EFFECT OF ACID RAIN ON LIME AND CEMENT STABILIZED SOILS

MASASHI KAMON\textsuperscript{0}, CHANGYUN YING\textsuperscript{0} and TAKESHI KATSUMI\textsuperscript{0}

ABSTRACT

Infiltration and soak tests were conducted at different pH levels of artificial acid rain to experimentally simulate the erosion process on stabilized soils, which were used for subgrade and base course materials. The authors used three types of lime and cement stabilized soils, and focused on the physico-chemical and engineering behaviors of the eroded soils. Results obtained show that the pH values of the lime and cement stabilized soils generally decreased with continuous infiltration or soak and that these decreases were greater under a higher acid condition. A large reduction of the unconfined compressive strength obtained from the specimens eroded by the higher acid rain was observed in comparison to erosion from the weaker acid rain. In particular, the unconfined compressive strength of the lime stabilized decomposed granite soil (LDGS) eroded by the acid rain with pH 2.0 decreased to 1/6 of its initial value after a small flux of infiltration. The X-ray diffraction patterns show that the straelingite (2CaO·Al₂O₃·SiO₂·8H₂O) was decomposed, but the gypsum (CaSO₄·2H₂O), calcite (CaCO₃) and unknown chemical crystals were formed in the lime stabilized soils eroded by acid rains with pH 2.0 and 3.0.

Key words: acid rain, neutralization, permeability, pH, stabilized soil, unconfined compressive strength (IGC: B12)

INTRODUCTION

The challenge to environmental-geotechnical engineering has become more important because of the deterioration of the environment due to industrialization. In particular, great attention has been paid to whether the acidification of rain is one of the environmental factors which will affect chemical-stabilized soils. Lime and cement are two common admixture stabilizers used to improve the engineering properties of soft and compressible soils. The stabilized soils have, in general, a high alkalinity which results in a high strength, because lime and cement are highly alkaline. When acid rain fails over a long period of time, the stabilized soils may be neutralized by acid rain and their engineering properties may be affected. Not only internal factors affecting stabilized soils, such as chemical admixture, additive content, soil component and soil properties, have been studied (e.g. So and Ying, 1994); but studies concerning the leaching characteristics of stabilized soils and the effect on environment were also undertaken as follows. Goh and Tay (1993) investigated the leaching properties of fly ash stabilized soils. Broderick and Daniel (1990) reported that the lime and cement stabilized soils are less vulnerable to attack by organic chemicals in comparison to untreated soils. Effects of long-term permeation of inorganic leachate solutions on compacted pozzolanic fly ash liner and the changes in the chemical composition of seepage solution were reported by Edil et al. (1992). Poran and Ahtchi-Ali (1989) investigated the engineering properties of stabilized solid waste incinerator fly ash and some environmental aspects related to fly ash applications. Furukawa et al. (1994) investigated the variation of the engineering properties of freshly cement stabilized decomposed granite soil cured in water and 0.2 N acid solution and indicated that the CBR obtained from the specimens cured in the 0.2 N acid solution was lower than that cured in water. Except for Furukawa’s study, little research has been conducted to determine whether acid rain will affect properties of the lime and cement stabilized soils. Additional studies are, therefore, necessary to explain the erosion mechanism of the lime and cement stabilized soils due to acid rain.

In general, it is recognized that lime and cement stabilized soils are strengthened by both physical action and chemical reaction (CMSTSS, 1991 and CAJ, 1994). The physical action often involves the cation adsorption such as Ca²⁺ ion adsorbed by soil particles under an alkaline

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condition. Chemical reactions, such as pozzolanic reaction, between additive and clay mineral in soil form calcium hydrates to develop strength.

\[ \text{[Lime]} \text{ or } \text{[Cement]} + \text{Soil} + \text{H}_2\text{O} \rightarrow \text{[Hydrate]} + \text{Ca-Soil} + \text{Ca}^{2+} + \text{OH}^- \]

where [Hydrate] stands for CaO–SiO_2–H_2O, CaO–Al_2O_3–H_2O etc.

The \text{Ca}^{2+} ions exist in the lime and cement stabilized soils at the free, adsorbed and hydrated states. If the lime and cement stabilized soils are eroded by acid rain, the \text{Ca}^{2+} ion will be released to leach due to ion-exchange reaction between \text{Ca}^{2+} and \text{H}^+, and may result in the neutralization of stabilized soils. The objectives of this study are therefore: (1) to investigate the physico-chemical behaviors and engineering durability of the stabilized soils according to a simulation of the erosion process by acid rain and (2) to clarify the erosion mechanism of the lime and cement stabilized soils due to acid rain.

### EXPERIMENTS CONDUCTED

#### Materials

The three soils (decomposed granite soil, Kanto Loam and alluvial clay) used in this study were obtained from sites in Otsu City (Shiga), Machida City (Tokyo) and Higashi Osaka City (Osaka), respectively. Decomposed granite soil and Kanto Loam were prepared by passing the original soils through a 2-mm openings sieve. The properties of the non-stabilized soils are summarized in Table 1.

#### Determination of Additive Contents Required

Before the infiltration and soak tests, we determined the additive contents of lime and cement required, based on the unconfined compressive strengths obtained from the stabilized soils having various additive contents. The variations in the unconfined compressive strengths of the stabilized soils with additive contents are shown in Fig. 1. The three stabilized soils showed different changes in strength. For a given curing period, the unconfined compressive strength of the lime decomposed granite soil increased sharply with increasing additive content in the lower-additive stage, and then the increase became smaller. Nearly no change in the unconfined compressive strength of the lime stabilized Kanto Loam with additive content was observed in the lower-additive stage, although the strength increased significantly with increasing additive content after that. In the cement stabilized alluvial clay, the unconfined compressive strength increased with increasing additive content throughout. Thus, the additive contents of lime for the stabilized decomposed granite soil and the stabilized Kanto Loam were determined to be 5% and 12%, respectively, in accordance with an unconfined compressive strength of 0.7 MPa after curing for 9 days in air and 1 day in water. The additive content of cement for the stabilized alluvial clay was determined to be 7.5% in accordance with an unconfined compressive strength of 0.98 MPa after curing for 6 days in air and 1 day in water. The amounts of admixtures were based on the dry mass of the soils. The lime and cement used in this study are available in the normal market. In this paper, the 5% lime stabilized decomposed granite soil, the 12% lime stabilized Kanto Loam, and the 7.5% cement stabilized alluvial clay were designated as LDGS, LKL, and CAC, respectively, in the following chapters. The basic properties of these stabilized soils are presented in Table 2.

### Table 1. Properties of non-stabilized soils

<table>
<thead>
<tr>
<th></th>
<th>w_d (%)</th>
<th>w_s (%)</th>
<th>P_p (%)</th>
<th>I_p</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>DGS</td>
<td>7.6</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>6.10</td>
</tr>
<tr>
<td>KL</td>
<td>74.9</td>
<td>114.0</td>
<td>87.2</td>
<td>26.8</td>
<td>6.17</td>
</tr>
<tr>
<td>AC</td>
<td>64.0</td>
<td>93.0</td>
<td>34.2</td>
<td>58.8</td>
<td>7.72</td>
</tr>
</tbody>
</table>

Note: DGS, KL and AC stand for decomposed granite soil, Kanto Loam and alluvial clay, respectively.

### Table 2. Properties of stabilized soils

<table>
<thead>
<tr>
<th>Sample</th>
<th>(\gamma_s) (g/cm³)</th>
<th>(q_u) (MPa)</th>
<th>(k) (cm/s)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDGS</td>
<td>1.717</td>
<td>2.64</td>
<td>1.80 \times 10^{-5}</td>
<td>12.2</td>
</tr>
<tr>
<td>LKL</td>
<td>0.967</td>
<td>0.61</td>
<td>1.71 \times 10^{-4}</td>
<td>11.3</td>
</tr>
<tr>
<td>CAC</td>
<td>1.288</td>
<td>1.05</td>
<td>1.50 \times 10^{-6}</td>
<td>10.2</td>
</tr>
</tbody>
</table>

Note: LDGS, LKL and CAC stand for lime stabilized decomposed granite soil, lime stabilized Kanto Loam and cement stabilized alluvial clay, respectively.

### Experimental Methods

Test specimens were made by compactive effort, following the testing standard of CAJ, in which compactive effort equals one of JISA1211. Vibratory compaction of
the LDGS and LKL specimens in a polyvinyl chloride (PVC) mold (φ 5 cm × 10 cm × 0.5 cm) was carried out with a compactive effort of 5, 10, 10 and 20 times x 4 layers.

The specimens of the CAC were manufactured using the static compaction method.

The artificial acid rain was produced by diluting the sulfurous and nitric acids using distilled water. Referring to the chemical components of rain water (SO4^2-: 4.63 g/m^2 y, NO3^-: 1.68 g/m^2 y, EA, 1992), the rate of sulfurous acid versus nitric acid was purposely fixed 3:1, and the pH levels of the artificial acid rains were determined as 5.6, 5.0, 4.0, 3.0 and 2.0.

The flux of artificial acid rain was determined based on the average annual precipitation throughout the country in the infiltration test. The flux of artificial acid rain for each specimen in the infiltration test is at a rate of 1.2 l/y (c.f. Appendix), and in the soak test at 6.0, 12.0, 24.0, 36.0 and 48.0 l for 5, 10, 20, 30, and 40 years soaking (Kamon et al., 1995).

In this study, flow in the infiltration test was oriented vertically downward with an initial head of water of 1.0 m. The head fell as the test continued, but was not allowed to fall below 80% of the initial head. The specimens compacted in the PVC mold were soaked in artificial acid rain in the soak test. The specimens were cured for 4 months in the water before performing the infiltration and soak tests, and it is expected that the strength has remained constant. After each infiltration flux and soak period, the specimens were extracted and the unconfined compressive strength, permeability, pH and neutralization tests were carried out.

The neutralization test was conducted using the Luox 3 Particle Analyzer. The specimens eroded by the artificial acid rain were cut open vertically and the cut section was sprayed with 1% phenolphthalein solution. The neutralization area was determined using a picture analysis method based on the shade of the vertical section. The neutralized depth was calculated from the neutralized area.

RESULTS AND DISCUSSIONS

Infiltration Test

1) pH Values of Specimens

Figure 2 shows the pH values obtained from parts of the top and bottom surfaces of the LDGS specimens and the average of both values. Because the simple average of pH values cannot represent the change of H^+ concentration exactly and is different with an average of H^+ concentration, it was used as only an index parameter of neutralization in this paper. The pH values obtained from parts of the top surfaces were greatly lower than that of the bottom one. The reason is that the acid rain was buffered due to ion-exchange, ion adsorption and chemical reaction in the infiltration process and that the acidity of the acid rain became weak as it flowed to the bottom surface.

As illustrated in Fig. 2, the average pH values of the LDGS specimens eroded by the acid rains with pH over 4.0 decreased similarly until infiltrating with approximate 10 l, but the decreasing rates increased with a drop in the pH level of the acid rain after being infiltrated 10 l. It is commonly known that the alkalinity of lime stabilized soils is caused by the additive lime and is strongly related to the chemical status of stabilized soil. In the lime stabilized soil, the main chemical components provided by the additive lime are Ca^{2+} and OH^- . The Ca^{2+} ions exist at the free, adsorbed and hydrated states. The free Ca^{2+} exists in the soil water and the adsorbed Ca^{2+} is adsorbed by the soil particles. The hydrated Ca^{2+} exists in the chemical hydrates and leaches very little compared to others. The alkalinity is mainly contributed by both the free and adsorbed Ca^{2+} ions, but depends little on the hydrated Ca^{2+} ions. The result is explained by the fact that because the free Ca^{2+} ions leached more easily in comparison to the adsorbed and hydrated Ca^{2+} ions, the leaching of Ca^{2+} ions is mainly contributed by the free Ca^{2+} ions in the early stage, independent of the pH level of the acid rain. The leaching of the Ca^{2+} ions resulted in a neutralization of the stabilized soil which caused a decrease in the pH values of each specimen. After being infiltrated with 10 l, the free Ca^{2+} ions were almost completely leached and the adsorbed Ca^{2+} ions began to be released. The significant leaching of the adsorbed Ca^{2+} ions from the specimens eroded by the acid rains with pH 4.0 resulted in a greater decrease in the pH values than did that leached by the acid rains with pH levels of 5.0 and 5.6. While using the acid rains with pH levels of 2.0 and 3.0 particularly, the average pH values decreased to 6.0-7.0 after being infiltrated with 6.0 and 12.0 l (equivalent to the precipitation of 5 and 10 years), respectively. It seems that all the free and adsorbed Ca^{2+} ions were released and the specimens were neutralized under the higher acid condition. In addition, the hydrated Ca^{2+} ions may have
been exchanged partially and the hydrated structure may have been disrupted.

2) Neutralized Depth of Specimens

The neutralized depth of the eroded LDGS specimens is shown in Fig. 3. The neutralized depth generally increased with infiltration and there were deeper neutralized depths in the specimens eroded by the higher acid rains in comparison to the weaker ones. As shown in this figure, the neutralized depth eroded by the weaker acid rains with pH levels of 4.0, 5.0 and 5.6 reached about 2 cm when the flux of infiltration was over 30 l. In the specimens eroded by the acid rains with pH levels of 2.0 and 3.0 particularly, the neutralized depths increased to 4 and 6 cm after infiltrated with approximately 6 and 30 l, respectively. It is suggested that only a small amount of adsorbed Ca\(^{2+}\) ions leached from specimens when the weaker acid rains were infiltrated, but that the larger adsorbed Ca\(^{2+}\) ions, even hydrated ions, were released when infiltrated using the higher acid rains. From the analysis of the relationship between the neutralized depths and the pH values of the specimens, it is clear that the neutralization of the lime stabilized soils results in a decrease in the pH values.

3) Strength Characteristics

The variations of the $q_u$ values of the eroded LDGS are shown in Fig. 4. The $q_u$ values decreased with infiltration and showed a small decreasing rate in the early infiltration stage using the acid rains with pH levels over 3.0. When the acid rains were infiltrated for about 12 l (equivalent to the precipitation of 10 years), a large decrease in strength was observed and the $q_u$ values finally decreased to $1/3 - 1/2$ of their initial values. The strength of stabilized soil may be affected by polynomial factors. The release of the adsorbed and hydrated Ca\(^{2+}\) ions will result in a decrease in the strength, but the chemical compounds which consisted of crystalline and non-crystalline substances will be formed to plug the pores of the specimens. In particular, the re-crystals such as CaSO\(_4\)·2H\(_2\)O and CaCO\(_3\) may strengthen the stabilized soils. In the early stage, the main change of the chemical status of LDGS was the leaching of the free Ca\(^{2+}\) ions when the acid rains with pH levels over 3.0 flowed through the specimens but not the adsorbed Ca\(^{2+}\) ions. The leaching of the free Ca\(^{2+}\) affected the strength little, although it made the alkalinity become weak. With an increase in the flux of infiltration to 12.0 l, the free Ca\(^{2+}\) ions were almost completely leached and the adsorbed Ca\(^{2+}\) ions began to leach. This change resulted in a significant decrease in the strength of the stabilized soils. The $q_u$ decreased rapidly to $1/6$ of its initial value when the acid rain with pH 2.0 was infiltrated for a flux of 6.0 l (equivalent to a precipitation of 5 years). The free and adsorbed, even hydrated Ca\(^{2+}\) ions were sharply released to leach under the higher acid condition and this reaction caused a great decrease in the strength. It is possible that the durability of the lime stabilized soils may be decreased by lowering of rain pH, and the erosion process will be accelerated when rain water is further acidified in the future.

Finally, the authors plotted the correlation between $q_u$ and the average of pH of the specimens (shown in Fig. 5).

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Fig. 3. Neutralized depth of LDGS eroded by infiltration test

Fig. 4. Unconfined compressive strength of LDGS eroded by infiltration test

Fig. 5. Relationship between $q_u$ and pH value of LDGS eroded by infiltration test
The $q_{w}$ values decreased with a decrease in the pH values of the specimens, and a linear relationship could be observed. This relationship explained the fact that the neutralization of lime stabilized soils resulted in a decrease in strength. It is evident that the alkalinity is an effective agent for stabilization.

Deformation changes of LDGS used in the infiltration test are shown in Fig. 6. The $E_{50}$ values generally decreased with an increase in the flux, and these show a similar trend with the $q_{w}$ values. The final $E_{50}$ values, when the specimens were eroded by the acid rains with pH levels of 4.0, 5.0 and 5.6, decreased to 1/3–1/4 of the initial values. While the acid rains with pH levels of 2.0 and 3.0 were infiltrated, however, the $E_{50}$ values fell to about 1/10 and 1/15 of their initial values after being infiltrated with 6.0 and 35.0 l, respectively. It seems that parts of the top surface of the specimens were heavily neutralized by the higher acid rain, a great deformation in the parts of the top surface resulted in a larger reduction in the $E_{50}$ values. The results indicate that the lower $E_{50}$ of the eroded soil, in comparison to the un-eroded soil, may cause a greater settlement in the field.

4) Permeability ($k$)

Figure 7 shows the effect of acid rain on the permeability of LDGS. Although the $k$ for the non-stabilized DGS is about $10^{-1}$ cm/s, the $k$ of the LDGS compacted at its maximum density is two orders of magnitude smaller than that of non-stabilized DGS. The majority of the $k$ of all the specimens was of an almost identical order of magnitude (except for the $k$ infiltrated by the acid rain with pH 3.0 which was comparably greater than the others). At pH levels of acid rains over 3.0, the $k$ for each of the specimens was reduced by more than half after being infiltrated 30 l in comparison to its initial values. The reduction of the $k$ was attributed by the formation of the substance such as CaSO$_4$·2H$_2$O and CaCO$_3$ which plugged the pores of the specimens. In the case of pH 2.0, the $k$ decreased sharply at the early infiltration stage, because a quantity of substances was generated. These results indicate that the acid rain with pH level of 2.0 strongly influenced the permeability of LDGS although no great effect of the weaker acid rain could be detected.

5) X-Ray Diffraction

In order to examine the change in the chemical status of eroded soils, the authors investigated the hydrates and crystals in the specimens with X-ray diffraction. Figures 8 and 9 show the X-ray diffraction patterns obtained from LDGS and eroded LDGS, respectively. The peak of the straelingite was found in the LDGS before the acid rain was infiltrated, but they could not be observed in the eroded LDGS when the acid rain with pH 2.0 was infiltrated with 6.0 l. The formations of CaSO$_4$·2H$_2$O, CaCO$_3$ and some unknown chemical crystals in the
eroded LDGS has been confirmed. These changes in the chemical status, such as the decomposition of hydrates and formation of crystals, caused the change in the engineering properties of stabilized soils.

6) SO$_4^{2-}$ Ion in the Specimens

The contents of SO$_4^{2-}$ ions in the specimens are shown in Fig. 10. The contents of SO$_4^{2-}$ ion in specimens were investigated by using an ion chromatography method. The contents of SO$_4^{2-}$ ions increased with continuing infiltration and there was a significant increase in the specimens eroded by the acid rain with pH 2.0. Since a quantity of SO$_4^{2-}$ ions was adsorbed by soil particles and much crystals such as CaSO$_4$·2H$_2$O were formed in the specimens when the higher acid rain flowed through the specimens, the contents of the SO$_4^{2-}$ ions in the specimens significantly increased. A large amount of crystals plugging the pores of the specimens was also a cause of the decrease in permeability under higher acid conditions.

Soak Test

1) pH of Specimens

The pH values obtained from the specimen surfaces exposed to acid rain in the soak test are shown in Figs. 11 to 13. The pH values of the LDGS specimens soaked in acid rains with pH levels over 3.0 decreased to about 10 after soaking for 120 days. When the specimens were soaked in acid rain with pH 2.0, the pH values of the specimens sharply decreased and reached 4.5 finally. The decreasing trend in the pH values in the soak test coincided with that in the infiltration test. For LKL, although the pH values of the specimens fell from 11.3 to about 10 after soaking for 120 days, less influence of the pH level of the acid rain on the pH of the specimens has been seen comparing with LDGS. In the eroded CAC, however, the authors found that the decreasing rates of the pH values were significantly associated with the pH of acid rain. Greater reductions in the pH values of the specimens soaked in the acid rain with pH levels 2.0 and 3.0 have been observed than did in the weaker acid rain. As indicated by the infiltration test, the decreases in the pH values of the lime and cement stabilized soils were caused by their neu-
neutralization due to acid rain. These results indicate that the stabilized soils were easily neutralized under a higher acid condition. A comparison of pH values between LDGS and LKL indicates that the decrease in the pH values of LDGS was greater than that of LKL. The reason is that the LDGS had a lower lime additive ratio (5%) than LKL (12%) and was easily neutralized by acid rain. Since the same change in the pH values as seen in Figs. 11 and 12 was observed in the cement stabilized soil, the same basic mechanism might cause the physico-chemical changes in the cement stabilized soil.

Figure 14 indicates the changes in the pH values of soaked LDGS specimens with depth from the specimen surface exposed to acid rain. A greater reduction in the pH values obtained from the top surface exposed to acid rain was observed, but the reduction in the pH values decreased with increasing depth. There was little change in the pH value on the inside of the specimens. It is suggested that the shallow parts of stabilized soils were easily neutralized due to acid rain, but there was less influence of acid rain on the depths of the stabilized soils.

2) Strength Characteristics

Figures 15 to 17 show the $q_u$ values of LDGS, LKL and CAC in the soak test. The $q_u$ values of LDGS generally decreased with soak period and reached about 2.0 (MPa) after soaking for 120 days. When the LDGS specimens were soaked in acid rain with pH levels of 2.0 and 3.0, the decreasing rates of the $q_u$ values were greater in the early soak stage up to 40 days than in the following soak periods. A comparison between the infiltration and soak tests indicates that there were higher reductions of the $q_u$ values in the infiltration test and the effect of acid rain was limited to only those parts of the specimen surface exposed to acid rain in the soak test. For LKL and CAC, the $q_u$ values obtained from the both soils showed a similar changing trend. There was nearly no change in the $q_u$ values of the specimens soaked in acid rains with pH over
4.0, but a significant reduction in the $q_s$ values was observed when the specimens were soaked in the higher acid rains. The final $q_s$ values of LKL and CAC soaked in the acid rain with pH 2.0 decreased to 1/2 and 3/4 of their initial values, respectively. The soaking may cause two simultaneous opposing effects on the strength of stabilized soils. The strength will increase with soak period because of formation of re-crystal, but the lime stabilized soils may be weakened due to the neutralization caused by acid rain. In addition, because the higher acid rain provided necessary H$^+$ ions to exchange the adsorbed and hydrated Ca$^{2+}$ ions and the lime stabilized soils may be strongly neutralized, disrupted, or both, the $q_s$ values would significantly decrease in a short soak period. The reason why the $q_s$ of the lime stabilized soils decreased more rapidly when soaked in the higher acid rain is that a quantity of adsorbed Ca$^{2+}$ ions leached, and even hydrates may be disrupted by the higher acid rain. Plotting relationship between the $q_s$ and pH values of the LDGS specimens (Fig. 18), the same relationship as the infiltration test was observed. The lower the pH values of the soaked specimens, the smaller the $q_s$ values were.

The changes of the $E_{50}$ values of LDGS related to soak period are shown in Fig. 19. The $E_{50}$ of LDGS generally decreased and an almost constant rate in the decreases could be observed. While the specimens were soaked in the acid rain with pH over 4.0, the $E_{50}$ values decreased to approximately half. When soaked in the acid rain with pH 2.0, the $E_{50}$ values decreased to 1/3 of the initial value after soaking for 120 days. Comparing both tests, the eroded specimens used in the infiltration test had a greater reduction in the $E_{50}$ values than did the soaked specimens.

CONCLUSIONS

In a new attempt to vitalize environmental geotechnics, the authors investigated changes in the properties of lime and cement stabilized soils due to acid rain, and tried to explain the erosion mechanisms by imitating the permeation process of acid rain on the subsoil profile. The results obtained from this study can possibly be used to assess and estimate the effect of acid rain on chemical-stabilized soils.

The acid rain significantly influenced the physico-chemical properties of the lime and cement stabilized soils. The stabilized soils become less alkaline as they continued to be eroded and a larger reduction in the pH values of the specimens was observed under higher acid conditions. The LDGS was completely neutralized when acid rains with pH levels of 2.0 and 3.0 were infiltrated for the fluxes equivalent to the precipitation of approximate 5 and 10 years (equivalent to fluxes of 6 and 12 l), respectively, under the experimental condition.

The shallow parts of stabilized soils were easily neutralized due to acid rain, but there was less influence of acid rain on the depths of the stabilized soils. The comparison between the three soils shows that the neutralization of LDGS was more significant than those of LKL and CAC.

In the eroded soils, the straelingite was decomposed, but the CaSO$_4$·2H$_2$O, CaCO$_3$ and unknown chemical crystals were found.

These changes of the chemical status of the stabilized soils caused changes in the engineering properties. Although nearly no change in the unconfined compressive strength of the LDGS was observed before the acid rains with pH levels over 3.0 were infiltrated for a flux equivalent to the precipitation of approximately 10 years, the unconfined compressive strengths sharply decreased to 1/3~1/2 of their initial values after that. The unconfined compressive strength rapidly decreased to 1/6 of its initial value when the acid rain with pH 2.0 was infiltrated for a flux equivalent to the precipitation of 5 years. The soak test indicates that the unconfined compressive strengths of the three soils decreased with soak period and with dropping the pH of acid rain, but the decreasing rates were smaller in comparison to the infiltration test.

The coefficient of permeability obtained from the samples eroded by the acid rains with pH levels over 3.0 decreased to below half after being infiltrated with 30 l.
While the acid rain with pH 2.0 flowed through the specimens, the coefficient of permeability decreased to an order of magnitude lower than its initial value.

Overall, the erosion mechanism due to acid rain appears to be caused by: 1) The leaching of the free cations which makes the alkalinity of the stabilized soils weak. 2) The release of the adsorbed and hydrated cations results in a decrease in the strength. 3) The formation of the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, CaCO$_3$ and unknown chemical substance affect the engineering properties such as permeability.

The most important result of this study was that the engineering and physico-chemical properties of the lime and cement stabilized soils would change if the soils were eroded by acid rain for a long time. The effect of acid rain on the lime and stabilized soils has, therefore, been considered to date and some countermeasures should be developed as soon as possible.

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REFERENCES


APPENDIX

The flux of acid rain is calculated based on the assumption that 1/3 of the precipitation will infiltrate below the ground surface. Since the average annual precipitation throughout the country is approximately 1800 mm, the flux of acid rain equivalent to annual precipitation can be calculated as:

$$F_{\text{lux}} = 1/3 R_{\text{ave}} \times A$$  \hspace{1cm} (1)

where $R_{\text{ave}}$ and $A$ stand for annual average precipitation and section area of specimens. Therefore,

$$F_{\text{lux}} = 1/3 \times 180 \text{ cm} \times (1800 \text{ mm}) \times 21.4 \text{ cm}^2 \times 1200 \text{ ml}$$

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