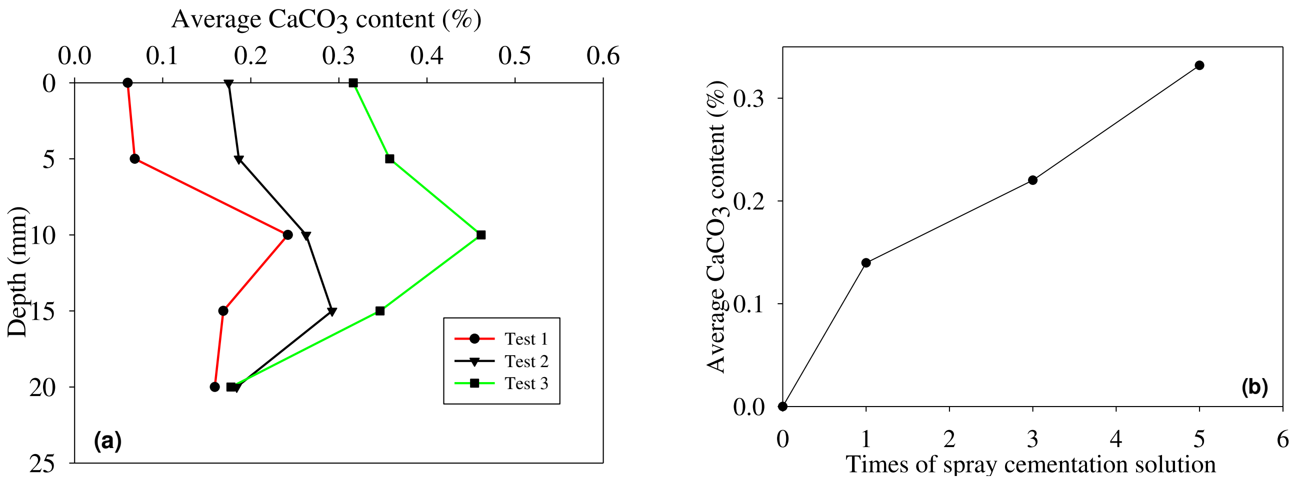

Figure 3. Summary for Part I; (a) average CaCO3 content with depth for Tests 1, 2 and 3; (b) average CaCO3 content for each sample with cementation solution amount.

For the second set of experiments, Figure 4 shows the average $CaCO_3$ content with depth for different parts of the tray specimens. The $CaCO_3$ content at the surface ranges from 0.21 to 0.65%. The maximum $CaCO_3$ content ranges from 0.63 to 1.03%. The results also show that the maximum $CaCO_3$ content was at ~5 mm. Similar to Figure 2, this figure illustrates the variation of $CaCO_3$ content in different parts, which could be attributed to the non-uniform distribution of the bacteria and cementation solutions as well as the efficiency of the bacteria. However, comparing the results in Figures 2 and 4, the depth of maximum $CaCO_3$ content moved upward from ~10 mm to ~5 mm, which could be attributed to using more than one bacteria application. This could improve the soil resistance to wind loading reducing the airborne particles. The average values of $CaCO_3$ with depth are shown in Figure 5(a), while Figure 5(b) shows the average value for each sample as a function of pore volumes used in each application. As expected, the measured $CaCO_3$ content increases as the amount of bacteria and cementation solution increases.

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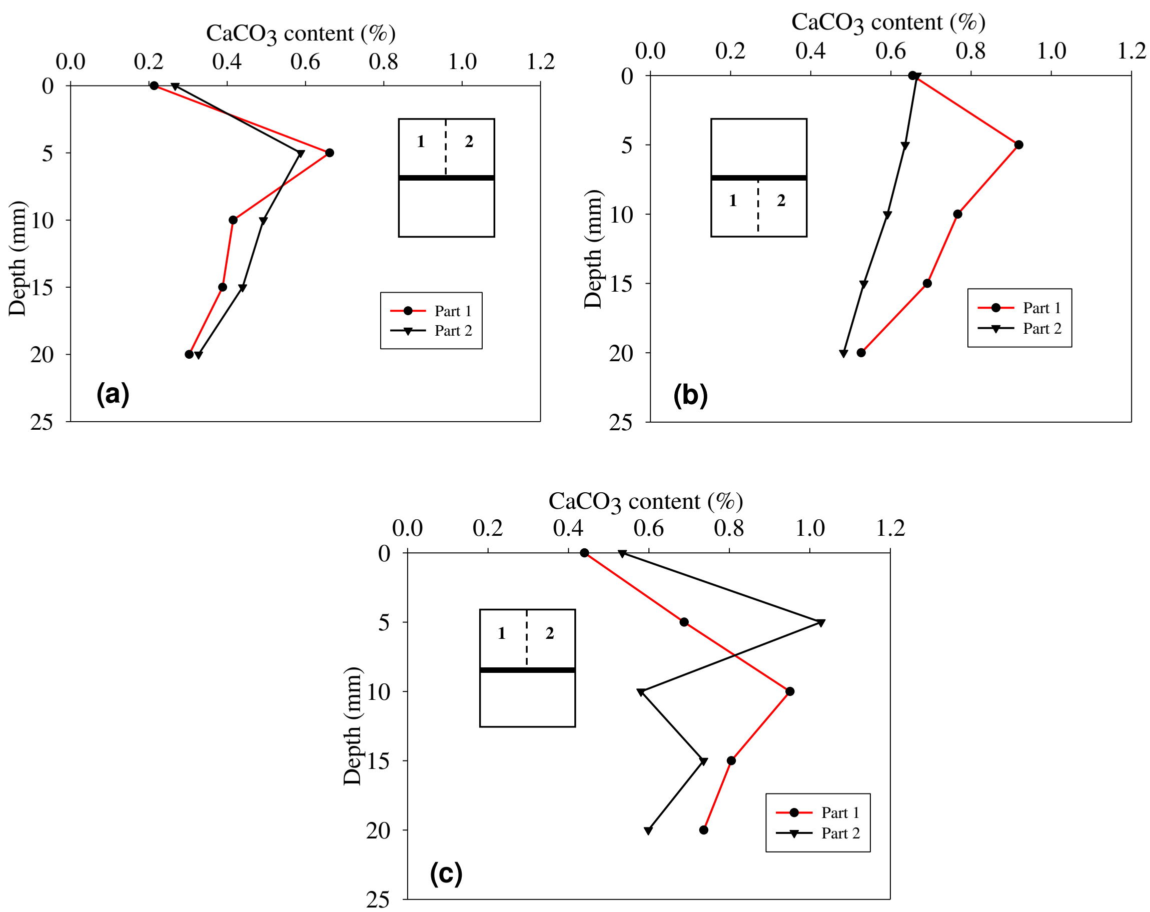

Figure 4. Measured CaCO3 content with depth; (a) Test 4; (b) Test 5; (c) Test 6.

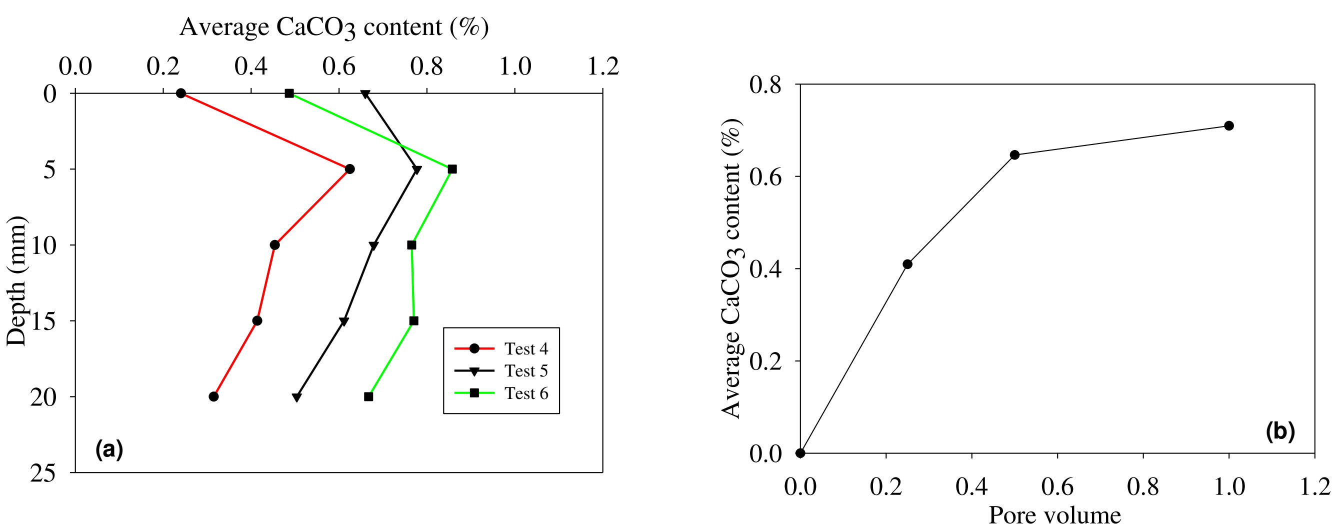

Figure 5. Summary for Part II; (a) average CaCO3 content with depth for Tests 4, 5 and 6; (b) average CaCO3 content for each sample with different pore volumes.

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SUMMARY AND CONCLUSIONS

The research summarized in this paper focuses on evaluating the use of MICP for wind erosion application. The results presented in this paper represent the initial attempt to optimize the field application/process of applying MICP. In future, this will be followed by more detailed study and wind tunnel experiments. A series of spray experiments were conducted on bar sand with different bacterial and calcium chloride ($CaCl_2$) applications. After each test, samples were collected to measure $CaCO_3$. Two procedures were used to treat sand specimens; one with constant volume one bacteria application and different applications of cementation media, while the other with constant number of applications of bacteria and cementation solutions but different volumes. The results show non-uniform distribution of $CaCO_3$ content at the same depth and at different depths, which could be attributed to the non-uniform distribution of the bacteria and cementation solutions and non-uniform efficiency of the bacteria. When comparing the results of Part I and II, the depth of maximum $CaCO_3$ content moved upward from ~10 mm to ~5 mm indicating that increasing the number of bacteria solution applications will improve the soil particles near the surface. Based on the results of these tests, a series of instrumented wind tunnel experiments will be conducted.

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Field Strength Properties of Cement Stabilized Soil by Pneumatic Flow Tube Mixing Method

Masaki Kitazume, Ph.D.[1]; Ali Maher, Ph.D.[2]; Masoud Janbaz, Ph.D.[3]; Robert Miskewitz, Ph.D.[4]; and David Yang, Ph.D.[5]

[1]Dept. of Civil and Environmental Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8550, Japan. E-mail: kitazume.m.aa@m.titech.ac.jp
[2]Dept. of Civil and Environmental Engineering, Rutgers, The State Univ. of New Jersey, 100 Brett Rd., Piscataway, NJ 08854-8058. E-mail: mmaher@rci.rutgers.edu
[3]Dept. of Civil and Environmental Engineering, Rutgers, The State Univ. of New Jersey, 100 Brett Rd., Piscataway, NJ 08854-8058. E-mail: mj365@scarletmail.rutgers.edu
[4]Dept. of Civil and Environmental Engineering, Rutgers, The State Univ. of New Jersey, 100 Brett Rd., Piscataway, NJ 08854-8058. E-mail: rmiskewitz@envsci.rutgers.edu
[5]JAFEC Inc., 2025 Gateway Place, Suite 180, San Jose, CA 95110. E-mail: Davidyang@jafecusa.com

Abstract

The pneumatic flow tube mixing (PFTM) was developed in Japan for land reclamation and land development, in which dredged clay is stabilized with a small amount of binder in a transporting pipeline. The soil mixture forms several separated mud plugs in the pipeline and is thoroughly mixed by means of turbulent flow during the transport. The PFTM has the potential to reduce treatment costs by eliminating costs associated with material transport and improve the final product by creating a more uniform amended sediment. This method was conducted at a sediment management site in Kearny, NJ from July through September of 2015, and demonstrated to be an efficient and rapid method for soft-sediment stabilization. In this study, the in-situ strength of the field stabilized soil by the PFTM was investigated to evaluate the long-term strength.

INTRODUCTION

The Port of New York/New Jersey Harbor is the largest on the East Coast of the U.S. and the third largest in the country. The U.S. Army Corps of Engineers maintains approximately 400 km of navigation channels with depths up to 16 meters. Maintenance of these waterways requires dredging of 3 to 5 million m^3 of sediment annually. Management of the dredged sediment is

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complicated, by the presence of contamination, which limits the potential pathways for disposal. In 1997, environmental regulations were put in place that limited the potential for ocean disposal (NJDEP, 1997). These regulations have promoted beneficial reuse of stabilized dredged material as a capping or filling material for landfills, industrial sites, and abandoned mines (Douglas et al., 2003).

A technique was developed in the late 1990's in Japan that involved mixing and placement of soft sediments in a single step called Pneumatic Flow Tube mixing (PFTM). The PFTM is a method for stabilization and solidification of soft sediments. The PFTM mixes sediments with a small amount of binder in a pipeline with the help of compressed air during the transport from a source to the final placement site (Ministry of Transport, The Fifth District Port Construction Bureaus, 1999; Coastal Development Institute of Technology, 2008; Kitazume, 2016). The mixture of soft sediment and binder exhibits many separated mud-plugs in the pipeline, and these are thoroughly mixed during transport via turbulent flow generated within the plug. The softsediment stabilized with binder has a rapid increase in strength which can be easily controlled by changing the amount of binder and/or water content of the sediment. The sediment mixture deposited and cured at the site can gain relatively high strength rapidly so that no additional sediment improvement is required. This technique has been used successfully in many land reclamation projects including the Central Japan International Airport Construction project (Kitazume and Satoh, 2003, 2005) and the Tokyo/Haneda International Airport Expansion project (Mizukami and Matsunaga, 2015). The PFTM has the potential to reduce treatment costs by eliminating costs associated with material transport and improve the final product by creating a more uniform amended sediment. The evaluation of the PFTM method was conducted at a sediment management site in Kearny, NJ, USA operated by Clean Earth Inc., of Hatboro, PA, from July through September of 2015. The PFTM apparatus was brought from Japan and erected at the site. The PFTM was demonstrated to be an efficient and rapid method for soft-sediment stabilization with the resulting material showing the uniform quality of mix meeting NJ Department of Environmental Protection's (NJDEP) geotechnical and environmental fill placement criteria (Maher et al., 2016). In this study, the long-term strength properties of the soils stabilized by the PFTM and cured at the field was investigated by the unconfined compression test. The test results revealed that the strength of the stabilized soil increased.

FIELD TESTS

Equipment. The PFTM apparatus was brought from Japan and assembled at the site. The pneumatic flow tube mixing facility called K-DPM method (Ikegami, 1999) was one of the line addition type methods, in which the pipe diameter and transporting distance were 300 mm and around 200 m respectively. An inlet air pressure of 300 to 400 kPa was adopted in this test according to the accumulated experiences. Figure 1 shows the equipment, which consisted of a sand hopper, mixing plant, injection tube, transporting pipeline and control system. The dredged soil transported to the site was initially passed through a sieve as shown in Figure 1(a) to remove

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any cobbles or debris, and then transported to the injection tube. Next, the unit weight and volume of original soil were measured by a γ- ray densitometer and a flowmeter respectively. The cement slurry of U. S. Type II Portland cement was then injected into the mixing tube, as shown in Figure 1(b). The soil and cement mixture was transported towards the outlet, while they were mixed inside the pipeline with the help of high inlet air pressure, as shown in Figure 1(c). Finally, the stabilized soil was placed in the pond (Figure 1(d)). Figure 1(e) shows the control system, which monitored and recorded the unit weight and volume of original soil and the amount of cement slurry continuously every second.

(a) Sand hopper, sieve and mixing plant.

(b) Injection tube.

(c) Transporting pipeline.

(e) Control system.

Figure 1. Equipment for pneumatic flow tube mixing method.

Procedure of field test. The field test was carried out at the Clean Earth Dredging Technologies - Claremont from July through September of 2015. The sediment was provided by U.S. Army Corps of Engineers' AK4 site located in the Arthur Kill, NJ and transported to the Clean Earth site for processing. The physical properties of the contaminated black organic sediment are

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presented in Table 1. In order to investigate the effect of cement content on strength gain properties of the soil-cement mixture, three cement content, a_w' (defined as weight of cement divided by wet weight of soil), 4, 8 and 12% were used to create mixture ponds. The slurry water-cement ratio was kept as 100% throughout this study. Three deep and three shallow ponds were created for considering the sampling depth. The deep ponds' size were 5 m x 5 m x 2 m and the shallow ones were 5 m x 5 m x 0.5 m. Each pond were filled with the processed soil with its respective cement content. Immediately after filling the pond, five 2inch-polyvinyl chloride (PVC) pipes were installed into each pond for future sampling for unconfined compressive strength test as shown in Figure 2.

Table 1. Physical properties of dredged soils.

Pond	Liquid limit, w_L (%)	Plastic limit, w_P (%)	Plasticity index, I_p	Soil particle specific gravity, G_s	Natural water content, w_n (%)	Organic content (%)
FF4D	93	40.9	52	2.27	117.4	7.44
FF4S	82	39.3	43	2.39	204.4	6.99
FF8D	70	42.9	27	2.53	128.4	6.83
FF8S	66	35.1	31	2.42	80.8	4.61
FF12D	70	37.0	33	1.94	116.9	7.06
FF12S	55	40.6	14	2.02	124.7	7.36

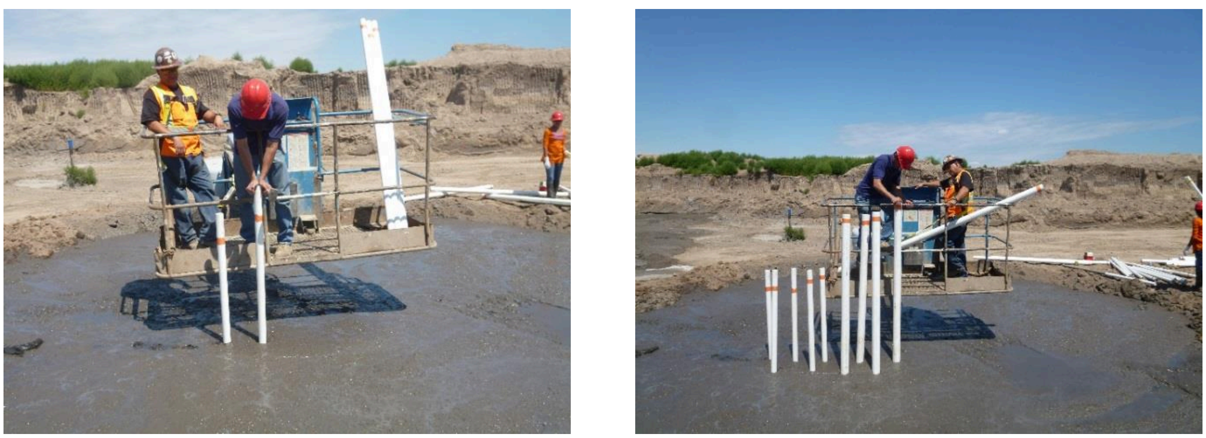

Figure 2. Installation of sampling pipes in the stabilized soil.

Monitoring and controlling execution at the field. The unit weight and volume of original soil were measured at the injection tube. The water content of the original soil was calculated by the measured unit weight with the assumption of full saturation (S_r = 100%). Figures 3(a) and 3(b) show an example of the time record of unit weight and volume of original soil for the 8% deep pond (FF8D), which scattered around 1.34 ton/m^3 and 42.5 m^3/hr respectively. The target and actual volumes of cement slurry are plotted with time in Figure 3(c), which shows the actual volume could be well adjusted based on the target volume of cement slurry. The a_w' value shown in Figure 3(d) was also well controlled except some fluctuations.

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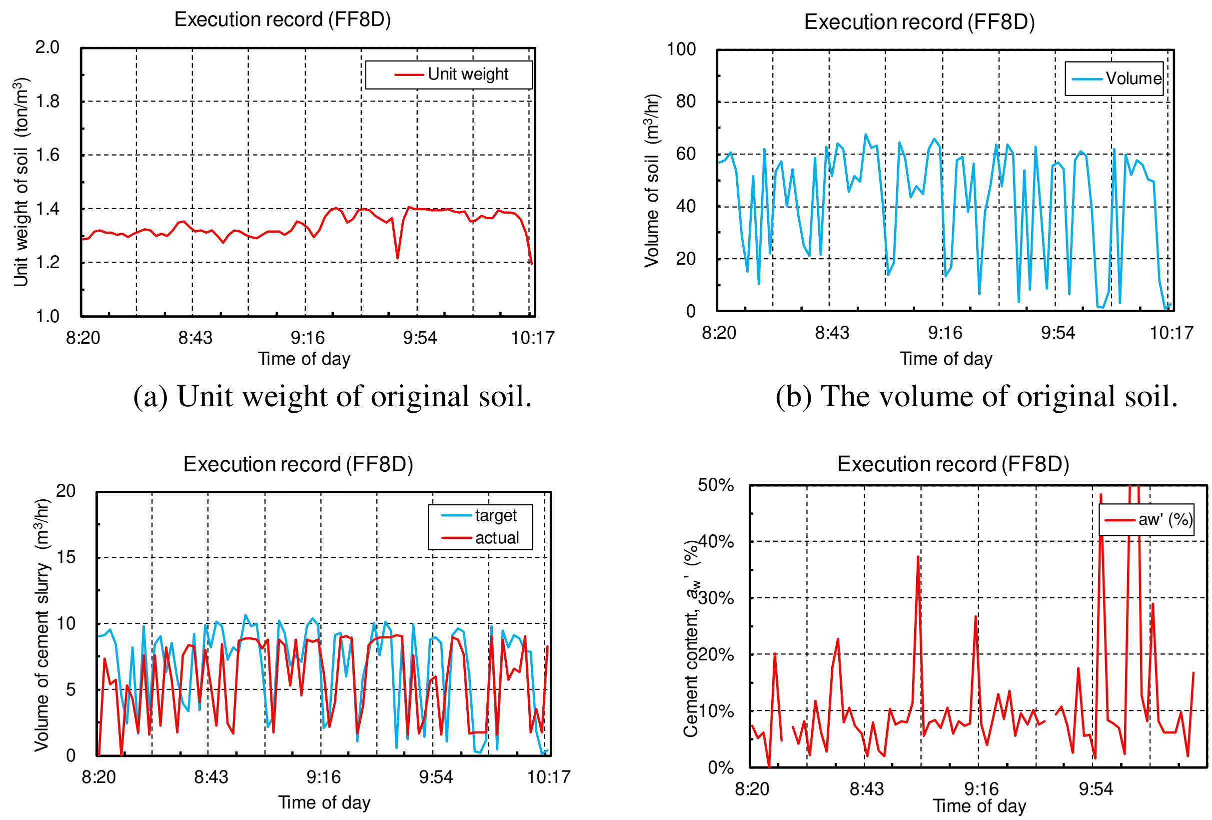

(a) Unit weight of original soil.

(b) The volume of original soil.

(c) Target and actual volume of the cement slurry.

(d) Cement content, a_w'.

Figure 3. Execution record of 8 % deep pond.

The summary of the execution is shown in Table 2. In the table, the cement content, a_w (defined as weight of cement divided by dry weight of soil) is also presented. The actual cement contents in all the test cases are slightly larger than the target values. The precision of meeting the target cement content highly depends on the initial water content measurement. The actual cement contents in Table 2 are slightly higher than the target cement content because the initial water content of the sediment were not precisely determined in this project. The control system, which controls the amount of cement in the cement slurry, assures the target cement content by using the measured unit weight and volume of the original soil. Therefore, the initial water content measurement plays an important role in determining the target cement content.

Table 2. Summary of the execution.

Pond	target cement content, a_w'	actual cement content, a_w'	actual cement content, a_w
FF4D	4 %	5.4 %	15.3 %
FF4S	4 %	5.3 %	13.3 %
FF8D	8 %	10.9 %	25.7 %
FF8S	8 %	10.7 %	25.2 %
FF12D	12 %	12.0 %	27.9%
FF12S	12 %	13.8 %	33.9%

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STRENGTH PROPERTIES OF FIELD STABILIZED SOIL

Soil sampling and testing. At 28, 205 and 362 days after the pond preparations, the PVC pipes were extracted by carefully excavating the ground next to the pipes and then the pipes were sealed to avoid moisture loss and transported to the laboratory for further testing as shown in Figure 4. The PVC pipes were cut and trimmed to make specimen with 2inch diameter and 4inch height for the unconfined compression test. The apparatus used for the test is shown in Figure 5, whose strain rate was determined as 1 %/min.

Figure 4. Soil sampling on August 2016.

Figure 5. Unconfined compression test apparatus.

Strength and water content profiles along the depth. Figure 6 shows the unconfined compressive strength, q_u and water content profiles along the depth at 28, 205 and 362 days curing. The q_u value varies along the depth at each curing period, and has the same pattern as target cement content increases. The water content profile shows the same variation in pattern with depth and curing period. The lowest water content is recorded for FF8D ($a_{w'}$ =8% deep pond) while the FFD4 and FFD12 have almost the same water content.

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