TDR 2006
Purdue University

Application of TDR on LKD and Cement-Treated Soils

R. P. Chen, Y. M. Chen, J. X. Wang and V. P. Drnevich

Ref.: Chen, R. P., Chen, Y. M., Wang, J. X. and Drnevich, V. P., “Application of TDR on LKD and Cement-Treated Soils", Proc. TDR 2006, Purdue University, West Lafayette, USA, Sept. 2006, Paper ID 38, 11 p., https://engineering.purdue.edu/TDR/Papers

Application of TDR on LKD and Cement-Treated Soils

R.P. Chen[1], Y.M. Chen[2], J.X. Wang[3], and V. P. Drnevich[4]

[1] Associate Professor, Department of Civil Engineering of Zhejiang University, Zheda Road 38#, Hangzhou 310027 China, chenrp@zju.edu.cn

[2] Head of Geotechnical Engineering Research Institute and Vice Dean of School of Civil Engineering and Architecture, Zhejiang University, Zheda Road 38#, Hangzhou 310027 China

[3] Graduate Student, Department of Civil Engineering of Zhejiang University, Zheda Road 38#, Hangzhou 310027 China

[4] Professor, Department of Civil Engineering, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907-2051, drnevich@purdue.edu

Abstract

Lime, lime kiln dust (LKD), and cement are being used for treating soft soils. Various physicochemical reactions take place in the mixture of soils and lime, LKD, and/or cement. These reactions result first in an increase in electrical conductivity over that for the untreated soil. Then electrical conductivity and dielectric constant decrease and the strength of the mixture increases with time. The simultaneous changes of the electrical and mechanics properties show their inherent relationships. The monitoring results indicate a strong relationship between the decrease of the electrical conductivity and the increase of the strength with time for LKD treated soil. It was concluded that the electrical conductivity and the dielectric constant measured by TDR may be used to predict the development of shear strength and to estimate the water content, respectively.

Key Words: time-domain reflectometry, lime kiln dust, cement, dielectric constant, electrical conductivity, strength

INTRODUCTION

Soil stabilization and modification by addition of chemical admixtures are widely used to facilitate the construction and enhance the engineering properties of soil. Traditional chemical admixtures include quicklime, hydrated lime, and cement. Recently, a number of by-products, like lime kiln dust (LKD), cement kiln dust (CKD), and fly ash materials are recycled as chemical additives and have been used as stabilizers. Most often engineers and researchers study the changes in physical and engineering properties of chemically treated soils [1~3]. Generally, the chemical changes in a system are associated with the simultaneous changes in its electrical properties. Boardman et al.[4] suggested that the electrical conductivity of lime treated soil decreases with time and the measurement of electrical conductivity can be used as an effective quality control of lime stabilized subgrades. However, they did not develop or propose a procedure for performing the in situ monitoring. Yu and Drnevich[5] showed that electrical conductivity measured by TDR was an accurate and effective indicator of the progress of hydration in the lime stabilized soils. Daita et al.[6] showed that electrical conductivity measured by TDR was useful for quality assessment of LKD treated soils.

The present paper describes the behavior of LKD treated soils and cement treated soils in terms of electrical properties. The electrical conductivities and the dielectric constants of two treated soils were measured using different TDR apparatus. Penetration resistance was measured at different curing times for LKD treated soil. The work explored the potential of using TDR to determine the amount of chemical admixtures present in a soil and to estimate the development of the shear strength of the mixture from the electrical conductivity measurements. It shows the application of TDR method as a quality control method for a chemically treated soil.

MATERIALS

Soils and LKD

Orchard clay and Grundite were used in the tests of LKD treated soil. Orchard clay was locally collected from West Lafayette, Indiana. Grundite was obtained from the Illinois Clay Products Company. The Orchard clay was air-dried at room temperature and passed through a 4.75mm (No.4) sieve. Index properties of each soil are shown in Table 1. It was found that a 1:1 mixture by volume of water and dry Orchard clay is slightly alkaline, whereas that of Grundite is extremely acidic[7]. Since Grundite is extremely acidic, the LKD Modification Optimum (LMO)[8] of Grundite is higher than that of Orchard clay.

TABLE 1—*Basic properties of Orchard clay and Grundite.*

Property	Orchard clay	Grundite
Particle Size Analysis	Sand-28%, Silt-47%, Clay-25%	Sand-23%, Silt-51%, Clay-26%
Liquid Limit	35.0	46.7
Plasticity Index	19.0	20.7
AASHTO Classification	A6 (11)	A6(11)
USCS Classification	Lean Clay (CL)	Lean Clay (CL)
Compaction Characteristics	$\gamma_{d\max}$ = 18.1 kN/m^3, w_{op} =16.5 %	$\gamma_{d\max}$ = 16.2kN/m^3, w_{op} =19%
Soil pH in 1:1 H_2O	7.74	2.2-2.4
LKD modification optimum[8]	4%	11%

The LKD used in the experiments was from the Buffington plant of Mount Carmel Sand and Gravel. The chemical composition of the LKD was characterized by X-ray diffraction experiments in the natural and hydrated states. The X-ray diffraction patterns indicate that the main components of natural LKD are CaO, $CaCO_3$, $CaMg(CO_3)_2$, $CaSO_4$, and $Ca(OH)_2$.

Soils and cement

Xiaoshan clay was selected for the study of cement treated soil, which was locally collected form Xiaoshan, Hangzhou, China. The index properties are shown in Table 2. Type I Portland cement was used in the monitoring tests. The cement mainly consisted of tricalcium silicate 3Ca•SiO_2 (C_3S), dicalcium silicate 2Ca•SiO_2 (C_2S) and tricalcium aluminate 3Ca•Al_2O_3.

Table 2 *Index properties of Xiaoshan clay*

γ (kN/m^3)	G_s	w_p (%)	w_l (%)	I_p	I_l	c_{cu} (kPa)	φ_{cu}
17.93	2.744	25	58	33	0.709	15.4	12.6

In Table 2, γ is the total unit weight, G_s is the specific gravity of solids, w_p is the plastic limit, w_l is the liquid limit, I_p is the plasticity index, I_l is the liquidity index, and c_{cu} and φ_{cu} are the cohesion and angle of shearing resistance, respectively, from CU triaxial tests.

SPECIMEN PREPARATION

Specimens Preparation for LKD Treated Soil

For each test the parent soils were mixed with a target water content using tap water and sealed in the plastic bags for 24 hours. For Orchard clay, the plastic bags were put in the humid room, which was maintained at a temperature of 10^{o}C. For Grundite, the plastic bags were put in a conventional room at a temperature of 22^{o}C. Different temperatures were used to study the temperature increase caused by the addition of LKD into the soils. Different humidity was used to study the effect of humidity on the change of water content of parent soil after curing for one day. The following day, the required amount of LKD was added and mixed using a mechanical mixer for five minutes. All the mixtures were compacted in three lifts with 25 blows per lift in a standard metal compaction mold, with a diameter of 101.6 mm and a height of 116.4 mm following the procedure of ASTM D698[9].

For each monitoring test, two replicate specimens were prepared. One specimen was prepared for measuring the electrical properties of the treated soil by inserting a stainless steel rod through a template into the center of the specimen. The replicate specimen was used for determining the needle penetration resistance. Tops of the compacted specimens were covered with wax to prevent loss of moisture during curing. Table 3 shows the water content and LKD dosage the of six specimens in the monitoring tests.

Specimens Preparation for Cement Treated Soil

The soils were dried at 105^{o}C and were then cooled in a desiccation chamber. The parent soils were mixed with a target water content using tap water and sealed in plastic bags for 24 hours. The following day, the required amount of cement was added and mixed manually for ten minutes. All the mixtures were compacted in three lifts with 25 blows per lift in a specially designed PVC molds, with a diameter of 170 mm and a height of 160 mm. Then the TDR probes were installed into the specimens immediately. The specimens were put in a room, which was maintained at a temperature of 20^{o}C. Tops of the compacted specimens were covered with wax to prevent water infiltration and evaporation during curing. Table 4 shows the water contents and cement dosages of the specimens in the monitoring tests.

Table 3 *Measurements profile of LKD treated specimens*

Test group identification	LKD dosage by dry weight of soil solids %	Target water content of mixture after mixing %	Water content after mixing %	Water content after monitoring %
ORC 4-15	4	15	14.39	14.24
ORC 4-17	4	17	17.82	17.22
ORC 4-19	4	19	18.70	18.18
GRU 11-13	11	13	12.62	12.71
GRU 11-17	11	17	17.13	17.21
GRU 11-21	11	21	20.21	20.41

Notes: In the identification of test group, "ORC" means the Orchard clay and "GRU" means the Grundite; the first number indicates the percentage of LKD; the second number indicates the target water content. The water content was measured by the oven-dried method. The slight increase of water content after monitoring in comparison with water content just after mixing might be caused by the test errors.

Table 4 *Measurements profile of cement treated specimens*

Test group identification	Cement dosage by wet weight of soil, %	Target water content of mixture after mixing, %	Water content after mixing %	Water content after monitoring %
Specimen 1	7	50	50.3	48.4
Specimen 2	10	50	50.2	48.0
Specimen 3	15	30	30.3	27.9

MEASUREMENTS

TDR Measurement

The Purdue TDR apparatus[5,6] was used to measure the electrical conductivity and dielectric constant of LKD treated soil. It makes use of a Campbell Scientific TDR100 tester connected to a specially designed coaxial head by a 1.8m long, 50 ohm coaxial cable. The coaxial head sits on an adapter ring seated on top the metal mold. The signal generator sends a step voltage pulse to the cable, the coaxial head, and the soil-filled cylindrical mold with a coaxial center rod. Reflections occur as the step pulse reaches the top and the bottom of the probe. The apparent dielectric constant is calculated from the travel time between the two reflections. Analysis of the long-term response of a TDR system allows for calculating the bulk d.c. electrical conductivity, which is related to the long-term TDR voltage level[10]. Apparent dielectric constant and bulk electrical conductivity are both temperature dependent, but the electrical conductivity is the more sensitive of the two. The temperature was measured using a thermocouple embedded in the soil within the mold at a depth of approximately 50mm from the surface. The TDR measurements and temperature were taken automatically every hour.

For monitoring cement treated soil, a specifically designed three-rod probe was used. The three rods were made of 8 mm diameter stainless steel, 95 mm long, with a center spacing of 26 mm between the outer and inner rods. Before monitoring soil-cement mixtures, the probe was calibrated with deionzed water and the constant in Giese and Tiemann's formula[10] was calibrated with 0.01 mol KCl electrolyte. The rods were fully inserted and there was no air cap left between the specimen surface and the probe head. The temperature was measured using a thermometer embedded in the material in the mold.

Penetration Resistance Measurements

Strength and modulus of treated soil are of interest to engineers for use in design. Unconfined compression tests on cores from the field or on specimens compacted in the laboratory are frequently used to measure both modulus and strength. Many correlations between various field tests and unconfined compression test have been developed[11]. Because stabilized soil is very brittle when compared to the parent soil, the unconfined compression test may not be the best test for such brittle material. The needle penetrometer test[12] was used to determine the penetration resistance as an indicator of the strength. The needle penetration tests of LKD treated soil were performed at the following time intervals: just after compaction, one day, and 3 days after compaction or later.

RESULTS AND DISCUSSION

Temperature

The temperature was measured during the curing process. For LKD treated soil, the temperature of the Orchard clay specimens increased only slightly because the parent soils were put in the room at a temperature of 10^{o} C, and for the Grundite specimens there were significant temperature increases because of the parent soils were put in the conventional room at a temperature of 22^{o} C.

For cement treated soil, specimens 1 and 2 almost had no temperature variation over the curing time, even initially. The temperature of specimen 3 increased 3^{o}C in comparison with the room temperature within an hour after compaction and then decreased to the room temperature within three hours. The heat of hydration from the cement interacting with the water in the soil caused the temperature increase. The larger temperature increase in specimen 3 was expected because it contained the largest amount of cement.

Apparent Dielectric Constant

Apparent dielectric constant is an indicator of free water in soil. However, measurement of the apparent dielectric constant is challenging during the first few hours in stabilized soils because the high electrical conductivity results in attenuation that prevents a second reflection in TDR waveforms. With time after preparing the specimen, the electrical conductivity decreases and the second reflection in the TDR waveforms appears which allows the apparent dielectric constant to be calculated.

The apparent dielectric constants of the specimens with the same water contents are close to each other, and decrease slightly during curing. The curing process in the treated soil apparently does not change the free water content for the LKD treated soil from the measurements of water content just after compaction and after monitoring (Table 3). And the water content of the cement treated soil decreased slightly during monitoring (Table 4). The decrease of apparent dielectric constant with time from TDR waveforms measured in chemical admixtures treated soil needs further study.

Electrical Conductivity

Figure 1 presents the variations in electrical conductivity with time for the Orchard clay and Grundite treated with LKD. Figure 2 shows the changes of electrical conductivity with time for cement treated soil. Bulk electrical conductivity of soil is a function of pore fluid conductivity, surface conductivity, and the phase fractions. The pore fluid conductivity decreases because of a decrease in ionic strength of the pore water due to complexes forming from free ions. Reduction in surface conductivity may also be occurring as cement films cover the mineral surfaces for cement treated soils. The cation exchange itself is an immediate process. However, the pulverization and mixing of soil with cement and lime can not ensure a close contact between hydrated cations and clay particles. Therefore, the LKD or cement must diffuse through the soil lumps and the existing reaction product and, as a result, the reaction rate is reduced.

In Figure 1 the decrease of electrical conductivity with time varied with the water content after temperature compensation. The rates depended on the LKD percentage and water content.

Figure 2 shows the changes in electrical conductivity for cement treated soils. The initial electrical conductivity of Specimen 3 was much lower in comparison with Specimens 1 and 2 even though Specimen 3 had higher cement content. However, the water content for Specimen 3 was only 30% compared to 50% for the other two specimens. Specimen 2 with higher cement content shows higher initial electrical conductivity than Specimen 1 even though both have the same water content. It is because the higher cement content generates more free ions which results in a higher initial electrical conductivity. For both Specimens 1 and 2, which have the same water content but different cement dosage, the electrical conductivity increased slightly during the first few hours and then decreased. This is probably caused by the high water content of the specimens. Then the pozzolanic reactions occur and consume a lot of free ions and the hydration reaction product, which causes the electrical conductivity to decrease. There appears a

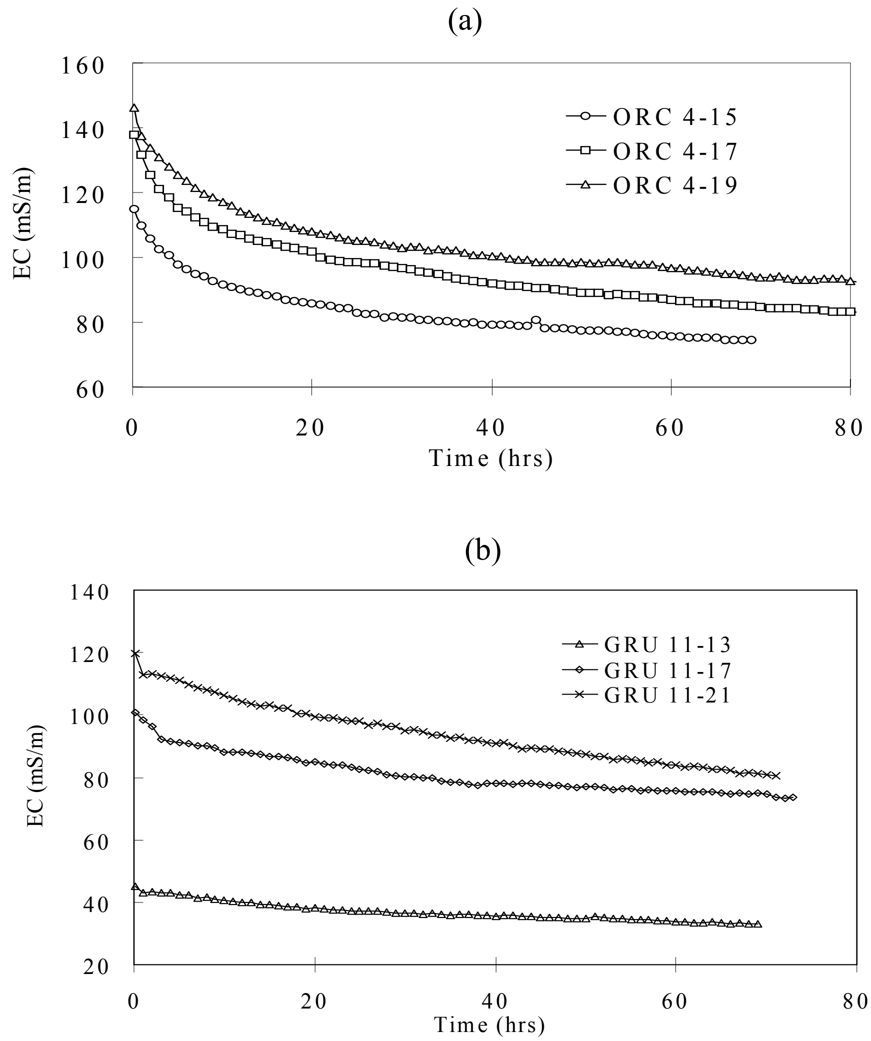

FIG. 1—*Decrease of electrical conductivity with time for LKD treated (a) Orchard clay and (b) Grundite.*

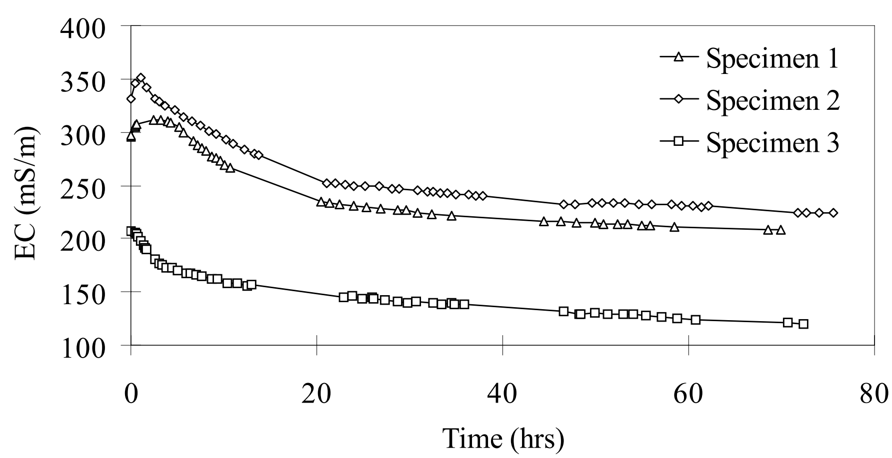

FIG. 2—*Variation diagram of electrical conductivity with time*

strong correlation between electrical conductivity and the physicochemical reactions in the treated soil, which provide the increase in strength. This suggests a correlation between electrical conductivity and the strength.

Strength Development

A substantial improvement in the strength can be expected immediately after the addition of lime due to the short-term reactions of cation exchange, flocculation, and agglomeration[13]. The long-term strength gain is related to the pozzolanic reaction, which lasts for months, even for years. The strength increase measured by penetrometer test is mainly associated with the short-term reactions. The development of penetrometer resistance for LKD treated Orchard clay and Grundite is shown in Figure 3. The initial strength of the treated soil is strongly influenced by the water content of the soil. The combination of high water content and high LKD percentage provides the highest strength. The development of the strength indicates most of the strength of treated soil is achieved within one day.

Since the electrical conductivity and the strength both evolve with the physicochemical reactions, there might be some relationship between the electrical conductivity and strength. Figure 4 indicates the measured penetration resistance versus the electrical conductivity at the same times. The measured penetration resistance increases as the electrical conductivity decreases.

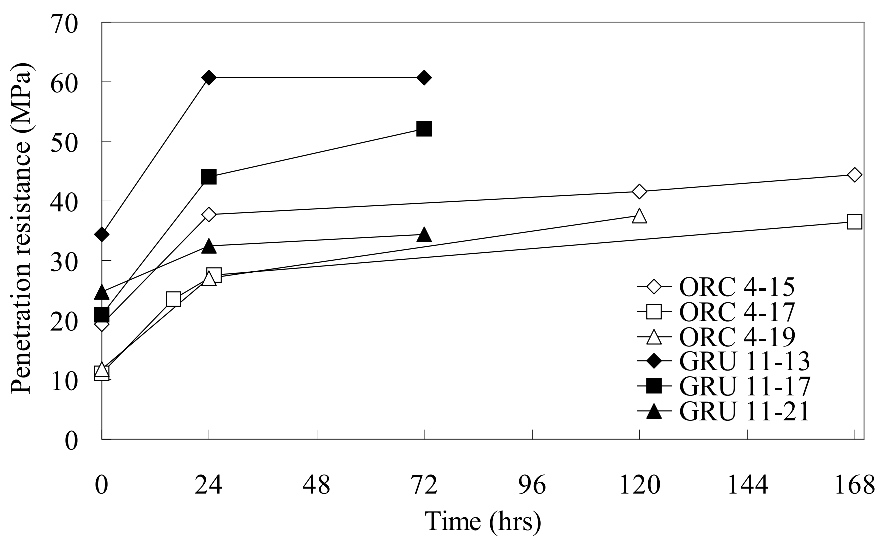

FIG. 3—Increase of penetration resistance with time for LKD treated soils

SUMMARY AND CONCLUSIONS

The laboratory study investigated the electrical properties of LKD and cement treated soils. Apparent dielectric constant and electrical conductivity were measured by TDR. Dielectric constant decreased slightly with time and electrical conductivity decreased significantly with time. Electrical conductivity is affected by the chemical reactions in the chemically treated soils.

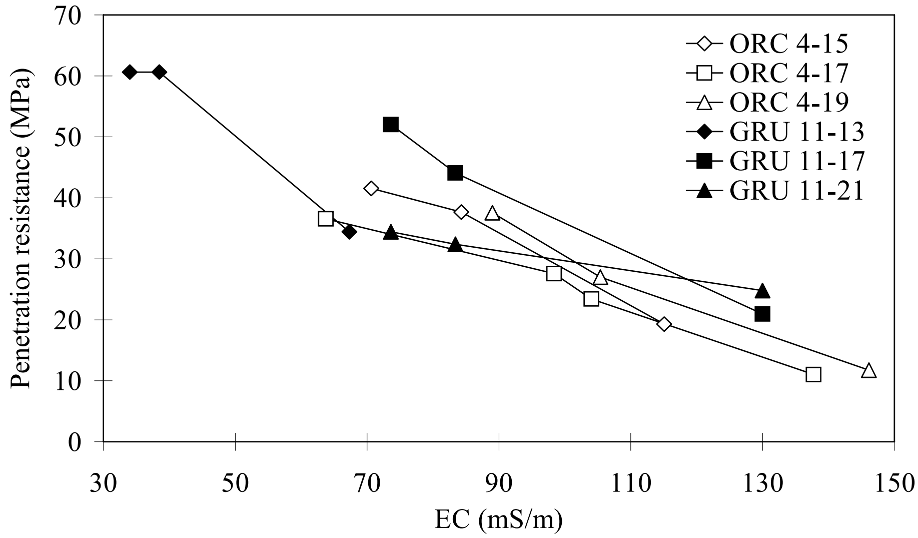

FIG. 4—*Penetration resistance vs electrical conductivity for LKD treated soils.*

The electrical conductivity, which acts as an indicator of the pozzolanic reactions, is strongly correlated with the needle penetration resistance of the LKD-treated soil. Therefore, simple electrical conductivity measurements could be used for field quality control of chemically treated soils.

Acknowledgements

The study on LKD modified soil (Project: SPR 2850) was supported by the Joint Transportation Research Program administered by the Indiana Department of Transportation and Purdue University. The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the Federal Highway Administration and the Indiana Department of Transportation, nor do the contents constitute a standard, specification, or regulation. The authors are grateful to the Federal Highway Administration/ Indiana Department of Transportation/ Joint Transportation Research Project for supporting this research. The authors acknowledge the assistance provided by Janet Lovell (Lab Manager), R. K. Daita, D. H. Kim, X. L. Wan in this research.

The first author gratefully acknowledges Chinese Natural Science Foundation (Project: 50308026) for the financial support.

REFERENCES

[1] Little, D. N., 1999, Evaluation of Structural Properties of Lime Stabilized Soils and Aggregates, *National Lime Association,* Arlington, Virgina, 2000.

[2] Puppala, A. J., Mohammad, L. N., and Aaron, A., 1996, Engineering behavior of lime-treated Louisiana subgrade soil, *Transportation Research Record*, No. 1546, pp. 24-31.

[3] Tuncer B. Edil, Hector A. Acosta and Craig H. Benson, 2006, Stabilizing Soft Fine-Grained Soils with Fly Ash, *Journal of Materails in Civil Engineering*, Vol. 18, No. 2, pp. 283-294.

[4] Boardman, D. I., Glendinning, S., Rogers, C. D. F., and Holt, C. C., 2001, In situ monitoring of lime-stabilized road subgrade, *Transportation Research Record*, No. 1757, pp. 3-13.

[5] Yu, X. and Drnevich V. P., 2004b, Time domain reflectrometry for compaction control of stabilized soils, *Transportation Research Record*, No. 1868, pp. 14-22.

[6] Daita, R. K., Drnevich V. P., Kim, D. K., and Chen R. P., Quality assessment of lime kiln dust (LKD) treated soils by electrical conductivity measurement with time domain reflectometry (TDR). *Transport Research Record*. (Accepted)

[7] Robarge, W. P. and Johnson, D. W., 1992, The effects of acidic deposition on forested soils, *Advances in Agronomy*, Vol. 47, pp. 1-83.

[8] ASTM D 6276-99, Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization. *Annual Book of ASTM Standards*, Vol.04.08. West Conshohocken, PA: ASTM International, 1999.

[9] ASTN D 698-00, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft3 (600 kN-m/m3)), ASTM International, *Annual Book of ASTM Standards*, Vol.04.08. West Conshohocken, PA: ASTM International, 2000.

[10] Giese, K. and Tiemann, R., 1975, Determination of the complex permittivity from thins sample time domain reflectometry: Implications for twin rod probes with and without dielectric coatings, *Water Resource Research*, Vol. 32, No. 2, pp. 271-279.

[11] Janoo, V. C., Fricano, A. J., Barna, L. A., and Orchino, S. A., 1999, Field testing of stabilized soils, *Journal of Cold Regions Engineering*, Vol. 31, No. 1, pp. 37-53.

[12] ASTM D1558-99, Standard Test Method for Moisture Content Penetration Resistance Relationships of Fine-Grained Soils. *Annual Book of ASTM Standards*, Vol.04.08. West Conshohocken, PA: ASTM International, 1999.

[13] TRB (1987). *Lime stabilization: reactions, properties, design, and construction*, State of the Art Report 5. Transportation Research Board, National Research Council, Wash., D.C.

Biographical Information

Dr. Renpeng Chen received his M.S. degree in Geotechnical Engineering in 1997 and his Ph.D. degree in Civil Engineering in 2001 from Zhejiang University. He is currently an Associate Professor of the Department of Civil Engineering of Zhejiang University. His research interests embrace foundation engineering, soil improvement and geoenvironmental Engineering.

Dr. Yunmin Chen: received his B.S., M.S. and Ph.D. degree in Civil Engineering from Zhejiang University. He is the head of Geotechnical Engineering Research Institute of Zhejiang University, vice dean of School of Civil Engineering and Architecture. His research interests include foundation engineering, geoenvironmental engineering, and soil dynamics.

Jinxue Wang obtained his B.S. degree in Civil Engineering from Henan University. He is currently a master candidate in Department of Civil Engineering of Zhejiang University.

Vincent Drnevich obtained his B.S. and M.S. degrees in civil engineering at the University of Notre Dame and his Ph.D. degree from the University of Michigan in Ann Arbor. He was on the civil engineering faculty at the University of Kentucky for 24 years before moving to Purdue University as Professor and Head of Civil Engineering. In 2000, he stepped down from the Head position to devote more time to teaching and research.