学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Low environmental impact type ground improvement methods using biomineral precipitation
(バイオミネラル析出を利用した低環境負荷型地盤改良工法)

With the rapid growth of population in the world, the range of lands that can be used for human needs has been limiting. The development of infrastructures with lack of useful lands has also become a major issue with some environmental factors including climate, topography, and soil characteristics. Engineers are facing new challenges to modify existing ground which are insufficient for the desired land use. Construction on soft ground area is a great challenge in the field of geotechnical engineering. Many geotechnical engineering problems in the form of slope instability, bearing capacity failure or excessive settlement could occur either during or after the construction phase due to low shear strength and high compressibility of soil. Particularly in geotechnical engineering, liquefaction of saturated loose sand is one of the most catastrophic phenomenon induced by earthquake.

Due to some major environmental issues in current soil improvement techniques, novel "green" practices are trying to be applied. This thesis discusses such soil improvement techniques under two main topics named as soil improvement using calcium phosphate compounds (CPCs) precipitation and soil improvement using plant-derived urease induced calcium carbonate (CC) precipitation (PDUICCP).

In Chapter 1, the research background, literature review, objectives and originality of the thesis are discussed.

Chapter 2 and Chapter 3 of this thesis are discussed about the soil improvement using CPCs-based biomineral precipitation (CPC-Chem method) and CPCs along with some powder materials (CPC-Powder method) respectively. In Chapter 2, the UCS of sand test pieces made using calcium acetate (CA) and dipotassium phosphate (DPP) as Ca^{2+} and PO_4^{3-} sources respectively was analyzed by changing Ca^{2+} and PO_4^{3-} concentrations, Ca/P ratio, curing time and sand type. When the concentrations of both sources increased, the UCS increased regardless of the Ca/P ratio. The Ca/P ratio changed the final pH in the CPC mixture. When the 1 day UCS was less than about 20 kPa at low concentrations of Ca^{2+} and/or PO_4^{3-}, the rate of self-setting was low or almost zero compare with high concentrations and hence, a significant strength could not be obtained with time. The objective UCS of 100 kPa was obtained for Toyoura sand test pieces after 28 days of curing time from the test case with CA=0.75M and DPP=1.5M (Ca/P=0.5). Furthermore, the best concentration range to achieve 100 kPa at early stage rather than 28 days is CA=0.75-1.0 M and DPP=1.5-2.0 M. For Ca/P=1, the above mentioned range is CA=DPP=0.75-1.0M. These ranges are also suitable for Mikawa sand. However, it gives little higher values rather than Toyoura sand during selected ranges of concentration. These results indicate the feasibility of using novel CPC grouts as low environmental impact chemical grout.

In Chapter 3, the purpose of using CPC-Powder method is to improve the strength of CPC-Chem by using two kinds of phosphate powders (TCP; MgP) and two kinds of carbonate powders (CC; MgC) as seed crystals, and exceed the UCS more than 100 kPa. The maximum UCS values relevant to 0, 1, 5 and 10 %, TCP were 113.1, 174.7, 189.1 and 322.6 kPa respectively after 28 days with CA=0.75M and DPP=1.5 M. In case of the UCS of CC-added test pieces, it showed 114.6, 202.2

and 196.9 kPa for 1, 5 and 10 % of CC respectively. The UCS of test pieces with 1, 5 and 10 % TCP additives was maintained at a level exceeding 200 kPa even after 180 days. According to the results, there is a possibility to reduce the selected concentrations of CA and DPP by adding TCP or CC powder to achieve the objective UCS of 100 kPa. Furthermore, there is a possibility to use low cost TCP and CC powders instead of commercially available TCP and CC powders to make it cost effective ground improvement method. During the ground liquefaction, backfill soil may tend to subside and manholes and pipelines in the soil may tend to be pushed upward. Hence, back fill soil can also be reinforced using this method as a counter- measure against such occurrences because the UCS requirement for backfill soil is about 100-200 kPa. The addition of magnesium compounds was not effective for increasing the UCS by using CPC-Chem. The Mg^{2+} ions in magnesium compounds may exchange with the Ca^{2+} in the CPC solution and reduce the precipitation of CPCs.

In Chapter 4, the PDUICCP is introduced as an alternative method for microbially induced carbonate precipitation (MICP). The crude extract of crushed watermelon (*Citrullus lanatus*) seeds was used as the urease source for this study and small scale test specimens (ϕ=2.3 cm, h=7.1 cm) made from commercially available Toyoura, Mikawa and Mizunami sands were cemented and estimated UCS of several kPa to MPa was obtained by changing the concentration of $CaCl_2$-urea, urease as well as injection period. The increase of injection period and the increase of $CaCl_2$ urea concentration from 0.3 to 0.7 M caused to increase the estimated UCS value. The effect of urease activity on estimated UCS was different for different concentrations of $CaCl_2$-urea solutions. The urease activity of 3.912 U/mL was suitable for 0.7 M $CaCl_2$-urea solutions and 0.877 U/mL for 0.3 and 0.5 M $CaCl_2$ urea solutions. The average estimated UCS obtained after 14 day injection period for 0.7 M $CaCl_2$-urea and 3.912 U/mL urease was around 3.0 MPa and for 0.3 and 0.5 M $CaCl_2$-urea and 0.877 U/mL urease was around 1.5-2.0 MPa for Mikawa sand at 25 宔. The effect of temperature on estimated UCS could not be evaluated due to uneven changes in urease activity with temperature. Out of 15, 25 and 35 宔 temperatures, 25 宔 is favorable for this study. Out of three types of sands, the practical difficulties such as penetration of injection solution, etc. were less with Mikawa sand. Although the injection was not a difficult problem for Mizunami sand, the strength gain was low compare with Mikawa sand. Therefore, Mikawa sand with 870 μm of mean diameter is suited for this study. By changing each and every parameters mentioned above, there is a possibility to apply this method for some applications such as strength improvement of weak unconsolidated soil, specially saturated loose sand to mitigate the liquefaction, protection and restoration of limestone monuments and statuaries, artificial stone formation like sandstone, etc. The urease obtained from the crude extract of crushed watermelon seeds has a potential to be applied instead of commercially available urease for carbonate precipitation.

Finally, Chapter 5 is summarized of all the results obtained from each chapter and some guide for future research works in above areas.