Role of Fly Ash on Strength and Microstructure Development in Blended Cement Stabilized Silty Clay. *Soils and Foundations.* 49(1):85-98. https://doi.org/10.3208/sandf.49.85.

Jamnongpipatkul P, Dechasakulsom M, Sukolrat J (2009) Application of air–foam stabilized soil for bridge-embankment transition zone in Thailand. GeoHuman International Conference, Geotechnical Special Publication 190:181-193. DOI: 10.1061/41042(349)24

Kikuchi Y, Nagatome T, Mizutani TA, Yoshino H (2011) The effect of air foam inclusion on the permeability and absorption of light weight soil. Soils and Foundations 51(1):151-165. https://doi.org/10.3208/sandf.51.151

Peethamparan S, Olek J, Diamaond S (2009) Mechanism of stabilization of Na-montmorillonite clay with cement kiln dust. Cement and Concrete Research 39 (7):580-589. https://doi.org/10.1016/j.cemconres.2009.03.013

Amadi AA (2014) Enhancing durability of quarry fines modified black cotton soil subgrade with cement kiln dust stabilization. Transportation Geotechnics 1(1):55-61. https://doi.org/10.1016/j.trgeo.2014.02.002

Safari E, Ansari M, Ghazban F (2017) Preliminary assessment of cement kiln dust in solidification and stabilization of mercury containing waste from a chlor-alkali unit. J Mater Cycles Waste Manag 19:406–412. https://doi.org/10.1007/s10163-015-0437-0

Pavesi TB, Rohden AB, Garcez MR (2021) Supporting circular economy through the use of red ceramic waste as supplementary cementitious material in structural concrete. J Mater Cycles Waste Manag 23:2278–2296. https://doi.org/10.1007/s10163-021-01292-7

Tang YX, Miyazaki Y, Tsuchida T (2001) Practice of reused dredgings by cement treatment. Soils and Foundations 41(5):129–143. https://doi.org/10.3208/sandf.41.5_129

Mitsui T, Yoshikawa T, Ikeda A, Aoyama K, Nakagawa K (2001) A Basic Study of Improved Soils with Different Fine Grain Contents by Laboratory Mixing Tests (in Japanese). Japan Society of Civil Engineers 693:117–129. https://doi.org/10.2208/jscej.2001.693_117

Horpibulsuk S, Suddeepong A, Chinkulkijniwat A, Liu MD (2012) Strength and compressibility of lightweight cemented clays. Applied Clay Science 69:11-21. https://doi.org/10.1016/j.clay.2012.08.006

Abrams DA (1919) Design of concrete mixtures. Structural Materials Research Laboratory, Bulletin (1), 20 pp, Lewis Institute, Chicago, USA

Horpibulsuk S, Miura N, Nagaraj TS (2005) Clay–water/cement ratio identity of cement admixed soft clay. Journal of Geotechnical and Geoenvironmental Engineering ASCE 131(2):187-192. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:2(187)

Jongpradist N, Jumlongrach S, Youwai S, Chucheepsakul S (2010) Influence of fly ash on unconfined compressive strength of cement-admixed clay at high water content. Journal of Materials in Civil Engineering 22 (1):49-58. https://doi.org/10.1061/(ASCE)0899-1561(2010)22:1(49)

Babasaki R, Terashi M, Suzuki T, Maekawa J, Kawamura M, Fukazawa E (1996) Influencing Factors on Strength of Stabilized Soil. Proceedings of the Symposium on Cement Stabilized Soil (in Japanses). Geotechnical Engineering Society, February 1, Japan

Mitsui T, Yoshikawa T, Ikeda A, Aoyama K, Nakagawa K (2001) A Basic Study of Improved Soils with Different Fine Grain Contents by Laboratory Mixing Tests (in Japanses). Japan Society of Civil Engineers 693:117–129. https://doi.org/10.2208/jscej.2001.693_117

Takehisa M, Yasuo S, Yoshinobu O, Shozo S (1986) Properties of Kibushi clay modified with chemical treatment (in Japanese). Clay Science 26(3):151-156. https://doi.org/10.11362/jcssjnendokagaku1961.26.151

Erdogdu K, Turker P (1998) Effects of fly ash particle size on strength of portland cement fly ash mortars. Cement and Concrete Research 28(9):1217–1222. https://doi.org/10.1016/S0008-8846(98)00116-1

JIS A 1203 (2020) Test method for water content of soils. JIS A 1203, The Japanese Geotechnical Society, Tokyo, Japan.

JIS A 1210 (2020) Test method for soil compaction using a rammer. JIS A 1210, The Japanese Geotechnical Society, Japan.

JIS A 1228 (2020) Test method for cone index of compacted soils. JIS A 1228, The Japanese Geotechnical Society, Tokyo, Japan

Horpibulsuk S, Shibuya S, Fuenkajorn K, Katkan W (2007) Assessment of engineering properties of Bangkok clay. Canadian Geotechnical Journal, 44(2):173-187. https://doi.org/10.1139/t06-101

Olphen HV (1963) An Introduction to Clay Colloid Chemistry. Soil Science, 97(4):290.

DOI:10.1097/00010694-196404000-00013

Zhang RJ, Santoso AM, Tan TS, Phoon KK (2013) Strength of High Water-Content Marine Clay Stabilized by Low Amount of Cement. Journal of Geotechnical and Geoenvironmental Engineering 139(12):2170-2181. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000951

Horpibulsuk S, Miura N, Nagaraj TS (2003) Assessment of strength development in cement-admixed high‑water content clays with Abrams' law as a basis. Géotechnique 15(4):439-444. https://doi.org/10.1680/geot.2003.53.4.439

Horpibulsuk S, Rachan R, Chinkulkijniwat A, Raksachon Y, Suddeepong A (2010) Analysis of strength development in cement-stabilized silty clay from microstructural considerations. Construction and Building Materials 24(10):2011-2021. https://doi.org/10.1016/j.conbuildmat.2010.03.011

Wang DX, Edine AN, Rachid Z (2013) Strength and deformation properties of Dunkirk marine sediments solidified with cement, lime and fly ash. Engineering Geology 166 (2013):90-99. https://doi.org/10.1016/j.enggeo.2013.09.007

Yoobanpot N, Jamsawang P, Horpibulsuk S (2017) Strength behavior and microstructural characteristics of soft clay stabilized with cement kiln dust and fly ash residue. Applied Clay Science 141(1):146-156. https://doi.org/10.1016/j.clay.2017.02.028

Aoyama K, Miyamori T, Wakiyama T, Kikuchi D (2002) The influence of physico-chemical property on improved soil character (in Japanese). Journal of JSCE 721:207-219. https://doi.org/10.2208/jscej.2002.721_207

Babasaki R, Terashi M, Suzuki T, Maekawa J, Kawamura M, Fukazawa E (1996) Influencing Factors on Strength of Stabilized Soil (in Japanese). In: Proceedings of the Symposium on Cement Stabilized Soil, Geotechnical Engineering Society. Japan, Tokyo, pp. 20-41.

Uchida K, Fukubayashi Y, Yamashita J (1985) Effect of Humic Acid in Soil on Hydration of Irwin Cement (in Japanese). The annual report of Cement and Concrete Engineering (Japan Cement Association) 39:486-489. DOI: 10.11501/2308567

Miura N, Horpibulsuk S, Nagaraj TS (2001) Engineering behavior of cement stabilized clay at high water content. Soils and Foundations 41(5):33-45. https://doi.org/10.3208/sandf.41.5_33

Nagaraj TS, Lutenegger AJ, Pandian NS, Manoj M (2006) Rapid estimation of compaction parameters for field control. Geotechn Test J, ASTM 29 (6):1-10. https://doi.org/10.1520/GTJ100009

Sakka, H., Ochiai H, Yasufuku N, Omine K (2002) Evaluation of deformation-strength properties of cement-stabilized soils by falling weight deformation measurement apparatus (in Japanese). Japan Society of Civil Engineers 2002(701):283-292. https://doi.org/10.2208/jscej.2002.701_283

Kalim TP, Tsuchida T, Tang YX, Kang G-o (2017) Strength behavior of cement-treated dredged clay with various sand content. Journal of Japan Society of Civil Engineers B3(Ocean Engineering) 73(2):318-328. https://doi.org/10.2208/jscejoe.73.I_318

Tsuchida T, Tang YX, Shimakawa N, Abe T (2013) Study on the strength-time relationship of cement-treated marine clays with high water contents (in Japanese). Journal of Geotechnical Engineering 8(1):53-70. https://doi.org/10.3208/jgs.8.53

Omine K, Ochiai H, Yasufuku N, Sakka H (1999) Prediction of strength-deformation properties of cement-stabilized soils by nondestructive testing. Pre-failure deformation characteristics of geomaterials, Sep 28, Torino Italy.

Kaneshiro T, Sakemaki K, Tasaka Y, Takakura T (2004) Principles and applications of soil consolidation:3. Properties of improved soils (in Japanese). Soil mechanics and foundation engineering 52(11):59-66, The Japanese Geotechnical Society, Japan.

Horpibulsuk S, Yangsukkaseam N, Chinkulkijniwat A, Du YJ (2011b) Compressibility and permeability of Bangkok clay compared with kaolinite and bentonite. Applied Clay Science 52(1-2):150-159, https://doi.org/10.1016/j.clay.2011.02.014

Okabayashi S, Omori H, Yanagihara H, Takahashi S (2004) Principles and applications of soil hardening: 2. Cement and cement-based solidifying material chemistry (in Japanese). Soil mechanics and foundation engineering 52(10):47-54, The Japanese Geotechnical Society, Japan.

Flemmy S, Omine K, Zhang Z (2019) Soft clay improvement technique by dewatering and dewatering sandy soil. International Journal of GEOMATE 17: 9-16, DOI: 10.21660/2019.63.03627

Flemmy SO, Omine K, Zhang Z (2022) Simple dehydration technique using drainage string to treat drinking water sludge for utilization as geomaterial. J Mater Cycles Waste Manag. https://doi.org/10.1007/s10163-022-01420-x

5. Investigation on Improving Method of High Water Content Clay under Low Environmental Load

5.1 Introduction

Reservoir clay has high water content, high compressibility, and low shear strength. Therefore, the mechanical properties of clay must be improved to make effective use of reservoir clay. Clay improvement using cement-based solidifying agents has been extensively used in highway and port construction in many countries, such as Japan and Thailand (Satoh, 2003; Satoh et al, 2001; Jamnongpipatkul et al, 2009; Chompoorat et al, 2021; Chompoorat et al, 2021). Despite the significant advantages of solidifying agents such as ordinary portland cement (OPC), fly ash (FA), and coal mines in stabilizing soft clay (Chompoorat et al, 2022; Julphunthong et al, 2018; Chompoorat et al, 2021; Amiri et al, 2021), environmental and rising costs problems caused by the production of solidifying agents should still be considered. For example, a large amount of carbon dioxide is emitted during the production of cement, a major greenhouse gas.

In 2020, Japan's oyster production was 158 900 tons, with oyster shells (OS) accounting for 80% of the weight (Ministry of Agriculture, Forestry and Fisheries, 2020; Okayama Agriculture, Forestry and Fisheries Department, 2013). Even though these wastes can be used as fertilizers, most waste OS are not effectively used (Imokawa and Souda, 2001). In an attempt to recycle OS in large quantities, some studies used OS as a substitute for aggregates to increase the strength of stabilized clay, particularly as a partial fine aggregate replacement (Yang et al, 2010; Wang et al, 2013; Mo et al, 2018). However, a higher OS substitution leads to a decrease in the aggregate-paste bond (decreasing mechanical performance), an increase in porosity. It also affects the hydration process, and has the potential to negatively influence the concrete's long-term strength increment (Martinez-Garcia et al, 2017; Cuadrado-Rica et al, 2016). The oyster shell aggregate mixing content should be considered to obtain the optimum strength (Yang et al, 2005). These attempts are highly applicable from the perspective of improving the strength of stabilized clay and the effective utilization of waste, but the utilization rate is very low.

Oysters are renewable natural resources, and the main component of OS ash is calcium carbonate (Chiou et al, 2014; Yoon et al, 2003); which can be converted into lime by calcination. The quicklime-based fixation/stabilization of heavy metals in contaminated soil is considered an effective remediation technology and has been widely applied (Zhang et al, 2022; Yi et al, 2015; Ok et al, 2010; Kostarelos et al, 2006). Numerous studies have investigated the use of calcium oxide extracted from calcined oyster shells (COS) (Chiou et al, 2014; Khan et al, 2018) and considered the possibility of using COS as a cementitious material additive (Li et al, 2015; Seo et al, 2019; Naqi et al, 2020). However, the

process of converting $CaCO_3$ into CaO by calcination usually occurs at a relatively high-temperature (about 1000 °C), and continuous high-temperature calcination brings extremely high production costs. At the same time, the large amount of CO_2 produced during calcination is an important contributor to the greenhouse effect (Shakoor et al, 2021). Therefore, although COS is an excellent soil stabilizer, the amount of COS must be reduced. The use of waste materials in the solidifying agent mixture can reduce the use of solidifying agents and solve the problem of waste recycling. The possibility of using waste rubber powder (WRP) instead of cement and coarse aggregate as environmentally friendly concrete has been investigated in the new research. However, a considerable amount of cement is still needed to maintain the strength of the sample, and whether it is suitable for improving high water-content clay remains to be investigated.

It was reported that domestic animal excrement in Japan was more than 8.0×10^7 tons in 2020. The yield of cow dung reached 4.5×10^7 tons, 286 times that of OS (Ministry of Agriculture, Forestry and Fisheries, 2020). The accumulation of domestic animal excrement is a public resource. In addition, there are many problems in the storage and use of raw manure, such as odor and emissions of harmful compounds, which poses a challenge to its effective treatment and application. Although fertilizer are available as subsidiary agricultural products, cow dung compost production is much more than annual utilization. In an existing studies, carbonized cow dung compost has been considered a replacement for wood charcoal (WC) as fuel (Sanaa, 2011). Biochar (BC) is a carbonaceous product formed by heating raw biomass under anaerobic or low-oxygen conditions (ur Rehman et al, 2020). Compared with waste materials such as rice husk ash, blast-furnace slag and silica fume, BC has achieved the most promising results in improving the mechanical behavior of composites (Arif et al, 2021; Navaratnam et al, 2021; Taiwo et al, 2022). In the extensive research on BC, BC is considered a new green gel material due to its low cost (Mian et al, 2018), high adsorption capacity and geological abundance (Guo et al, 2016). Studies have shown that BC formed after carbonization of cow dung compost and waste wood improves soil aggregates by utilizing its porous surface structure (Kameyama et al, 2021; Glaser et al, 2002; Hayashi et al, 2014; Lee et al, 2015; Navaratnam et al, 2021; Taiwo et al, 2022). Compared to COS, BC has lower costs owing to its low carbonization temperature and short carbonization time. Therefore, COS-stabilized clay with BC as its aggregate can be an efficient, environmentally friendly and economical new solidifying agent applied to stabilize high water content dredged clay. However, there is less literature available on BC than on solidifying agents to stabilize high water content clay.

Research on the utilization of carbonized cow dung compost (CC) as a substitute to COS in stabilized clay can contribute to the disposal of CC and the development of new solidifying agents. The objective of this research was to clarify whether recycled materials such as COS and CC can be used as solidifying agents for stabilizing clay with high water content and as substitute materials. Based on a cone index test, the effects of COS and OPC on the clay improvement were compared. According to the mixing amount of carbonized material (CC and WC), the effect of carbonized

Process	Scrubbing	Grinding	Calcining
Image of the resultant product			
Description	1. The surface of collected oyster shell wastes is washed with a brush to remove surface organic matter and soaked in water for a week or more to remove salt and foreign substances. 2. Washed oyster shell was dried for 24h in a 110℃ electrical furnace.	1. Place oyster shells at room temperature and pulverize to pass a 2-mm sieve.	1. A crushed oyster shell was calcined in an electric furnace at 1000℃ for 2.5h. 2.The calcined oyster shell powder was slowly cooled down to room temperature in the electric furnace and then pulverized to pass a 2-mm sieve.

Fig.5.1 Calcium oxide powder was prepared by calcining oyster shell waste.

materials replacing COS on stabilized clay was quantitatively investigated. To elucidate the hydration characteristics and microstructure of the stabilized clay, scanning electron microscopy (SEM) and energy-dispersive X-ray spectrometry (EDS) were conducted.

5.2 A case study of improving high water clay by calcined oyster shell and carbonized cow dung compost

5.2.1 Materials and Test Procedure
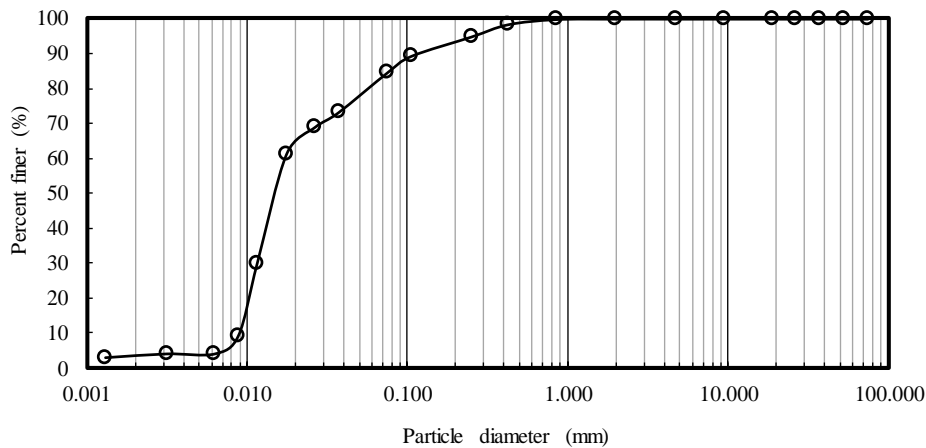
Fig.5.2 Grain size distribution of Kaolin clay.

Table.5.2 Physical properties of Kaolin clay.

Properties	Kaolin clay
Liquid Limit, w_L (%)	44.4
Plastic limit, w_p (%)	24.28
Plasticity index, I_p	20.12
Density ρ_s (g/cm^3)	2.62
Ignition loss Li (%)	11.82
Fine particle content Fc (%)	84.6

The waste oyster shells used in this study were from the southern coast of Japan. The process flow of calcining waste oyster shells to prepare calcium oxide (CaO) powder is shown in Fig. 5.1. In order to remove salt and organic matter attached to the surface, the oyster shell (OS) surface is brushed and soaked in water for at least 7-days. The washed oyster shells were dried in an electrical furnace at 110 °C for 24 h. The temperature was lowered to room temperature and then pulverized to pass through a 2-mm sieve. The crushed oyster shell powder was calcined at 1000 °C for 2.5 h. The ignition loss (ignition loss = mass loss / mass before calcination × 100) of all COS powder was controlled at approximately 45 %. The COS powder will cool in an electric furnace until it reaches room temperature and then be crushed again. CaO was obtained from Hayashi Pure Chemical Co., Ltd. (CaO content is above 93%). The EDS results for the obtained COS are shown in Table 5.1. The content of CaO in COS obtained by the EDS test is 94.16%, which is close to the content of CaO in commercial CaO (95.46%).

Kaolin clay was obtained from nendoyasan.com, Japan. The grain size distributions of the kaolin clay are presented in Fig. 5.2. The physical properties of the kaolin clay are listed in Table 5.2.

The fermented cow dung compost was supplied by pastures in Kyushu, Japan. The cow dung compost was placed in an electric furnace at 110 °C for more than 24 h to obtain dry cow dung compost. Different calcination temperatures will affect the mesopore volume of carbides, thus affecting the adsorption capacity of carbides. In order to obtain the heating temperature for the best adsorption capacity, the heating temperature of the metal tank filled with dry cow dung compost (approximately

Table.5.1 Comparison of chemical ingredient of commercial CaO and COS (unit; wt, %).

Elementary analysis (%)	Experimental material (kg/m³)	
	COS	Commercial CaO
CaO	94.16	95.46
C	5.21	2.95
MgO	–	1.59
SO$_3$	0.45	–
SiO$_2$	0.08	–
FeO	0.09	–
Al$_2$O$_3$	0.01	–

(a) CC (400°C)

(b) SEM micrographs for CC (400°C)

(c) WC

(d) SEM micrographs for WC
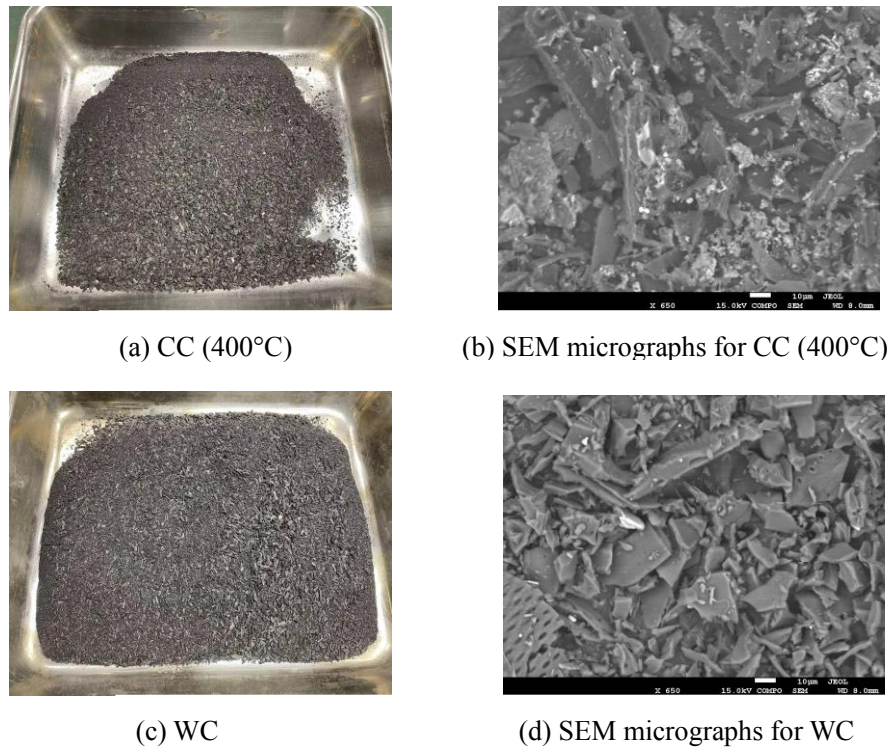
Fig.5.3 Carbide in test and SEM micrographs for carbonized cow dung compost (CC: calcination temperature is 400 °C) and wood charcoal (WC).

500 g) was set to 200–900 °C. A set of water absorption rate tests were carried out every 100 °C in this temperature range, and the sample was maintained under an isothermal condition for 30 min. Remove the sample from the furnace and cool it to room temperature. The obtained carbonized cow dung compost (CC) was passed through a 2 mm sieve to remove coarse particles. The water absorption rate was determined according to the water absorption rate test method of JIS A 1110 and reflected the adsorption capacity of the carbide (JIS A 1110; 2020). To illustrate the effectiveness of the experiment, the WC obtained from NAFCO Co., Ltd. was used as the experimental control material. WC is crushed and passed through a 2mm sieve to obtain WC particles of the same size as CC. The particles of the WC and CC (400 °C) were observed using SEM, which illustrated that the particles have a smooth surface, sharp corners, and are non-uniformly shaped, as shown in Fig. 5.3.

5.2.2 Preparation of sample

Cement-water ratio ($C/(w/100)$) has been generally proved to be an important parameter to evaluate the mechanical properties of cement-stabilized clay (Zhang et al; 2022). In the experiment, to compare the improvement effects of COS and OPC on clay with high water content, the stabilized clay needed to be effectively evaluated. Therefore, the initial water content (w: %) and the content of

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solidifying agent (C: kg/m³), which are used to describe the mixing conditions of the solidifying agent, were set as test variables. As shown in Table 5.3, in the preparation of sample Series 1, stable clay samples were prepared by changing the content of solidifying agent based on a determination of the initial water content of clay (COS stabilized clay w = 70%; OPC stabilized clay w = 44%). Series 2 are the stable clay samples obtained by adjusting the initial water content based on the constant content of the solidifying agent (C = 30 kg/m³ for COS improvement and 100 kg/m³ for OPC improvement). Finally, based on the cement-water ratio (C/(w/100)), the mixing conditions of stabilized clay samples were described uniformly. The specific water content adjustment was achieved by adding water or natural drying.

As shown in Table 5.4, to evaluate the contribution of carbides to the strength of COS-stabilized clay, COS of 30 kg/m³ and carbide were added to the clay with an initial water content of 70 % at the same time in the test of mixed carbide prepare the mixed sample. The content of COS (30 kg/m³) and the initial water content of clay (70%) were constant in the test. To compare the difference in improvement effect caused by the mixing amount of two carbides (CC and WC), the mixed amounts of carbides were 30, 60, 90 and 120 kg/m³, respectively.

During specimen preparation, the clay was first uniformly mixed using a mortar mixer. The solidifying agent and water-absorbent materials were then added simultaneously to the clay and fully mixed until the entire sample attained uniform consistency. The unit mass of the samples ranged from 1.6×10^3 to 1.7×10^3 kg/m³ depending on the amount of water. The test sample was sealed with macromolecular polyethylene to prevent evaporation and moisture absorption, and the sealed sample

Table.5.3 Mixture proportion of COS and OPC.

Series	Water content w (%)	Content of solidifying agents C (kg/m³)		Cement-water ratio C/(w/100) (kg/m³)
		COS	OPC*	
1	70	20, 30, 40, 50	–	29, 43, 57, 71
	44	–	20, 40, 60	45, 91, 136
2	40, 50, 60, 70	30	–	75, 60, 50, 43
	70, 80, 90	-	100	143, 125, 111

(*OPC: Ordinary Portland Cement, from Terada Co., Ltd.)

Table.5.4 Mix proportions of COS and carbonized material.

Sample	Water content w (%)	Content of COS C (kg/m³)	Mixed amount of carbides (kg/m³)	
			WC	CC
COS30C30			–	30
COS30C60	70	30	–	60
COS30C90			–	90
COS30C120			–	120
COS30W30			30	–
COS30W60	70	30	60	–
COS30W90			90	–
COS30W120			120	–

was placed at constant temperature (25 ± 3 °C) and humidity ($90\% \pm 3\%$). The stabilized clay samples were subjected to testing after 28 days of curing. A cone penetration test was performed on COS-stabilized clays to determine the cone index. In this study, the cone index was used as an important parameter to evaluate the improvement.

5.2.3 Testing procedure

Sample preparation is based on the standard of the Japanese Geotechnical Society's method of preparing samples by 'Practice for making and curing compacted stabilized clay specimens using a rammer' (JGS 0811, 2020). Table 5.5 lists the cone penetration test conditions. After 28 days of storage, the sample was compacted in a mold with a height of 127 mm and diameter of 100 mm using a hammer mass of 2.5 kg and a drop height of 300 mm. The sample was pressed into the mold in three compaction layers. Approximately 40 mm intervals were set between compaction layers to press the sample into the mold three times. Each layer had 25 cycles of compaction (JIS A 1210 A-c method: compaction energy approximately 550 kJ/m^3) (JIS A 1210, 2020), except that part of the weakly stabilized clay specimen was unable to compact. Subsequently, a cone penetration test was performed immediately. The penetration resistance of the test samples at 50, 75, and 100 mm was measured, and the average value divided by the cone bottom area was defined as the cone index. At least three samples for each sample type were tested under the same conditions to ensure consistency. In most cases, results obtained under the same testing conditions were reproducible.

When COS is used as the curing agent, it is necessary to evaluate the changes in the main components that transforms to CaO under high-temperature OS conditions. X-ray diffraction (XRD) analysis was performed to compare the composition changes of OS and COS to clarify this. The structural characterization of the samples was performed using a Rigaku MiniFlex 600 powder X-ray diffractometer operated at 40 kV and 15 mA, and phase identification was performed using the PDXL2 (Rigaku) software. Thermogravimetric analysis (TGA) was performed using thermogravimetric-differential thermal analysis (TG-DTA) (Shimadzu: DTG-60, resolution = 1 µg) equipment with a thermogravimetric analyzer and the temperature difference between the sample and a standard substance (DTA). It was used to evaluate the thermal decomposition of calcium carbonate ($CaCO_3$) at a rate of 10 °C/min from 0 to 1000 °C. In addition, TGA was also used to determine the mass change rate of CC in the range of 0-900 °C. The sample mass used for the testing was 10 mg.

SEM analysis was used to further investigate changes in the microstructure of the stabilized clay. The stabilized clay reaction products were studied using EDS.

Table.5.5 Test program and cone penetration test conditions.

Clay	Kaolin clay
Type of solidifying agent	COS and OPC
Type of carbides	WC and CC
Mixing condition	The solidifying agent and carbides were then added simultaneously to the clay.
Mixing method	Use a mortar mixer to mix until the entire sample reaches a uniform consistency.
Curing condition	The samples were stored in a sealed state and maintained at a constant temperature (25 °C) and constant humidity (90 %) state.
Solidification time	28days (Cone index test after 28 days of mixing)
Press the sample into the mold	The sample was pressed into the mold in three compaction layers using a rammer. Each layer was set with 25 compaction cycles with an interval of 40 mm.
Mold	Inner diameter is 100mm, and the capacity is about 0.001m^3
Rammer	The weight of the heavy hammer is 2.5kg, the falling height is 300mm, and the falling method is free fall
Cone penetrometer	Tip angle 30°, bottom area 320 mm^2
Penetration Rate	1cm/s
Measuring method	The penetration resistance force at the time of penetration of 50, 75, 100 mm is measured, and the value obtained by dividing the average value by the cone bottom area is defined as the cone index.
Product type of load measurement	RZTA-1000N produced by IMADA

5.3 results of test on site

5.3.1 XRD and TG-DTA analyses

Figure 5.4 shows the XRD results for OS, COS, and commercial CaO powders. The main crystalline phase of OS was determined to be $CaCO_3$ by XRD patterns. In addition, the main crystalline phase of COS and commercial CaO was CaO. The diffraction patterns (relative intensity and peak positions) of COS and commercial CaO were similar. A small number of peaks from $Ca(OH)_2$ were also observed in commercial CaO. Based on the XRD analysis, it can be demonstrated that COS obtained by the calcination of OS and commercial CaO possess similar crystal phases and chemical compositions.

The TG-DTA results of bulk oyster shell waste are shown in Fig. 5.5. OS exhibits weight loss in two ranges: from 20 to 560 °C and from 560 to 750 °C. A weight loss of 7.7% by mass when the temperature reaches 560 °C corresponds to the ignition of organics in oyster shell waste (Arias and Fernandez, 2003). The primary endothermic reaction of OS between 560 and 750 °C is considered the thermal decomposition of $CaCO_3$. The product CaO is generated, and carbon dioxide (CO_2) is emitted.
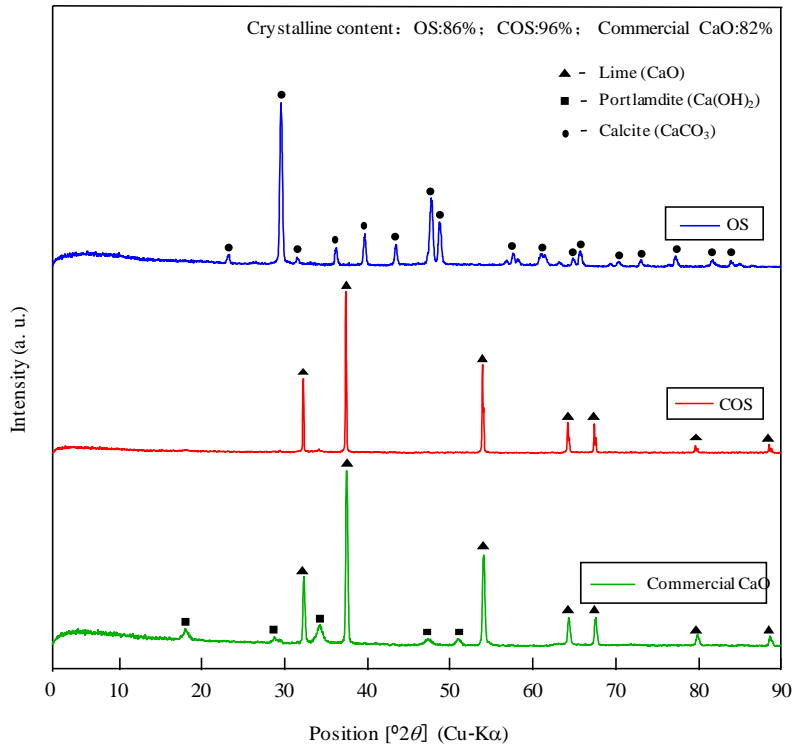
Fig.5.4 XRD test results of OS, COS and Commercial CaO.
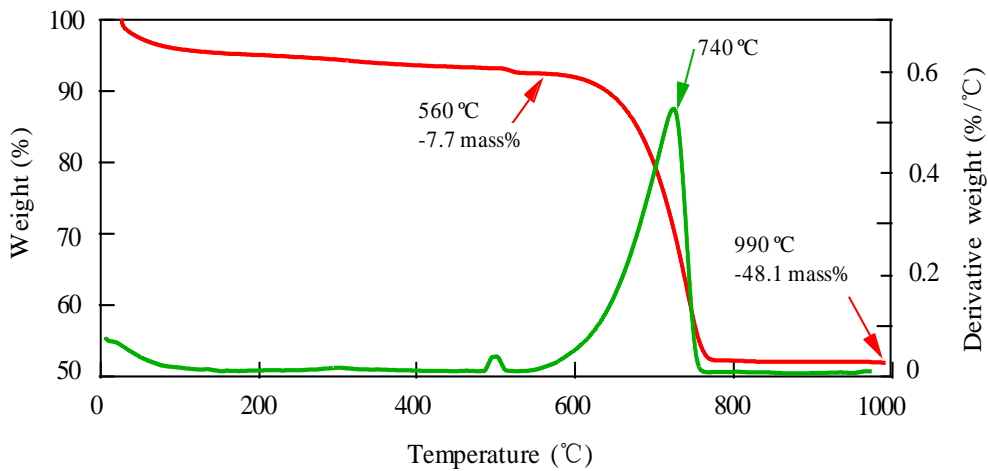
Fig.5.5 Thermogravimetric (TG-DTA) data for oyster shell powder (OS).

The actual mass change ratio attributed to CO_2 emissions was measured as 40.4 mass% for OS (48.1% – 7.7% = 40.4%). The value is slightly lower than the theoretical mass change ratio of 44% (100% – 56% = 44%). Therefore, the calcination of OS powder was considered to be the conversion of calcium carbonate to calcium oxide. When the temperature reached 990 °C, calcium carbonate was almost completely converted to calcium oxide. This result was also confirmed from the XRD results of the COS powder.

5.3.2 Investigation of water absorption rate

Figure 5.6 shows the effect of calcination temperature on the water absorption rate of the cow dung compost and the TGA results. When the temperature was maintained at 400 °C for 30 min, the water absorption rate peaked to 348% (water absorption rate is calculated as $(m_s/m_w) \times 100$, where, m_s is the mass that is in a saturated surface-dry condition after water absorption and m_w is the mass that is in an absolutely dry condition), which is more than twice that of WC (the water absorption rate of WC is 160%) as shown in Fig. 5.6(a). Compared to other temperature conditions, cow dung compost has a larger average pore size and mesoporosity at 400 °C, which may lead to higher adsorption capacity (Qian et al, 2007). The results of the TGA in Fig. 5.6(b) show that the yield decreased at
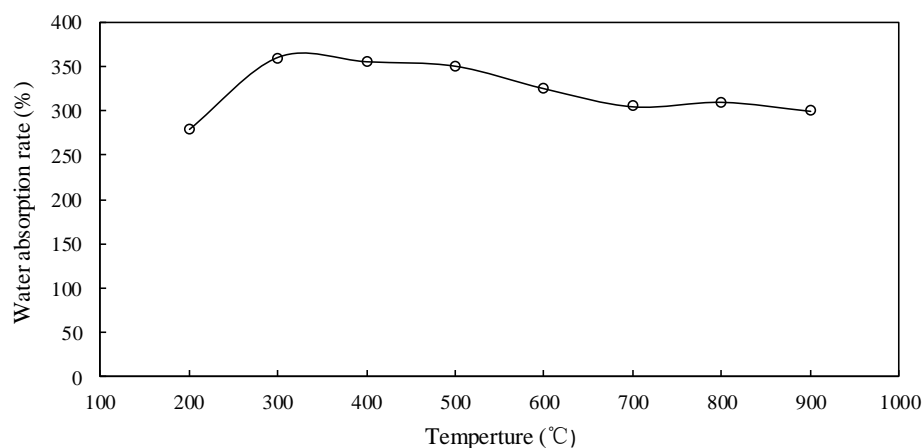
(a) Effect of temperature on water absorption rate of CC
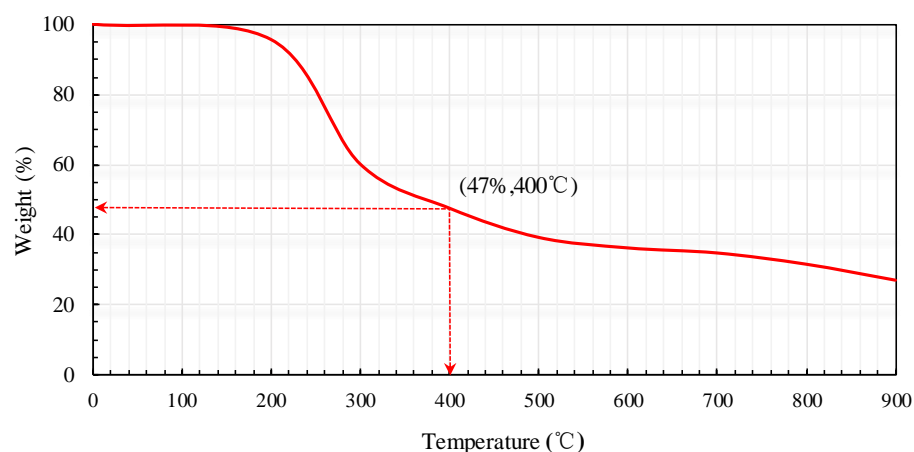
(b) Thermogravimetric analysis results (TGA) of CC

Fig.5.6 Effect of temperature on CC; (a) effect of temperature on water absorption rate of CC, (b) thermogravimetric analysis results (TGA) of CC.

higher pyrolysis temperatures because of carbon burning-off and tar volatilization. At 400 °C, the carbonized cow dung compost yield was 47% of the initial yield.

5.3.3 Evaluation of the improvement effect of COS stabilized clay

In this study, the mechanical properties of OPC-stabilized clay at a curing time of 28 days were used as a reference to explain the effectiveness of calcined oyster shell (COS) improved clay. In previous studies, the contents of the solidifying agent (C) and water (w) were proven to be the main factors affecting improvement (Horpibulsuk et al, 2003; Horpibulsuk et al, 2006; Horpibulsuk et al, 2011). Zhang et al. utilized $C/(w/100)^d$ to effectively evaluate the improvement effect of cement stabilized high water content dredged clay (Zhang et al, 2022). The control parameter d represents the effect of the water content, mainly affected by clay organic matter content. When the ignition loss L_i is less than 13 %, the clay is classified as a ' low organic matter content zone ', and the clay $d = 1$ in this zone can still maintain a high coefficient of determination (Zhang et al, 2022). Therefore, in this study, the solidifying agent/water ratio, $C/(w/100)$ (kg/m^3), was used as an essential parameter to evaluate the improvement effect of solidifying agent stabilized clay. Figure 5.7 shows the cone index (q_c) and $C/(w/100)$ of all samples in Table 5.3 at 28 days of curing. Furthermore, the R^2 of the evaluation formula reached 0.97 in the evaluation process of COS stabilized clay by the solidifying agent/water ratio $C/(w/100)$. It was confirmed that the solidifying agent/water ratio $C/(w/100)$ could be applied to the evaluation of COS-stabilized clay.

In contrast to the hydration process of cement, the improvement effect of lime stabilized clay is mainly due to cation exchange, flocculation, and agglomeration. Subsequent pozzolanic reactions cause stable clay to exhibit long-term strength (Bell, 1996; Kassim and Chern, 2004; Prusinski and Bhattacharja, 1999). Therefore, the COS-stabilized clay exhibited a higher improvement effect than the OPC-stabilized clay for 28 days. Compared with OPC, the addition of COS required for the cone index q_c to reach 500–1000 kN/m^2 was significantly reduced (approximately 43%–46% reduction). When the cone index reached the maximum value of 1630 kN/m^2, the mixing amount of COS decreased by 47% compared with OPC. In other words, when effective improvement is achieved, the cement content required under the same water content is almost twice than that of COS. Onitsuka et al. obtained similar results after comparing the improved strength of high water-content clay stabilized by quicklime and cement. After 28 days of curing time, when the quicklime mixing amount is in the range of 5 % - 10 %, the mixing amount of cement is twice that of quicklime under the same improved strength condition. From the improvement effect, COS is similar to quicklime. It can be concluded that COS has the potential to be used as a cementitious material to enhance stabilized clay with high water content.
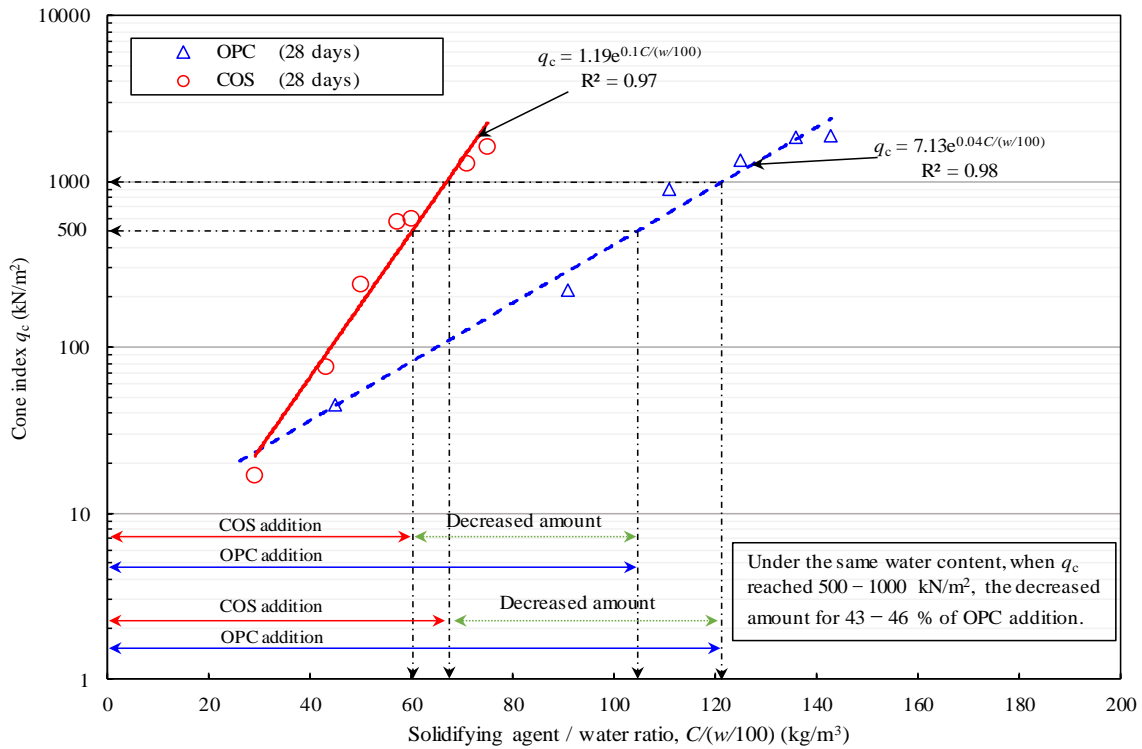
Fig.5.7 The improvement effect development up to 28-days for COS and OPC.

5.3.4 Influence of mixing water-absorbent material

Although COS-stabilized clay improves the mechanical characteristics of clay, it has some limitations. Carbon dioxide (CO_2) is one of the main factors contributing to warming (Zhang et al, 2012). COS manufacturing emits CO_2 via calcined oyster shells, burning fossil fuels, electricity, and transportation. Therefore, high-temperature calcination of oyster shell for a long time emits CO_2 in large amounts. For the above reasons, this study considered using carbides (CC and WC) to replace parts of COS to alleviate the environmental and cost problems caused by COS production.

The improvement effect within a curing time of 28 days with a 30 kg/m³ of COS addition was used as a reference to determine the effectiveness of both carbides (CC and WC) in this study. Figure 8 presents the cone index (q_c) development for all stabilized clay specimens. The cone index increased slowly with increasing CC and WC contents in the initial range of 0–30 kg/m³. The cone index increases rapidly when the CC content exceeds 30 kg/m³. When the CC content reached 120 kg/m³, the cone index, q_c, was 621 kN/m². According to the evaluation formula for COS and OPC in Fig. 5.7, under the same water content (w = 70%), the COS mixing amount required for q_c = 621 kN/m² is 44 kg/m³, and the OPC mixing amount is 78 kg/m³. Compared with CC, the cone index development of

WC was slow. When the mixing amount of CC was approximately 80 kg/m^3, the cone index was the same as that when the mixing amount of WC was 120 kg/m^3.

Similar to CaO, COS modifies the properties of clay through cation exchange, flocculation, agglomeration, and pozzolanic reactions. In the process of adding carbides to improve the improvement effect of COS-stabilized clay, the following factors are mainly considered to cause changes in the improvement effect. With the addition of carbide, the water content in the mixture decreases, and the cone index increases significantly because the content of the solidifying agent remains unchanged. Further screening of CC and WC samples using a 0.075 mm sieve yielded a 0.075 mm particle pass rate of 6.5 % for WC and 7.04 % for CC. Therefore, the incorporation of WC or CC as an aggregate effectively fills the clay in terms of particle size. Therefore, the cone index significantly increased with the addition of carbides. Furthermore, it may lead to a reduction in the available water for the reaction process with an increase in the CC content and a stronger water absorption capacity. When the mixing amount of CC was more than 90 kg/m^3, the cone index began to decrease, as shown in Fig. 5.8. This can be attributed to the mixing of a large amount of CC with high water absorption in the stable clay, and the lack of sufficient water in the stabilized clay that reacts with COS, which affects the development of the improvement effect. Considering that the water absorption rate of WC was lower than that of CC, the improvement effect of WC was relatively lower than that of CC at the same content.

As shown in Fig. 5.9(a), when adequate quantities of COS were added to high-water-content clay, the pH of the soil rapidly increased. Strong alkaline conditions (pH $\geq$ 10.5) released silica and alumina from the clay minerals and eventually reacted with lime to form new cementation products (Guney et al, 2017). Studies have shown that the density of charge decreases with increasing pH for the process
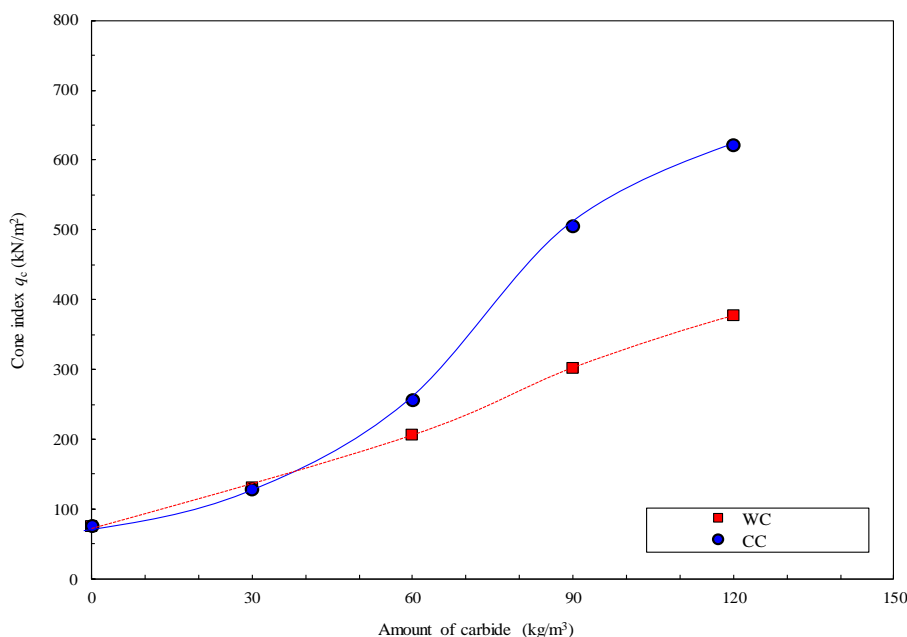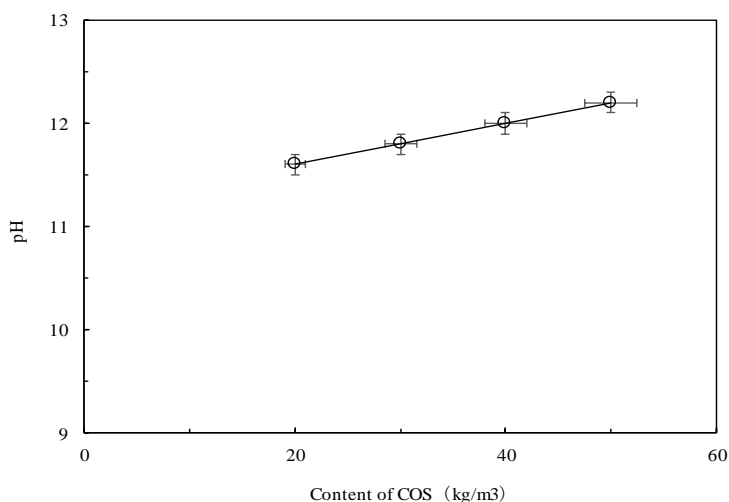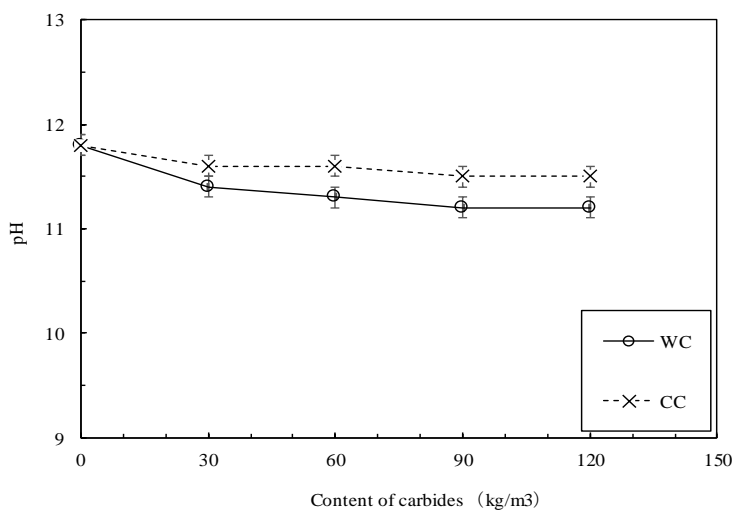

Fig.5.8 Effect of carbide content on COS-stabilized clay.

(a) Effect of COS mixing amount on pH of clay.

(b) The effect of the mixing amount of absorbent materials

on the pH of COS-stabilized clay.

Fig.5.9 The pH change of the sample with COS and absorbent materials

of lime stabilized kaolin. The edge becomes slowly uncharged because of the increasing negative edge charges generated through dissociation of Si-OH, and in the stronger alkaline range, through Al-OH dissociation (Ghobadi et al, 2014). The stabilizer must be capable of maintaining a high-pH environment for a long period of time for pozzolanic bonding to become a significant factor in improving the strength and durability of the system. Because the alkalinity of the water-absorbent material was lower than that of calcined oyster shells, adding water-absorbent material diluted the overall alkalinity of the stabilized clay (Fig. 5.9 (b)). The pH value of stabilized clay was maintained at 11.5 when the mixing amount of CC was 120 kg/m³, which was greater than the required alkaline conditions for releasing silica and alumina from the clay mineral. Therefore, it can be considered that even if the mixing amount of CC is four times the mixing amount of COS, its impact on the alkaline

environment is weak and cannot hinder the pozzolanic reactions that produce calcium silicate hydrates (C-S-H).

5.3.5 Changes in microstructures of stabilized clay using SEM observation

When quicklime (COS) is added to clay soil in an aqueous medium, the following lime hydration reactions occur:

$$CaO + H_2O \rightarrow Ca(OH)_2$$
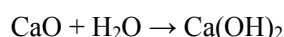
On one hand, incorporating COS absorbs part of the free water in the clay. On the other hand, the heat produced during the reaction drives off some of the water in the clay in the form of water vapor, thereby reducing the water content in the test sample. The reactions between lime, water, silica, and alumina in clay to form cementitious products are referred to as soil–lime pozzolanic reactions (Nidzam and Kinuthia; 2010). The formed C-S-H, C-A-H, and C-A-S-H flocculent gel crystals connected clay particles, carbides, and a small amount of calcite combined the entire matrix. Owing to these reactions, the strength of the COS-stabilized clay mixed with carbonized materials increased.

The microstructure of clay with a high-water content stabilized by COS and carbides as cementing materials was observed by SEM. Because the pozzolanic reaction and further dissociation of lime in the long-term reaction consumed $Ca(OH)_2$, portlandite was not observed in the stabilized clay. In the SEM images, C-S-H gel was the major gel material in the two types of carbides added to the COS-stabilized clays. Observe Figs. 10 (a) and 10 (b), the flocculent C-S-H gel was distributed on clay aggregates and absorbent particles. In Figure 11, EDS test results support this statement. Figures 11 (a) ~ (c) present the EDS test results of the sample. Al, Si, and Ca in the EDS element mapping represent C_3S, C_2S, and C_3A phases, which were detected in the form of oxides. Although EDS analysis confirmed that the main products were C-S-H and C-A-H, and the C-S-H gel formed a cross-linked structure by bonding particles, significant gaps between aggregates can still be observed in both COS30C30 and COS30W30 after pulverization in anhydrous phases distributed (Saussaye et al, 2015; Snellings et al, 2014). This is due to the limited adsorption and filling ability of low-dose of carbides to high water-content clay. In Fig.8, it is reflected that when the mixing amount of carbonized materials is $30kg/m^3$, no obvious improvement effect is shown.

When the carbides content increased to 90 kg/m³, a denser cementation structure was observed in Fig.10 (c) and (d). Owing to the incorporation of more water-absorbent materials, the decrease of water content in the mixture caused the decrease of pores between particles, which will facilitate the cementation of the hydrated product. Therefore, it was observed that the C-S-H gel was distributed

and filled the void space between the clay and water-absorbent material particles. This reduces the void volume in the clay structure, resulting in an overall denser structure.

Furthermore, the main reason for the difference in the improvement of WC and CC when the carbide blending amount is 90 kg/m^3 in Fig.8 is attributed to the difference in carbide adsorption capacity. The stabilization method of the mixture sample is the effective filling of the pore space composed of soil particles and carbide particles with water and products such as C-S-H gel (Maki and Goto, 1982). A smaller pore space CC is more conducive to improving the cementation and strength between particles. Therefore, carbides with strong water absorption reduce the pores between clay particles and make the clay denser by adding carbide particles.

(a) COS30W30

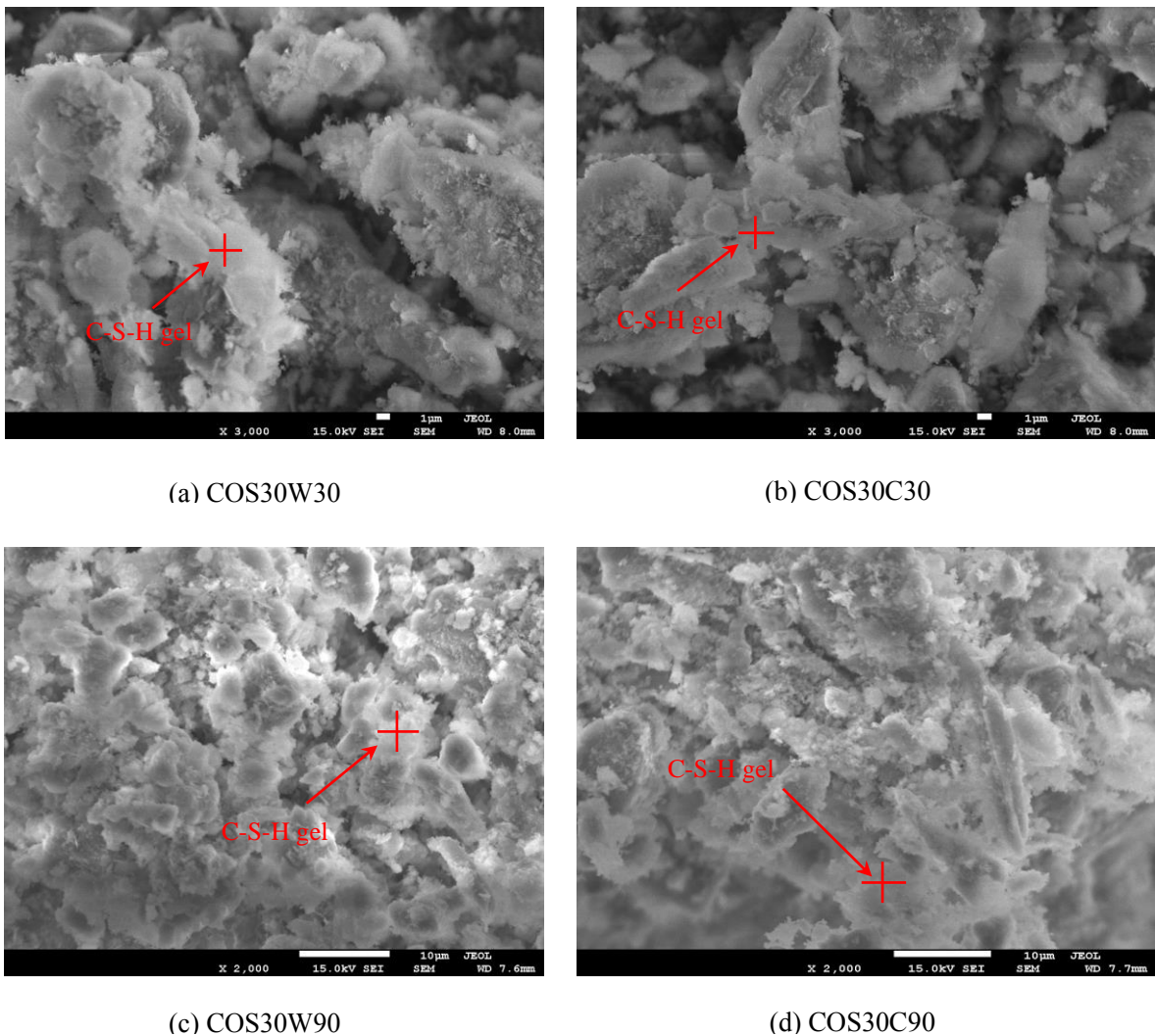(b) COS30C30

(c) COS30W90

(d) COS30C90

Fig. 5.10. SEM micrograph of calcining oyster shell clays stabilized by carbonized cow dung compost (CC) and Wood charcoal (WC).
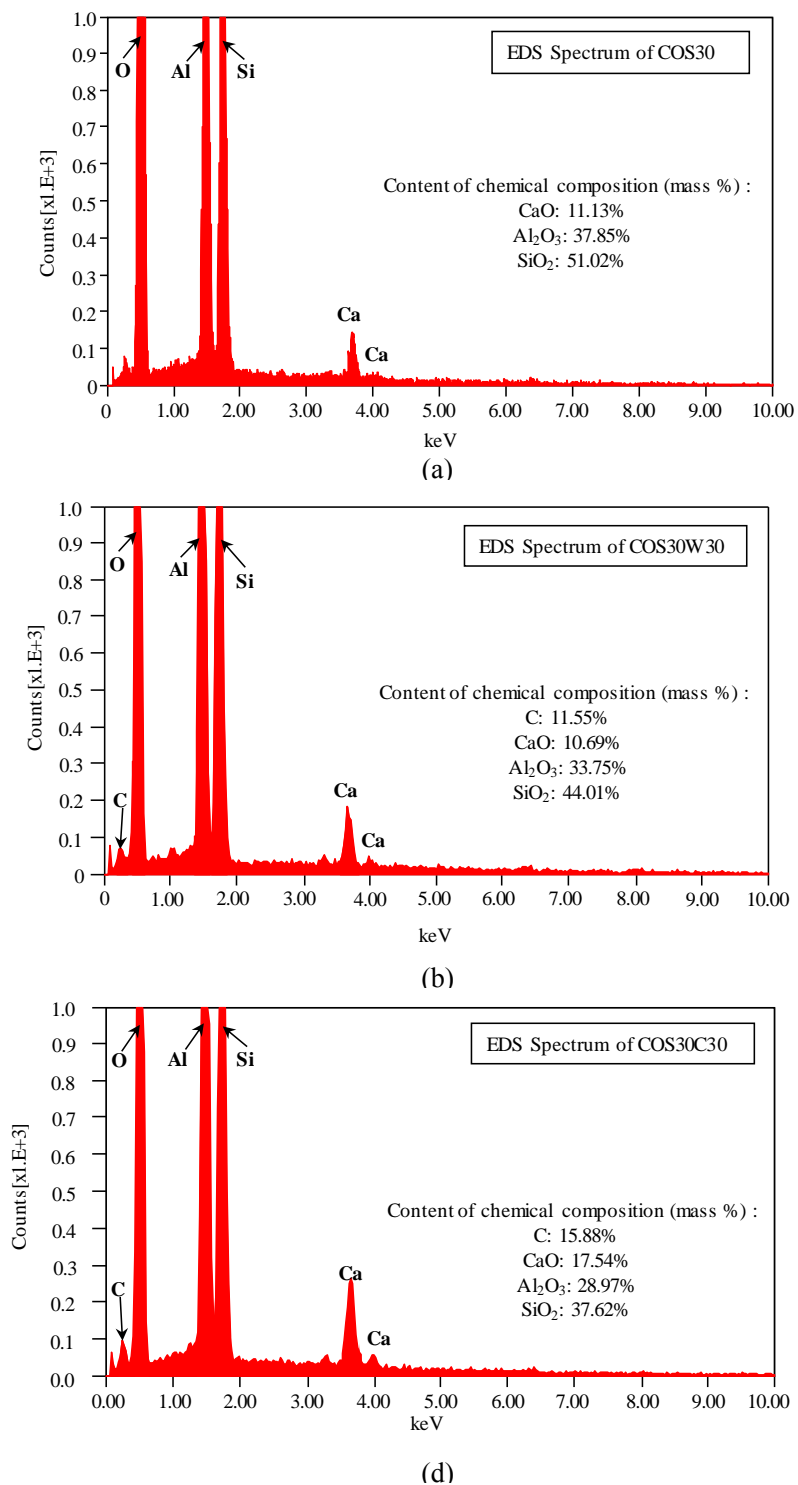
Fig. 5.11. Chemical element compositions of COS30C30, COS30W30 and COS30 in 28 days were measured with an energy dispersive X-ray spectrometer (EDS) as weight %.

5.4 Conclusions

In this study, the improvement effect of COS-stabilized clay was first investigated. Secondly, the possibility of using CC to reduce COS incorporation in COS-stabilized clays was studied. SEM, EDS, and cone penetration tests were performed to investigate the microstructure and mechanical properties of the stabilized clay. Based on this investigation, the following conclusions were drawn:

1. COS has the potential to stabilize high water-content clay. Compared with ordinary portland cement, the amount of calcined oyster shell (COS) required for effective improvement is significantly reduced (approximately 43%–46% reduction). Considering the problems of the environment and cost, the content of COS in stabilized clay should still be controlled.

2. The addition of carbides CC with a high-water absorption rate significantly improved the improvement effect of COS-stabilized clay in the range of 0-120kg/m^3. Under 400 °C calcination temperature condition, the water absorption rate of CC was the highest, reaching 348%

3. The SEM and EDS analysis results showed that the main products of COS hydration were C-S-H and C-A-H. Compared with WC, the carbide CC with stronger adsorption capacity is beneficial to shorten the particle spacing, and the hydrated C-S-H gel fills the pores between particles.

References

Amiri M, Hatami F, Golafshani EM, (2021), Evaluating the synergic effect of waste rubber powder and recycled concrete aggregate on mechanical properties and durability of concrete, *Case Stud Constr Mat*, 15, e00639. https://doi.org/10.1016/j.cscm.2021.e00639.

Arias JL, Fernandez MS, (2003), Biomimetic processes through the study of mineralized shells, *Mater. Charact*. 50, 189–195. https://doi.org/10.1016/S1044-5803(03)00088-3.

Arif M, Liu G, Yousaf B, Ahmed R, Irshad S, Ashraf A, Zia-ur-Rehman M, Rashid MS, (2021), Synthesis, characteristics and mechanistic insight into the clays and clay minerals-biochar surface interactions for contaminants removal-A review, *J. Clean. Prod*. 310, 127548. https://doi.org/10.1016/j.jclepro.2021.127548.

Bell FG, (1996), Lime stabilization of clay minerals and soils, *Eng. Geol*. 42, 223–237. https://doi.org/10.1016/0013-7952(96)00028-2.

Chiou IJ, Chen CH, Li YH, (2014), Using oyster-shell foamed bricks to neutralize the acidity of recycled rainwater, *Constr. Build. Mater*. 64, 480–487. https://doi.org/10.1016/j.conbuildmat.2014.04.101.

Chompoorat T, Likitlersuang S, Sitthiawiruth S, Komolvilas V, Jamsawang P, Jongpradist P, (2021), Mechanical properties and microstructures of stabilised dredged expansive soil from coal mine, *Geomech Eng*, 25, 143-157. https://doi.org/10.12989/gae.2021.25.2.143.

Chompoorat T, Likitlersuang S, Thepumong T, Tanapalungkorn W, Jamsawang P, Jongpradist P, (2021), Solidification of sediments deposited in reservoirs with cement and fly ash for road construction, *Int J Geosynth Groun*, 7, 1-12. https://doi.org/10.1007/s40891-021-00328-0.

Chompoorat T, Thepumong T, Khamplod A, Likitlersuang S, (2022), Improving mechanical properties and shrinkage cracking characteristics of soft clay in deep soil mixing, *Constr Build Mater*, 316, 125858. https://doi.org/10.1016/j.conbuildmat.2021.125858.

Chompoorat T, Thepumong T, Taesinlapachai S, Likitlersuang S, (2021), Repurposing of stabilised dredged lakebed sediment in road base construction, *J Soil Sediment*, 21, 2719-2730. https://doi.org/10.1007/s11368-021-02974-3.

Cuadrado-Rica H, Sebaibi N, Boutouil M, Boudart B, (2016), Properties of ordinary concretes incorporating crushed queen scallop shells, *Mater. Struct.* 49, 1805–1816. https://doi.org/10.1617/s11527-015-0613-7.

Ghobadi MH, Abdilor Y, Babazadeh R, (2014), Stabilization of clay soils using lime and effect of pH variations on shear strength parameters, *Bull. Eng. Geol. Environ.* 73, 611–619. https://doi.org/10.1007/s10064-013-0563-7.

Glaser B, Lehmann J, Zech W, (2002), Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal: A review, *Biol. Fert. Soil.* 35, 219–230. https://doi.org/10.1007/s00374-002-0466-4.

Guney OC, Firoozi AA, Baghini MS, (2017), Fundamentals of soil stabilization. *Geo-Engineering*. 8, 26. https://doi.org/10.1186/s40703-017-0064-9.

Guo X, Dong H, Yang C, Zhang Q, Liao C, Zha F, Gao L, (2016), Application of goethite modified BC for tylosin removal from aqueous solution, *Colloids Surf.* 502, 81–88. https://doi.org/10.1016/j.colsurfa.2016.05.015.

Hayashi J, Okuma O, Fukuda S, Kageura N, (2014), Utilization of cow manure compost as humidity conditioning material, *J. Japan Soc. Civ. Eng.* 93 (2014) 958–963. https://doi.org/10.3775/jie.93.958.

Horpibulsuk S, Katkan W, Sirilerdwattana W, Rachan R, (2006), Strength development in cement stabilized low plasticity and coarse grained soils: Laboratory and field study, *Soils Found.* 46, 351–366. https://doi.org/10.3208/sandf.46.351.

Horpibulsuk S, Rachan R, Suddeepong A, Chinkulkijniwat A, (2011), Strength development in cement admixed Bangkok clay: Laboratory and field investigations, *Soils Found.* 51, 239–251. https://doi.org/10.3208/sandf.51.239.

Imokawa A, Souda T, (2001), Research on effective use in field of water quality purification material which uses oyster shell, Bull. Nagasaki Agric. For. Techn. Dev. Cent. 27, 81–95. https://www.pref.nagasaki.jp/e-nourin/nougi/theme/research_report/PDF/27-2.pdf

Jamnongpipatkul P, Dechasakulsom M, Sukolrat J, (2009), Application of air-foam stabilized soil for bridge-embankment transition zone in Thailand, in: GeoHuman International Conference 2009, American Society of Civil Engineers, Changsha, China, pp. 181–193. https://doi.org/10.1061/41042(349)24.

Japanese Geotechnical Society, JGS 0811: Practice for making and curing compacted stabilized soil specimens using a rammer. Japanese Geotechnical Society, Tokyo, Japan, 2020.

Japanese Standards Association, JIS A 1110: Methods of test for density and water absorption of coarse. Japanese Standards Association Tokyo, Japan, 2020.

Japanese Standards Association, JIS A 1210: Test method for soil compaction using a rammer. Japanese Standard Association, Tokyo, Japan, 2020.

Julphunthong P, Thongdetsri T, Chompoorat T, (2018), Stabilization of soft Bangkok clay using Portland cement and calcium sulfoaluminate-belite cement, In *Key Engineering Materials* 775(2018), 582-588. Trans Tech Publications Ltd. https://doi.org/10.4028/www.scientific.net/KEM.775.582.

Kameyama K, Iwata Y, Miyamoto T, Kitagawa I, Kubota Y, (2021), Effects of incorporation of wood-based biochar and composted cattle manure on physical and chemical properties of a sandy soil, *Trans. Jpn. Soc. Irrig. Drain. Rur. Eng*. 89, 119–126. https://doi.org/10.11408/jsidre.89.I_119.

Kassim KA, Chern KK, (2004), Lime stabilized Malaysian cohesive soils, *Malays. J. Civil. Eng*. 16, 13–23. https://doi.org/10.11113/mjce.v16.15658.

Khan MD, Ahn JW, Nam G, (2018), Environmental benign synthesis, characterization and mechanism studies of green calcium hydroxide nano-plates derived from waste oyster shells, *J. Environ. Manag*. 223, 947–951. https://doi.org/10.1016/j.jenvman.2018.07.011.

Kostarelos K, Reale D, Dermatas D, Rao E, Moon DH, (2006), Optimum dose of lime and fly ash for treatment of hexavalent chromium-contaminated soil, *Water Air Soil Poll*. 6, 171–189. https://doi.org/10.1007/s11267-005-9005-2.

Lee SS, Shah HS, Awad YM, Kumar S, Ok YS, (2015), Synergy effects of biochar and polyacrylamide on plants growth and soil erosion control, *Environ. Earth Sci*. 74, 2463–2473. https://doi.org/10.1007/s12665-015-4262-5.

Li G, Xu X, Chen E, Fan J, Xiong G, (2015), Properties of cement-based bricks with oyster-shells ash, *J. Clean. Prod*. 91 279–287. https://doi.org/10.1016/j.jclepro.2014.12.023.

Maki I, Goto K, (1982), Factors influencing the phase constitution of alite in Portland cement clinker. *Cement and Concrete Research*, 12(3), 301-308, https://doi.org/10.1016/0008-8846(82)90078-3.

Martinez-Garcia C, Gonzalez-Fonteboa B, Martinez-Abella F, Carro-Lopez D, (2017), Performance of mussel shell as aggregate in plain concrete, *Constr.Build. Mater*. 139, 570–583. https://doi.org/10.1016/j.conbuildmat.2016.09.091.

Mian MM, Liu G, Yousaf B, Fu B, Ullah H, Ali MU, Abbas Q, Mujtaba Munir MA, Ruijia L, (2018), Simultaneous functionalization and magnetization of BC via NH3 ambiance pyrolysis for efficient removal of Cr (VI), *Chemosphere*, 208, 712–721. https://doi.org/10.1016/j.chemosphere.2018.06.021.

Ministry of Agriculture, Forestry and Fisheries JPN, Origin and yield of oysters. https://www.maff.go.jp/j/heya/sodan/1510/01.html, 2020 (accessed 3 August 2022).

Ministry of Agriculture, Forestry and Fisheries JPN, Production and management of livestock excreta, https://www.maff.go.jp/j/chikusan/kankyo/taisaku/t_mondai/02_kanri/, 2020 (accessed 3 August 2022).

Mo KH, Alengaram UJ, Jumaat MZ, Lee SC, Goh WI, Yuen CW, (2018), Recycling of seashell waste in concrete: A review, *Constr. Build. Mater*. 162, 751–764. https://doi.org/10.1016/j.conbuildmat.2017.12.009.

Naqi A, Siddique S, Kim HK, Jang JG, (2020) Examining the potential of calcined oyster shell waste as additive in high volume slag cement, *Constr Build Mater*, 230, 116973. https://doi.org/10.1016/j.conbuildmat.2019.116973.

Navaratnam S, Wijaya H, Rajeev P, Mendis P, Nguyen K, (2021), Residual stress-strain relationship for the biochar-based mortar after exposure to elevated temperature, *Case. Stud. Constr. Mat*. 14, e00540. https://doi.org/10.1016/j.cscm.2021.e00540.

Nidzam RM, Kinuthia JM, (2010), Sustainable soil stabilisation with blastfurnace slag—A review, *Constr. Mater*. 163, 157–165. https://doi.org/10.1680/coma.2010.163.3.157.

Ok YS, Oh SE, Ahmad M, Hyun S, Kim KR, Moon DH, Lee SS, Lim KJ, Jeon WT, Yang JE, (2010), Effects of natural and calcined oyster shells on Cd and Pb immobilization in contaminated soils, *Environ. Earth Sci*. 61, 1301–1308. https://doi.org/10.1007/s12665-010-0674-4.

Okayama Agriculture, Forestry and Fisheries Department JPN, Guidelines for comprehensive bottom sediment improvement using oyster shells. https://www.pref.okayama.jp/uploaded/life/338186_1621075_misc.pdf, 2013 (accessed 3 August 2022).

Prusinski JR, Bhattacharja S, (1999), Effectiveness of Portland cement and lime in stabilizing clay soils, *Transp. Res. Rec*. 1652, 215–227. https://doi.org/10.3141/1652-28.

Qian Q, Machida M, Tatsumoto H, (2007), Preparation of activated carbons from cattle-manure compost by zinc chloride activation, *Bioresour. Technol*. 98, 353–360. https://doi.org/10.1016/j.biortech.2005.12.023.

Sanaa E, (2011), Carbonization of cow dung and characterization of the char, *Japan Carbon. Res*. 7 68–75. https://doi.org/10.32143/wcr.7.2_68.

Satoh T, (2003), Application of pneumatic flow mixing method Central Japan International Airport construction, *J. Japan Soc. Civ. Eng.* 749 33–47. https://doi.org/10.2208/jscej.2003.749_33.

Satoh T, Tsuchida T, Mitsukuri K, Hong Z, (2001), Field placing test of lightweight treated soil under seawater in Kumamoto port, *Soils Found.* 41 145–154. https://doi.org/10.3208/sandf.41.5_145.

Saussaye L, Boutouil M, Baraud F, Leleyter L, (2015), Influence of sulfate and chloride ions on the geotechnical and microstructural properties of soils treated with hydraulic binders: Individual and coupling effects. *Engineering Geology*, 189, 98-103. https://doi.org/10.1016/j.enggeo.2015.01.023.

Seo JH, Park SM, Yang BJ, Jang JG, (2019) Calcined oyster shell powder as an expansive additive in cement mortar, *Materials*. 12, 1322. https://doi.org/10.3390/ma12081322.

Shakoor A, Shakoor S, Rehman A, Ashraf F, Abdullah M, Shahzad SM, Farooq TH, Ashraf M, Manzoor MA, Altaf MM, Altaf MA, (2021), Effect of animal manure, crop type, climate zone, and soil attributes on greenhouse gas emissions from agricultural soils—A global meta-analysis, *J. Clean. Prod*. 278, 124019. https://doi.org/10.1016/j.jclepro.2020.124019.

Snellings R, Bazzoni A, Scrivener K, (2014), The existence of amorphous phase in Portland cements: Physical factors affecting Rietveld quantitative phase analysis. *Cement and Concrete Research*, 59, 139-146. https://doi.org/10.1016/j.cemconres.2014.03.002.

Taiwo LA, Obianyo II, Omoniyi AO, Onwualu AP, Soboyejo AB, Amu OO, (2022), Mechanical behaviour of composite produced with quarry dust and rice husk ash for sustainable building applications, *Case. Stud. Constr. Mat*. 17, e01157. https://doi.org/10.1016/j.cscm.2022.e01157.

ur Rehman MZ, Batool Z, Ayub MA, Hussaini KM, Murtaza G, Usman M, Naeem A, Khalid H, Rizwan M, Ali S, (2020), Effect of acidified BC on bioaccumulation of cadmium (Cd) and rice growth in contaminated soil, *Environ. Technol. Innov*. 19, 101015. https://doi.org/10.1016/j.eti.2020.101015.

Wang HY, Kuo WT, Lin CC, Po-Yo C, (2013), Study of the material properties of fly ash added to oyster cement mortar, *Constr. Build. Mater*. 41, 532–537. https://doi.org/10.1016/j.conbuildmat.2012.11.021.

Yang EI, Kim MY, Park HG, Yi ST, (2010), Effect of partial replacement of sand with dry oyster shell on the long-term performance of concrete, *Constr. Build. Mater*. 24 758–765. https://doi.org/10.1016/j.conbuildmat.2009.10.032.

Yang EI, Yi ST, Leem YM, (2005), Effect of oyster shell substituted for fine aggregate on concrete characteristics: Part I. Fundamental properties, *Cem. Concr. Res*. 35, 2175–2182.

https://doi.org/10.1016/j.cemconres.2005.03.016.

Yi Y, Gu L, Liu S, (2015), Microstructural and mechanical properties of marine soft clay stabilized by lime-activated ground granulated blastfurnace slag, *Appl. Clay Sci.* 103, 71–76. https://doi.org/10.1016/j.clay.2014.11.005.

Yoon GL, Kim BT, Kim BO, Han SH, (2003), Chemical–mechanical characteristics of crushed oyster-shell, *Waste Manag.* 23, 825–834. https://doi.org/10.1016/S0956-053X(02)00159-9.

Zhang XF, Zhang SY, Hu ZY, Yu G, Pei CH, Sa RN, (2012), Identification of connection units with high GHG emissions for low-carbon product structure design, *J. Clean. Prod.* 27 (2012) 118–125. https://doi.org/10.1016/j.jclepro.2012.01.011.

Zhang Y, Ong YJ, Yi Y, (2022), Comparison between CaO- and MgO-activated ground granulated blast-furnace slag (GGBS) for stabilization/solidification of Zn-contaminated clay slurry, *Chemosphere*. 286, 131860. https://doi.org/10.1016/j.chemosphere.2021.131860.

Zhang Z, Omine K, Flemmy SO, (2022), Evaluation of the improvement effect of cement-stabilized clays with different solidifying agent addition and water content, *J. Mater. Cycles Waste Manag.* 1–12. https://doi.org/10.1007/s10163-022-01477-8.

Zhang Z, Omine K, Flemmy SO, Li C, (2022), The Liquid Limit as a Factor in Assessing the Improvement of Stabilized Cement-Based Highwater Content Clayey Sediments, *Materials*, 15, 7240. https://doi.org/10.3390/ma15207240.

6. Summaries

In this thesis, firstly, from the perspective of reducing the mixing amount of solidifying agents such as cement, a simple and effective improvement method is proposed based on the field test of Kumamoto reservoir clay. Then, the influence of the physical properties of different clays on the improvement effect was investigated, an empirical formula for predicting the improvement effect based on the physical properties of clay was introduced. Finally, a new consolidation material of calcined oysters mixed with carbonized cow dung compost was proposed to realize waste recycling and reduce the addition of traditional solidification materials such as cement. This chapter summarizes the main conclusions.

Chapter 2 investigates the feasibility of using composite materials to carry out simple on-site treatment of clay, followed by a mix of solidifying agents to achieve high water content clay improvement. Through the confirmation of the accumulation of dredged clay on site, as well as the study of the effect of the on-site dehydration test and the mechanical properties of the samples mixed with the solidifying agent, a set of schemes for treating dredged clay with high water content was summarized. Firstly, the field test results of Kumamoto Ohkirihata reservoir indicated the presence of mass sediments of clay with high water and high organic matter within 1–2 m of the reservoir sediment. Second, the dehydration effects of two kinds of composite materials on high water-content dredged clay are similar. That is, after one week the water content of clay was below the liquid limit, and after one month the water content decreased by about 40 %. In addition, DF was applicable to the improvement of Kumamoto clay, although the required content was much larger than that of OPC. DF is a recycling material composed primarily of fly ash; hence, it affords less environmental pollution owing to its low CO_2 emission. Third, after the high-water content dredged clay is simply dehydrated by inserting the composite material, the improvement of the high water content dredged clay under the low solidifying agent mixing amount can be realized.

In Chapter 3, two types of cement-based solidifying agents, i.e., OPC and DF, were added to three samples obtained from different locations, and a cone penetration test was performed. Using the initial water content of clay and the mixing amount of the solidifying agent as experimental variables, a cone penetration test is performed on the solidifying-agent-stabilized clays to obtain the cone index (q_c). The results show that the water cement ratio (w/A_w), an important parameter for evaluating mechanical properties in previous studies, is not suitable for Kumamoto clay with high water content and organic matter content as an improved parameter for evaluating OPC or DF stabilized clay. Considering the effect of the liquid limit of the samples, the modified content of the solidifying agent, K_L, was introduced to evaluate the cone index of the stabilized soils. It was discovered that the proposed equation unified the assessment of the improvement of the three Kumamoto clay samples in a unified manner owing to the new parameter K_L.

In Chapter 4, the improvement effect of cement-stabilized clays with different solidifying agent addition and water content was investigated based on the test results of cone index using five kinds of clays. Two types of solidifying agents, namely ordinary portland cement (OPC) and fly ash-containing solidifying agent (DF), were used. An empirical equation of the cone index with the modified content of solidifying agent was proposed based on the experimental results. The validity of the proposed equation was confirmed for all the stabilized clays with different water content and two types of solidifying agents. It was clarified that the parameters on the empirical equation in different types of clays relate to liquid limit, ignition loss and type of solidifying agent. The proposed empirical equation has a guiding role in determining the required content of solidifying agent in different water content of clay.

Chapter 5 introduces a methods of stabilizing high-water content clay under low environmental load. The effect of calcined oyster shells (COS) on the mechanical properties of clay was investigated. In addition, biochar (BC) was considered in the study to reduce the incorporation of the solidifying agent in COS-stabilized soil. Compared with ordinary portland cement, the amount of calcined oyster shell (COS) required for effective improvement is significantly reduced (approximately 43%–46% reduction). Addition of carbonation materials with high water absorption rate improves the improvement effect of COS stabilized clay. Under 400 °C calcination temperature condition, the water absorption rate of cow dung compost was the highest. Mixing absorbent materials is beneficial to hydrate C-S-H gel in filling the pores between soil particles.

Chapter 7 summarizes the major conclusions obtained from the studies of this thesis.