LABORATORY AND FIELD EVALUATIONS OF RECYCLED GYPSUM AS A STABILIZER AGENT IN EMBANKMENT CONSTRUCTION

ALY AHMEDI, KEIZO UGAII and TAKESHI KAMEII

ABSTRACT

Approximately 1.6 million tons of gypsum waste plasterboard are produced annually in Japan. As such, it is essential to find an alternative way to reduce the quantities of this waste material to avoid environmental problems and the high cost of disposal in landfill. This paper describes a case study focused on the use of recycled gypsum, which is derived from gypsum waste plasterboard, to improve the strength of soft clay soil for embankment construction projects taken in consideration environmental impacts. Four different recycled gypsum contents ranging from 0 to 10% was investigated. Two different types of cements—Portland and Furnace slag type B—with a content ranging from 0 to 3% was used to develop solidification for recycled gypsum and improve environmental properties. For this purpose, a series of unconfined compression tests were conducted to evaluate strength performance of treated clay. While a series of environmental tests were conducted to explore the solubility concentration of fluorine, boron, and hexavalent chromium in the untreated and treated soil specimens. Furthermore, hydrogen sulfide and pH were investigated. Results showed that compressive strength and unit weight of treated clay soil increased with the increase of recycled gypsum content. The strength obtained in the field for treated soil with recycled gypsum was found to be greater than that obtained in the laboratory. The early curing days for soil-gypsum mixture had a significant effect on strength performance compared to the later days. The additives of recycled gypsum for tested soil swiftly increased the strength. This is a vital property for improvement embankment trafficability that helps to reduce the construction time and cost. The use of recycled gypsum within the investigated limits had no adverse effect on pH value and hydrogen sulfide gas was found to be less than the standard permitted limits. As well, the solubility concentrations for fluorine, boron, and hexavalent chromium were found within the permitted standard limits in Japan. The curing time had a significant effect on the reduction the release of harmful substance elements investigated. Furnace cement type B had the potential to improve the mechanical and environmental functions for soil-gypsum mixture. It is recommended that Furnace cement type B be used as a solidification agent for soil treated with recycled gypsum because it has low cost and it is more environmentally friendly than Portland cement.

Key words: embankment, environment, gypsum waste plasterboard, recycled gypsum, soil stabilization (IGC: D10)

INTRODUCTION

Plasterboards, drywalls and wallboards are the principle wall materials used in the USA, Japan and Europe. They are made originally from gypsum sheets, which are reinforced with synthetics fibers and are covered on both sides with paper. Large quantities of gypsum waste plasterboard (approximately 1.6 million tons) are produced annually in Japan during production, construction and demolition (Ahmed et al., 2010). The disposal of gypsum waste plasterboard in landfill sites in Japan presents many challenges due to the high costs involved and restricted environmental regulations. Furthermore, gypsum waste plasterboard in landfills under certain circumstances is known to release hydrogen sulfide gasses, which potentially are harmful and cause soil contamination. It is essential to find an alternative way to use gypsum wastes instead of disposing of it in landfills to avoid such dangers as well to reduce the cost of disposal in landfill sites. The use of recycled gypsum, which is derived from gypsum waste plasterboard, in ground improvement is not widely spread over the world but has recently started in Japan. This application has many challenges due to the solubility of gypsum especially when water is introduced. Subsequently, hydrogen sulfide gas may be generated and the solubility content of fluorine may exceed the approved standard value in the Japanese environmental quality. Furthermore, the boron and hex-
avalent chromium contents may also exceed the permitted limits, and result in soil contamination and a negative effect on the surrounding environment.

In general, results obtained from laboratory investigations for the utilization of recycled gypsum in ground improvement are not adequate to evaluate the use of recycled gypsum as a stabilized material since the application of such results in the field is not an easy task especially in the case of stabilized soft clay soil. This is attributed to the following reasons; 1) the in-situ behavior of clay soil is mostly very complex due to various geological patterns for the soil in the same site, 2) the water content of the clay soil changes from time to time during the construction period due to weathering factors such as rainfall, humidity, temperature and season changes, 3) it is difficult to mix the stabilized material with clay soil because clay is usually sticky, thus in the field it is difficult to obtain homogenous and isotropic properties for the mixture of clay and stabilized agent compared to samples prepared in laboratory, 4) information about the use of recycled gypsum in ground improvement projects has not been clarified yet and the data for this issue are limited. For these reasons, it is evident that both laboratory and field investigations are essential to evaluate the incorporation of recycled gypsum as a stabilizing agent in ground improvement projects to meet the required mechanical ground function and sound environment.

The main objective of this study is to evaluate the use of recycled gypsum, which is derived from gypsum waste plasterboard, as a stabilized agent for clay soil in embankment construction taken in consideration environmental impacts. Both laboratory and field investigations were prepared to evaluate the mechanical ground function of the tested soil in terms of compressive strength as well environmental function in terms of pH, hydrogen sulfide and the solubility of harmful substances elements such as fluorine, boron, and hexavalent chromium. Field investigation involved the case for embankment construction using recycled gypsum as a stabilized material in Ota city at Gunma prefecture, Japan.

PREVIOUS WORK

The stability of soil plays an important role for infrastructure projects such as embankment, dams, retaining walls and highway. The common materials used previously in chemical or cement soil stabilization techniques are lime and Portland cement. Additionally, several studies investigated the use of different types of waste materials as stabilizing agents to improve the mechanical properties of soil. In general, utilization of waste and recycled materials in ground improvement projects has many environmental and economical benefits. It helps to reduce the huge quantities of waste materials, which have increased rapidly over the world, and cut the cost of common stabilized materials used in ground improvement. For that target, extensive research efforts have been directed to use recycled and waste materials in ground improvement applications to protect the environment and reduce the cost of ground improvement. Examples of such waste materials used to improve the strength of soil include cement kiln dust (CKD), fly ash, bottom ash, blast furnace slag, incinerated sewage sludge ash, rice husk ash, industrial waste lime, and waste plasterboard (Miller and Azad, 2000; Arora and Aydilek, 2005; Jha and Gill, 2006; Lin et al., 2007; Kamei et al., 2007; Khattab et al., 2008; Maslehuddin et al., 2008; Ahmed et al., 2008; Chen and Lin, 2009; Ahmed et al., 2009; Ugai and Ahmed, 2009; Ahmed et al., 2010; Ahmed et al., 2011). The use of recycled gypsum, which is derived from gypsum waste plasterboard, in ground improvement is limited around the world and has only it recently started in Japan. For that reason, there is very limited literature available in this area. As such, this section deals with previous studies which investigated the use of different types of waste and recycled materials including gypsum waste plasterboard in ground improvement. The earliest study investigated the use of gypsum waste plasterboard in ground improvement was conducted by Kamei et al. (2007). They used different contents of bassanite, which is derived from gypsum waste plasterboard, to improve the strength of sand and clay soils. Their results indicated that gypsum waste plasterboard had potential for use as a stabilizing agent to improve the stress-strain behavior of tested soils. Ahmed et al. (2010) conducted a series of unconfined compression, splitting tensile and capillary rise tests to examine the performance of sandy soil reinforced with gypsum waste plasterboard in conjunction with waste plastic trays. Plaster waste was used as a cementation agent to improve the compressive strength while strips of waste plastic trays were used to enhance the tensile strength of samples treated with gypsum wastes. Results indicated that both compressive and splitting strengths increased with the presence of recycled gypsum content. The increase of gypsum waste had a more significant effect on compressive strength than on the tensile strength. Chen and Lin (2009) studied the use of different contents of incinerated sewage sludge ash with cement as stabilizing agent to enhance the strength performance of soil. Their results indicated that the unconfined compressive strength of specimens treated with incinerated sewage sludge was 3 to 7 times better than identical untreated samples. They reported that incinerated sewage mixed with cement had the potential to improve geotechnical properties of tested soil. Lin et al. (2007) investigated the use of sewage sludge ash which is mixed with hydrated lime to stabilize soft cohesive sub-grade soil. The results indicated that using such waste with hydrated lime improved the geotechnical properties of cohesive soil. The effectiveness of using cement kiln dust as a stabilized agent to improve the strength of soil was investigated by Miller and Azad (2000). They found that unconfined compressive strength increased with the addition of cement kiln dust. Also, the cement kiln dust was used by Ahmed et al. (2009) to enhance the performance of weak sub-grade soil in roadway works. Their results confirmed that cement kiln dust improved the compressive strength, tensile strength, and CBR while the capilla-
ry rise time and permeability were reduced. In general, recycled gypsum, which is derived from gypsum waste plasterboard, has the potential to be used as a stabilizing agent due to its chemical compositions which helps to produce the cementation properties of soil-gypsum mixture.

MATERIALS AND METHODS

Soil Samples

Soil samples were collected from two locations in site A, which is specified for the construction of embankment located in Ota city of Gunma prefecture in Japan. Samples were taken from a depth ranged between 2 to 5 m below the original ground level and samples extracted using pit excavation method. The soil samples which taken from 2 to 3 m depth below the ground level are labeled “upper soil”, while those taken from 3 to 5 m depth below the ground level are labeled “lower soil”. The samples were transported to the laboratory in plastic bags. Both gravels and solid portions were extracted from the soil samples and then the two soil samples mixed by hand firstly with a ratio 1:1 and then stored at room temperature in plastic bags until required. The initial water content for soil sample was determined by an oven drying soil sample for 24 h at 105°C. For each tested sample, water content was determined before and after testing. Soil particle size distribution was carried out using hydrometer method in accordance with ASTM D421–58. The composition of tested soil sample were clay 41.11%, silt 36.24% and fine sand 22.65%. All the physical and mechanical properties of tested soil are listed in Table 1. Soil was classified as clay with high plasticity (CH) according to the unified soil classification system (USC), and according to the AASHTO system, it was classified as clay soil (A 7–6).

Recycled Gypsum

The recycled gypsum, which is derived from gypsum waste plasterboard, used in this project was brought from a local construction company located in Gunma prefecture. The scientific name for the produced recycled gypsum is “Bassanite” or hemi-hydrate calcium sulfate (CaSO4.1/2H2O). Procedures used to produce the recycled gypsum from gypsum waste plasterboard were provided in the previous work (Kamei et al., 2007; Ahmed et al., 2010). The dried-air gypsum waste plasterboard, which is collected from different construction sites, was crushed by crushing machine and then screened to remove any solid wastes such as synthetic fibers, paper and wood. Subsequently, the crushed gypsum (CaSO4.2H2O) was heated at a temperature of 140°C for a certain time to produce a hemi-hydrate calcium sulfate or it is called bassanite (CaSO4.1/2H2O). Particle size distribution curve for bassanite samples used in this project is shown in Fig. 1. These samples represent the recycled gypsum used in both laboratory and field investigations. The content of bassanite with regards to the whole weight of recycled gypsum was determined for two samples and the average value was found 80.50%. This percent was determined based on the chemical analysis which is used to identify compositions of the produced recycled gypsum as illustrated in Table 2. Three different contents of recycled gypsum, (B/S), of 5, 7.5 and 10% based on soil weight were investigated.

Solidification Agents

It is well-known that recycled gypsum is soluble in water and this feature is considered one of the most important negative points for the use of recycled gypsum in ground improvement. As a result, two types of cement, Portland cement and Furnace slag cement type B, were used as the solidification agents. The main reason for using a solidification agent in the soil-gypsum mixture is to prevent the solubility of recycled gypsum and develop solidification for the soil-gypsum mixture and to improve its environmental properties. For each cement type, three different contents, (C/S), of 1.50, 2.25, and 3.00%, were used based on the soil weight. It is essential to determine

Table 1. Physical and mechanical properties of tested soil

<table>
<thead>
<tr>
<th>Engineering property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit, LL, (%)</td>
<td>65.00</td>
</tr>
<tr>
<td>Plastic limit, PL, (%)</td>
<td>27.40</td>
</tr>
<tr>
<td>Plasticity index, PI, (%)</td>
<td>37.53</td>
</tr>
<tr>
<td>Specific gravity, Gs</td>
<td>2.699</td>
</tr>
<tr>
<td>Clay content (&lt;0.005 mm), (%)</td>
<td>41.11</td>
</tr>
<tr>
<td>Silt content (0.005–0.075 mm), (%)</td>
<td>36.24</td>
</tr>
<tr>
<td>Sand content (0.075–2 mm), (%)</td>
<td>22.65</td>
</tr>
<tr>
<td>pH</td>
<td>6.88</td>
</tr>
<tr>
<td>Unit weight, γ (kN/m²)</td>
<td>17.50</td>
</tr>
<tr>
<td>Initial water content, (%)</td>
<td>48.55</td>
</tr>
</tbody>
</table>

Table 2. Chemical compositions for used recycled gypsum (Bassanite)

<table>
<thead>
<tr>
<th>Composition contents (%)</th>
<th>Sample-1</th>
<th>Sample-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaSO₄</td>
<td>1.00</td>
<td>1.60</td>
</tr>
<tr>
<td>CaSO₄.1/2H₂O (Bassanite)</td>
<td>81.10</td>
<td>79.90</td>
</tr>
<tr>
<td>CaSO₄.2H₂O</td>
<td>17.20</td>
<td>14.60</td>
</tr>
</tbody>
</table>
Table 3. Chemical compositions for different cement types used

<table>
<thead>
<tr>
<th>Chemical compositions</th>
<th>Percentage (%)</th>
<th>Furnace cement-B</th>
<th>Portland cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>26.30</td>
<td>20.72</td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>8.70</td>
<td>5.37</td>
<td></td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.90</td>
<td>3.08</td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>54.10</td>
<td>64.74</td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>3.70</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>SO₃</td>
<td>2.00</td>
<td>2.07</td>
<td></td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.26</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>K₂O</td>
<td>0.42</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>R₂O</td>
<td>0.54</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>TiO</td>
<td>0.69</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>P₂O</td>
<td>0.08</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>0.28</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>0.007</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Ignition loss</td>
<td>0.80</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>Insoluble residue</td>
<td>0.20</td>
<td>**</td>
<td></td>
</tr>
</tbody>
</table>

Note: ** Not provided from the supplier

the appropriate content and type of cement needed to achieve the design strength and improve environmental properties of soil-gypsum mixture and to prevent gypsum solubility as well. Furnace cement type B is produced in Japan by mixing 30% to 60% of Blast Furnace slag with cement according to JIS R 5211 specifications, and consequently, Furnace cement is significantly cheaper than Portland cement. It is produced from waste materials and mainly considered a co-generated product of Portland cement manufacturing. The chemical compositions of the two types of cement used in this research are tabulated in Table 3. These chemical compositions were provided by the suppliers of the cement.

Experimental Investigation

The performance of clay soil stabilized with recycled gypsum and Furnace cement was evaluated based on its mechanical ground and environmental functions. To evaluate the ground mechanical function, a series of unit weight and unconfined compressive strength tests were conducted on clay soil samples stabilized with recycled gypsum. Furthermore, the effect of curing time, cement content, cement type and recycled gypsum content was investigated to study the performance of soil-gypsum mixture. Measurements of pH, H₂S and solubility concentration for fluorine (F), boron (B), and hexavalent chromium (Cr⁶⁺) were conducted to evaluate the environmental properties of clay-gypsum mixture. In laboratory investigation, clay soil samples brought from the site were used as-is except for the removal of gravels and solid portions, in order to represent the field conditions. The main reason for the removal of gravel and solid portions from clay soil samples was to avoid any enhancement in the strength due to the friction between clay fractions and solid portions. Thus, the induced enhancement in the strength of stabilized clay can be attributed only to the use of recycled gypsum and cement.

Sample Preparation

Firstly, the recycled gypsum and cement was mixed dry and then the mixture was added to the tested soil and mixed for 5 minutes using an automatic mixer to obtain, as much as possible, homogenous and isotropic properties for the mixture. The water content was determined for each sample before and after mixing process to know the effect of adding recycled gypsum on the water content. The unit weight for untreated and treated soil samples was determined by placing the sample in a cylindrical steel container with a known volume. The sample was placed in three layers and then each layer compressed with a static pressure of 33 kPa, which is equivalent to the induced stress by compactor roller machine used for compaction process in the site. Subsequently, the sample was trimmed and the weight of sample was measured. By knowing the weight of the sample and container volume, the unit weight was determined. Specimens for compressive strength were modeled using cylindrical molds, which are made from plastic to prevent the friction between soil and inner sides of the molds during extraction process. The samples were placed in the molds in three layers and then compacted statically using a surcharge load equivalent to the induced pressure (33 kPa) by a roller compactor machine used in this project. Figure 2 shows preparation arrangements for stabilized soil sample till testing. Oil was used to lubricate the inner sides of the molds to ensure no friction occurs during sample extraction. The weight of the tested soil needed to form the cylindrical stabilized soil specimen is determined based on the unit weight of the mixture of soil-gypsum-cement and volume of the mold. The soil samples were extracted from the molds after 1 hour from placing and great care was taken during the extraction process to avoid any pre-stress for the specimens before testing. Subsequently, samples were subjected to different curing times of 1, 3, 7, 14 and 28 days at temperature (21 ± 1°C) and approximate relative humidity 98% before testing.

Unconfined Compressive Strength Test

Unconfined compressive tests were conducted on pure and stabilized soil samples in accordance with ASTM D
The use of compressive strength to evaluate the performance of stabilized clay is one of the most important design parameters used in earthwork projects (Yarbasi et al., 2007). Furthermore, the design criteria used in this embankment project considered compressive strength a major factor to evaluate embankment stability. Cylindrical stabilized soil specimens 50 mm in diameter and 100 mm in height were used in unconfined compressive tests. The load was applied to the specimen with a constant strain rate of 1 mm/min and the loading process continued until failure occurred or 20% strain was achieved. Both the load and settlement were measured automatically using an LVD and load cell, respectively and then the stress-strain relationship was plotted. For each tested specimen, the tests were repeated on three identical specimens and the average of the peak stress was considered.

**pH Measurement**

In general, the pH of the soil refers to its acidity or alkalinity, and is a measure of the concentration of free hydrogen ions (H\(^+\)) in the soil solution. The pH value is considered one of the most important parameters when evaluating the quality of the ground water, especially when waste materials are introduced in earthwork projects. In addition, the pH value is essential for the continued pozzolanic activity for cement stabilization, and is responsible for promoting chemical activity between stabilized cement agent and the soil (Miller and Azad, 2000). The pH value of different soil samples (un)treated with recycled gypsum and cement was determined according to the method used in previous work (Miller and Azad, 2000). The tested soil was mixed with distilled water at a proportion of 5 to 1, the samples were periodically shaken, and then after one hour, the pH was measured using the pH-meter. The effect of curing times on the pH value of soil samples treated with recycled gypsum was investigated. For that purpose, the solution of stabilized soil sample and distillated water (5:1) was placed in a plastic container covered tightly and kept in a curing room at relative humidity 98% and temperature (21 ± 1°C). The pH was measured after curing times of 0, 3, 7, 14, 28, 56, 120 and 180 days. In the site investigation, the pH was measured at different intervals during and after construction by collecting water samples from the drainage system which had been installed in the embankment body to protect the embankment against rainfall hazards.

**H\(_2\)S Measurement**

The emission of hydrogen sulfide, H\(_2\)S, was measured using a Gastec gas sampling pump device. Actually, to obtain real values for the generation of H\(_2\)S gas at the investigate site due to the use of recycled gypsum was difficult since there has been no report of a similar nature, and therefore there is no standard method to explore the emission of H\(_2\)S in the field of ground improvement. Furthermore, it is difficult to install some specified sensors or implantation controlled system to measure H\(_2\)S emissions in such a project due to the temporary construction process and the high cost of such a measuring system. Nevertheless, the installation of controlled and measuring system for H\(_2\)S emission in landfill sites is considered acceptable because such sites are specified to deal with huge quantities of such waste on a permanent basis. Therefore, authors suggest a simple method for measuring the generation of H\(_2\)S gas due to the use of recycled gypsum in ground improvement using a Gastec gas tube device. The methodology is presented in detail herein. The samples used in the measurement of H\(_2\)S were the same samples used in the compressive strength test and were exposed to the same curing regime. After completing the process of remolding for stabilized soil samples, the tested sample was broken by hand and placed in a specified plastic air bag and then the bag was sealed with a heating-sealing machine. The other side of the bag is connected with a tube joined to a valve which controlled the volume of nitrogen gas inside the bag. The volume of tested soil used in this method was 200 cm\(^3\). The main reason for breaking the tested sample is to increase the surface area of the sample exposed to the nitrogen gas inside the bag, to speed up the release of H\(_2\)S rapidly. The procedure used to measure H\(_2\)S are as follows. (1) After placing the sample inside the bag, the air inside the bag was completely removed by vacuum after the valve was properly sealed. (2) The plastic bag was filled with nitrogen gas (N\(_2\)) a volume of 200 cm\(^3\), which is approximately the same volume of tested soil sample, and then the valve was closed. Since the volume ratio of soil to nitrogen was 1:1, a critical situation was expected to occur. (3) The plastic bag including tested sample was placed in a curing room and subjected to the same curing regime used previously in the compressive strength tests. (4) After curing, the Gastec device was connected with the plastic bag through a rubber pipe made for this purpose, and the H\(_2\)S was measured. Figure 3 shows the steps taken to measure the H\(_2\)S gases using this method.

In the in site investigation, the measurement of H\(_2\)S was done by two methods. The first method was the same
as used in laboratory except the tested sample used in testing was brought from the site during and after construction. The second method was done by excavating a 15 to 20 cm deep pit in an embankment body which had been stabilized with recycled gypsum. Subsequently, the Gastec device was connected to the bottom of the pit and then the H₂S was measured. The measurement of H₂S was done during and after construction. The main reason for using nitrogen gas instead of air in this method was to prevent the reaction between H₂S gas and the Oxygen in the air. Furthermore, the emission of hydrogen sulfide is also a product of the bacterial breakdown of organic matter in the absence of oxygen in a process called anaerobic digestion. Thus, the use of nitrogen gas instead of air activates the growth of the bacteria in the tested soil, which will help to generate H₂S more rapidly. This case represents the critical situation expected to occur at the site.

Measurement of Harmful Substances Elements

The solubility concentrations of fluorine (F), boron (B), and hexavalent chromium (Cr⁶⁺) for untreated and treated soil samples were measured to investigate the effect of using recycled gypsum on the environment. It is well-known the plaster contains fluorine and gypsum waste plasterboard in ground improvement is subjected to ground water or rainfall. Because the concentration of fluorine is expected to increase over the standard limits, a solidification agent was used to improve the environmental properties for soil-gypsum mixture. A high fluorine concentration in the water supply is a health hazard for both humans and animals. The maximum limit for fluorine concentration in tap water according to United States Public Health Service is ranging between 2.4 to 1.4 mg/L, which corresponds to a maximum daily air temperature ranging from 10°C to 32.5°C, respectively (USPHS, 1962). The Japanese environmental regulations are strict: the standard limit for fluorine dissolution are set at less than 0.80 mg/L by the soil and environmental standards in Japan (EQS). Furthermore, other chemical elements, such as boron (B) and hexavalent chromium (Cr⁶⁺), may be released when the gypsum-cement mixture is subjected to water. If the concentration of such elements is over the standard limits, the soil may be toxic to humans or animals. Therefore, it is essential to explore the effect of using recycled gypsum in ground improvement on the release of such harmful substance to ensure a sound environment.

The solubility of fluorine (F), boron (B), and hexavalent chromium (Cr⁶⁺) was measured by two methods. The first method is described in the soil contamination countermeasures law enforcement regulation in Japan and is referred to herein as “the standard method”. In this method, the tested soil sample is pulverized to provide 2 mm coarse clods of soil particles, mixed with distilled water, and then shaken for six hours using automatic shaker machine. After shaking is completed, the sample was sent for testing. More details about this method are provided in the guidelines of Environmental Quality Standard for Soil Pollution, Ministry of Environment in Japan (EQS). This method represents the critical case, from a chemical point of view, which may occur at the site, but it is impossible to apply such conditions at the site. At the site, water can be expected to flow through the embankment body due to rainfall or any other source of water. The release of harmful substances elements most likely will be due to the leaching of the soil-gypsum mixture.

A leaching tank was used in the second method used in this investigation. Though this tank was specifically designed to test the solubility of hexavalent chromium, it was used for all harmful substances elements investigated in this study. In this method, the tested soil mixed with distilled water with a ratio of 1 (solid) to 10 (water) and kept for 24 hours. After that, the solubility of the required elements was measured in the solution. More details about this method are provided in the guidelines for environmental testing measurements, Ministry of Land and Infrastructure, Japan (MLIT, 2001). Because this method simulates the real conditions in the field, it was to test all the harmful substances elements investigated. The tests were carried out in a chemical laboratory of an environmental company in Gunma prefecture, Japan. The environmental samples tested were taken from the destroyed samples of the unconfined compressive test, and these samples, which were subject to the same curing regime used in the compressive strength tests, were tested after 7, 14 and 28 days of curing. In the investigation at the site, samples were collected during and after construction and then were sent to the laboratory where the same substances elements measured in the experimental investigation were measured.

Site Investigations

Site investigations were conducted to evaluate the incorporation of recycled gypsum, which is used as a stabilized material, in embankment construction project. The site is located in Ota city, in Gunma prefecture, Japan, as shown in Fig. 4. The main objective of this project is to construct two embankments, A and B, as barriers to protect some new industrial projects in this area. The site in-
Investigation was done only on embankment A because it has weak soil compared to site B. This embankment covered an area of approximately 776 m² with a height of 2.40 m. The majority of soil type in this site is soft clay soil and the strength of soil samples through a depth 0 to 2.40 m was ranging between 10 to 42 kPa according to boring reports. The design strength for embankment foundation after 28 days is 130 kPa. Since the factor of safety with a value of two was considered necessary in this project, the strength required at the site was 260 kPa. The optimal values for both recycled gypsum and cement contents, which were obtained from laboratory results, were applied in embankment construction. The procedures of using recycled gypsum as a stabilized material in embankment construction follow. (1) A specified volume of soil was collected and then put in trapezoidal shape, as illustrated in Fig. 5. (2) The required volume of recycled gypsum and cement were determined based on the volume of soil weight. (3) The soil, recycled gypsum and cement were mixed by using a heavy machine specified for mixing in the site, as illustrated in Fig. 5 and the mixing process was prolonged for 30 minutes or more. (4) After completing the mixing process, the stabilized soil was compacted in layers using a compactor roller machine, which induced a pressure of 33 kPa. A cone penetration test was done for each compacted layer in different locations and the average value for the strength was considered. This test was done directly after the compaction process at different time intervals. Environmental tests including pH, H₂S and the measurement solubility of F, B and Cr⁶⁺ were done during and after embankment construction to compare with the results of experimental investigation.

MECHANICAL GROUND FUNCTION RESULTS

Unit Weight

Generally, in the construction of embankments, highway, earth dams and many other engineering projects, the unit weight needs to be known in advance because the strength mainly depends on the value of unit weight. Therefore, the effect of recycled gypsum content on the unit weight performance of stabilized clay soil was examined. The values of unit weight for different samples treated with recycled gypsum were plotted against the content of recycled gypsum and are presented in Fig. 6. Obviously, the increase of the content of recycled gypsum is associated with a significant increase in the unit weight for all different cement contents used. The increase of unit weight when recycled gypsum is added to the clay soil can be attributed to the tendency of the calcium component of recycled gypsum to encourage the soil particles to flocculate; thus, the soil particles become linked together. Flocculation occurred because the clay particles normally carry negative charges and attract calcium, which carries two positive charges (Ca⁺⁺). Furthermore, the recycled gypsum, which is a hemi-hydrate calcium sulphate (CaSO₄·½H₂O), can absorb water from clay soil, and was able to recover three quarters of the water which went missing during the heating process, to become hydrate calcium sulphate (CaSO₄·2H₂O) again. The absorption of water from the particles of clay soil is associated with the decrease of voids between the soil particles. As a result, the volume for the same weight of clay-gypsum mixture decreased, and the unit weight increased. The effect of the content and type of cement on the unit weight...
weight is presented in Fig. 7. The curve shows the same trend in this case as the curve for recycled gypsum. The increasing unit weight in the case of cement is slightly less than recycled gypsum. This can be attributed to the higher absorptive properties of gypsum compared to cement. In addition, the reaction between gypsum and the soil particles takes place rapidly because it takes less time for gypsum to set than cement. This figure also indicates that the type of cement has little impact on the unit weight of the clay-gypsum mixture.

**Laboratory Compressive Strength**

Unconfined compressive testing for soil-gypsum specimens is performed to determine the suitability of using recycled gypsum as a stabilizing agent for the embankment construction in Ota project. The purpose of using compressive strength data in this study are: (1) to determine if the tested soil will achieve a significant strength increase with the addition of recycled gypsum; (2) to determine the optimal content of recycled gypsum and cement needed to achieve the design strength for the embankment construction; (3) to study the effects of variables, such as the type of cement, curing time, cement content and recycled gypsum content. The ultimate compressive strength against the content of recycled gypsum for different tested samples are plotted and presented in Fig. 8. It is clear that the compressive strength increased with the increase of recycled gypsum content for the different samples tested compared to identical untreated samples. This can be explained by the hardening of the soil particles in the clay soil after the addition of recycled gypsum, resulting in an increase in the cohesion strength between the soil particles. The hardening between the soil particles and recycled gypsum is due to the following: (1) The change in the chemical composition of bassanite (hemihydrate calcium sulphate) (CaSO\(_4\cdot1/2\)H\(_2\)O) to hydrate calcium sulphate (CaSO\(_4\cdot2\)H\(_2\)O), followed by water being absorbed from the clay soil, which reduces the voids between soil particles and therefore strengthens the soil; (2) The chemical composition of hydrate calcium sulphate as oxide contains a significant amount of calcium lime (CaO) (Mineralogy Database), which has been used as a cohesive agent in soils because of its ability to increase the strength of cohesive (Bell, 1996); (3) Gypsum contains a significant amount of calcium sulfate, which, when mixed with the soil, dissolves slowly and dissociates into Ca\(^{2+}\) and SO\(_4^{2-}\) ions. The calcium (Ca\(^{2+}\)), being positively charged, becomes attracted to clay particles, which commonly have negative charges, and is not leached from soils. The attraction between the soil particles and calcium improves the bonding between the soil particles and strengthens the soil.

Figure 9 shows the effect of curing time on the improvement stress ratio for tested samples at different recycled gypsum contents used. The improvement stress ratio is defined as the ratio between the value of ultimate stress in case of samples treated with recycled gypsum and the value of ultimate strength for identical untreated samples. It is clear from this figure that the strength of stabilized soil-gypsum increased with the curing time, and this concurs with the results provided in previous work (Kamei et al., 2007; Ahmed et al., 2010). It can be stated that the curing time has a significant effect on the strength of stabilized clay-gypsum up to the first 7-days curing, and beyond that time, the effect of curing on strength is less significant. This is because the setting time for gypsum is short, and most of reactions between gypsum and the soil particles take place rapidly, so the clay-gypsum mixtures strengthen quickly. In general, this property is vital in this project for the improvement of trafficability, and it shows the compaction process can be started directly after mixing. The presence of gypsum increased the strength of clay soil rapidly, and the stabilized soil was shown to sustain a pressure of the 33 kPa induced by the compactor machine used in this project. This translates to a reduction in construction time and therefore a reduction in cost. In general, it is difficult to start compaction or open the embankment for trafficability when using stabilized soft clay soil directly after mixing even when cement is used as a stabilizing agent because some time is needed for the soil to develop the strength capable of sustaining the induced pressure by compactor machine or vehicles.

Figures 10 to 12 show the effect of the cement content on the strength of clay-gypsum mixtures at the different
Fig. 10. Effect of cement content on the compressive strength of clay treated with different recycled gypsum contents in case of curing time = 0 day

Fig. 11. Effect of cement content on the compressive strength of clay treated with different recycled gypsum contents in case of curing time = 3 days

Fig. 12. Effect of cement content on the compressive strength of clay treated with different recycled gypsum contents in case of curing time = 7 days

curing times of 0, 3 and 7 days, respectively. As expected, increasing the cement content is associated with an increase in the compressive strength. The same behavior was obtained for samples tested at the different curing times investigated. In general, the main target for the use of cement in this study is not only to increase the strength but also to prevent the solubility of gypsum and improve environmental properties for clay-gypsum mixture. From these figures, it can be noticed that the required design strength of 130 kPa was obtained with a 5% recycled gypsum content and 2.25% cement content after 3 days of curing. Therefore, the effect of the cement type was studied at a recycled gypsum content of 5%. Figures 13(a) and (b) show the effect of cement type on the compressive strength of clay-gypsum mixture at the different curing times used. The Portland cement type has a significant effect on the improvement of strength, as illustrated in Fig. 13(b), compared to the effect of Furnace cement type B as illustrated in Fig. 13(a). The difference in behavior between the two types of cement may be because of the lower strength of Furnace cement type B, which may be attributed to the use of by-product cement in its production. Even though Portland cement is considered the standard one used in construction projects, both types of cement used gave the required design strength for the embankment, as illustrated in Figs. 13(a) and (b). It is important to note that Furnace cement type B is cheaper than that of Portland cement and the required strength
was achieved with Furnace cement.

From these figures, it is clear that the effect of curing time on the strength increase of gypsum-clay mixture treated with cement is significant up to 14 days of curing. After that, the effect of curing time on the strength is not significant. It has been shown that 14 days of curing for soil-gypsum mixture treated with cement is adequate for the reaction between the soil and stabilizing agents used to be completed. The effect of curing time on the strength increases in the case of Furnace cement type B is significant for all different contents used as illustrated in Fig. 13(a). In the case of Portland cement, however, the effect of curing is significant only at the highest cement content of 3% compared to the other cement contents.

In-site Compressive Strength Results

Based on laboratory results, the content of recycled gypsum and cement needed to achieve the required strength for embankment construction were selected at 4% and 2.5%, respectively. Furnace cement type B was selected as the solidification agent. The selection for this type of cement is attributed to the fact that Furnace cement is cheaper than Portland cement and has been shown to achieve the required strength. In addition, environmental tests indicated that Furnace cement is more environmentally friendly than Portland cement, which will be discussed later. A penetration cone test was conducted to obtain the actual ultimate strength of the stabilized soil in site. For each layer, the test was repeated at least 5 to 10 times at different locations and the average value of ultimate strength was considered. Figure 14 shows the relationship between the ultimate compressive strength and the elapsed time after construction in the field and the laboratory. It is clear from this figure that the ultimate strength for stabilized soil in the field increased with time. The main reason for this phenomenon is mentioned earlier in laboratory results section which dealt with curing time. Also, the design strength for embankment of 130 kPa is obtained after 2 hours of construction and this is vital for trafficability and saving on construction time. The strength obtained in the field is greater than that obtained in the laboratory. It is attributed to the following. Firstly, those samples used in laboratory for molding the specimens for testing were brought from a particularly weak point at the site. Secondly, laboratory soil samples were brought from a depth of 5 m below the ground level and it is well-known that the water content in lower parts is higher than in the upper parts. Subsequently, a higher water content is associated with a decrease in the improvement of strength. Thirdly, gravel and solid portions were removed completely from the soil samples used in laboratory as mentioned before. The presence of gravel and solid portions in soil matrix develops friction between them and the soil particles, subsequently increasing the strength. Figure 15 shows the relationship between the field strength and number of layers. The strength was measured one hour after completing the construction of the layer. This figure indicates that the filed strength increased as the number of layers increased, most likely because the lower layers behave as a strong foundation for the coming layer and the increasing height of layers prevents the stresses from reaching the weak layer. The measured strength after one hour for different layers is more than the design strength after 28 days, as presented in Fig. 15.

ENVIRONMENTAL RESULTS

pH Data

In Fig. 16, the pH values for different contents of recycled gypsum mixed with clay soil at different cement contents used in the laboratory tests are shown. It appears that the additive of pure recycled gypsum (without cement) to clay soil has an insignificant effect on the value of pH. As aforementioned, the pH of the soil is defined as the hydrogen ion (H\(^+\)) content of the soil and thus any change for the pH of soil needs to convert the H\(^+\) into another acidic or alkaline form of H or result in the presence of minerals which can change the H\(^+\). The reaction of gypsum with soil does not change the form of soil H\(^+\) because gypsum is more soluble than alkaline earth carbonates (Smith et al., 1994), so no change in soil pH occurred due to mixing soil with gypsum. A very limited change in the value of pH for clay soil was observed when
reused gypsum was introduced. It may be attributable to the presence of some unknown chemicals or treatment used in the past to produce plasterboards. Since the measured pH values were found to be between 6 to 7, which are the neutral values acceptable in environmental regulations, the use of reused gypsum in ground improvement does not have any negative effect on the pH of soil. On the contrary, when cement was introduced to the tested soil, the pH value increased rapidly and this related to the cement is being alkaline material. For example, the pH value for the mixture of 1.5 cement, 5% gypsum and soil was 11.6, is greater than that in the mixture of 0% cement, 5% gypsum and soil by 5. The same behavior was observed in both two types of cement used. The pH value increased a little with the increase of cement content for both cement types used as illustrated in Fig. 17. The data presented in this figure is only for reused gypsum contents of 0 and 5% because the same behavior was observed with the other contents of reused gypsum used. For example, the pH value for soil sample mixed with the mixture of 3% cement and 10% gypsum was 10.93, greater than that in the mixture of 1.5% cement and 10% gypsum by 0.8, approximately. However, the increase in the pH value for other cases using different cement contents is limited, most likely because there was little difference in the difference between the cement proportions used. Generally, increasing cement content is associated with an increase in the alkalinity concentration in the mixture of soil-gypsum-cement, and that occurred in this case. The larger effect of increasing cement content on the increase of pH value in the case of Portland cement may be attributed to the difference in the chemical compositions of the two different types of cement.

The pH value of different mixtures of soil-gypsum-cement reduced with the increase in curing times, as presented in Fig. 18(a). This behavior is attributed to the saturation principle of calcium and the mechanism of cement stabilization in earthworks (Lin et al., 2007; Chen and Lin, 2009). The content of calcium in the stabilized soil reduced with time due to the progress of the stabilization process, and a decrease in the initial levels of calcium resulted in a decrease of calcium saturation (Chen and Lin, 2009). Furthermore, cement which contains Calcium Oxide (CaO) and Aluminum Oxide (Al₂O₃) reacts with gypsum to produce ettringite, which is considered the major factor for the development of solidification property. To complete this reaction, the consumption of the calcium helps to reduce the pH, ettringite is also able to lower the pH value (CA, 1985). The effect of curing time on the pH of soil samples stabilized only with reused gypsum is not significant compared with the pH values of soil-gypsum mixture treated with cement, as
presented in Fig. 18(b). This phenomenon is most likely because gypsum is not alkaline and the reaction occurred between clay particles and calcium due to the exchange of charges. In the case of additives cement, however, the reaction was due to cement hydration and alkaline properties of the cement. The pH measurements at the site were done during and after embankment construction by collecting water samples from different locations, as mentioned previously. Figure 19 shows some of the pH values measured during and after construction. In this figure, the measured pH in the laboratory after 180 days of curing was used as a reference for comparison with site data. Obviously, the pH measured on site during and after construction was smaller than that measured in the laboratory after 180 days of curing. The average values for pH in the laboratory, during construction and after construction were found to be 9.5, 8.55 and 6.61, respectively. The difference between laboratory and site data is explained by proportion of solid to water in the solution for pH measurements: in the laboratory, the proportion was 1:5, which is the standard method, while in the field, there was more water flowing through the embankment body. Subsequently, due to the leaching property and time progress the pH measured at the site was less than that measured in the laboratory, and also the pH measured after construction was less than that measured during construction due to the amount of time elapsed and leaching. Based on this data, it can be stated that the use of recycled gypsum in ground improvement does not have any adverse effect on ground water quality in term of pH value. 

H₂S Data

The measurements of H₂S gases in the laboratory for different tested samples treated with recycled gypsum and cement indicated that the level of H₂S is less than 0.01 ppm, as indicated in Fig. 20. The same result was obtained at different curing times in the on site investigation. In general, the measured H₂S was found to be less than the standard permitted range, which is ranging between 0.02 to 2 ppm, according to Japanese environmental regulations. It is evident that the use of recycled gypsum within the limits investigated in this study is safe and does not have any adverse effect on environment in term of the emission of H₂S gases. This result may be because the content of recycled gypsum used in this study was not adequate to produce large quantities of H₂S gas compared to the volume of soil mass. Furthermore, the use of cement in the soil-gypsum mixture developed solidification, which reduced the H₂S gas generating activity of the gypsum. As such, the emission of hydrogen sulfide was low.

Harmful Substance Elements

As mentioned earlier in this paper, there are three different harmful substance elements, fluorine (F), boron (B), and hexavalent chromium (Cr⁶⁺), which may be generated when the gypsum-cement mixture is introduced in ground improvement. Two types of cement, Portland and Furnace slag type B, were examined in order to ascertain how to reduce the leaching of such harmful substances and how to improve the environmental properties of soil-gypsum mixture. It should be noted that the standard limits for the presence of fluorine, boron, and hexavalent chromium in soil-water are 0.80, 1.00 and 0.05 mg/L respectively, according to the Japanese environmental regulation (EQS). Subsequently, the release of any of those elements due to the use of the suggested amounts of recycled gypsum and cement in embankment construction must be within or less than the standard limits to ensure a sound environment. Measurements of harmful substance elements were conducted on stabilized samples with 5% recycled gypsum and different contents and types of cement used. The effects of the content and type of cement on the solubility concentrations of F, B and Cr⁶⁺ after 28 days curing for soil-gypsum mixture are presented in Figs. 21 to 23. An increase in the cement content for both cement types was shown to reduce the release of fluorine, as can be seen in Fig. 21(a). For example, fluorine solubility reduced from 1 to 0.7 when the content of Furnace cement was increased from 1.5 to 3. The same behavior was observed in the case of Portland cement. The reduction of fluorine solubility when cement is introduced is because cement develops the solidification of the soil-gypsum mixture and helps to constrain the
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Fig. 21. Effect of cement content and type on fluorine solubility from leaching soil-gypsum

a) In case of standard solubility method

b) In case of leaching tank method

Fig. 22. Effect of cement content and type on boron solubility from leaching soil-gypsum mixture

Fig. 23. Effect of cement content and type on hexavalent chromium solubility from leaching soil-gypsum mixture

reactions between recycled gypsum and water, resulting in less fluorine being released with increasing cement content. Also, from this figure, it is clear that the fluorine solubility was significantly lower in Portland cement than in Furnace cement type B. This phenomenon is because Portland cement strengthens more quickly than Furnace cement (CA, 1985); that is, Portland cement can produce the required solidification for reducing the release of fluorine in a short time. A lower content of Portland cement is required than Furnace cement to get the same effect: 1.75% content of Portland cement is adequate to achieve solidification for fluorine soil contaminant and meets the standard permitted limit of fluorine (<0.8 mg/L), whereas, in the case of Furnace cement, 2.5% content is needed to achieve the same function (see Fig. 21(a)). It is important to mention that results presented herein were determined using the standard method, which is based on the crushing of the tested soil sample to determine the solubility of fluorine. As mentioned previously, this method did not represent the real conditions at the site. This method was used to explore the critical situation that may theoretically occur in the field for unknown reasons, and also because there is no standard method for determining such harmful substances in the field of ground improvement.

The leaching tank test method is the most appropriate method for representing the field conditions. The results obtained from this method are presented in Fig. 21(b). The results obtained from the leaching tank method showed the same trends and indicated the same performance as those from the standard method. The values of fluorine solubility obtained from the leaching tank method for both types of cement are smaller than those obtained from the standard method. This may be because the leaching tank method depends on the leaching of elements from the outer side of soil particles due to the flow of water through soil particles. Thus, the fluorine solubility measured in this method is only the effect of the Fluoride film over the outer surface area of soil particles, whereas the effect of the fluorine inside and outside the soil particles was established in the standard method since the soil was crushed and shaken before testing. The solubility of fluorine for original soil without any additives was found to be 0.52 mg/L. Thus, results obtained from the standard method were higher than results obtained from leaching tank method because of the presence of fluorine in the composition of original soil. In general, 2.5% content of Furnace cement type B is recommended for use as a solidification agent to prevent fluorine soil contamination. Even though Portland cement gave results better than Furnace cement, Furnace cement is recommended for use as a solidification agent for the following reasons. Firstly, the cost of Furnace cement is
lower than the cost of Portland cement. The second reason is that Portland cement has some negative effects on the environment when it is introduced in ground improvement in terms of pH in the early ages, and also the release of hexavalent chromium, as will be presented later. Thirdly, Furnace cement is considered as a by-product of Portland cement waste produced by the manufacturing of cement.

The increase of Furnace cement content was shown not to have any adverse effect on the solubility of boron or hexavalent chromium, as can be in Figs. 22 and 23. The measurement values for the two substances elements were null and this meets the environmental regulation. In the case of Portland cement, an increase in the content is associated with the increase of boron and hexavalent chromium solubility. The highest value for boron solubility was found to be 0.1 mg/L, which is lower than the standard permitted limit of 1 mg/L. The highest value for hexavalent chromium in this case was found to be 0.05 mg/L at a cement content of 2.25%. Since this value did not meet the environmental regulations, which require less than 0.05 mg/L, Portland cement is not recommended for use from an environmental perspective.

The effect of curing time on the solubility of F, B and Cr\(^{+6}\) obtained from leaching soil-gypsum mixture treated with different types and contents of cement are examined. For this purpose, the three different curing times of 7, 14 and 28 days were used. Some of these results are presented in Fig. 24 to 26 which are corresponding to the fluoride, boron and hexavalent chromium solubility, respectively. In general, an increase in the curing time reduced the release of F, B and Cr\(^{+6}\) and the same behavior was observed for the different cases investigated. For example, fluoride solubility was reduced from 1.2 to 0.7 in case of Furnace cement when the curing time was extended from 7 to 28 days. The reduction of fluoride solubility with increasing curing time is most likely because as the reaction between cement and gypsum progresses, an insoluble fluoride is produced due to the solidification property of cement and also because the ability of the soil-gypsum mixture to release the fluoride declines as the curing time progresses. The same behavior occurred with both boron and chromium. A highly alkaline environment is needed to promote the solubility of hexavalent chromium, but the alkalinity of the cement-gypsum mixture decreased with increasing curing time, and therefore, an increased curing time helps to reduce the solubility of hexavalent chromium.

To sum up, the negative point for using recycled gypsum in ground improvements is the release of fluoride, whereas the problem is the release of hexavalent chromium when using cement. Thus, the suggested proportions of the design mix need to be decided upon after taking the environmental impact, as well as the strength, into consideration. The recommended proportions for the design mix are 4% recycled gypsum and 2.5% Furnace cement type B, which meet the required strength. Figure 27 shows the measured values of fluoride solubility for the design mix in both experimental and site investigations.

In the site investigation, these values were measured both during and after construction. Measurements during and after construction were found to be less than those that obtained in the laboratory, but the results both in the laboratory and from the on-site investigation are less than the standard limits of 0.8 mg/L. Neither boron nor hexavalent chromium were found in on-site measurements during or after construction. The content of 4% recycled...
CONCLUSIONS

The main contribution of this work was to show the potential application of recycled gypsum (Bassanite), which is derived from gypsum waste plasterboard, in embankment constructions. The effect of recycled gypsum on the strength of clay soil, taking into consideration the environmental impact, was evaluated based on experimental and on-site investigations. The use of recycled gypsum in embankment construction mainly comprised of clay soil, significantly improved its stability and did not show any adverse effect on the environment within the investigated ranges. Based on the results obtained from experimental and site investigations, the following conclusions can be drawn:

1. The treatment of clay soil with recycled gypsum significantly improves its unit weight and strength performance. Both the unit weight and compressive strength of clay-gypsum mixture increased with the increase of recycled gypsum content. The soil-gypsum mixture exhibited brittle behavior during unconfined compression and the strain failure decreased with the addition of recycled gypsum.

2. The addition of recycled gypsum rapidly increases the unconfined compressive strength after the compaction process and this is a vital property for improvement embankment trafficability and reducing both the time and cost of construction.

3. The type of cement has no significant effect on the increasing unit weight for the gypsum-soil mixture. Portland cement is better in terms of improving the strength of soil-gypsum mixture than Furnace cement type B.

4. The amount of curing time has a significant effect on the strength of clay-gypsum mixture in the early stage up to 7 days; however, beyond that, the effect of curing time is insignificant. While in the case of soil-gypsum mixture treated with cement, the curing time is significant up to 14 days; after that, the effect of curing time declines.

5. The strength measured at the site was found to be higher than that measured in the laboratory. Site strength increased with increasing layers. The site strength measured after 2 hours was found to be higher than the design strength for the embankment after 28 days curing time.

6. The leachate of recycled gypsum does not have any adverse effect on the pH; the average for the measured value was found to be neutral. However, the pH increased when cement was introduced to soil-gypsum mixture; in this case, the pH increases slightly with the increase of cement content.

7. The pH of soil-gypsum-cement mixture decreased with the increase in curing time. The pH measured at the site during and after construction was found to be less than that measured in the laboratory.

8. The emission of hydrogen sulfide gases (H₂S) due to the utilization of recycled gypsum in ground improvement was found to be less than 0.01 ppm in both laboratory and at the site. This confirms that using recycled gypsum in earthworks, within the investigated ranges in this study, is safe against H₂S hazards.

9. The presence of cement in the soil-gypsum mixture develops the solidification and reduces the release of the harmful substances; increased cement content reduces the release of fluorine (F). The increase of Furnace cement does not have any adverse effect on the environment, while the increase of Portland cement increased the solubility of hexavalent chromium and boron. Furnace cement with a content of 2.5% or more was shown to be adequate for the solidification of the soil-gypsum mixture and also was shown to be more environmentally friendly than Portland cement.

10. The increase of curing time of soil-gypsum-cement mixtures has a significant effect on the release of harmful substances elements. The suggested contents of recycled gypsum 4% and Furnace cement 2.5%, which were applied in the embankment construction studied in this site investigation, achieved the design strength and met sound environmental guidelines.

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