ABSTRACT

題　目　Analysis of Strength Development Mechanism of Cement-Treated Soils under Different Curing Conditions through Chemical and Microstructural Investigations

（異なる養生条件下のセメント改良土の強度発現機構に関する化学・微細構造分析）

Ho Si Lanh

Owing to the increasing of the population as well as urbanization, it is an urgent issue to build new structures that often face to difficult conditions such as soft ground. To overcome the soft ground problem, there are many ground improvement methods, which are introduced and applied such as material replacement, use of vertical drains, and cement treatment. The use of cement-treated or cement-stabilized soils is an economical and environmentally friendly solution. This method has been employed for soft ground improvement as well as stabilization of heavy metal for approximately half of the century. The compressive strength of cement-treated soils is usually considered as a key parameter to characterize the soil behaviour. In general, the strength development of cement-treated soils is mainly attributed to cement hydration and pozzolanic reaction. In addition, studies on cement-stabilized heavy metals and cement-treated sand found that carbonation could contribute to the strength development. Besides, water content also has a considerable influence on the measured strength of cement-treated soils. Although the strength development of cement-treated soils is clearly explained by chemical and microstructural changes caused by cement hydration and pozzolanic reaction, to the best knowledge of the author, no studies mentioned clearly chemical and microstructural changes due to carbonation combined with cement hydration and pozzolanic reaction, and water content change.

The carbonation process of cementitious materials depends on several parameters such as those related to mix proportion (e.g., water/cement ratio) and environmental conditions (e.g., curing condition, relative humidity, temperature, and CO_2 concentration). Some studies revealed that altering the internal water content via sprayed water can affect carbonation and in turn influence the strength of cement-treated soils. However, the effect of the change in the internal water content (through sprayed water) on the carbonation process parameters (e.g., carbonation rate and the carbonate concentration profile) as well as on compressive strength have not yet been reported adequately. In the field of concrete engineering, the strength at an early age was accelerated by high-temperature curing; however, it was stated that the long-term strength of concrete decreased under high-temperature curing. On the other hand, previous studies on cement-stabilized clay found that the strength development in both short and long-term increased under high curing temperature. In addition, high early strength Portland cement (HPC) has been used to accelerate early strength of concrete; thus the use of HPC combined with different curing temperatures need to be studied. Hence, a study on strength development of cement-treated soils under different curing conditions such as sealed, drying, water adjustment, temperature to consider interaction among couple reactions (cement hydration, pozzolanic reaction, and carbonation) will be useful to analysis strength development mechanism.

This study focused on investigating the strength development of cement-treated soils under different curing conditions. First, to investigate strength development of cement-treated soils concerning the combination of cement hydration, pozzolanic reaction, carbonation, and water content; three types of soil treatment with specimen size 50 mm in diameter and 100 mm in height were prepared (sand, sand–loam, and sand–clay). For all mixtures, the cement content was designed to be 8% (cement/dried soil = 8%). The specimens were prepared and cured under different conditions (sealed, drying, and water content adjustment) to investigate strength development. The compression test was performed to examine strength development. The chemical and microstructural tests such as thermogravimetry (TG-DTA), X-ray diffraction (XRD), and mercury intrusion microscopy (MIP) were conducted in order to explain the strength development. Second, to investigate the effect of internal water content on carbonation process of cement-treated sand and the effect of carbonation on strength development of cement-treated sand. Cement-treated sand specimens with 100 mm in diameter and 200 mm in height were prepared using 8% of cement (cement/dried sand = 8%), then the specimens were cured under different conditions: sealed, drying, and water spraying. The compression test was conducted to examine strength development. The phenolphthalein and thermal analysis tests were performed in order to assess carbonation process of the specimens for explaining the effect of carbonation on strength development. Finally, to investigate effects of cement type and temperature curing on strength development, two types of soil mixture with specimen size 50 mm in diameter and 100 mm in height were prepared with three types of cement. Cement content was designed to be 8% (cement/dried soil = 8%). In addition, two types of mortar specimens with water/cement ratios of 0.5 and 1.0 were also prepared. After that, both the specimens of cement-treated soils and mortars were sealed and cured under 20 and 40°C. The compression test was conducted to measure compressive strength. The thermal analysis was performed in order to explain strength development.

As a result, it was found that the strength development of cement-treated soils depended on curing conditions. The compressive strength of all mixtures increased gradually because of cement hydration and pozzolanic reaction. The strength development is explained by the porosity changes (showing increased gel pore and decreased capillary pore, with the total porosity from 0.006 μm to 10 μm remaining constant) with the decrease in portlandite content caused by pozzolanic reactions. Under the drying condition, the mineralogy of the mixture had an impact on strength development. The compressive strength increased rapidly for all mixtures at the early age. After that, the strength slightly increased for the sand and sand-loam mixtures, but slightly decreased for the sand-clay mixture in the later age. The rapid short-term increase is explained by the suction effect and carbonation under drying, while the slight long-term increase may be explained by suction and pozzolanic reaction. Progression of carbonation under the drying condition was also detected by the increase in the weight loss under heating (from TG-DTA test) and in the amount of calcite (from the XRD test). A positive contribution by portlandite carbonation at the early age and a negative impact by C–S–H carbonation in the later age are suggested with the measured porosity changes in the three mixtures. The slight decrease in the long-term compressive strength of the sand-clay mixture may be caused by bentonite shrinkage or by a strong negative impact of C–S–H carbonation. Indeed, MIP measurement on the specimen under drying for 1 year detected an increase in large capillary pore volume associated with calcite precipitation. Carbonation changed pore size distribution, resulted in the coarser pore. In addition, the relationship between the strength and water content was well established, and the effect of suction was quantified using an equation proposed on the basis of the experimental results. Under the sealed condition, the strength development mechanism mainly included cement hydration and the pozzolanic reaction. However, the mechanism under the drying condition was different from that under the sealed condition; strength development was provided not only by cement hydration and the pozzolanic reaction but also by carbonation and the suction effect.

The carbonation coefficient determined by the phenolphthalein spray test was the highest under the drying condition without water sprayed and decreased as the water content increased by water sprayed. On the other hand, the amount of $CaCO_3$ determined by thermal analysis was the highest under the medium moisture condition brought about by a small amount of water sprayed and also decreased with an increase in the water content. The amount of $Ca(OH)_2$ consumed by carbonation under the medium moisture condition was larger than that under the low moisture and wet conditions. Spraying appropriate amount of water can extend the semi-carbonated zone, resulted in the increase in compressive strength. The relationship between the compressive strength and the amount of $CaCO_3$ showed a good correlation. The compressive strength increased linearly with the amount of $CaCO_3$. It indicates that the amount of $CaCO_3$ is a good indicator to represent the effect of carbonation on the strength development of cement-treated sand.

Finally, the compressive strength of cement-treated soils increased for both short and long-terms under 40^{o}C when using OPC. However, the compressive strength of the specimens decreased under 40^{o}C when using HPC. It was revealed that the compressive strength of the specimen using HPC was much higher than that of the specimen using OPC under 20^{o}C. With regard to the HPC under 20°C, the compressive strength increased with the decrease in cement content. It suggests that HPC has a significant impact on strength development in cement-treated soils than in mortar, and HPC is a potential binder for applying in cement-treated soils to achieve high strength in both short and long-term. In conclusion, this study has investigated and analyzed the strength development mechanism of cement-treated soils under different curing conditions. It could provide an insight of cement-treated soils in terms of the strength development that considering many factors from the viewpoint of physic-chemical and microstructural aspects.