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Study on long-term strength property of compacted soil with treatment by cement

Etude sur les propriétés de résistance à long terme de sols traités au ciment

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ABSTRACT: The results of the boring survey on the actual embankment and the laboratory experiment were summarized in this paper, to clarify the durability and stability of cement-treated soil which was compacted to construct road embankment. The boring survey was conducted on the embankment after 9 years from its construction by cement-treated soil. It was found that the unconfined compressive strengths in the whole length of the sample were larger than the designed values. According to the comparison of unconfined compressive strengths at the depth below groundwater level, strength obtained in this study was hardly increased from the strength nine years ago. The effect of environmental exposure conditions on the long-term strength property of soil treated by cement was investigated in the laboratory. As the result of the experiments until about 2 years from specimen preparation, the unconfined compressive strengths of the soaked specimens were found to be the smallest, while those of the sealed specimens were the largest. It was inferred that the differences in the strengths were caused by the changes in physical properties such as degree of saturation, and chemical properties due possibly to the leaching of hydration products such as ettringite during soaked curing.

RÉSUMÉ : Une investigation in situ couplée à des essais de laboratoire a été réalisée sur un site de remblai routier afin de clarifier la durabilité et la stabilité des materiaux traités au ciment utilisés lors de sa construction. Des échantillons non remaniés ont pu être prélevés sur une profondeur totale de 18 mètres, 9 ans après la fin de la construction. Les résultats montrent que la résistance à la compression uniaxiale reste supérieure à celle considérée lors du dimensionnement, mais que celle des échantillons situés sous la nappe phréatique n'a pas significativement augmentée en comparaison de celle mesurée il y a 9 ans. Les effets dus à l'exposition environnementale sur les propriétés de résistance à long terme de ces sols traités au ciment ont alors été évalués par une série d'essais de compression uniaxiales. Les résultats obtenus jusqu'à 2 ans après la préparation des échantillons indiquent que la résistance est la plus élevée pour les échantillons préparés en conditions hermétiques et que celles des échantillons préparés en conditions humides est la plus faible, suggérant que les differences constatées ci-dessus sont dues aux variations de propriétés physiques telles que celles du degré de saturation et de propriétés chimiques probablement par lixiviation des produits d'hydratation durant le processus de durcissement en conditions humides.

KEYWORDS: Cement-treated soil; long-term strength; exposure conditions; degree of saturation; leaching of ettringite.

1 INTRODUCTION.

In Japan, it has been promoted to utilize construction generated soils which are generated by earthworks such as cutting and excavations. Currently, about 80 % of the construction generated soils have been employed in earthworks, according to the survey of construction by-product which was conducted by the Ministry of Land, Infrastructure, Transport and Tourism, Japan in 2020. The construction generated soils with less strength or trafficability have been adopted by applying chemical stabilization using binders such as cement. These treated soils have been used frequently as fill materials of road embankments.

The durability and stability of the road embankments are affected by the change in the long-term mechanical properties of the treated soil. In general, it is well known that the strength of the treated soils increase with curing time under controlled laboratory conditions, due to the chemical reactions between the cement, water, and the soils. On the other hand, it was also recognized that the in-situ strength can be affected by several conditions, including the variation of soils, the degree of mixing, curing temperature and exposure conditions. There are many studies on the treated soils having large amount of cement and high degrees of saturation, such as the cement columns made by deep mixing method (e.g. Kitazume et al. 2003; Hashimoto et al. 2016; Ngoc et al. 2016; Takahashi et al. 2017). However, fewer studies were conducted on the compacted soils treated with a small amount of cement for the construction of embankments. In the case of road embankment made of cement-treated soil with an unsaturated condition, the effect of water infiltration caused by rainfall and groundwater would not be negligible on the mechanical property of the treated soil.

This paper summarized the results of the boring survey on the actual embankment and the series of exposure tests in the laboratory to clarify the durability and stability of cement-treated soil which was compacted to construct road embankment, particularly focusing on the effect of water infiltration.

2 LONG-TERM STRENGTH PROPERTY OF ROAD EMBANKMENT MADE OF CEMENT TREATED SOIL

The boring survey was conducted on the embankment after 9 years from its construction by cement-treated soil. Chronological change in the strength of the embankment was investigated (Miyashita et al. 2018).

2.1 *Overview of road embankment investigated*

A large embankment made of compacted soil with treatment by cement was investigated in this study. This embankment whose volume of 414340 m^3 and a maximum height of about 40 m was made to fill a valley to construct a highway in Shizuoka prefecture, Japan. 29 types of soils which were generated in neighboring construction sites were used as the fill materials of the embankment. One of the major soils was volcanic clay (loam) having high water content. Cement treatment was applied to improve the quality and the strength of the soil. Design strength by unconfined compressive strengths on 28 days, denoted hereafter as q_{u28_design}, were determined as shown in Table 1, while considering the result of slope stability analysis of the embankment.

A stationary plant at the construction site was selected to mix cement with the soils as uniformly as possible. The amount of the cement was in the range of 32 to 225 kg/m^3. As several types of soils were irregularly provided to the plant every day, the mixing amount of the cement depended on the quality of the each soil. Ranges and average values of the unconfined compressive strengths obtained at the plant on 28 days are indicated in Table 1 as q_{u28_plant}. Cement-treated soils were compacted by a swamp bulldozer with its mass of 21 t within the day of mixing, to construct the embankment.

Table 1. Unconfined compressive strength used in design and at plant.

Parts of embankment	*Upper part*	*Lower part*
Design strength on 28 days, q_{u28_design} (kN/m^2)	190	500
Strength at plant after 28 days, q_{u28_plant} (kN/m^2)	239-1654 (avg. 914)	562-1584 (avg. 1022)

2.2 *Procedure of boring survey and laboratory tests*

A boring survey was conducted at the embankment after 9 years of its construction. Cross-section of the embankment and the position of the borehole are presented in Figure 1. The blue node indicates the place where the unconfined compressive strength at the time of the construction could be identified. Those strengths were obtained as one of the data for quality control of the embankment. The position of the borehole was selected to be adjacent to this place at the depth of about 18 m. The boring was started from the middle height of the embankment to the depth of the original ground. The undisturbed core sample was taken with a diameter of 70 mm and a length of 21 m.

Visual observation combined with the application of phenolphthalein solution was conducted to check the uniformity and alkalinity of the fill material. To obtain strength distribution of the whole length of the sample, three types of mechanical tests were conducted; unconfined compression test, soil hardness test, and needle penetration test compliant with JIS A 1216, JGS 1441, and JGS 3431, respectively. Unconfined compressive strengths were measured at intervals of 2 m, while soil hardness and needle penetration tests were applied at intervals of 100 mm.

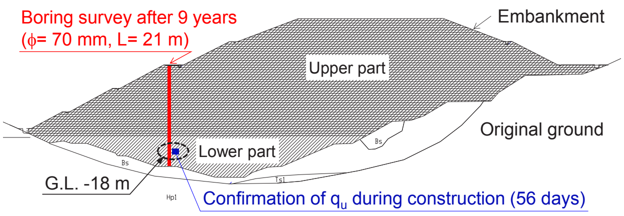

Figure 1. Cross-section of embankment and location of boring survey.

2.3 *Results of boring survey and laboratory tests*

In general, the sample was well cemented except for the cracks associated with drilling. Varieties of colors, types, and diameters of gravels, and structures of soil particles were observed throughout the height of the sample, as the type of soils used in the embankment was not unique. The groundwater level was confirmed at the depth of 15.2 m. It was suggested that groundwater always permeated part of the embankment made of cement-treated soil.

A typical example for the comparison between before and after applying phenolphthalein solution to the sample is presented in Figure 2. It was observed that the color of the surface and the cross-sections of the whole sample changed to red-purple. Such change in color suggested the alkalinity of the sample by the reaction of phenolphthalein, even after 9 years from the construction of the embankment. It was inferred from the result that the cement and soils had been mixed very well throughout the entire period of construction.

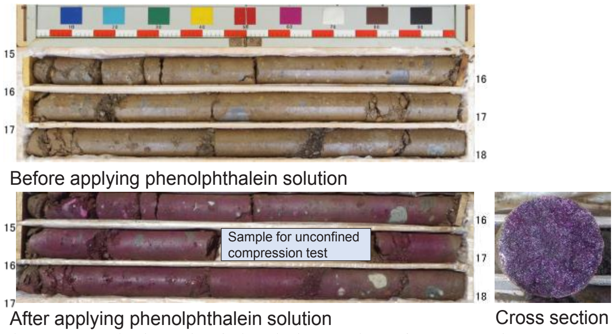

Figure 2. Typical result of visual observation of core sample.

Figure 3 shows the depth distribution of unconfined compressive strength by unconfined compression tests (denoted hereafter as q_{u_UC}). Ranges of variation in q_{u_UC} values were 449-1070 kN/m^2 and 920-3820 kN/m^2 in the upper and lower part of the embankment, respectively. Despite the differences in the types of soils, macro structures of soil particles, and amount of cement, q_{u_UC} values correlated with water contents and dry densities as indicated in Figure 4. Consequently, it was confirmed that one of the contributing factors in the variation of q_{u_UC} values was the difference in the physical property of the cement-treated soils.

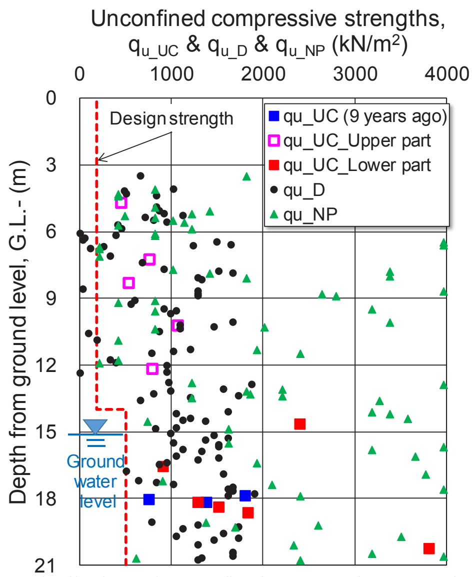

Figure 3. Distribution of unconfined compressive strengths of core sample.

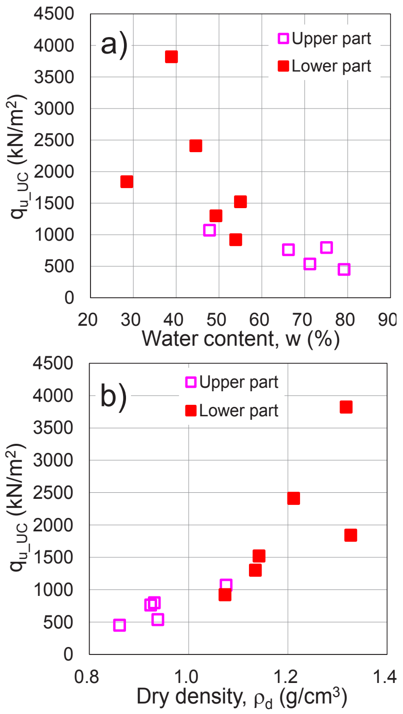

Figure 4. Relationships between unconfined compressive strength, water content (a) and dry density (b).

Hardness index by the soil hardness test and needle penetration gradient by the needle penetration test were converted to unconfined compressive strengths, denoted hereafter as q_{u_NP} and q_{u_D}, using the formula proposed by the Japanese Geotechnical Society (2018) and the manufacturer (Maruto Testing Machine Company), respectively. It was seen in Figure 3 that q_{u_NP} and q_{u_D} values exhibited tolerable agreement with q_{u_UC} values, while a larger variation of q_{u_NP} values was observed due possibly to the existence of gravels close to the surface of the sample. It could be judged in general that the unconfined compressive strength on 9 years was larger than the design strengths presented by a doted red line in Figure 3, throughout the whole length of the sample. It was found that some of the q_u values were much larger than the design strengths. It might be caused by the variation of the soils and the way of assessing the amount of cement at the time of construction, rather than the increase in strength during 9 years as explained in section 2.4.

2.4 *Comparison of changes in strength of cement-treated soils over time*

q_{u_UC} values obtained at the depth of 18 m on 56 days and 9 years are compared in Figure 5. The average of q_{u_UC} values on 9 years was 1.2 times larger than that on 56 days. The strength increment exhibited in this study was smaller as compared to that of cement columns (JCA Committee of Geocement 2014) as shown in Figure 5. These cement columns with a diameter of 450 mm and a height of 2 m were made by filling a mixture of volcanic clay and cement slurry to a site above the groundwater level. Characteristics of material, construction technique, amount and type of cement, and curing conditions were different from those of this study. These factors would affect to their long-term mechanical properties.

13 case histories in 12 previous studies on the long-term mechanical property of chemically treated soils had been summarized by the JGS Committee on Properties and Testing Methods of Cement -Treated Soils (2005). It was reported that the ratios of q_{u_UC} after more than 10 years to q_{u_UC} on 28 days in those studies were in the range of 1.6 to 8.6, while those ratios were obtained without or with less effect of deterioration due to exposure conditions. The ratio of q_{u_UC} on 9 years to q_{u_UC} on 28 days at the depth of 18 m of the embankment in this study could be in the range of 1.0 to 2.8, by the average of q_{u_UC} values on 9 years (1553 kN/m^2) and the range of q_{u28_plant} values of the lower part of the embankment (562-1584 kN/m^2) from Figure 5. Exposure condition at the depth of 18 m in this study, that is, the existence of groundwater might be affecting the strength after 9 years, while several other factors might also influence too.

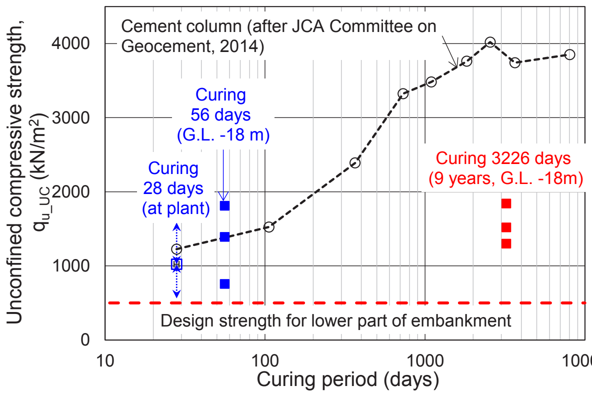

Figure 5. Relationships between unconfined compressive strength and curing period of the sample at depth of about 18 m.

3 STRENGTH PROPERTY OF CEMENT TREATED SOIL UNTIL 2 YEARS BY EXPOSURE TEST IN LABORATORY

The effect of the environmental exposure conditions on the long-term strength property of soil treated by cement was investigated in the laboratory (Miyashita et al. 2019). The result of the experiments until about 2 years from specimen preparation were summarized while adding new data here.

3.1 *Materials and procedures of specimen preparation*

Sand with fines which is called hereafter as Miho sand was used in this study. It was said that the chemical reaction between cement and allophane which was one of the components of the volcanic clay investigated in chapter 2 was complicated (e.g. JSCE Concrete committee 345, 2018). In this fundamental study, Miho sand was selected instead of the volcanic clay, to simplify the possible chemical reaction. The physical and mechanical properties of Miho sand are summarized in Table. 2.

Table 2. Physical and mechanical properties of Miho sand.

Type of soil	*Sand with fines*
Specific gravity (g/cm^3)	2.693
Fines content (%)	46.3
Plasticity index	25.4
Optimum water content (standard proctor) (%)	21.6
Maximum dry density (standard proctor) (g/cm^3)	1.624
Cone index with water content of 31 % (kN/m^2)	68

A cement-based product was employed to improve the strength of Miho sand. This product called hereafter as cement was developed in Japan to make the effectiveness against low-quality soils higher than that of Ordinary Portland Cement.

Table 3. Chemical components of Miho sand and cement

	SiO_2 (wt%)	TiO_2 (wt%)	Al_2O_3 (wt%)	Fe_2O_3 (wt%)	MnO_2 (wt%)	MgO (wt%)	CaO (wt%)	Na_2O (wt%)	K_2O (wt%)	P_2O_5 (wt%)	S_{total} (wt%)	SO_3 (wt%)
Miho sand	61.7	0.73	19.9	6.86	0.11	1.29	1.48	1.18	1.54	0.10	0.03	-
Cement			not measured				56.4		not measured		3.13	6.08

Chemical components of Miho sand and the cement by X-ray Fluorescence analyses are presented in Table 3. SO_3 in the cement was analyzed by wet chemistry (JIS R 5202).

Content of the cement by dried weight of Miho sand was selected as 5.3 % while considering the level of unconfined compressive strength of the lower part of the embankment investigated in chapter 2. The water content of Miho sand was set to 31 %. The cement and Miho sand were mixed uniformly by a soil mixer for 5 minutes. Cylindrical specimens with 50 mm in diameter and 100 mm in height were prepared by applying static compaction. The dry density of the specimens was set to 1.4 g/cm^3, by referring to the result of large-scale model tests to study the characteristics of compaction using actual construction machines.

3.2 *Conditions of exposure test*

The specimens were cured under 2 different conditions as schematically shown in Fig. 6. In case 1 which is called hereafter as sealed curing, specimens were wrapped with plastic sheets to avoid moisture transportation. A part of the embankment with less effect of water infiltration was simulated in this case. To evaluate the effect of soaking from the early curing period on the strength, the second set of specimens were cured under artificially made acidic water, after applying sealed curing for initial 3 days. It was classified as soaked curing (case 2). A constant temperature within the range of 17 to 23 degrees Celsius was kept in both of the cases.

pH value of the acidic water was set to 4.5 by mixing pure water with sulfuric acid (H_2SO_4), nitric acid (HNO_3), and hydrochloric acid (HCl) by 5:2:3 proportionally to simulate the actual acid rain in Japan. The volume ratio of a specimen and water soaking was set to 1:5. In the initial 28 days, the water soaking was exchanged once a week. Duration for the exchange was increased to 2 weeks until 168 days, while it was increased again to 4 weeks after 168 days.

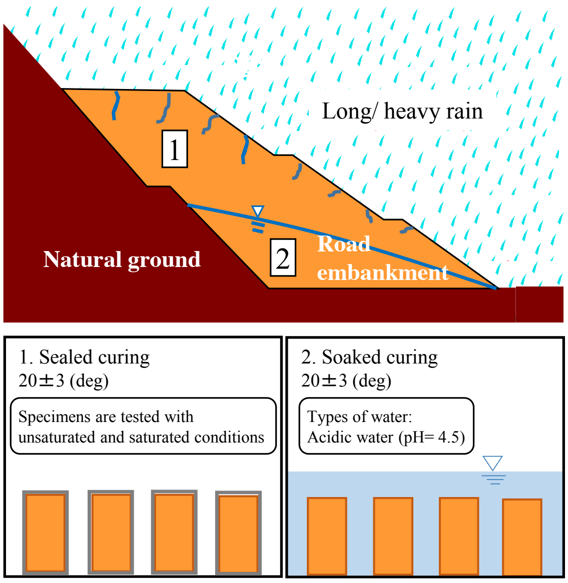

Figure 6. Schematic figure of relationship between in-situ exposure conditions of treated soil assumed and curing conditions in laboratory.

3.3 *Procedures of mechanical and chemical tests*

Unconfined compression tests (JIS A 1216) were conducted on the specimens on 7, 28, and 168 days, 1 and 2 years from their preparation. In every curing period, three specimens cured in case 1 were saturated by applying vacuum pressure under pure water 1 day prior to the corresponding curing date, whereas another three specimens in case 1 were tested as they were.

The water after soaking from case 2 was collected to measure pH value, concentrations of Ca and SO_4. pH value was measured by the glass electrode method using a compact analyzer (Horiba LAQUA twin B-712). The concentration of Ca was obtained by the ion electrode method using another compact analyzer (Horiba LAQUA twin B-715). The concentration of SO_4 was quantified by ion chromatography (JIS K 0102 41.3). It was identified that the measurements of Ca concentration by the compact analyzer were 2.1 times larger than that by atomic absorption analysis which was a more accurate method, along the way of the series of tests. The values of Ca concentration by the compact analyzer were divided by 2.1 and evaluated, as the measurements by the atomic absorption analysis at the beginning of the series of tests were lacked.

Soil samples were trimmed 5 mm from the surface to the inside of the specimens tested on 7 days, 28 days and 2 years. X-ray diffraction (denoted hereafter as XRD) analyses were applied to those soil samples which had been dried by immersion in acetone.

3.4 *Effect of physical properties on strength of treated soil*

Relationships between the values of unconfined compressive strength (denoted hereafter as q_u) of the specimens and the curing period are summarized in Fig. 7. The strength of sealed specimens in case 1 increased depending on the curing period until 1 year, while those on 2 years were the same levels as 1 year. In every curing period, q_u values of sealed-unsaturated conditions were the highest. By applying saturation to the sealed specimens, q_u values became lower than those of unsaturated specimens. The strength of soaked specimens in case 2 increased until 168 days, whereas that gradually decreased after 1 year. Lower q_u values than those of sealed-saturated specimens were obtained from soaked specimens after 168 days.

To identify the effect of changes in physical properties on the strengths, relationships between strength ratio, dry density and degree of saturation (denoted hereafter as S_r) on 28 and 168 days, 1 and 2 years were exhibited in Fig. 8. The strength ratio was defined as the ratio of the average of q_u values in each condition to the average of q_u values in sealed-saturated condition at a particular curing period. There was no distinct trend on the change in dry density while exhibiting variations. On the other hand, levels of S_r values in sealed-saturated conditions were always higher than those in unsaturated conditions. It was inferred that the q_u values in sealed-saturated conditions were lower due possibly to the decline of the strengths derived from the suction force. Strength ratios in the soaked specimens treated by cement gradually decreased with the increase in the period of soaked curing, while achieving the same levels of S_r values as sealed-saturated conditions. It was not possible to explain the difference of the strengths in the soaked condition and the sealed-saturated conditions only by the physical properties.

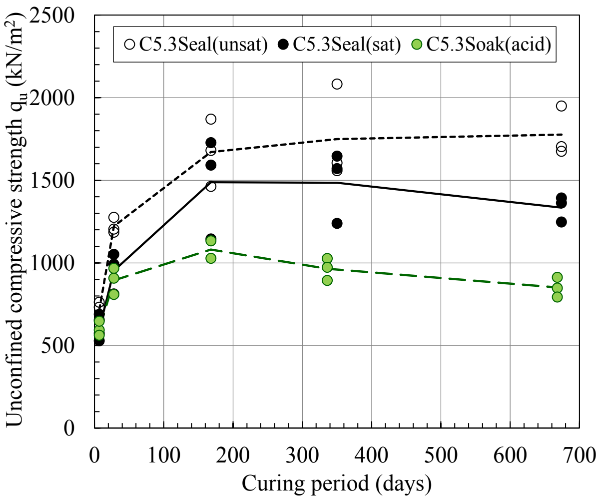

Figure 7. Relationships between unconfined compressive strength and curing period.

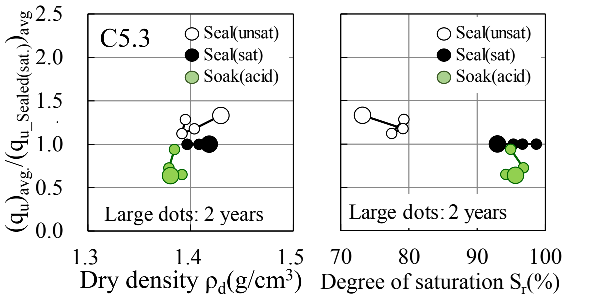

Figure 8. Relationships between strength ratio, dry density and degree of saturation.

3.5 *Effect of chemical properties on strength of treated soil*

The relationships between the strength ratio, pH value, remaining ratios of Ca and SO_4 on 28 and 168 days, 1 and 2 years in soaked condition are shown in Fig. 9. According to the chemical compositions, as shown in Table 3, the representative amount of Ca in every single specimen due to the addition of the cement was calculated. The Amount of Ca leached from the specimen in soaked condition was assumed to be the same as the corrected measurement of Ca on the water after soaking by the compact analyzer. The remaining ratio of Ca in the soaked specimens was defined by the ratio of the difference between the amount of Ca added and leached to the amount of Ca added. The remaining ratio of SO_4 was also calculated in the same manner as Ca while assuming that the component of S_{total} in the cement was derived from SO_4. It was also assumed here that the leaching of Ca and SO_4 occurred not from the components of the soil, but those of the cement. The pH value of the water after soaking decreased from 11.4 on 28 days to 8.6 on 2 years. The strength ratio in the soaked condition decreased with the decline of the remaining ratios of Ca and SO_4.

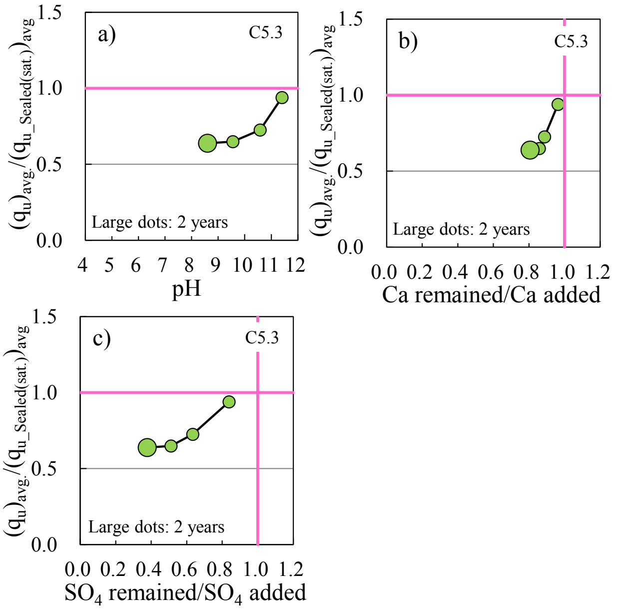

Figure 9. Relationships between the strength ratio, pH value, remaining ratios of Ca and SO_4.

Results of XRD analyses were presented in Fig. 10. Peaks suggesting the existence of ettringite in soaked specimens on 7 and 28 days could be observed from the samples. Ettringite,

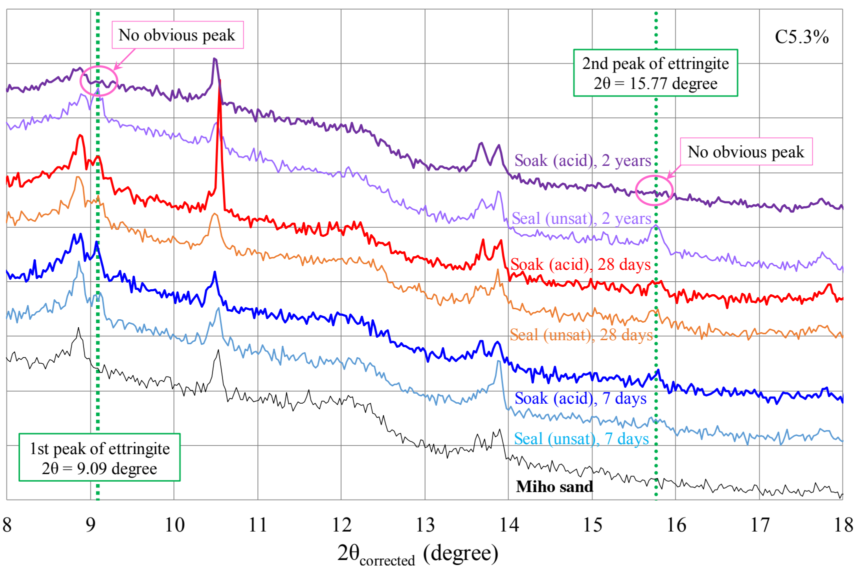

Figure 10. Results of XRD analyses on cement-treated soils.

which is one of the hydration products formed by the chemical reaction of cement, water and soil is believed to be related to the strength of cement-treated soils. On the other hand, those peaks were not obvious in the samples of soaked specimens for 2 years.

It was reported in the previous studies that the leaching of Ca with the decrease of pH value suggested the failure or dissolution of the hydration products and caused the decline in the strength of cement-treated soils in the soaked conditions (e.g. Kamon et al. 1996; Kitazume et al. 2003; Ghobadi et al. 2014; Takahashi et al. 2017). In this study, progression of the leaching of Ca and SO_4 with the decrease of pH value, and the dissipation of ettringite from the surface of the specimens in soaked condition were observed, as shown in Figs. 9 and 10, respectively. It was estimated that these changes of chemical property contributed to the difference of strength between the soaked condition and the sealed-saturated conditions. Further investigations will be conducted on larger curing periods to study the long-term strength property of cement-treated soil while introducing different types of soil.

4 CONCLUSIONS

The results of the boring survey on the actual embankment and the series of exposure tests in the laboratory were summarized to clarify the durability and stability of cement-treated soil which was compacted to construct road embankment, particularly focusing on the effect of water infiltration. The main findings of this paper include:

- It was found from the site investigation of the actual embankment that the unconfined compressive strengths of the whole length of the undisturbed core sample after 9 years were larger than the design strengths.
- According to the comparison of strength at a certain depth below the groundwater level, unconfined compressive strength after 9 years was 1.2 times larger than that on 56 days. The strength increment which was exhibited under this study was not high when compared to the results of the previous studies on the long-term mechanical property of the cement-treated soils without or with less effect of deterioration due to exposure conditions.
- It was obtained from the series of exposure tests in the laboratory that the unconfined compressive strengths of the soaked specimens were the smallest, while those of the sealed specimens with keeping unsaturated conditions were the largest after 2 years.
- One of the reasons for the differences in the strengths of cement-treated soil was detected as the changes in physical property such as degree of saturation. Another was estimated to be the changes in chemical property due to the leaching of hydration products such as ettringite during soaking.
- It could be suggested from these results that chronological change in the strength of the compacted soil with treatment by cement was not drastic, to the extent that the soil was used for a road embankment with sufficient considerations for its design and construction techniques.

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