

## ABSTRACT

**Title:** A Study on Strength Development of Cement-Treated Dredged Clay

(セメント固化浚渫粘土の強度発現に関する研究)

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The coastal development project is a major issue due to growing of rapid industrial development, in recently Japan. Therefore, a lot of raw materials for construction and reclamation are required in coastal development projects. However, it is increasingly difficult to supply the raw materials, sand and crushed stone, due to the fact that excessive collection of these raise the environmental problems. On other the hand, huge amount of soft clayey soils are dredged annually for the maintenance of navigation channels and seaports. The lack of dumping site to dispose the dredged clays and the high construction cost for closed waste-dumping facility are serious concerns. In order to solve these problems, the dredged clays treated with cement have been used as a construction material for a number of projects, which requires low design strength, ranging from 100 to 500 kPa. In general, the cement-treated dredged clay was used as construction filling material, such as backfilling of quay wall, artificial barrier layer of waste disposal site, and submerged embankment, and usually constructed by Pneumatic Flow Mixing Method; mixing the clay and cement milk inside the pipeline by means of turbulent flow is generated during transportation, or in a special working ships, where the cement-treated clay passes through a transport pipe connected to the construction site. However, although cement-treated clay are used for various purposes, previous literatures are mainly focused on the cement treatment by Deep Mixing or Jet Grouting methods, which include the high design strength (2000 to 5000 kPa), high cement content (more than 15 %), low water content (lower then dredged clay), long-term curing time (more than 3 days), and type of clay (only one type of clay obtained from construction site). In addition, the strength of cement-treated clay has been evaluated through laboratory tests, such as the unconfined compression test and the triaxial compression test. These laboratory tests require a number of specimens at different curing times, and thus require a great deal of time and cost. Hence, we considered that a non-destructive bender element test, which measures the shear velocity of a single specimen, can be alternatively used to monitor the strength development with curing time. However, the measurement of the shear modulus for the cement-treated dredged clay has not yet been sufficiently studied, and research to date has not suggested clear correlations to estimate strength based on the shear modulus at various curing times. Humic acid is representative organic matter involved in dredged clay. The humic acid retard the cementation process of cement-treated soils by delaying hydration reaction, which requires high pH in dissolving process of cement, by decreasing pH of pore water. Hence, a study on strength development of cement-treated clay with various conditions, humic acid content, cement content, and curing time will be

useful to analyze the effect of humic acid for the hydration and pozzolanic reactions of cement.

In this study, the strength development of cement-treated marine clays was carried out by laboratory vane shear and unconfined compression tests with various conditions, such as water content (1.5 to 2.5  $w_L$ ), cement content (2 to 20 %), type of clays (four clays), and curing time (0.5 hours to 90 days). The equations to predict strength of cement-treated clay with various curing time from immediately after mixing were proposed based on two indices, initial water content and specific volume normalized by water content and specific volume at liquid limit. In addition, to overcome the disadvantage of traditionally destructive tests, unconfined compression test and triaxial compression test, a bender element test was conducted with water content (1.5 and 2.0  $w_L$ ), cement content (10 to 30 %), and curing time (0.5 hours to 90 days) to monitor the strength development of cement-treated clay at single sample by determining the small-strain shear modulus. The equations for estimating the strength of cement-treated clay were proposed with different curing time based on relationship unconfined compressive strength and small-strain shear modulus. Furthermore, effect of humic acid for strength development of cement-treated clay was investigated using vane shear, unconfined compressive with various condition, cement content (10 and 20 %), water content (1.5 and 2.0  $w_L$ ) curing time (0.5 hours to 90 days), and humic acid (0, 10, and 20 %). The equations for predicting the strength of cement-treated clay added with humic acid based on normalized initial water content and specific volume were proposed in accordance with groups in  $c^* - H$  relation, which consider the effect of cement and humic acid contents. Finally, the microstructural effects of organic matter on cement-treated clay were evaluated using X-ray diffraction (XRD), scanning electron microscope (SEM), and energy dispersive spectroscopy (EDS), tests.

As results, the strength development in cement-treated dredged clays showed clear tendency depending on the curing time. Therefore, the relationship between strength development and curing time can be divided into two stages; early stage (within 3 days) and later stage (after 3 days). It was shown that the strength,  $2s_u$ , obtained from LVS test is 2 times greater than that of unconfined compression test. The strength at 1 hour curing ( $a_1$ ) was determined by two indices, initial water content and specific volume normalized by water content and specific volume at liquid limit. The strength increment coefficient ( $b_1$ ) within 3 days (early stages) was found to be nonlinearly increased with cement content. The strength increment coefficient ( $b_2$ ) after 3 days (latter stages) was found to be linearly increased with cement content. Based on the  $a_1$ ,  $b_1$ , and  $b_2$ , the equations for estimating the strength of cement-treated dredged clay were proposed. The development of shear modulus and strength with curing time followed essentially the same trend, which changes dramatically before and after 3 days. It was observed that shear modulus is 298 times greater than strength for the entire curing time. In addition, the relationships between shear modulus and strength for the early and later curing stages are proposed as  $G_0 = 159 q_u^{1.17}$  and  $G_0 = 542 q_u^{0.89}$ , respectively. Based on the proposed relationships and the estimation formula of shear modulus, a formula to estimate strength was proposed. It was conformed that in the early stages,

strength at 2 days and 3 days of curing could be calculated based on the formula that is used to estimate strength within 3 days using shear modulus at 1 hour curing  $\alpha_1$  and shear modulus increment coefficient  $\beta_1$  obtained within 1 days of curing. Furthermore, strength at 28 days and 90 days of curing could be estimated based the formula to predict strength after 3 days using the increment rate in the later stage  $\beta_2$  within 7 days of curing at later stages. Also the effect of humic acid on strength development of cement-treated clay was changed with cement content. The strength development of samples added with humic acid also changed before and after 3 days curing except for samples ( $c^* = 10\%$  and  $H = 10\%$  in 1.5 and 2.0  $w_L$ ). The strength at 1 hour  $a_{1(c^*, H)}$  of cement-treated clay added with humic acid can be determined by two indices, initial water content  $w'/w_L$  and specific volume ratio  $v'/v_L$  normalized by water content and specific volume at liquid limit, with  $c^* - H$  relation to consider the effect of cement and humic acid content. In addition, the strength at 1 hour  $a_{1(c^*, H)}$  were classified as three groups in this study: group 1 ( $c^* - H = 10$  or  $20\%$ ), group 2 ( $c^* - H = 0\%$ ), and group 3 ( $c^* - H = -10\%$ ). The strength increment coefficient  $b_{1(c^*, H)}$  of cement-treated clay with humic acid can be proposed as two zones, inactive and active zone, with different samples without humic acid. The increment coefficients  $b_{2(c^*, H)}$  at later stages after 3 days curing was almost constant irrespective of clay type, cement and humic acid contents in  $c^* - H$  relation. The threshold cement content, which overcome the harmful effect of humic acid for strength development of cement-treated clay, exhibited with humic acid content. According to cement and humic acid contents used in this study, the strength loss could be divided three zones, inactive, inert, and active zone, in  $c^* - H$  relation. The percentage of CSH + CASH was increased with decrease in humic acid content and with increase in cement content based on results of XRD analysis. It was observed that the new compound is formed with the reticulation structure, flocculated clay-cement, and ettringite when humic acid add into cement-treated clay except for sample in inactive zone ( $c^* = 10\%$  and  $H = 20\%$ ). Based on result of EDX analysis, it was presumed that the insoluble compound found in cement-treated clay with humic acid is synthetic cementitious compound combined with humic acid.

It was concluded from the results that proposed equation can be determined for samples of cement-treated dredged clay prepared with different conditions, water content (1.5 to 2.5  $w_L$ ), cement content (2 to 20 %), different clay types, curing time (0.5 hours to 90 days). In addition, it was confirmed that the small-strain shear modulus is able to successfully describe the improvement effect of cement-treated clay and that it is possible to effectively measure the strength using the proposed formulas. It was observed that the humic effect on cement-treated clay can be expressed by  $c^* - H$  relation. The threshold cement content, which overcome the harmful effect of humic acid for strength development of cement-treated clay, was varied with humic acid content ( $c^* - H$  relation).