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The Variation of Density and Settlement for Contaminated Sediments During Electrokinetic Sedimentation and Remediation Processes

오염퇴적토에 대한 동전기적 침전 및 정화 공정에서의 시료 밀도 및 침하 변화 특성

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요지

본 논문에서는 유기물질로 오염된 퇴적토에서 동전기 침전 및 정화 기법을 이용하여 초연약한 퇴적토의 침하를 촉진시켜 밀도를 증진시키는 연구를 수행하였다. 본 논문에서는 인체에 무해한 에틸렌글리콜 유기물질을 일반수와 적정하게 섞은 오염수에 카오리나이트 점토를 혼합하여 함수비가 높은 슬러리 상태를 조성하여 만든 오염된 퇴적토를 시료로 사용하였다. 일반적으로 동전기기법을 이용한 전기영동 및 전기삼투에 의하여 슬러리내의 고형물 입자를 음극으로 이동시키고 간극수를 양극으로 배제시킬 수 있는 것으로 보고되고 있다. 본 연구에서는 오염된 퇴적토에 대하여 고형물함량, 공급전압 및 오염농도를 변화시키면서 동전기침전 및 동전기정화 시험을 연속적으로 동시에 수행하였으며 동전기침전 및 동전기정화 공정에서 발생한 시료의 침하 및 밀도 변화에 대하여 살펴보았다. 시험결과 오염퇴적토의 침하량은 공급전압이 클수록 고형물함량 및 오염농도가 작을수록 증가하는 것으로 나타났다. 그리고 오염퇴적토의 밀도는 동전기 침전단계에서는 시료의 침하에 의하여 증가하고 동전기 정화단계에서는 물보다 무거운 유기물질의 유출에 의하여 감소하는 것으로 나타났다.

Abstract

Generally, the sediments contain significant water, clay, colloidal fraction and contaminants, and can result in soft strata with high initial void, and its potential hazards in subsurface environments exist. Electrokinetic technique has been used in sedimentation for volume reduction of slurry tailing wastes and in remediation for extraction of contaminants from contaminated soils. In this research, the coupled effects of sedimentation and remediation of contaminated sediments are focused using electrokinetic sedimentation and remediation techniques from experimental aspects. A series of laboratory experiments including variable conditions such as initial solid content of the specimen, concentration level of the contaminant, and magnitude of applied voltage are performed with the contaminated sediment specimens mixed with ethylene glycol. Commercially available high specification Kaolin was used to simulate slurried sediment. From the test results, the settlement of specimen increases with increasing of applied voltage and decreasing of solid content and contamination level. The density of specimen increases due to settlement of specimen in the process of electrokinetic sedimentation and decreases due to extraction of organic contaminant in the process of electrokinetic remediation.

Keywords : Contaminant, Electrokinetics, Sediment, Sedimentation, Remediation

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1. Introduction

By the growth in industrialization and population all over the world, the quantity of sediments such as mineral wastes, mining wastes, industrial sludges, and dredging wastes is increasing significantly. If these sediments are to be contained in impoundment and landfill, they are usually placed hydraulically as slurry by open dumping. Design and management problems are associated with these impoundment and landfill include storage capacity, densification of filling materials, embankment stability, migration of contaminated pore fluid, and final land use. The significant clay, colloidal fraction and contaminants are contained in these sediments. This small sized fraction can result in soft strata with high initial void, and its potential hazards in subsurface environments are existing. In these cases, it is needed to sediment the slurry-typed waste for volume reduction and to remediate the contaminated waste for pollutant extraction (Acar et al., 1992, 1993; Buckland et al, 2000; Hamnet, 1980; Gularte, 1973; Yakawa et al, 1970).

In sedimentation at mining applications as a volume reduction for slurry tailing wastes and in remediation for environmental application as a potential in-situ remediation method for contaminated soils and wastes, the electrokinetic technique has been used (Shang, 1996a, 1996b). Thus electrokinetic technique can be used in sedimentation and remediation of sediments (Chung et al., 2000a, 2000b). In this research, the coupled effects of sedimentation and densification of contaminated sediments are focused using electrokinetic sedimentation and remediation techniques. Electrokinetic sedimentation and densification are discussed from experimental aspects.

Laboratory electrokinetic model tests including variable conditions such as initial solid content of the specimen, concentration level of the contaminant, and magnitude of applied voltage are performed with the contaminated sediment specimens mixed with ethylene glycol. Commercially available high specification Kaolin was used to simulate sediment. The electrokinetic experimental apparatus consisted of electrokinetic sedimentation and remediation units with direct current power supply. Investigated parameters in experiments are densities and settlements of the slurry specimen. This project has used an X-ray system to produce a continuous profile of density throughout slurry-type soil samples, allowing the effect of contaminant flow to be monitored. From the test results, a significant investigation is derived for the mechanisms associated with sediments contaminated with organic substance in which simultaneous sedimentation and remediation processes are involved by electrokinetics. The coupled effects of sedimentation and densification of slurry soil are analysed.

2. Experiments

2.1 Materials

The Speswhite Kaolin produced in United Kingdom admixed with organic substance was used to simulate contaminated sediments. Tables 1 contain the physical and chemical properties of Kaolin used in this experiment. The index properties of Speswhite Kaolin are specific gravity 2.61, liquid limit 62~69%, plastic limit 32~38%, and the percent finer than 2μ is 82%. The organic matter content is 13.14%. The mineralogical composition is as

Table 1. Engineering properties of Speswhite Kaolin

Items	Descriptions and Values
Type	Speswhite fine china clay
Visual appearance	White and floury when dry
Unified classification	CH-inorganic clay of high plasticity
Plasticity index	30~31 (%)
Plastic limit	32~38 (%)
Liquid limit	62~69 (%)
Specific gravity	2.61
Clay fraction	82 (%)
SiO_2	46.2 (%)
Al_2O_3	38.7 (%)
Fe_2O_3	0.56 (%)
CaO	0.2 (%)
MgO	0.2 (%)
K_2O	1.01 (%)
Na_2O	0.07 (%)
TiO_2	0.09 (%)
Loss on ignition	13.14 (%)

follows: SiO_2 46.2%, Al_2O_3 38.7%, Fe_2O_3 0.56%, etc.

The waste slurry in this study is artificially contaminated with organic substance of ethylene glycol ($C_2H_6O_2$). Ethylene glycol was used as representative of organic contaminant. Ethylene glycol is a colorless, and odorless liquid completely miscible with water and many organic liquids.

2.2 Testing Programs

Eleven tests were conducted by using one-dimensional electrokinetic test apparatus for sedimentation and remediation of contaminated waste slurries. Test parameters such as initial solid content in slurry, concentration level of the contaminant, and magnitude of applied voltage were chosen in these experiments. Eleven tests were named from EK1 to EK10, and GR, respectively. These tests can be divided into three groups: (1) tests EK1-EK4 for the effect of initial solid content, conducted under the same applied electric field intensity of 300 V/m and the same concentration level of 25% of ethylene glycol; (2) tests EK2 and EK5-EK8 for the effect of concentration level in specimen, conducted under the same applied electric field intensity of 300 V/m and the same initial solid content of 25% mass/mass; (3) tests EK2, EK9, EK10 and GR for the effect of applied electric field intensity, conducted under the same initial solid content of 25% mass/mass and the same of concentration level of 25% of ethylene glycol. Test GR was control test by gravitational sedimentation not applying electric field intensity.

The electric power is supplied by constant voltage conditions. The initial solid contents were 15, 25, 40 and 50% with ratio of weight of the dried Kaolin to liquid, the applied voltage used in this test were 0, 10, 20 and 30V, and the contamination level were 15, 25, 40 and 50% with ratio of weight of ethylene glycol to deionized deaired water (DDW) in the void of specimen.

Investigated were the variations of density and the change of settlement with the variation of each parameter. The electrokinetic experiments are summarized in Table 2.

2.3 Testing Methods

Figures 1 and 2 show a schematic diagram and photography of the electrokinetic sedimentation and remediation system. This system mainly consisted of electrokinetic cell and power supply. The electrokinetic cell was a cylindrical tube with 100 mm in length and 100 mm in diameter.

Table 2. Test summary for electrokinetic sedimentation and remediation

Test name	Specimen condition		Power supply		Testing period (hr)	Applied technique
	Initial Solid content (%)	Contamination level (%)	Applied voltage (V)	Electrode Position		
EK1	15	25	30	U(−), L(+)	24	EK Sedimentation
EK2	25	25	30	U(−), L(+)	24 44	EK Sedimentation
EK3	40	25	30	U(−), L(+)	24	EK Sedimentation
EK4	50	25	30	U(−), L(+)	24	EK Sedimentation
EK5	25	0	30	U(−), L(+)	24	EK Sedimentation
EK6	25	50	30	U(−), L(+)	24 55	EK Sedimentation
EK7	25	75	30	U(−), L(+)	42	EK Sedimentation
EK8	25	100	30	U(−), L(+)	42	EK Sedimentation
EK9	25	25	10	U(−), L(+)	24 17	EK Sedimentation
EK10	25	25	20	U(−), L(+)	24 44	EK Sedimentation
GR	25	25	Gravity	−	44	GR Sedimentation

(Remarks) EK: electrokinetic, GR: gravitation, U: upper part of the cell, L: lower part of the cell

Stainless steel electrode was used to prevent production of corrosion. To prepare a test sample, predetermined quantities of dry soil and organic solution were blended. Organic solution was a mixture of deionized distilled water and ethylene glycol. In the case of test EK2, the test sample was a mixture of 25% of gravimetric solid content and 75% of organic solution: organic solution was a mixture of 75% of distilled water and 25% of ethylene glycol, thus the initial fluid content of mixture was 300%. The mixture was poured into an electrokinetic cell. The cell was assembled to the electrokinetic test system. One stainless steel electrode was placed at the bottom of the cell and the other at the top of the sample, consisting of a parallel plate arrangement. The top electrode was removable for the convenience of sample preparation.

Two test steps namely, sedimentation and consolidation or remediation were applied. In the first step, a regulated voltage was applied on the testing sample, directed upward, top cathode (-) and bottom anode (+), to induce the movement of clay particles to downward due to electrophoresis. This is the electrokinetic sedimentation process. On the other hand, in the second step, a regulated voltage was applied on the testing sample, directed downward, top anode (+) and bottom cathode (-), to induce the movement of water and organic substance to downward due to electroosmosis. This is the electrokinetic consolidation or remediation process. In this step, the polarity reversal was employed and the bottom drainage channels were open.

The time dependent settlement and densification due to electrophoresis and electroosmosis were measured on a minute and hour basis. The settlement or interface height with time was recorded through reading the slurry line from the scales installed on the cell. The density of specimen due to electrokinetic sedimentation was measured on regular intervals. The density was measured by X-ray system at the Civil Engineering in University of Oxford. A highly collimated beam of X-ray is passed through the electrokinetic cell in Figure 3. The count rate recorded by this detector system is converted to density by assuming an exponential relationship between count rate and density, providing an accuracy in the measurement

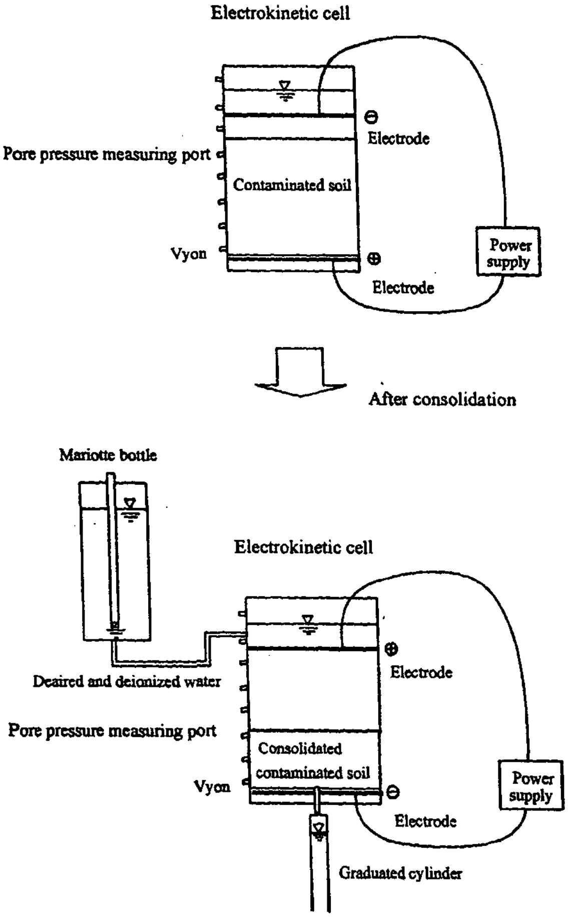


Fig. 1. A schematic diagram of the electrokinetic testing system

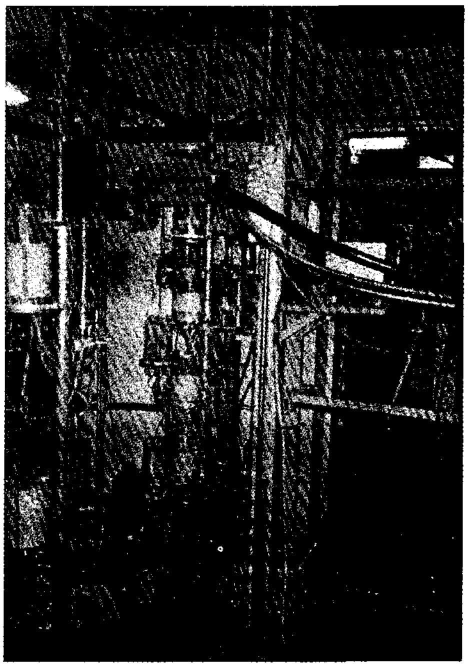


Fig. 2. Photography of the electrokinetic testing apparatus

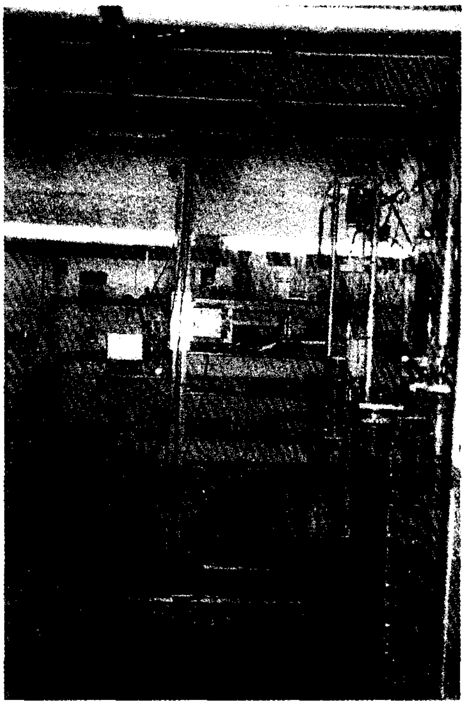


Fig. 3. Photography of X-ray assembly

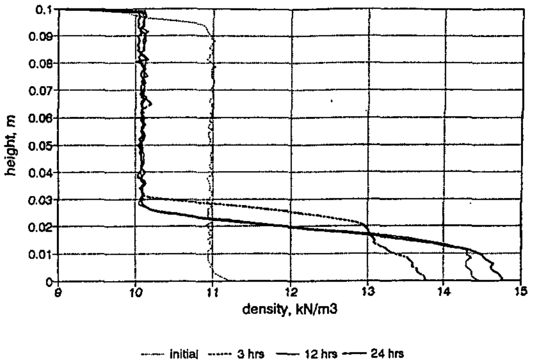
of density of the order of ±0.02 kN/m^3, with a spatial resolution of the order of 1 mm (Been & Sills, 1980).

For the present program, calibration was achieved by measuring the density of the water overlying the slurry with a Paar densiometer and attributing this measured density to the count rate measured with the X-ray system, assuming that the total vertical stress of the water and slurry at the base of the column remained constant. From the following results, it is shown that the X-ray system producing a continuous density profile can be effectively used to monitor the contaminant transport in soil sample.

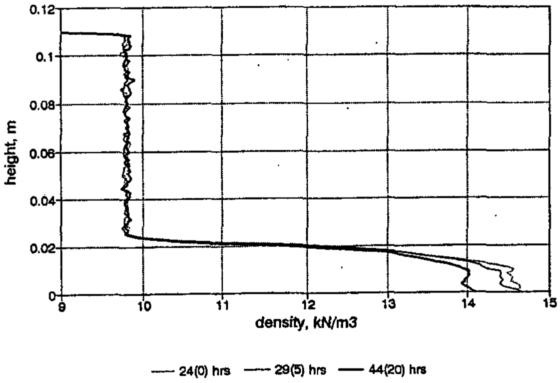
3. Results and Discussion

3.1 Density of Specimen in Electrokinetic Sedimentation and Remediation Process

Figures 4 (a), 5 (a), and 6 (a) show representatively the development of density versus height in time for electrokinetic sedimentation experiments in EK1, EK2 and EK6 test, respectively. The initial height of sample poured in electrokinetic cell is 10 cm. The initial day profile shows that the density of specimen poured in

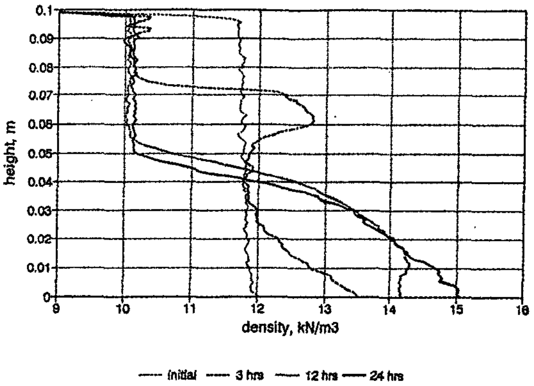


(a) density for the electrokinetic sedimentation process

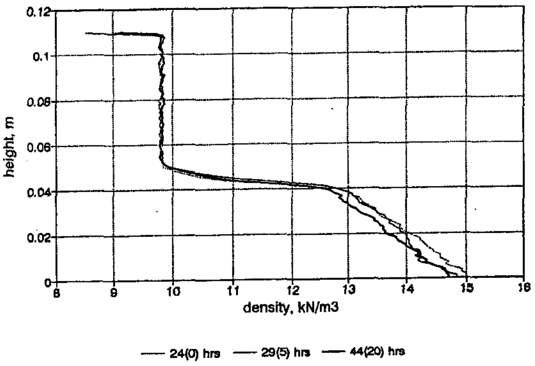


(b) density for the electrokinetic remediation process

Fig. 4. The variation of specimen density for EK1 test



(a) density for the electrokinetic sedimentation process

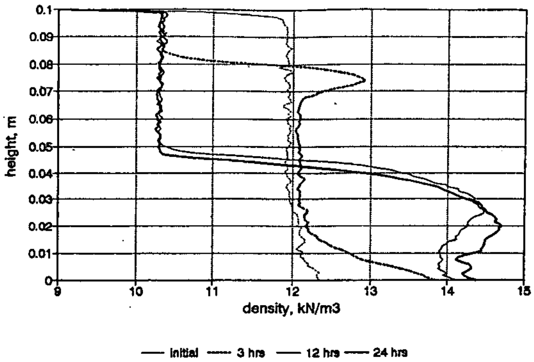


(b) density for the electrokinetic remediation process

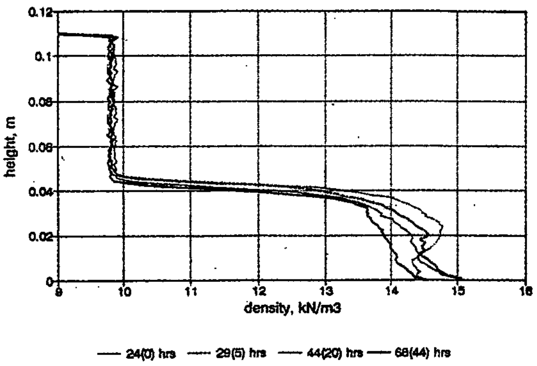
Fig. 5. The variation of specimen density for EK2 test

electrokinetic cell is almost uniform. While the middle day profiles show that the density near the base of the specimen has increased due to particle movement downward by self-weight consolidation and electrophoretic sedimentation, but the density near the top of the specimen has increased due to particle movement upward with pore water flow by electroosmosis. The final day profiles show that the density near the base of the specimen has increased because the particle movement downward by electrophoresis is larger than the particle movement upward with pore water by electroosmosis. From this result, we can recognize that the density of specimen increases and the height of specimen decreases compared with the initial condition in the step of electrokinetic sedimentation.

Figures 4 (b), 5 (b), and 6 (b) show the development of density versus height in time for electrokinetic remediation experiments in EK1, EK2, and EK6 test, respectively. It can be recognized that the density throughout entire length of specimen has decreased due to migration of contaminant from specimen by electrokinetic remediation. In this step of electrokinetic remediation, so called electrokinetic flushing, is introduced. Thus the contaminated pore water in specimen flows out of the electrokinetic cell and DDW (de-ionized de-aired water) applying mariotte bottle is replaced with contaminated pore water in specimen by electroosmosis. The DDW is lighter than the pore water contaminated by ethylene glycol, so the density of specimen decreases in the proceeding of electrokinetic flushing.



(a) density for the electrokinetic sedimentation process



(b) density for the electrokinetic remediation process

Fig. 6. The variation of specimen density for EK6 test

3.2 Settlement of Specimen in Electrokinetic Sedimentation Process

1) Settlement Characteristics by Solid Content

Figure 7 shows the results of settlement rate of contaminated waste slurries with time by solid content 15, 25, 40, and 50% for EK1, EK2, EK3, and EK4 tests under the same applied voltage and concentration level. Settlement increases with time elapsed in all tests by variation of solid content. Clay particles are negatively charged, so the movement of clay particles is developed to downward direction due to electrophoresis in electrokinetic sedimentation process. The electrophoretic sedimentation was accelerated in the first and middle stages, and lasted to last stage for electrokinetic sedimentation process even though some differences happened with experiment conditions. Settlement is attributed to both gravitational and electrophoretic effects.

The sedimentation rate is presented as ΔH/H, the amount of sedimentation divided by the initial sample height. The initial sample height was H=10 cm. At the

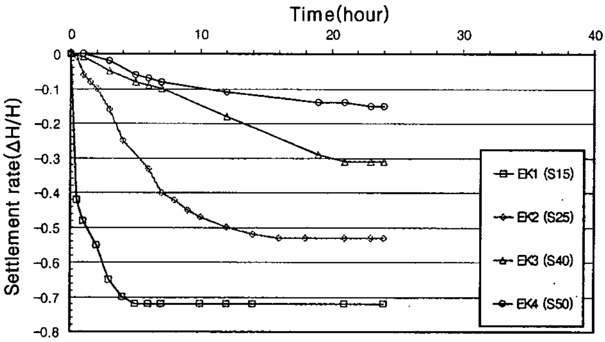


Fig. 7. Settlement rate with time by solid content

end of the test, the final height ratios of the samples are about 0.72, 0.53, 0.31, and 0.15 ΔH/H for EK1, EK2, EK3, and EK4 respectively. This means that the initial height was reduced by 72, 53, 31, and 15% respectively. The volume reduction of waste slurries was achieved by 72, 53, 31, and 15% respectively comparing with initial volume by electrokinetic sedimentation processing. The settlements of specimen are in the order of EK1, EK2, EK3, and EK4. This means that the settlement rate is high and rapid with decreasing of solid content, otherwise the settlement rate is low and slow with increasing of solid content. The length and volume of specimen is reduced due to extraction of pore water and settlement of specimen in the proceeding of electrokinetic sedimentation tests.

Figure 8 shows the relationship between maximum settlement rate and solid content under the same applied voltage and concentration level. The co-relative equation between maximum settlement rate, so-called final settlement rate, and solid content is derived from regression analysis and can be expressed as follows. The regression curve is linear.

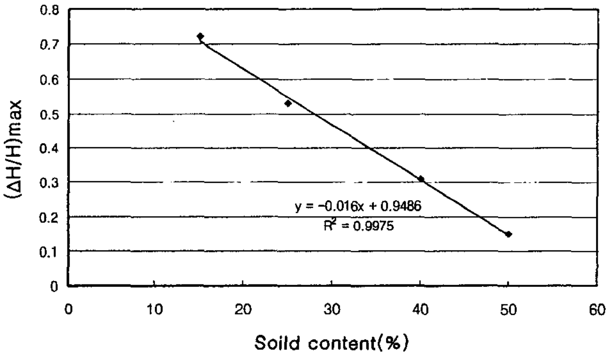


Fig. 8. Relationship between maximum settlement rate and solid content

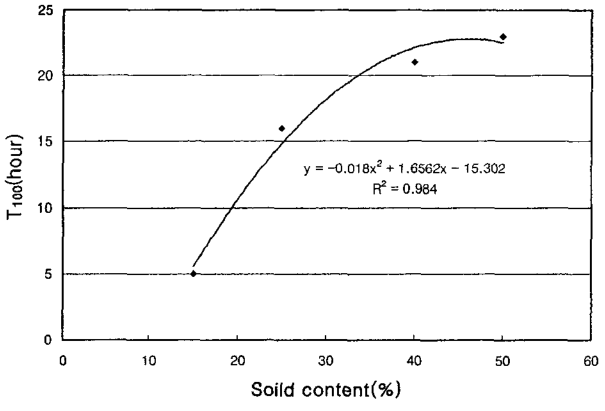


Fig. 9. Relationship between time to maximum settlement and solid content

$$(\Delta H/H)\text{max} = -0.016S + 0.9486 \qquad (1)$$

where ΔH is the settlement; H is the initial sample height; and S is the solid content.

Figure 9 shows the relationship between time to maximum settlement and solid content under the same applied voltage and concentration level. The co-relative equation between time to reach the final settlement and solid content is derived from regression analysis and can be expressed as follows.

$$t_{100} = -0.018S^2 + 1.6562S - 15.302 \qquad (2)$$

where t_{100} is the time to reach final settlement, and S is the solid content.

2) Settlement Characteristics by Applied Voltage

Figure 10 shows the results of settlement rate of contaminated waste slurries with time by applied voltage of 0, 10, 20, and 30 V, that is 0, 1, 2, and 3 V/cm, for GR, EK9, EK10, and EK2 tests under the same solid content and concentration level. Settlement increases with time elapsed in all tests by variation of applied voltage. The final sedimentation rates are 0.23, 0.45, 0.47, and 0.53 ΔH/H for GR, EK9, EK10, and EK2 respectively. This represents that the initial sample height was reduced by 23, 45, 47, and 53% respectively by electrokinetic sedimentation processing. It can be recognized that the settlement rate of specimen increases with increasing of

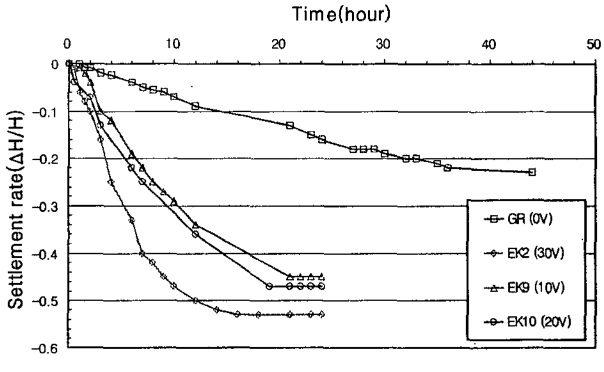


Fig. 10. Settlement rate with time by applied voltage

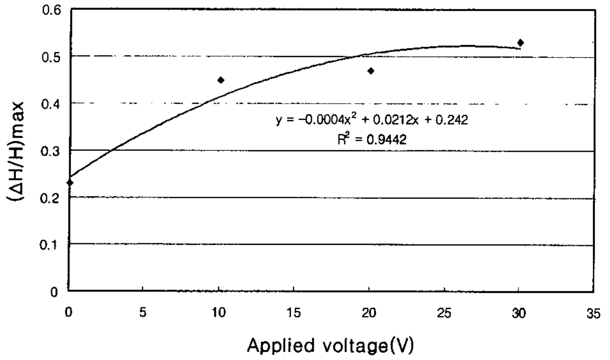


Fig. 11. Relationship between maximum settlement rate and applied voltage

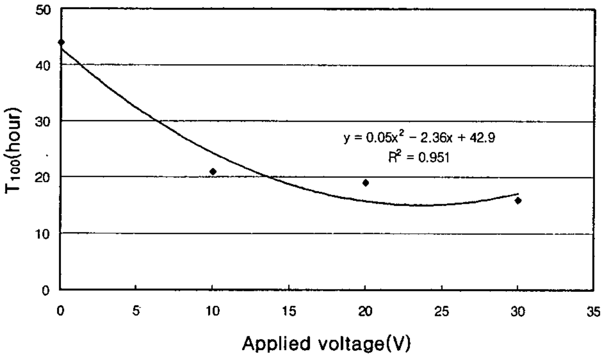


Fig. 12. Relationship between time to maximum settlement and applied voltage

applied voltage, on the other hand the settlement rate decreases with decreasing of applied voltage.

Figure 11 shows the relationship of the maximum settlement rate versus the applied voltage. The regressive equation between final settlement rate and applied voltage can be expressed as

$$(\Delta H/H)\text{max} = -0.0004V^2 + 0.0212V + 0.242 \qquad (3)$$

where V is the applied voltage.

Figure 12 shows the relationship between time to final settlement and applied voltage. The regressive equation between time reached to the final settlement and applied voltage is derived and can be expressed as

$$t_{100} = 0.05V^2 - 2.36V + 42.9 \qquad (4)$$

3) Settlement Characteristics by Concentration Level

Figure 13 shows the results of settlement rate of contaminated waste slurries with time by concentration level 0, 25, 50, 75, and 100% in the pore water of sample for EK5, EK2, EK6, EK7, and EK8 tests under the same solid content and applied voltage. Settlement increases with time elapsed in all tests by variation of concentration level. The final sedimentation rates are 0.47, 0.51, 0.52, 0.53, and 0.56 ΔH/H for EK5, EK2, EK6, EK7, and EK8 respectively. This indicated that the initial sample height was reduced by 47, 51, 52, 53, and 56% respectively by electrokinetic sedimentation processing. We can obtain the result that the settlement rate of specimen increases with decreasing of concentration level, on the other hand the settlement rate decreases with increasing of concentration level.

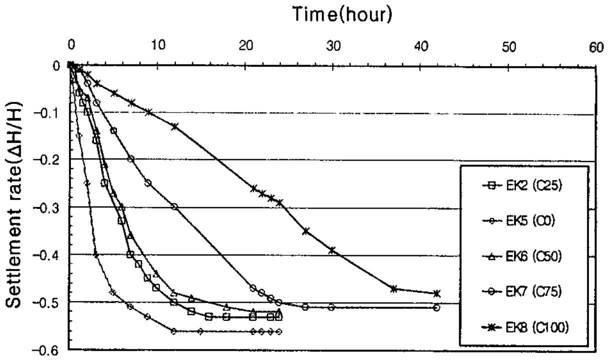


Fig. 13. Settlement rate with time by concentration level

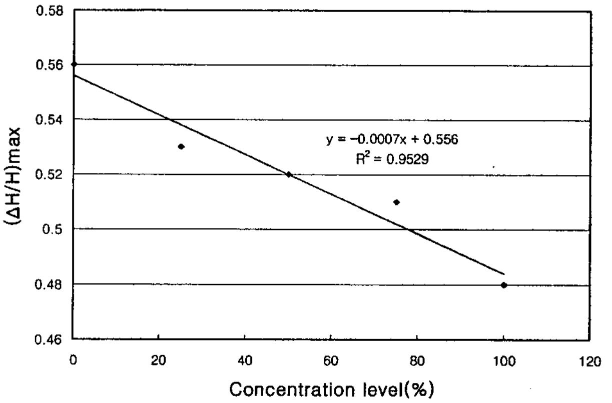


Fig. 14. Relationship between maximum settlement rate and concentration level

Figure 14 shows the relationship of the maximum settlement rate versus the concentration level. The regressive equation between final settlement rate and concentration level can be expressed as

$$(\Delta H/H)\text{max} = -0.0007C + 0.556 \qquad (5)$$

where C is the concentration level.

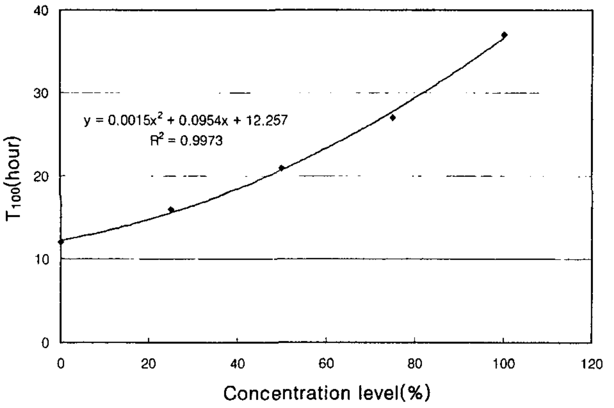


Fig. 15. Relationship between time to maximum settlement and concentration level

Figure 15 shows the relationship between time to final settlement and concentration level. The regressive equation between time reached to the final settlement and concentration level is derived and can be expressed as

$$t_{100} = 0.0015C^2 + 0.0954C + 12.257 \qquad (6)$$

4) Comparison of Settlement Characteristics by Different Conditions in Electrokinetic Sedimentation Process

Figure 16 shows the comparisons of sedimentation characteristics with different test conditions such as solid content, applied voltage, and concentration level in electrokinetic sedimentation process for EK1, EK2, EK6, and EK10 tests.

At the end of test, the heights of the test sample were 72, 53, 52, and 47 mm for EK1, EK2, EK6, and EK10 tests, respectively, compared with its initial height of 100 mm at the beginning of electrokinetic test. The electrophoretic sedimentation lasted for 5, 16, 21, and 19 hours. The settlement rates of 0.72, 0.53, 0.52, and 0.47 were achieved for EK1, EK2, EK6, and EK10 tests, respectively. This means that the settlement rate is high and rapid in the cases of higher applied voltage, lower concentration level, and lower solid content. In all cases, the length and volume of specimen will be reduced due to extraction of pore water and settlement of specimen in the proceeding of electrokinetic sedimentation tests.

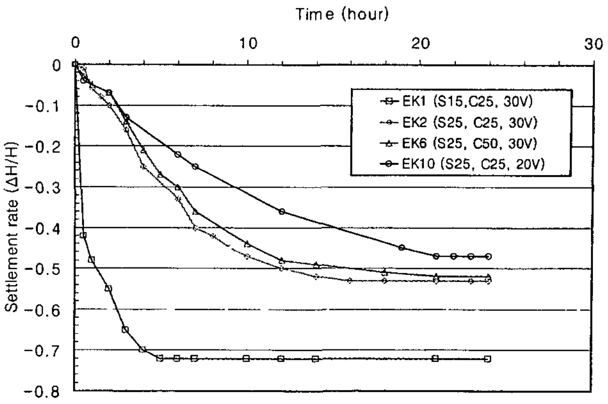


Fig. 16. Settlement rate with different test conditions

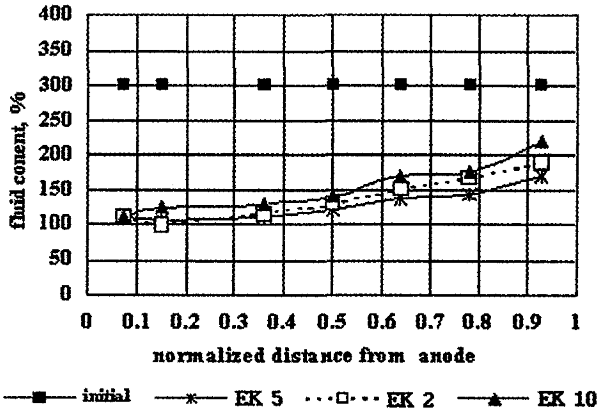


Fig. 17. Fluid content distribution across the specimen

3.8 Fluid Content Changes

At the end of electrokinetic remediation experiment, the soil fluid contents in the sliced samples were measured and shown in Figure 17. Three test conditions for EK5 (S25 C0 V30, EK2 (S25 C25 V30), EK10 (S25 C25 V20) were used for plotting in this figure. Where, S denotes solid content, C denotes contamination level, and V denotes applied voltage. The initial fluid content is the percentage of water weight 75% divided by solid weight 25%, that is 300%.

The initial fluid content was 300% and final fluid content was 100~200%. Thus the final fluid content decreased by 33~66% compared with the initial fluid content. The final fluid content was higher at the anode part than at the cathode part. The reason of this phenomena is the direction of electroosmotic water flow toward upward direction.

4. Conclusions

In this research, the coupled effects of sedimentation and densification of contaminated sediments are focused using electrokinetic sedimentation and remediation techniques. From the test results, a significant investigation is derived for the mechanisms associated with sediments contaminated with organic substance in which simultaneous sedimentation and remediation processes are involved by electrokinetics. The coupled effects of slurry soil sedimentation and densification are analysed. The main conclusions in this study are as follows.

(1) The effectiveness of electrokinetic sedimentation and remediation technologies for contaminated slurry wastes can be evaluated. The effects on settlement of specimen, reduction of volume and fluid content are achieved.

(2) The solid particles are moved to anode part by electrophoresis and the water is moved to cathode part by electroosmosis. Thus, the solid particles move downward and the water moves upward in electrokinetic sedimentation process. Clay particles are negatively charged, so the movement of clay particles is developed to downward direction due to electrophoresis in electrokinetic sedimentation process.

(3) The density of specimen increases and the height of specimen decreases compared with initial condition due to settlement of soil specimen in the step of electrokinetic sedimentation. On the other hand, the density of specimen decreases due to migration of contaminant from specimen in the step of electrokinetic remediation.

(4) The electrophoretic sedimentation was accelerated in the first and middle stages, and lasted to last stage for electrokinetic sedimentation process even though some differences happened with experiment conditions. Settlement rate increases with increasing of applied voltage and decreasing of solid content and concentration level. The settlement and the volume reduction are about 15～72% of initial height and volume depends on test conditions.

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