Effect of Microbial Induced Calcium Carbonate Precipitation on the Performance of Ponded Coal Ash

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Abstract-- The breach of the Kingston coal ash pond in December 2008 directed many concerns towards the mechanical stability of coal ash impoundments. The loss of shear strength as additional ash was deposited until the coal ash liquefied was the reason for this catastrophic failure. This failure led to contamination of watersheds totaling about 300 acres of the land. The poor mechanical performance of coal ash impoundments has prompted the need to investigate mitigation techniques. Microbial induced calcium carbonate precipitation (MICP) is a novel approach to improve the stability of the coal ash sediments by using natural, biological processes to cement the particles together. The tendency to capture some heavy metals remaining after coal combustion through co-precipitation is another advantage of using MICP treatment. The improvement in mechanical properties is evaluated with a series of laboratory tests and is illustrated through increases in shear stiffness, reduction in compressibility, and increases in undrained shear strength. Traditional incremental load consolidation apparatuses were modified to evaluate the effect of MICP on the compressibility and hydraulic conductivity of coal ash sediment. One-dimensional incremental load consolidation tests were performed after treating the specimens to target shear wave velocities, measured using bender elements. After finishing the incremental loading, the treated specimens were unloaded and reloaded to evaluate the degradation of the calcium carbonate bonds between particles. The effect of treatment and load application on hydraulic conductivity is evaluated by measuring imposed water pressure while injecting deionized water into the specimens. The results reveal that the compressibility of the ash material is reduced, and one-dimensional load cycling indicates that the compressibility remains improved even if the cemented bonds are degraded during the unloading-loading process. Furthermore, the maximum reduction of hydraulic conductivity caused by bio-cementation is one order of magnitude. The undrained shear strength of the treated coal ash was estimated using correlations relating constrained modulus, elastic modulus, and undrained shear strength of the material. The MICP-improved soil properties were used to evaluate the slope stability of the Kingston coal ash pond to demonstrate the potential improvement in system performance. The results indicated that increasing the initial shear wave velocity (V_s) of the coal ash to twice of its initial value using MICP could increase the factor of safety of the slope significantly.

I. Introduction

Coal Ash is a unique material compared to natural soils because of its distinct particle characteristics [1] and its chemical composition. This uniqueness leads to challenging stability-related issues. In general, coal ash ponds can face global stability issues over time due to loss of strength (e.g., Kington Spill of coal ash on December 2008 in Tennessee Valley), as well as, internal stability issues. Failures can lead to leaking of coal ash material (e.g., Dan River coal ash spill in February 2014). In addition, the potential of leaching trace elements from the stored coal ash into surface water and groundwater has also increased awareness of the environmental and human health risks posed by coal combustion residual (CCR) disposal facilities not well engineered. Reports of 40 confirmed and 113 potential damage cases of storage and disposal of CCRs has been documented in the EPA CCR Management Rule. Approximately sixty percent of induced damage in these cases is contamination of surface water and groundwater [2]. Higher concentration of chemical elements such as Arsenic, Boron, Molybdenum, Strontium, Chromium, and Selenium in some monitoring wells close to the coal ash impoundments were reported by Harkness et al. [3]. These elements might pose a risk to human health and wildlife.

Interdisciplinary research has given rise to innovative methods to improve the stability of subsurface material [4]. For instance, subsurface microbes can be employed to hydrolyze the urea in the pore fluid within subsurface porous media and convert it partially to carbonate, bicarbonate, carbonic acid, ammonia, and ammonium (equation 1). The alkalinity of the solution rises while urea is hydrolyzed which causes an increase in carbonate concentration base on acid-base equilibrium conditions. Increasing the carbonate concentration in a solution containing calcium ion saturates the porous media system leading to calcium carbonate mineral precipitation (equation 2). These minerals precipitate between the particles and bond them together which increases the strength and stiffness of the soil [5].

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$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_3 + H_2CO_3 \rightarrow 2NH_4^+ + CO_3^{2-} \quad (1)$$
$$CO_3^{2-} + Ca^{2+} \leftrightarrow CaCO_3(s) \quad (2)$$

Microbial induced calcium carbonate precipitation (MICP) is a bio-mediated improvement method that is being widely investigated for improving subsurface material properties. Current literature regarding MICP spans a broad range of applications, from geotechnical soil improvements [4]-[6] to environmental remediation of heavy metals [7]-[8]. This is also explored as a novel approach to improve stability issues of coal ash ponds using natural, biological processes. This method is ideal because it has the potential to increase the shear strength of ash sediments while maintaining the permeability of material for drainage during dewatering. Furthermore, the process has the potential of immobilizing heavy metals into the calcium carbonate mineral through precipitation and co-precipitation.

The study presented here is the first to apply MICP treatment to the coal ash material. Different material properties, such as particle size distribution, morphology, and hydraulic conductivity, are reviewed. The effect of MICP treatment on the compressibility, shear modulus, and hydraulic conductivity of the coal ash material is evaluated. These results are used to assess the effect of MICP treatment on the undrained shear strength of stabilized material. The contribution of a MICP-treated ash section to the slope stability of an ash impoundment is demonstrated by analyzing the failure case reported in Tennessee Valley [9].

II. Materials and Methods

A. Material

Each coal source and power plant produces coal ash with different characteristics. The material studied in this paper is a class-F fly ash, and it contains 3.4% carbon. Pycnometer (ASTM D 854-00), fall-cone (ISO/TS 17892-6:2004), and the falling head test [10] were conducted to measure the specific gravity, liquid limit, and the hydraulic conductivity of the material, respectively (Table 1).

The hydrometer and mechanical sieving analyses were performed in duplicate following ASTM D422-63, and the resultant grain size distributions are plotted in Figure 1.

TABLE 1.
GEOTECHNICAL PROPERTIES OF COAL ASH.

Property	Unit	Value
Specific gravity	-	2
Liquid limit	%	34
Hydraulic conductivity	ft/s (cm/s)	6.40E-6 (1.95E-4)

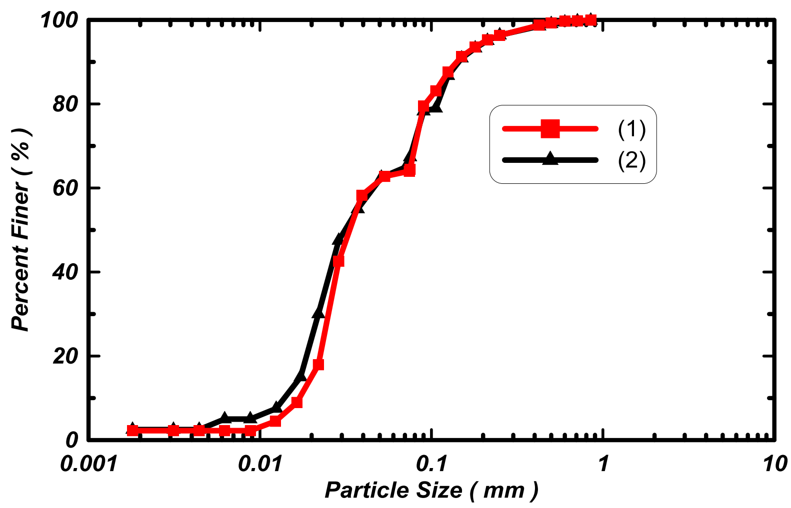

Figure 1.Grain size distribution, run in duplicate.

B. Bacteria and growth condition

Sporosarcina pasteurii (ATCC 11859), a urea hydrolyzing bacterium, was grown and used in this study. For this purpose, ammonium yeast extract medium (ATCC 1376) was used to grow the bacteria at 30 ºC. Each ingredient was autoclaved and mixed after sterilization. The growth medium was inoculated with *S. pasteurii* stock culture and incubated aerobically at 30 ºC with 200 revolutions per minute until the desired population of cells was reached assessed using optical density (i.e., OD600). Incubation stopped before reaching the plateau of growth curve to ensure likelihood of collecting active, viable cells. Cultures were centrifuged at 4000 g for 20 minutes in 15 ml vials. The spent supernatant media was replaced with fresh growth media and centrifuged a second time after suspending the cells in the growth medium. Harvested bacteria were stored at 4 ºC until used.

C. Treatment Protocol

To evaluate the effect of MICP treatment on coal ash, a modified consolidation set up was designed. Details of the new setup are presented in Figure 2. The bottom acrylic base has a port for injecting bio-treatment media; it is equipped with a piezoelectric bender element sensor at the center to monitor the stiffness of the specimens during treatment and consolidation. The acrylic top cap is equipped with the paired bender element sensor. An electrical pulse is sent to the bender element using a signal generator to make it vibrate which causes a shear wave to propagate in the material. The paired bender element sensor receives the shear wave and triggers an electrical signal due to piezoelectric properties of the transducer. The travel time of shear wave between the two benders is recorded using digital oscilloscope. Shear wave velocity (V_s) is computed by dividing the tip to tip distance of the benders by the travel time. The top cap has two holes to remove the effluent during the injection of the treatment solution. A stainless steel ring provides confinement; it also has the advantage of being electrically accessible to the specimen to reduce electrical crosstalk during shear wave velocity measurements by grounding the specimen. A porex high-density polyethylene filter material is fixated to the bottom and top caps to prevent migration of coal ash particles. The port of the bottom cap is connected to a burette with a tube to keep the specimen saturated by leveling the burette's water to the level of the specimen.

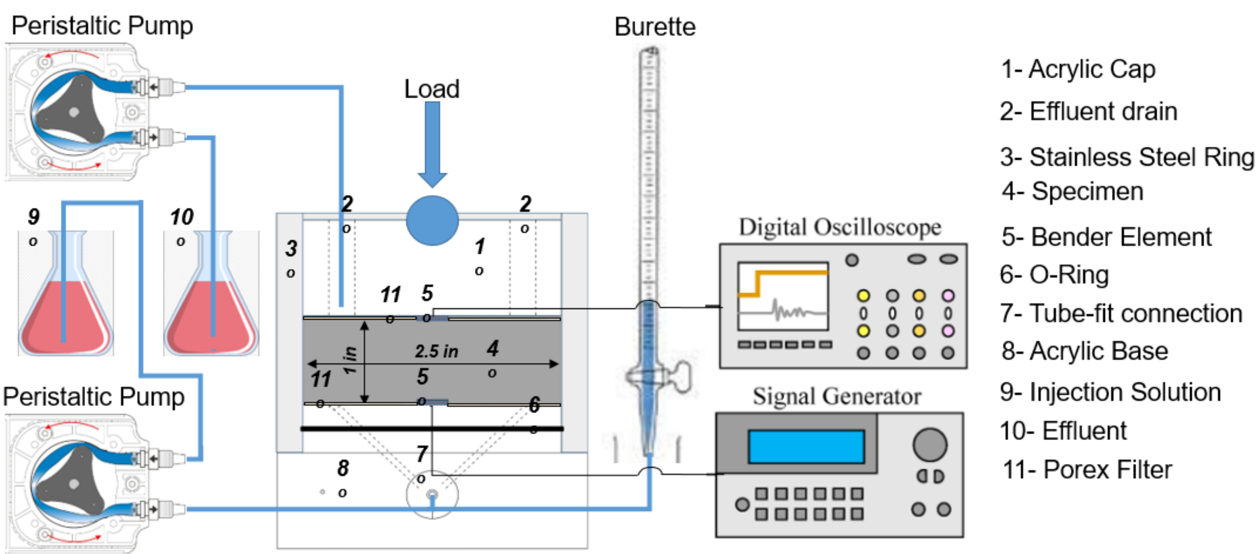

Figure 2. Schematic of devices are used in modified consolidation set-up

Fly ash was mixed with water at twice of its liquid limit to prepare a slurry sample, which was poured into the consolidation ring. Twenty-four hours was given to the specimen for deposition, and then the top cap was placed on the top of the specimen. The specimen was preloaded to 500 psf, and the initial permeability of the specimen was determined by passing water at a prescribed rate and measuring the corresponding pressure at the bottom of the specimen. Treatment of the specimen was performed by injection of bio-cementation media from bottom to top using a peristaltic pump at a rate of 11 ml/min. The recipe of the treatment media is presented in Table 2. One 15 ml of bacteria solution with an optical density of 1.0 was used for each 100 ml treatment solution. Twelve hours of retention time elapsed between each injection. Treatment stopped after reaching the target shear wave velocity (taken as 2, 3, and 4 times of the initial shear wave velocity) and two pore volumes of deionized water passed through the specimens to halt the bio-cementation process and to measure the hydraulic conductivity of the specimens after treatment. The initial height of the specimens is measured after unloading the 500 psf preload, and this height was used to calculate the initial void ratio. The last step was running the consolidation testing and recording deformation for each load increment.

TABLE 2.
RECIPE OF MODIFIED CONSOLIDATION TREATMENT.

Chemical Component	Urea (CH_4N_2O)	$CaCl_2.2H_2O$	NH_4Cl
Concentration (mM)	400	100	100

D. Mass of CaCO3(s)

The acid washing method was performed to measure the mass of calcium carbonate. The oven-dried mass of each soil column section was recorded before and after washing with 1 M of HCl. The dissolved calcium carbonate and acid solution were rinsed multiple times allowing the dissolved salts to be rinsed from the soil. The difference between the two measured masses was taken as the mass of calcium carbonate. The calcium carbonate percentage is calculated by dividing the mass of calcium carbonate to the mass of the soil [5]. Particles of fly ash are fine, and it takes a long time (dependent on the size of particles) for deposition of particles after each time acid washing. Therefore, the centrifuge was used to speed up the ash deposition process during acid washing process.

III. RESULTS

Four specimens were prepared using water pluviation method: one was a baseline (untreated) specimen, and three were treated to have three different levels of cementations. The target V_s of the specimens 1, 2, and 3 were 2, 3, and 4 times of the initial shear wave velocity (V_s), respectively. The initial V_s (V_{si}) was measured under 500 psf pressure. The shear wave velocity of the specimens was also measured before each injection to track the trend of treatment (Figure 3). The rate of increasing V_s was approximately 20 m/s (65 ft/s) per injection.

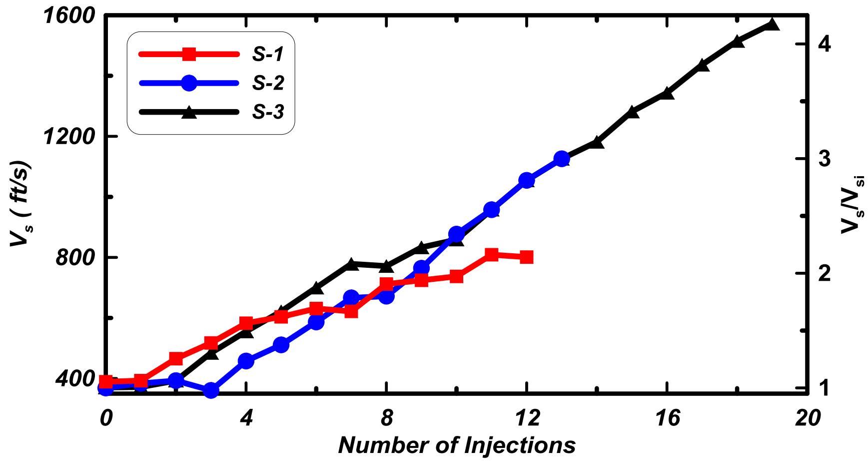

Figure 3. Shear wave velocity during treatment before consolidation test.

Hydraulic conductivity of the specimens was measured before and after the treatment (Table 3). By increasing the number of injections and the corresponding shear wave velocity, the hydraulic conductivity of the specimens slightly decreased. At the maximum level of cementation ($4V_{si}$), the permeability of the specimen decreased to 7% of the initial hydraulic conductivity with the same pressure.

The specimens were unloaded after treatment, and the initial height was measured. Incremental loading was applied to the specimens. In addition to measuring deformation and stress, hydraulic conductivity of the specimens was determined using the modified consolidation set up. The strain values at different incremental loads are plotted in Figure 4. In these graphs, BL1(T) and BL2(T) represents the results of consolidation test from "traditional" odometer testing. There is a proper compatibility between the results from the untreated specimen (BL(M)) using the modified set up and the results from "traditional" odometer test, and it shows that the modification does not impact the data obtained from modified consolidation test.

TABLE 3.
HYDRAULIC CONDUCTIVITY BEFORE AND AFTER TREATMENT.

Specimen	Pressure	Hydraulic conductivity		k/k_0
		Before treatment	After treatment	
-	psf	ft/s (cm/s)		-
Baseline	500	1.50 E-06 (4.57E-05)		1
S1		2.10E-06 (6.60E-05)	6.59E-07 (2.01E-05)	0.3
S2		3.02E-06 (9.22E-05)	5.51E-07 (1.68E-05)	0.18
S3		2.50E-06 (7.62E-05)	1.81E-07 (5.51E-06)	0.07

The effect of MICP on decreasing the compressibility of the specimens is significant. The strain at an applied stress of 32,000 psf is around 15% for the baseline specimen. This value is decreased to approximately 10% for specimens with 2 and 3 times the initial shear wave velocity. The strain magnitude is 7% in the case of the specimen stabilized to the level of four times initial shear wave velocity (less than half the value obtained for the baseline specimen). The effect of cementation is more significant at the lower levels of load. Increasing the load breaks the bonds between particles. As the load increases, the behavior of the specimens with different levels of cementation tends to be more similar. The coefficient of volume change (m_v) is estimated from load-strain curves (Figure 5). The data confirms that the compressibility of the specimens decreases with MICP treatment with such a decrease being more significant at lower levels of load.

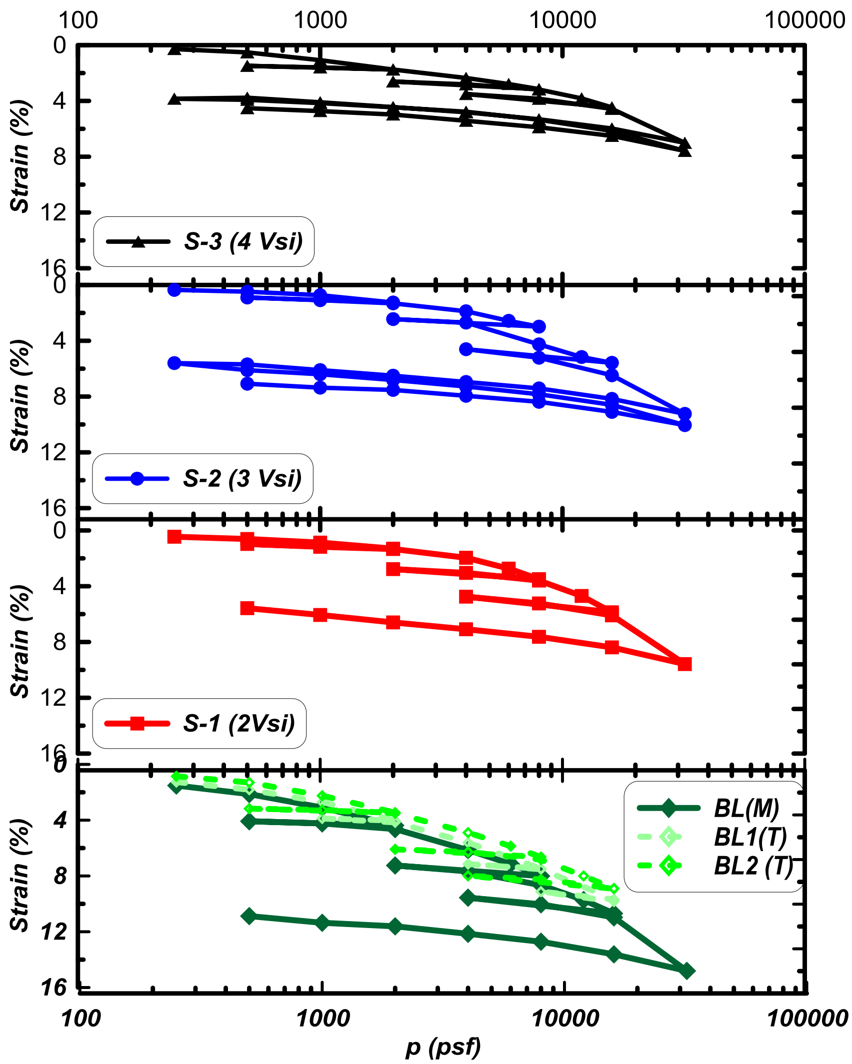

Figure 4. Resultant strain of incremental loading test.

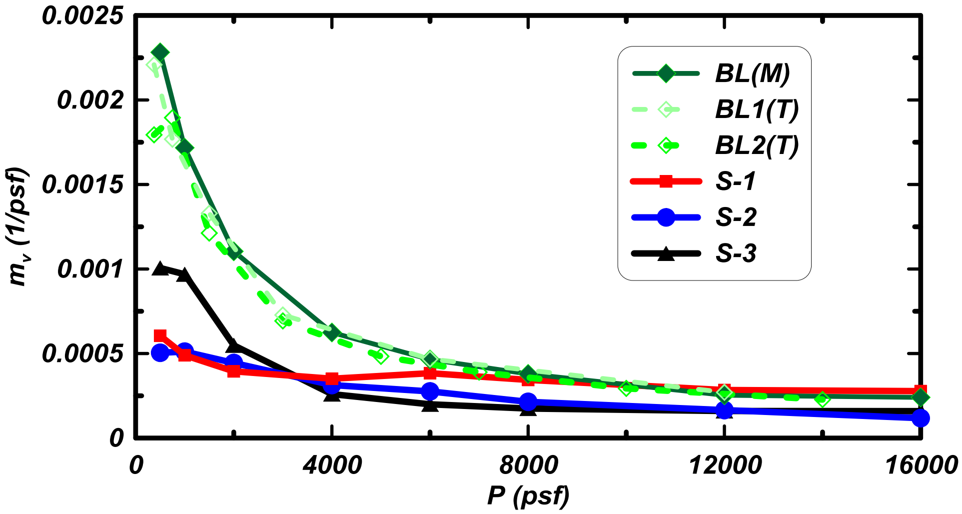

Figure 5. Coefficient of volume change.

Deionized water was injected into the specimens at a rate of 1 ml/min, and the pressure of the injection was measured after consolidation under each incremental loading. This pressure head was used to compute the hydraulic conductivity (Figure *6*). There are two points for treated specimens under 500 psf pressure in this figure, the higher value is related to the untreated condition, and the lower value is permeability of the specimen after reaching the target V_S.

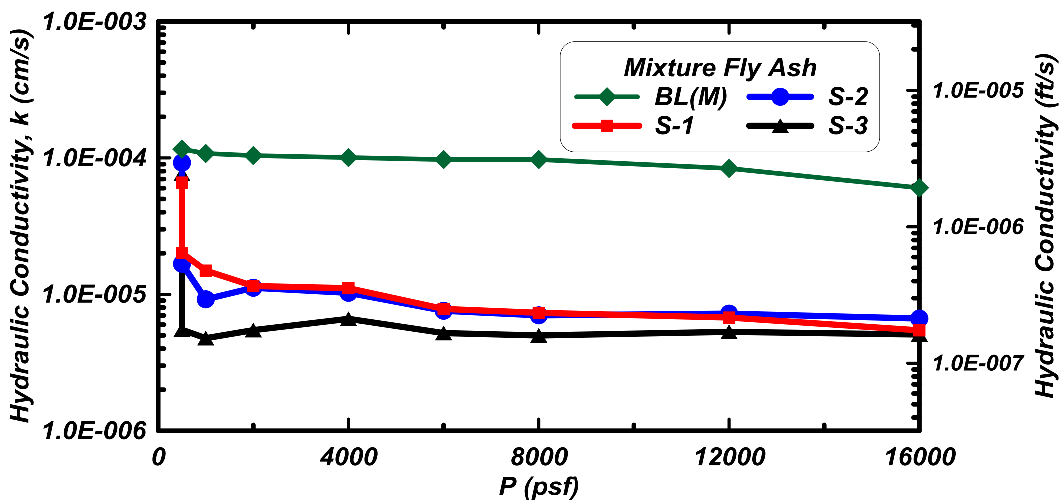

Figure 6. Hydraulic conductivity, modified consolidation test.

Percentage of calcium carbonate of the treated specimens was measured using acid washing method (Table 4). Two percent mass loss was observed on untreated specimens during the acid washing process; therefore, the mass of calcium carbonate was adjusted to account for mass change not associated with precipitated calcium carbonate. The height of the specimens was short, and the test was performed only on one sample per specimen, which represents the average percent of calcium carbonate.

TABLE 4.
PERCENT OF CALCIUM CARBONATE OF MICP TREATED FLY ASH SPECIMENS.

Specimen	CaCO3 (%)
S-1	3.3%
S-2	4.2%
S-3	7.0%

IV. CASE STUDY

After the Kingston dredge cell failure on December 22, 2008, AECOM Technology Corporation conducted a comprehensive analysis to determine the root cause of the failure. The conclusion of the study was failure occurred due to three major possible destabilizing factors; rainfall, rapid reservoir drawdown, and rate of loading due to increased height of fill. Based on the recorded data by Tennessee Valley Authority (TVA), On December 21, 2008, the level of rainfall was 8 inches higher than normal for one month. The level of water in Watts Bar reservoir pool was lowered nearly 3 feet after December 11 rain. The yearly vertical filling rate was at the highest rate based on TVA observations (4 to 6 ft /year). All these factors lead to an increase of pore water pressure (PWP) and decreasing the effective stress, which imposed loading in an undrained mode.

The pre-failure topographic information and the material properties of the failed cross section are extracted from AECOM report (2009) to model the slope and assess the effect of MICP treatment scenarios on stabilization of the slope. The selected section is the north-south section through the northwest part of Dredge Cell 2 where the initial failure occurred. The cross-section of the failed slope is presented in Figure 7, and the corresponding material properties are provided in Table 5.

The slope stability analyses were performed using SLOPE/W 2016 (Version 8.16.2). SLOPE/W™ is able to compute the global factor of safety by multiple traditional methods, for various slope geometries, stratigraphy, soil strength, porewater pressure and imposed loading, using a force and moment limit equilibrium approach. The analysis type selected for modeling the slope is Morgenstern-Price. In this type of analysis, the direction of the resultant interslice forces is initially defined using an arbitrary function. The fractions of the function value needed for force and moment balance is computed according to Morgenstern and Price approach [11].

Olson and Stark [12] indicated that the normalized peak undrained shear strength of the material is correlated to the void ratio. This ratio, also called peak strength ratio, can be utilized to estimate the peak undrained strength in-situ. Based on the stated results in the AECOM report (2009), a peak strength ratio of 0.3 is used in slope stability analysis for the coal ash material; this is similar to the slope stability analysis presented in the AECOM report (2009).

The resultant phreatic water surface from seepage analysis reported in the AECOM report is considered for modeling. Different slip surface options were tried, and the software program was allowed to change the shape of slip surface in order to minimize the resultant factor of safety. The block slip surface was defined in the slimes layer (see Figure 7) to force the slip surface to pass the weak layer. A factor of safety of 0.97 was determined using block slip surface. The same factor of safety (0.97) was reported in the AECOM report. To generalize the case study, the weak layers beneath the coal ash (e.g., the slimes) were replaced by the coal ash material. The new section was analyzed, and replacing the slime with coal ash increased the factor of safety slightly to 0.99. The generalized section is then used to assess at the effect of MICP treatment on the stability of the slope.

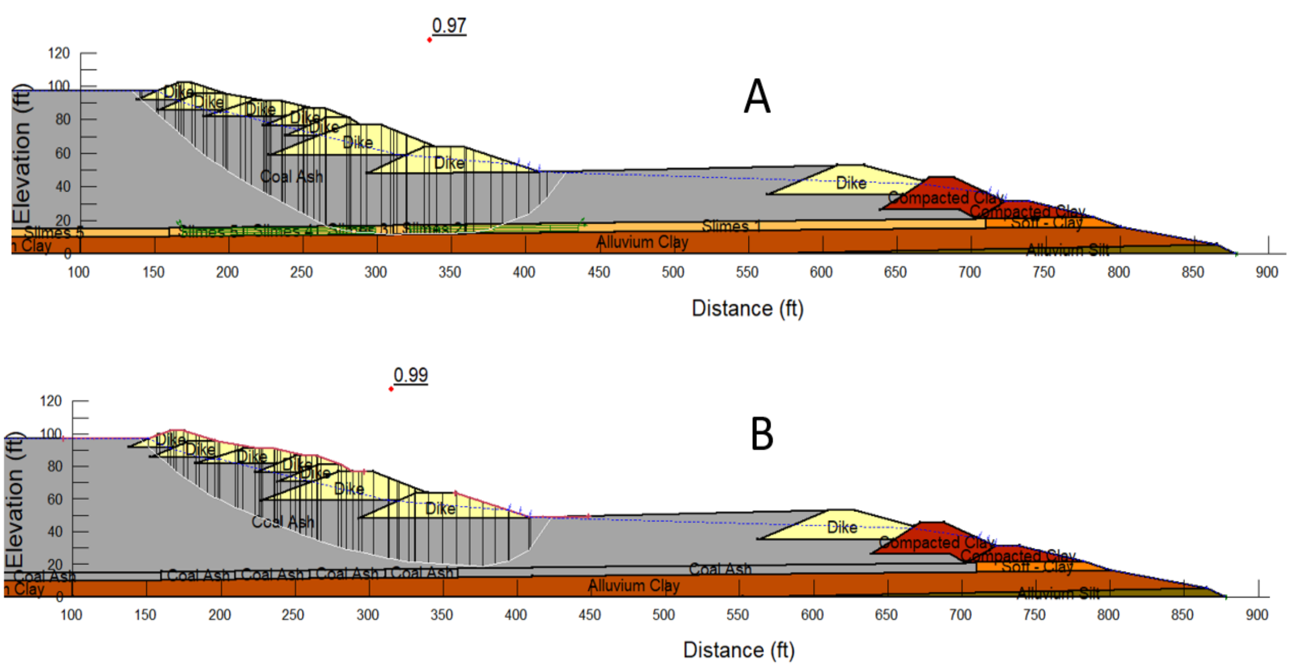

Figure 7. A) Cross section of failed slope in Dredge Cell 2, B) Generalized Section

TABLE 5.
MATERIAL PROPERTIES AND BEHAVIOR MODELS IN TVA SLOPE STABILITY MODELING

Martial	Unit weight (pcf) Below GW	Model	Analysis	type	value
Coal Ash	107	S = f (σ'_v)	Undrained	$S_u/\ \sigma'_v$	0.3
Dike	110	Mohr - Coulomb	Drained	φ'	37
Slime 1	90		Undrained	Su (psf)	600
Slime 2	90		Undrained	Su (psf)	700
Slime 3	90		Undrained	Su (psf)	800
Slime 4	90		Undrained	Su (psf)	1000
Slime 5	90		Undrained	Su (psf)	1250
Slime 6	90		Undrained	Su (psf)	1400
Alluvium - Clay	120		Undrained	Su (psf)	1200
Alluvium - Silt	130		Drained	φ'	30
	130			c' (psf)	600
Compacted Clay	120		Drained	φ'	15
	120			c' (psf)	600

V. EFFECT OF MICP TREATMENT ON THE SLOPE STABILITY

MICP treatment can improve the stability of the slope by increasing the shear strength of the coal ash. The results from modified consolidation testing are used to evaluate the undrained shear strength of the specimens. For this purpose, the correlation between the coefficient of volume change (m_v) and Young's modulus (E) (equation 3) is utilized to determine the elastic modulus of the coal ash specimens at different levels of effective vertical stress. The Poisson's ratio of the normally consolidated coal ash is determined using equation 4. The friction angle is assumed to equal to 30 degrees based on the AECOM report, and corresponding Poisson's ratio of 0.33 is used. The ratio of s_u/σ'_v of untreated specimens is equal to 0.3 based on AECOM report. The ratio of $K_i(\sigma'_v)= E/s_u$ at each vertical stress is determined for baseline (untreated) specimen, and these values are used to find the corresponding undrained shear strength of treated specimens (s_u=E(treated)/K_i). The effect of treatment on elastic modulus and undrained shear strength of coal ash is presented in Table 6 for the specimen treated to twice the initial shear wave velocity. Based on the overburden pressure and the unit weight of fly ash, the average depth of corresponding vertical effective stress are calculated in Table 6.

$$E=\frac{(1-2\upsilon)(1+\upsilon)}{(1-\upsilon)m_v} \qquad (3)$$

$$\upsilon=\frac{1-\sin\varphi}{2-\sin\varphi} \qquad (4)$$

TABLE 6.
ELASTIC MODULUS AND UNDRAINED SHEAR STRENGTH CALCULATIONS

σ'_v	0.3 * σ'_v	depth (ft)			Base-Line				Two Times		
					m_v	E	K_i	S_u	m_v	E	S_u
(psf)	(psf)	average	from	to	(1/psf)	psf	-	psf	(1/psf)	psf	psf
500	150	5	0	7.5	2.28E-03	29578	197	150	6.05E-04	111538	566
1000	300	10	7.5	15	1.72E-03	39307	131	300	4.90E-04	137810	1052
2000	600	20	15	30	1.10E-03	61107	102	600	3.95E-04	171018	1679
4000	1200	40	30	50	6.25E-04	108085	90	1200	3.51E-04	192308	2135
6000	1800	60	50	70	4.65E-04	145212	81	1800	3.84E-04	175970	2181
8000	2400	80	70	100	3.79E-04	177916	74	2400	3.44E-04	196253	2647

The results of untreated slope stability indicated that the critical slip surface is passing from an area close to the toe of tailing dams through the coal ash material. Improving the coal ash beneath the toe area and near the top of impoundment close to the tailing dams is the most feasible and efficient areas. These areas were considered to be improved by MICP treatment method to monitor its effect on the factor of safety. Three scenarios are defined in the modeling. For all of them, the width of improvement on the top of impoundment is 50 ft, and the width of the toe area is 80 ft. In scenario 1 and Scenario 3, the depth of improvement considered to be 15 and 30 ft, respectively. In scenario 2, the depth of improvement is 15 ft, in upstream area, and 30 ft in the toe area which is considered an intermediate alternative between scenarios 1 and 3. The unit weight of the treated fly ash has not changed in the modeling, and the undrained shear strength presented in Table 6 are the material properties introduced into the program for different layers of improvement. The undrained shear strength model is used to analyze the effect of improved layers. The results of modeling the slope stability analysis for different scenarios are demonstrated in Figure 8. The factor of safety for scenario 1, 2, and 3 increased to 1.11, 1.17, and 1.35, respectively. These results indicated that increasing the level of calcium carbonate corresponding to an increase in V_S to twice the initial V_S can improve the structural stabilization of coal ash.

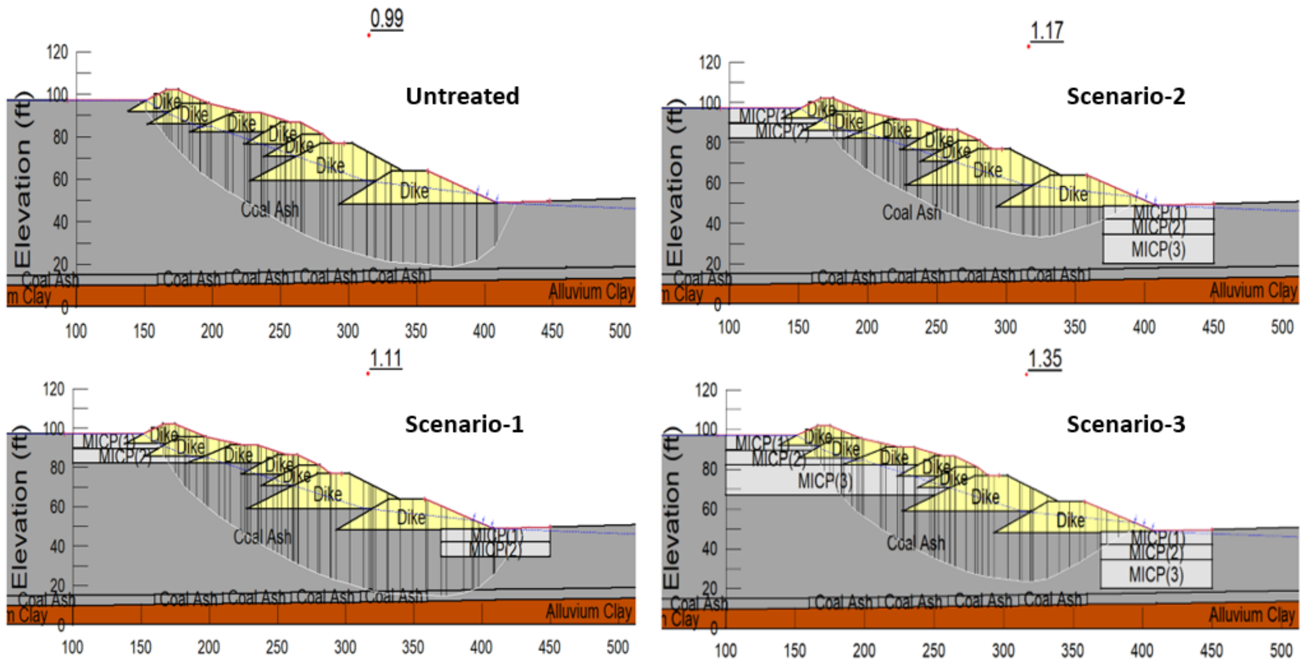

Figure 8. Effect of depth of MICP improved layer on critical failure surface and factor of safety.

VI. Conclusions

In the study presented herein, the effect of MICP treatment on the properties of coal ash is experimentally evaluated. For this purpose, the traditional consolidation set up was modified, and the ability to measure permeability and the shear wave velocity was added to the setup. The specimens were successfully treated using specified recipe, and the treatment rendered the specimens at the predefined target shear wave velocities ($2V_{si}$, $3V_{si}$, and $4V_{si}$) representing three different levels of cementation. The effect of MICP treatment on the hydraulic conductivity of the specimens was assessed, and the results indicated that maximum level of cementation of these tests could decrease the hydraulic conductivity by one order of magnitude. The incremental consolidation test was performed on the untreated and treated specimens to evaluate the effect of MICP treatment on the compressibility of the coal ash. The results indicate this method of treatment could decrease the compressibility significantly. At a vertical stress of 32,000 psf, the strain level of the treated specimens decreased to 9, 10, and 7% for $2V_{si}$, $3V_{si}$, and $4V_{si}$, respectively, compared to 15% strain for the untreated specimen. Increasing the pressure level on the specimens breaks the bonds between particles, and the behavior of the specimens with different levels of cementation tends to be more similar. Based on computed values of the coefficient of volume change, the effect of MICP treatment on reducing the compressibility decreased by increasing the level of pressure. The mass of calcium carbonate was measured using acid washing method with the assistant of the centrifuge, and it was 3, 4, and 7% for 2Vsi, 3Vsi, and 4Vsi, respectively.

The stability analyses of a cross section of failed coal ash impoundment in Kingston was modeled and validated using the information provided in AECOM (2009) report. The undrained shear strength of MICP treated specimens was assessed based on moduli data from consolidation testing. Three scenarios of ash stabilization, in terms of location, were introduced into the slope stability model to investigate the potential of improving the factor of safety. The properties corresponding to 2Vsi were used for the improved layers. The slope stability analyses indicated that by increasing the depth of treatment to 15, and 30 ft, the factor of safety was increased to 1.11, and 1.35, respectively, from a factor of safety of 0.99 with no treatment zones within the impoundment.

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Shahin Safavizadeh is a Ph.D. candidate in Geotechnical Engineering from North Carolina State University (NCSU). He is the president of Geo-Institute Graduate Student Organization (GI-GSO) at NCSU. He is working on the stabilization of coal ash impoundment using a novel approach, Microbial Induced Calcium Carbonate Precipitation (MICP). He is evaluating the effect of MICP treatment on improving the structural and leaching behavior of coal ash impoundments. His work includes both experimental work and numerical modeling. His research is the first study on the MICP treatment on the coal ash material.

Prior to his Ph.D., he received his Master's of Science in Geotechnical Engineering from Amirkabir University of Technology in Tehran, Iran. His Master's research was on the "Effect of top soil improvement on the performance of Piled Raft Foundations on a calibrated soft clayey soil." He received his Bachelor of Science in Civil Engineering also from Amirkabir University of Technology.

