Electrokinetics: Engineering Applications and Recent Development

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ABSTRACT. Electrokinetics (EK) is the general term used to describe responses of soil water systems to the application of an external electric field, which includes three predominant components, i.e. electro-osmosis, electrophoresis and electrochemical reactions. Electro-osmosis generates water flow in soil mass, electrophoresis induces movement of soil solids and electrochemical reactions lead to emission of oxygen and hydrogen gases, corrosion of anodes, and pH gradients in soil. Although electrokinetics has been studied over more than a century, the recent advances of anode technology have made electrokinetics a viable tool in geo-engineering. The applications of electrokinetics in geotechnical engineering and recent development of electrical vertical drains are reviewed in this paper. It is demonstrated that with solid understanding to principles, sound engineering design and proper implementation and execution, electrokinetics can provide viable solutions for challenges facing today's geotechnical engineers.

INTRODUCTION

When a direct current (DC) voltage is applied to soil via conductive electrode poles (Fig.1), the soil pore water is attracted towards the direction of the negative terminal (cathode) (known as electro-osmosis). In the meantime, fine soil particles with negative surface charges, have a tendency to move towards the anode (known as electrophoresis). If drainage is provided at the cathode and prohibited at the anode, the soil will be consolidated, resulting in reduced soil water content and compressibility and increased shear strength. In addition, electrochemical reactions associated with an electro-osmotic process alter the physical and chemical properties of the soil and lead to a further increase in the soil shear strength (Mitchell 1993). A two-dimensional electro-osmotic consolidation model was developed by Shang (1998) that can take the effects of both preloading and electro-osmotic consolidation into account. The electro-osmotic permeability, k_e, governs the rate of soil pore water flow under an electrical potential gradient. When both the anode and cathode are open to drainage and the hydraulic gradient is set to zero, k_e can be measured through the flow velocity across a soil plug (Mitchell 1993)

$$q_e = k_e E \qquad (1)$$

where q_e = water flow vector due to an electrical gradient (m/s); E = electric field intensity vector, defined as

$$E = -\nabla U \tag{2}$$

The power consumption per cubic meter of soil mass per hour is calculated from:

$$p = \kappa E^2 \tag{3}$$

where p = unit power consumption (kW /m^3) and κ = electrical conductivity of the soil (1/Ωm).

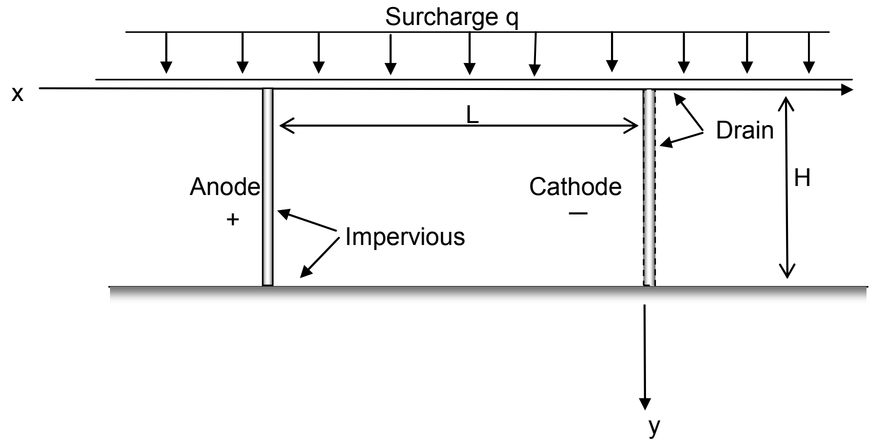


FIG. 1. Schematic of electro-osmotic consolidation (modified from Shang 1998).

Table 1 summarizes the typical ranges of soil and electrical properties that are suitable and have been used for electroosmotic consolidation.

Table 1. Design parameters and common soil properties in electro-osmotic consolidation.

Parameter	Unit	Typical Range
k_h, Hydraulic Conductivity	m/s	10^{-10}-10^{-8}
k_e, Electroosmotic Permeability	m^2/sV	~ 10^{-9}
κ, Electrical Conductivity of Soil	simens/m (1/Ωm)	0.01-0.5
E, Electric Field Intensity	V/m	20-100
c_v, Coefficient of Consolidation	m^2/s	10^{-8}-10^{-7}
P, Hourly Power Consumption	kWh/m^3	0.01-1

The most predominant electrochemical effects during an electrokinetic process include the development of a pH gradient, the generation of gases and heating. The pH of soil water will increase rapidly to as high as 11or 12 at the cathode and decrease to almost two at the anode. Consequently, metallic anodes will corrode. Oxygen gas is generated at the anode and hydrogen gas at the cathode due to hydrolytic reactions. The electrical current also generates heating, which should be controlled to reduce energy consumption.

EARLY APPLICATIONS - CASE STUDIES

Casagrande (1949, 1959) first applied the electrokinetics to strengthen and stabilize soft silty clays in the mid 1930s. Since then, successful field tests have been reported that using EK techniques to strengthen soft clays and silts and to stabilize earth slopes and dams (e.g. Bjerrum et al. 1967; Casagrande 1983; Lo et al. 1991). In this paper, two well documented case studies are presented to illustrate application of electrokinetic stabilization of soils.

Electro-Osmotic Stabilization of West Branch Dam (Fetzer 1967). West Branch Dam is a compacted earth dam located on Mahoning River in Northeastern Ohio, USA. The dam is 3000 m long and 24 m high, built on 25 m thick glacial deposits. Table 2 summarizes the soil properties. The construction of the dam commenced in May 1963. When the fill was raised from El. 999 ft (El. 305 m) to El. 1007 ft (El. 307 m), cracks occurred in the central body of the dam with a maximum opening of about 2.5 cm, caused by settlement of the foundation soil. The construction had to be stopped to allow for consolidation of the fill. However it was found that one year after the construction stopped, the excess pore pressures underneath the dam was still not completely dissipated because of the low hydraulic conductivity of the clay deposit. After comparing several alternatives, electroosmotic stabilization was selected as the best approach to stabilize the dam.

Table 2. Geotechnical properties of the soft silty clay (modified from Fetzer, 1967).

Parameter	Unit	Typical Range
w, Natural water content	%	21 - 40
w_L, Liquid limit	%	32 - 40
I_p, Plastic index	%	9 - 28
s_u, Undrained shear strength	kPa	21 - 54
γ_d, Dry unit weight	kN/m^3	14.5 - 15.1

The feasibility of electroosmotic stabilization was investigated by L. Casagrande. The electroosmotic conductivity, k_e, ranged from 3.0 x 10^{-5} cm/s to 6.2 x 10^{-5} cm/s based on an applied voltage gradient of 100 Volt/m. The electrodes layout consisted of three strips of anodes and cathodes over an area of 300 m^2. An 8-row strip at 6-m spacing was installed along the dam axis and a 6-row strip at 6-m spacing was installed at the outside edge of each berm. Total 660 anodes and 320 cathodes were installed. The anodes were made of 6.5 cm diameter double extra-strength black steel pipes with a plug in the tip. Steel railroad rails were used in the vicinity of the conduit as cathodes. The cathode electrodes consisted of a 5-cm diameter steel pipe. The schematic section of the installation is shown in Fig. 2. The anodes and cathodes were installed through 40 cm diameter drilled holes. To reduce the artesian pressure in the lower sand layer, the cathodes on the berms were installed into the sand layer. Before the dam was impounded, the upstream cathodes were sealed. The downstream cathodes were left opened to relieve artesian pressure in the lower silty sand. Two 300 kW, ten 200 kW, and two 90 kW generators were used, with capacities of 11000 amps at 150 V, 2500 amps at 140 V and 950 amps at 60 V, respectively. Significant reduction in piezometic levels took place during the treatment. The average settlement rate was 43 mm per month. A factor of safety 1.16 was achieved for the total-stress analysis. In the effective stress analysis, assuming the friction angle of 18°, the factor of safety was 1.56, which met the design criterion.

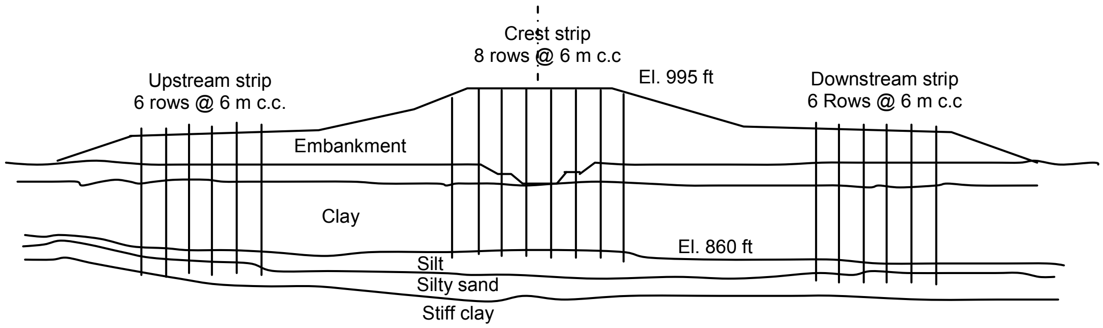
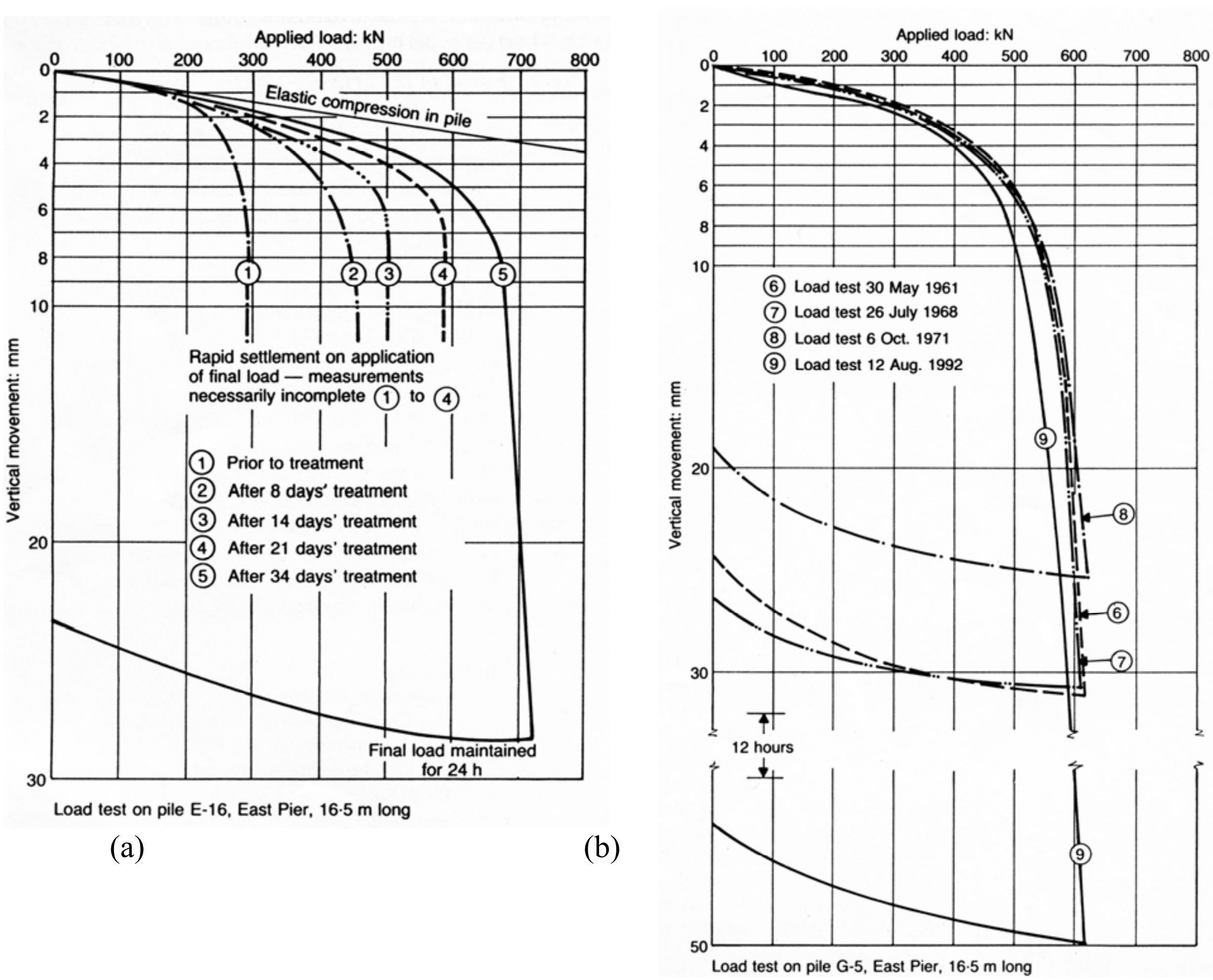


FIG. 2. Section through electrodes (modified from Fetzer, 1967).

First Application of Electro-osmosis to improve friction pile capacity (Soderman and Milligan 1961; Milligan 1995). Big Pic River Bridge is on the Trans-Canada Highway going round the north shore of Lake Superior. This bridge consists of three-span steel truss, over 180 m in length, supported by friction pile foundations. Valleys in this area are overburdened by very thick silts and clays. The standard penetration resistance (N value) decreased with depth from depths of 20 m to 50 m. Artesian pressure was observed at a depth of 50 m. At a depth of 80m, the pressure head rose up to 6 m above ground surface, and the SPT test N-value became zero. Pile loading tests were carried out on steel H-section piles (300 x 300 mm) at depths from 16.5 m to 50.5 m. With the artesian pressure, the ultimate bearing capacity of the pile was only 350 kN and reduced with pile penetration depths. Electrokinetic stabilization was conducted using two 16.5 m long piles, which was used as anodes. The average distance between the pile and cathodes was 7 m. Three diesel generators with an output of 70-120 V and 600-1000 amps per unit were used. The treatment period was 1060 hours (44 days). With a voltage of 115 V, the pile with an original ultimate load of 260 kN had increased up to 500 kN after three hours. The pile loading test results during treatment are shown in Fig. 3(a). The ultimate load increased from 300 kN prior to treatment to over 600 kN after 34 days of treatment, whereas no obvious trend in increases in soil shear strength and decreases in soil water content were observed. The long-term performance of the piles was monitored over a period of three decades, i.e., from 1960-1992. The results of pile loading tests are presented in Fig. 3(b). No reduction in ultimate capacity over 31 years was detected, and the settlement was within acceptable limits. This case demonstrates that the effects of electrokinetics are not limited to electro-osmotic consolidation. The primary mechanisms of the pile bearing capacity increase are likely electrophoresis, which enhanced bonding between steel piles and soil solids, and electrochemical reactions, which generated soil /pile cementation.

RECENT DEVELOPMENT

Recent development on electrokinetics in engineering applications includes electrical vertical drains (EVD) (Chew et al. 2004). Traditionally electrodes used in electro-kinetic treatment are made of steel, aluminum and copper. These metallic electrodes corrode rapidly during treatment, which is of environmental concern. Electrical vertical drains (EVD) are similar to prefabricated vertical drains (PVD) except that they have an electrically conductive core serving as electrodes, as shown in Fig. 4. The core is made of a copper foil encapsulated in a conductive polymer, which is wrapped by non-woven textile as a filter. An advantage of EVDs is that the conductive core is made of carbon polymer, which will not release metals to soil-water systems when decomposed.



(a) (b)

FIG. 3. Pile load test results (Milligan 1995) (a) during EK treatment (b) after EK treatment.

Studies have shown that EVDs can handle voltage gradients as high as 130 V/m over a period of about 15 days (Shang et al. 2009). Another advantage of EVDs is that they can be readily installed in a similar way as for PVDs. A field trial using EVD for electrokinetic treatment was carried out in a project of upgrading an access road to an oil terminal in Kuching, Sarawak, Malaysia (Rittirong et al. 2008). The proposed road structure consists of 1 m high embankment fill with approximately 0.5 m thick pavement. The soil on the site is of very soft to soft, light to dark grey, high plasticity silt (MH) with traces of fine sand up to 15 m depth. The void ratio and the compression index were about 0.8 and 0.5, respectively. The soil electrical conductivity is approximately 0.25 S/m. The groundwater table existed at near surface level. The undisturbed vane shear strength of the original soil ranged from 5 kPa at 2 m depth to 13 kPa at 6 m depth. The water content was 60% at a depth 2 m, which is higher than the liquid limit, and further increased with depth. It is estimated that the shear strength of the soil must be increased to 20 kPa to carry the design load. The treatment area was approximately 560 m × 4 m on each side of the existing road. The schematic diagram and the photograph of the test setup are shown in Figure 5. Three rows of EVD were installed in the treated area with distances between the rows, L_e, of 1.4 m, and the spacing between EVDs in the same row, S_e, of 1.0 m. Electric cables were connected to the copper foil inside the EVDs. The distance of the EVDs in the same row was less than the distance between the EVD rows to provide uniform electric field in the soil. The discharged water and gas bubbles were observed at the cathode within half an hour after the application of the electric current and stopped after one day. The flow was induced again by reversing the polarity of current in the second day. The water flow stopped after 3 days and the treatment was terminated at the end of day 5. Field vane shear tests were carried out at five locations over the entire treatment area after the completion of the electrokinetic treatment. Figure 6 shows the shear strength profile of treated soil compared to the original shear strength profile. The original undrained shear strength of the soil increases linearly with depth from 5 kPa to 13 kPa from depths of 2 m to 6 m. The shear strengths of the treated soil range from 15 kPa to 50 kPa. The average shear strength increased from 22 kPa to 39 kPa after only five days of treatment. Since the water flow stopped within two days of treatment, it was concluded that electrochemical reactions induced cementation may have contributed significantly to the strength gain.

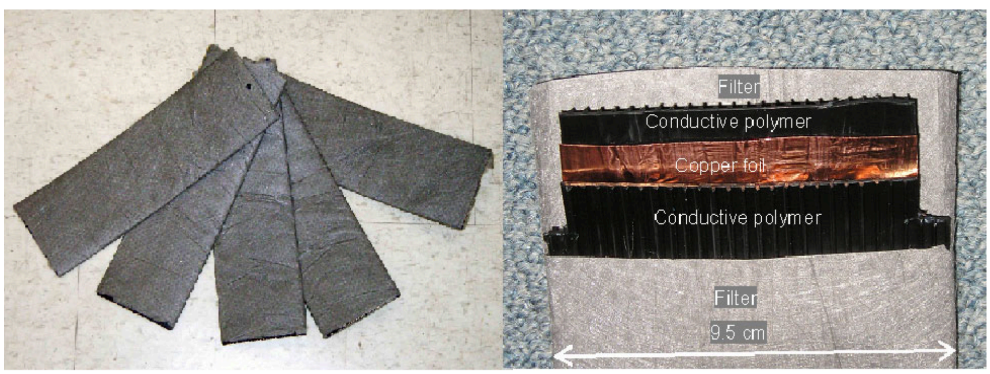


FIG. 4. Electrical vertical drains (EVDs).

CONCLUSION

The principles and case studies are presented to demonstrate that the electrokinetic treatment is a vital stabilization technique for soft clays and silts. It may be applied for stabilization and strengthening earth dams, embankments, foundations and slopes. The eletrokinetic process induces changes in physical and chemical properties of soil, in addition to consolidation. The efficiency of treatment can be improved by proper design of electrodes and operation control. Electrical vertical drains (EVD) have shown to be promising in increasing the soil shear strength within a relatively short time period.

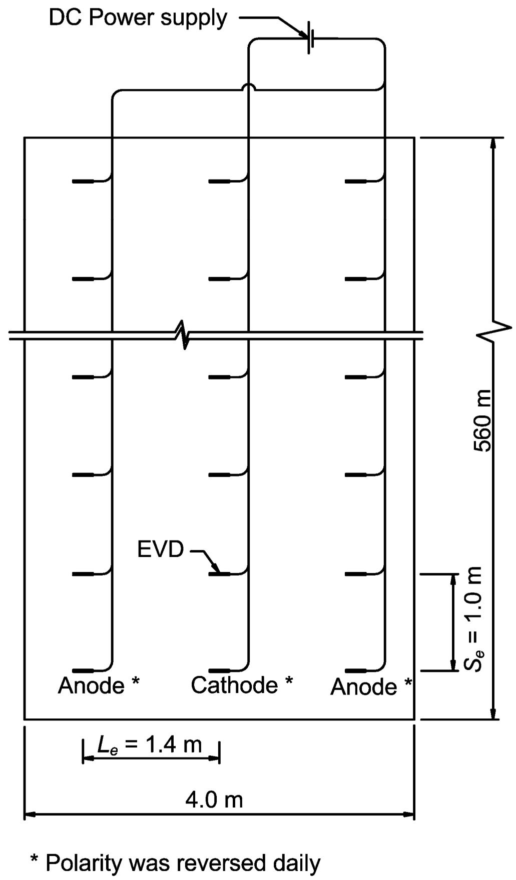


FIG. 5. Schematic of EVD Layout.

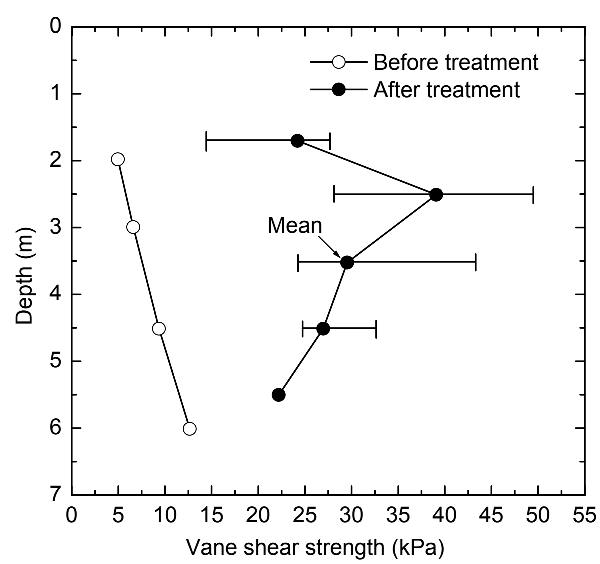


FIG. 6. Vane shear test results before and after EK treatment.

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Environmental Evaluation for Clayey Soil Stabilized with Gypsum Waste Plasterboard in Japan

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ABSTRACT: This paper presents results of a preliminary investigation of utilizing recycled gypsum derived from gypsum waste plasterboard to improve the strength of clayey soil for embankment construction, while considering environmental impacts. A case study was conducted to investigate different recycled gypsum content percentages, cement types, and cement content percentages. Four different recycled gypsum content percentages range from 0 to 10% were investigated. In this case study, cement was added to develop solidification for recycled gypsum and to improve environmental properties. Two different types of cements, the Portland and Furnace slag type B with a content range from 0 to 3% were used. A series of unconfined compression tests were conducted to evaluate the strength of treated clay. In addition, a series of environmental tests were conducted to explore the solubility concentration of Fluorine, Boron, and Chromium in the untreated and treated clay specimens. Furthermore, hydrogen sulfide and pH were investigated. Results showed that compressive strength of treated clay increased with the increase of recycled gypsum content. The use of recycled gypsum within the investigated limits has no adverse effect on pH value. The hydrogen sulfide gas is less than the standard permitted limits. The solubility of Fluorine, Boron, and Chromium leached from soil-gypsum mixture within the investigated limits were found less than the approved standard values.

INTRODUCTION

Approximately 1.6 million tons/year of gypsum waste plasterboard are produced during production, construction and demolition in Japan (Kamei, 2007). Disposing of gypsum waste plasterboard in landfill sites is expensive and has many challenges due to restricted environmental regulations in Japan. Furthermore, gypsum waste plasterboard in landfills under certain circumstances is known to produce hydrogen sulfide gasses, which potentially is harmful and cause soil contamination. Thus, an alternative way to get rid of gypsum wastes is required to avoid such dangerous situation as well as to reduce the cost of disposing in landfill sites. The application of recycled gypsum in ground improvement has many challenges as well due to the water solubility for gypsum. Subsequently, the hydrogen sulfide gasses may generate and the solubility content of Fluorine may exceed the approved standard value in the Japanese environmental quality (Kamei and Horai, 2008). Furthermore, the contents of Boron and Chromium may also exceed the permitted limits subsequently causing soil contaminations and problems on surrounding environment. Both laboratory and field investigations are essential to evaluate the use of recycled gypsum as a stabilizing agent in ground improvement to meet the required strength and environmental regulations.

The main objective of this study is to evaluate the use of recycled gypsum derived from gypsum waste plasterboard as a stabilized agent for clayey soil in embankment construction, while considering environmental impacts. Both laboratory and field investigations were conducted to evaluate strength performance and environmental impacts in terms of pH and hydrogen sulfide. In addition, the solubility of harmful substances elements such as Fluorine, Boron, and Chromium were considered. Embankment construction using recycled gypsum as a stabilized material was constructed in Ohta city at Gunma prefecture, Japan.

BACKGROUND

Several studies investigated the utilization of different types of waste and recycled materials as stabilizing agents to improve the soil mechanical properties. In general, the utilization of waste and recycled materials in ground improvement projects has many environmental and economical benefits. It helps to reduce the quantities of waste materials and the cost of stabilized materials used in ground improvement. Examples of such waste materials include: cement kiln dust; fly ash; bottom ash; blast furnace slag; incinerated sewage sludge ash; and waste plasterboard (Miller and Azad, 2000; Arora and Aydilek, 2005; Lin et al., 2007; Kamei et al., 2007; Chen and Lin, 2009; Ahmed et al., 2009; Ahmed et al., 2010; Ahmed et al., 2011). Few studies have been directed to the use of recycled gypsum in civil engineering applications (Kamei et al., 2007; Ahmed et al., 2010; Ahmed et al., 2011). 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 recycled gypsum derived from gypsum waste plasterboard, to improve the strength of sand and clay soils. Results indicated that, gypsum waste plasterboard had a potential to use as a stabilizing agent to improve the stress-strain behavior of tested soils. Laboratory and field investigations were conducted to develop effective novel cementation mixes using recycled gypsum for road foundation construction. A series of laboratory trials were carried out to determine the optimum proportions of recycled gypsum wastes used as a binder paste in order to achieve a higher compressive strength. Results indicated that recycled gypsum can be used in low-strength concrete mixes for the foundations of minor roads and car parking lot (WRAP, 2007). A series of unconfined compression and splitting tensile tests were conducted to examine the performance of sandy soil stabilized by gypsum waste plasterboard in conjunction with waste plastic trays (Ahmed et al., 2011). Plaster wastes were used as a cementation agent to improve the