ERDC/GSL TR-18-33

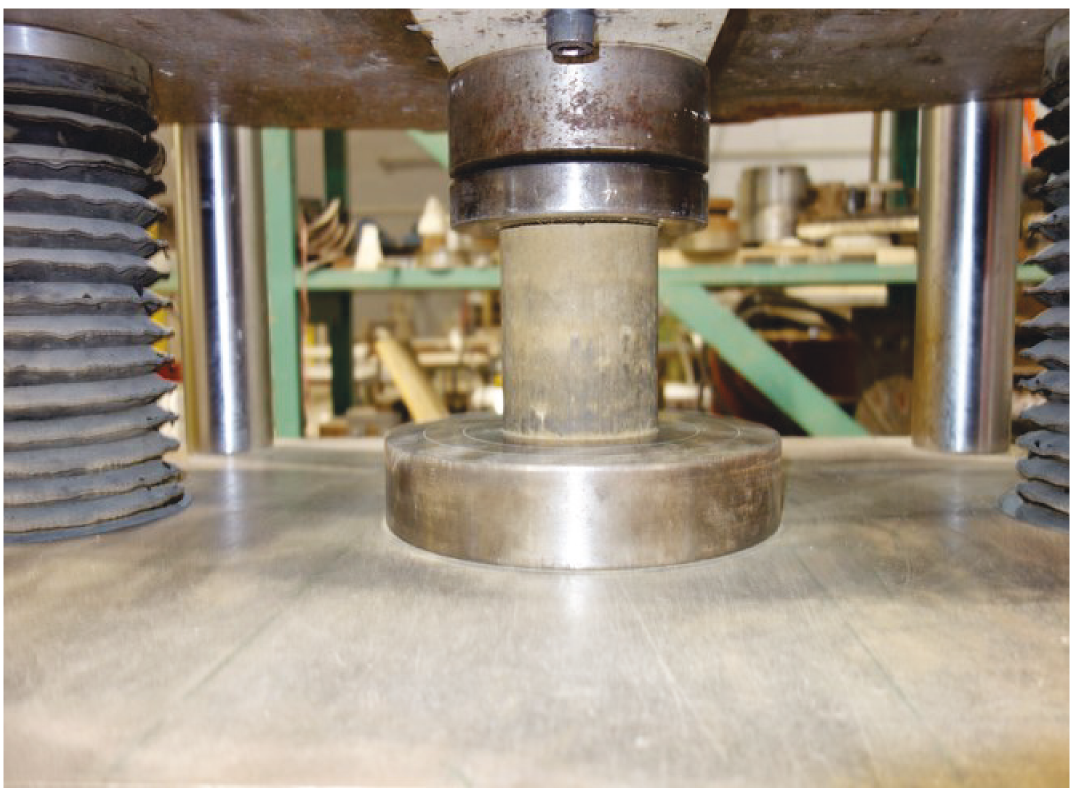
Geotechnical and Structures Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Laboratory Evaluation of Next-Generation Backfill Materials and Methods for Airfield Damage Repair

Tyler R. Johnson, Charles A. Weiss, Jr., Lulu Edwards, Jeb S. Tingle, Whittney S. Harmon, and Trevor J. Talbot

December 2018



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Final report

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Abstract

During the period March through October 2016, research was conducted at the U.S. Army Engineer Research and Development Center in Vicksburg, MS, to develop alternative backfill materials for rapid airfield damage repairs using a variety of commercially available products. The performance of a variety of additives, including 15 traditional and non-traditional materials, and a control comprised the test matrix of stabilization additives. The types of additives included cement, polymer, polyurethane, petroleum emulsion, and silicates. This report presents the technical evaluation of the laboratory and field performance of alternative backfill materials used in the subgrade of concrete repairs using Rapid Set Concrete Mix®. The additive performance criteria focused on bearing capacity, unconfined compressive strength at 2 hr and at 7 days, and durability of the specimen when partially submerged in water. Laboratory testing included mixing silty, clayey sand soil with each of the additives at specified application rates; compacting; curing; and conducting unconfined compressive strength and California Bearing Ratio testing. For the field evaluation, a repair consisted of preparing the subgrade with a selected additive and overlaying it with Rapid Set Concrete Mix®. Passes-to-failure rates for each repair were determined by using an F-15E load cart at a maximum of 3,500 passes.

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Preface

This study was conducted for the U.S. Air Force Civil Engineer Center (AFCEC) under the Rapid Airfield Damage Repair (RADR) Program. The technical monitor was Dr. Craig Rutland, AFCEC.

The work was performed by the Airfields and Pavements Branch (GMA) and the Concrete and Materials Branch (GMC) of the Engineering Systems and Materials Division (GM), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Dr. Timothy W. Rushing was Chief, CEERD-GMA; Mr. Christopher M. Moore was Chief, CEERD-GMC; Dr. G. William McMahon was Chief, CEERD-GM; and Mr. R. Nicholas Boone, CEERD-GZT, was the Technical Director for Force Projection and Maneuver Support. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Mr. Bartley P. Durst.

COL Ivan P. Beckman was the Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per inch	175.1268	newtons per meter
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.002204	grams
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
tons (force)	8,896.443	newtons

1 Introduction

1.1 Problem

The U.S. Army Engineer Research and Development Center (ERDC) has been continually refining airfield damage repair (ADR) solutions. Since 2006, the ERDC has conducted intensive research to develop and refine expedient concrete pavement repair techniques in an effort to update repair guidance for military airfields under the ADR Modernization Program. Expedient methods to repair damaged pavement as quickly and efficiently as possible has been the goal of the research at ERDC, with topics ranging from equipment and materials to placement techniques.

The ADR Modernization Program's objective is to improve the U.S. Air Force's (USAF) ability to rapidly repair damaged airfields for all of the diverse mission scenarios. The first mission scenario includes the ability to recover a main operating base after an attack. This includes the requirement to be able to repair a small number of large craters created by conventional weapons and a large number of small craters created by multiple warhead munitions. In a second scenario, USAF engineering forces are tasked with performing expedient repairs to open a base for initial operations after an attack, seizure by friendly forces, or a natural disaster. This scenario requires the ability to deploy minimal assets and perform rapid repairs of a temporary nature to provide initial operational capability for a particular airfield. Once U.S. forces have established operations at a forward installation, the repair mission shifts to a sustainment mission, where the objective is to perform maintenance and upgrades of the existing pavements to keep the airfield operational. Furthermore, in some deployed locations, it may become necessary to expand the operating surfaces to accommodate additional aircraft or to bypass severely damaged pavement sections.

Rapid Airfield Damage Recovery (RADR) focuses on optimizing the repair methods. Therefore, time is a critical factor, either to restore flying operations or to minimize airfield closures. The time required to return the airfield to operational status directly impacts capability to launch and recover aircraft sorties and meet air-tasking order requirements. Of comparable importance is the quality and durability of the repair as evidenced by the number of aircraft passes sustained by a repaired surface before repairs are needed again.

Previous research and development activities identified new materials, equipment, and processes for effectively repairing craters on the designated minimum aircraft operating surface (MAOS) runway/taxiway. The technical solutions were fully validated under realistic conditions during the Critical Runway AssessmenT and Repair (CRATR) Joint Capabilities Technology Demonstrations (JCTD). The Operational Utility Assessment (OUA) of the CRATR JCTD focused on the repair of several small craters.

One of the material solutions that has been proven for backfill is flowable fill, which is a low viscosity, grout-like, cementitious blend commonly composed of portland cement, fine aggregate, and water. Other materials such as fly ash, slag, foundry sand, bottom ash, and chemical admixtures are also commonly employed in flowable fill blends. Flowable fills can be designed for either conventional or rapid-setting times, depending upon the type and amount of cementitious materials and chemical admixtures used. The material is self-leveling and self-compacting and flows under gravity to fill all available voids.

Common applications of flowable fill include utility cuts and pipe bedding. Commercially available materials are limited in application to rapid pavement repair due to the requirement of developing the necessary strength to support rigid and flexible capping procedures immediately following placement. After 30 min, the flowable fill must possess significant bearing capacity to accommodate construction traffic in an expedient ADR scenario.

Rapid-setting flowable fill properties established to accommodate the RADR process include (1) an unconfined compressive strength of 250 psi after 30 min of cure time and 750 psi after 3 hr of cure time, (2) optimal flowability as indicated by 8 to 12 in. of flow consistency, and (3) minimal shrinkage and subsidence potential. Buzzi Unicem Utility Fill 1-Step 750 is a rapid-setting flowable fill material that has been selected for rapid ADR operations due to its additional ability of being placed without the need for external mixing.

Flowable fill is traditionally mixed and placed using either a drum or a volumetric type mixer. This technique uniformly distributes moisture, resulting in optimal flowability and the achievement of ultimate compressive strength. The Buzzi Unicem 1-Step 750 can also be placed by the dry method. The dry method is an expedient placement technique in which the pre-blended dry material is dispensed directly into the excavation, eliminating the requirement for a dedicated mixer. Following the placement of thin lifts of dry material (4 to 6 in.), water is metered (40–50 gal) onto the surface and allowed to percolate through the dry material. Placement using the dry method sacrifices some of the beneficial properties of flowable fill, including self-leveling and loss of up to 30% of the compressive strength. However, the material can be placed expediently with minimal equipment and provides sufficient bearing capacity for heavy aircraft pavement applications.

Another proven method for ADR is using Rapid Set Concrete Mix® for the repair cap. It has high early strength and meets load carrying capacity requirements for the ADR program after 2 hr of curing. This material was selected over the other materials for its ease of use. The main cementitious component in the mix is Rapid Set Cement, a proprietary, calcium sulfoaluminate-based material. The cement component differentiates the product from traditional high early strength concrete, which is typically composed of Type III portland cement and has a set time of several hours, compared to 30 min with Rapid Set Concrete Mix®. The aggregate contained in the mix is ⅜-in.-maximum-size pea gravel.

The dry blend of cementitious material and aggregate is stored in large 3,000-lb super sacks fabricated from woven geotextile material and lined with plastic. Each super sack of dry rapid-setting material provides approximately 25 ft^3 (0.926 yd^3) of repair material. The pre-blended material requires only the addition of water, does not require the use of local aggregates, and can be mixed in a variety of types of concrete mixing equipment.

Rapid Set Concrete Mix® has a fast set time of 20 to 30 min, depending on the air temperature. Bulk citric acid is typically added to the mix water to increase the working time of the material and to prevent flash setting of material within the mixer when the ambient temperature is above 50°F. In cold weather environments, an alternative additive, aluminum sulfate, is used in order to achieve a 2-hr cure time.

More recently, the ERDC has concentrated on the refinement of RADR techniques, specifically on methods to make the process lighter and leaner. The Rapid ADR (RADR) program offers solutions for the rapid-recovery-after-attack phase of ADR (Air Force Civil Engineer Center 2016). While the current methods of repair have been proved, alternatives must be provided in the instances that the large quantity of materials cannot be brought into the repair site. Utilizing locally available materials with minimal additives and additional equipment would be an ideal alternative solution.

1.2 Objective and scope

The objective of the research presented in this report was to develop alternative backfill materials that can withstand 3,500 passes of an F-15E aircraft load, while also reducing the Rapid Set (CTS Cement Co.) concrete mix cap thickness. The focus of this report centers on the laboratory testing in preparation for field evaluation of a subset of these materials. The field testing involved the repair of base and subbase layers of pavements while maintaining a 6-in. rapid-setting concrete cap. The performance of the repair was determined by visual inspection after a controlled number of passes of a vehicle that simulated the loading condition of a fully loaded F-15E aircraft. Following completion of these steps, design guidance for rapid placement for backfill of base materials will be developed or improved.

1.3 Literature review

Traditional laboratory tests of stabilized soils for airfield construction were completed to evaluate the soils' engineering properties, including compressive strength D 1633 (UCS; ASTM 2007c), California Bearing Ratio (CBR; ASTM 2016), and laboratory compaction using modified effort-modified Proctor (ASTM 2012). There are numerous references delineating the materials used for stabilization of soils that relate to the type of soil being stabilized. In an effort to find the most effective stabilizer for a given soil, a variety of nontraditional stabilization additives has led to various attempts to categorize products according to their active components. Oldham et al. (1977) gave an account of possible stabilizers identified by the Corps of Engineers researchers from 1946 to 1977. The report identified potential stabilizers including acids, asphalt, cement, lime, resins, salts, and silicates. It indicated that the performance of the type of stabilizer differed for different soil types. Many of the products the report evaluated no longer exist, making modern day comparisons to the research problematic.

Tingle et al. (2004) evaluated seven chemicals to stabilize both clay-rich and sandy soils. The researchers saw strengths approaching 700 psi for samples cured for 28 days. The typical minimum value recorded at 28 days for a cement-stabilized base course is 500 psi, and the typical subbase is 200 psi under rigid pavement (O'Donnell 2009; UFC 2001; UFC 2004). They subdivided stabilizers into the following groups: traditional additives, salts, acids, enzymes, ionic additives, polymers, lignins, silicates, and mineral pitches; and they evaluated them based on the way they stabilized soils. In addition, Tingle et al. (2007) investigated the mechanisms for stabilization of ionic additives, enzymes, lignosulfonates, salts, asphalt emulsions, polymers, and tree resins. The research related the particle size to the most effective type of stabilization: fine-grained soils such as clays and silts can be stabilized through chemical means, whereas coarser soils like sands are stabilized more effectively through physical stabilization.

A comprehensive reference on the recommended practice for stabilization of subgrade soils is given in a report supported by the National Cooperative Highway Research Program (Little and Nair 2009). It presents the protocol for use of calcium-based stabilizers such as portland cement, lime, and fly ash. In the protocol, the selection of each stabilizer is validated based on mixture testing; subsequently, the amount of stabilizer for a particular soil is defined based on consistency testing, strength testing, and in some cases modulus testing. A review on the effectiveness of a variety of stabilization techniques for clay-rich soils included the use of sodium hydroxide additive, fly ash geopolymeric binder, various ashes, and cementitious binders (Zaliha et al. 2013).

Kolias et al. (2005) evaluated the use of high-calcium fly ash and cement to stabilize clayey soils. The report points out the importance of improved subgrades for use with conventional flexible pavements. This research confirmed commonly held knowledge that stabilization through blending soils with materials such as cement and fly ash is an efficient method and has potential to produce great results.

Orts et al. (2007) described the use of polyacrylamide (PAM) copolymers that take advantage of their ability to stabilize and add structure to soil in order to eliminate sediment erosion. A mixture of PAM, aluminum chlorohydrate, and cross-linked poly (acrylic acid) superabsorbent at a ratio of 6:1:1 has been applied to create helicopter landing pads and was specifically developed to minimize dust clouds during landing of helicopters in fine, arid soils such as those potentially encountered in the Middle East. The authors also describe a biodegradable alternative to PAM, acid-hydrolyzed cellulose microfibrils, that show promise but must be applied at much higher concentrations than PAM. Liu et al. (2011) described the use of an acetic-ethylene-ester polymer for use in stabilization of clayey soil slopes. At levels of about 5%, the strength increased and the erosion rate lowered compared to nonstabilized soils. Kolay et al. (2016) studied the effect of a liquid acrylic polymer on fine-grained soils. The research centered on measurements made at the optimum water content for the soils and compared them with measurements of soils at lower water contents. The researchers point out that there was observable cracking in the soils made at optimum water content and that the ones at lower water contents had higher strengths. Bekkouche and Boukhatem (2016) evaluated the use of PVC and HDPE as an additive to stabilize clay-rich soils. They found that these materials have the ability to add toughness to the soils and reduce permeability. They also noted that the typical cure needed to yield positive results is typically longer than that of soils blended with cement and fly ash.

Graber et al. (2006) pointed out that the efficiency of a surface application of polymer for stabilization and lower erosion is related to the molecular weight of the polymer. They also show that the applicability of using lower weight polymers depends on soil texture. In finer-grained soils, a medium weight polymer can be used; in clay rich soils, however, a higher weight polymer is more efficient.

Jayanthi and Singh (2016) looked at the state-of-the-art in stabilization with an eye toward use of sustainable materials such as slag cement, kiln dust, silica fume, fly ash, rice husk ash, and alumina waste. They subdivided their treatise by type of stabilization method with type of soils studied and provided the amount of each material needed to stabilize that particular soil. They also considered the effect on the environment for each method.

Lekha et al. (2013) evaluated the use of an organosilane to stabilize a lateritic soil for pavements. The report showed improvement in strength, CBR, and fatigue life as well as a concomitant decrease in permeability.

In summary, a variety of materials is available to stabilize both fine-grained and sandy soils. This research evaluated one type of each on a single soil. The research evaluated the engineering properties of the soil as a precursor for evaluation of the material in the field.

2 Materials and Methods for Soils Analysis

2.1 General description

The silty, clayey sand (SC-SM) soil used in this study was chosen to most nearly represent the most abundantly available soil type across the earth's surface: silty sand (SM) (Robinson and Rabalais 1993). Soils were taken from local sources to the U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg, MS. A low plasticity silt (ML) and a poorly graded sand (SP) were blended for the testing. For more information about the blending ratios, see Figure A1. Forty cubic yards of blended silty, clayey sand soil were stockpiled for field testing, and 10 cubic yards of soil was placed in super sacks and stored in a controlled environment for laboratory testing. The additive list used in this study is commercially available and can be found in formulations of liquid and powder. These materials can be shipped by 55 gal drum or super sacks. The additives used were tested in application rates specified by the manufacturer, then adjusted according to lab analysis batching procedures. Water contents used during the mixing were based on the modified Proctor compaction of the control silty, clayey sand; the soil moisture and density relationship; the additive type; and the specified concentration. Optimum moisture content and 2% above and below optimum were targeted.

Section 2.2 describes the soils analysis and characterization methods used for classifying and testing of the soil. A detailed background on mechanical, compositional, and mineralogical analysis is given.

2.2 Laboratory analysis

SC-SM was selected for inclusion in this soil stabilization investigation. Each material was characterized by using a series of quantitative and qualitative tests including grain-size distribution, Unified Soil Classification System (USCS) soil classification, X-ray diffraction analysis, Atterberg limits (AL), specific gravity (G_s), moisture-density relationships, unconfined compressive strength (UCS), and California Bearing Ratio (CBR). Table 1 lists the test methods, properties measured, and associated ASTM for this study. Table 2 lists the engineering properties of the SC-SM soil used for this study.

Table 1. Test methods and properties measured for this study.

ASTM	Analysis	Properties Measured
D422	Grain Size Distribution	Gradation
D4318	Atterberg Limits	PL (plastic limit), LL (liquid limit), and PI (plasticity index)
D2487	Unified Soils Classification	Soil Type
D854	Specific Gravity	Weight Volume Relation
D1557	Modified Compaction	MDD (maximum dry density)
D1883	California Bearing Ratio	CBR
D1633	Unconfined Compressive Strength	UCS, Bearing Capacity
D421	Dry Preparation of Soils	Soil Constant
D75	Sampling Aggregates	Sampling
N/A	Durability Testing	Moisture Degradation

Table 2. Engineering properties of SC-SM.

Engineering Properties of Silty, Clayey Sand (SC-SM)	
USCS Classification	(SC-SM)
Liquid Limit	23
Plastic Limit	18
Plasticity Index	5
Coefficient of Uniformity (C_U)	36.36
Coefficient of Curvature (C_C)	0.22
Percent Sand Fraction	55
Percent Silt Fraction	36
Percent Clay Fraction	5
Percent Gravel Fraction	4
Specific Gravity	2.73
Optimum Dry Density (ASTM D1557) (lb/ft^3)	128.7
California Bearing Ratio (ASTM D 1883) (%)	96
Optimum Moisture Content (%)	7
*Unconfined Compressive Strength (ASTM D 1633) (PSI)	80
*Max strength found at 4% Wc (ASTM D1663)	

2.2.1 Grain-size distribution: ASTM D 422

Soils are frequently described by the size of their individual particles. The grain-size distribution for soils with the majority of particle sizes greater than 0.075 mm (No. 200 sieve) is determined by shaking the soil through a nest of sieves. The grain-size distribution for soils with a significant percentage of particles smaller than the No. 200 sieve is determined by a sedimentation test using a hydrometer. All three soils were subjected to a sieve analysis according to ASTM D422 (2007b). The grain-size distribution results are shown in Figures 1, 2, and 3.

2.2.2 Atterberg limits: ASTM D 4318

The plastic behavior of soils is typically verified by the material's Atterberg limits (ASTM 2010b). The Atterberg limits consist of three rudimentary tests designed to characterize the soil's plastic behavior. The liquid limit (LL) is defined as the soil moisture content at which a standard groove cut in a pat of soil will close over the length of ½ in. or 12.7 mm when the cup containing the soil is dropped 25 times from a height of 1 cm onto a resilient synthetic base. The plastic limit (PL) is defined as the soil moisture content at which the soil just begins to crumble when rolled into 0.125-in. (3.2-mm-) diam threads. The shrinkage limit (SL) is defined as the moisture content at which further decreases in moisture content do not cause further shrinkage. The shrinkage limit is seldom used in the United States. Atterberg limits are performed only on the portion of the molded sample passing the No. 40 sieve. The plasticity index (PI) of the soil is used as an index of the material's plasticity. The PI of the soil is determined by subtracting the PL from the LL. For the soil, the LL was 23, the PL was 18, and the PI was 5. The Atterberg limit results are shown in Figure 4.

Figure 1. Grain-size distribution of blended silty, clayey sand (SC-SM).

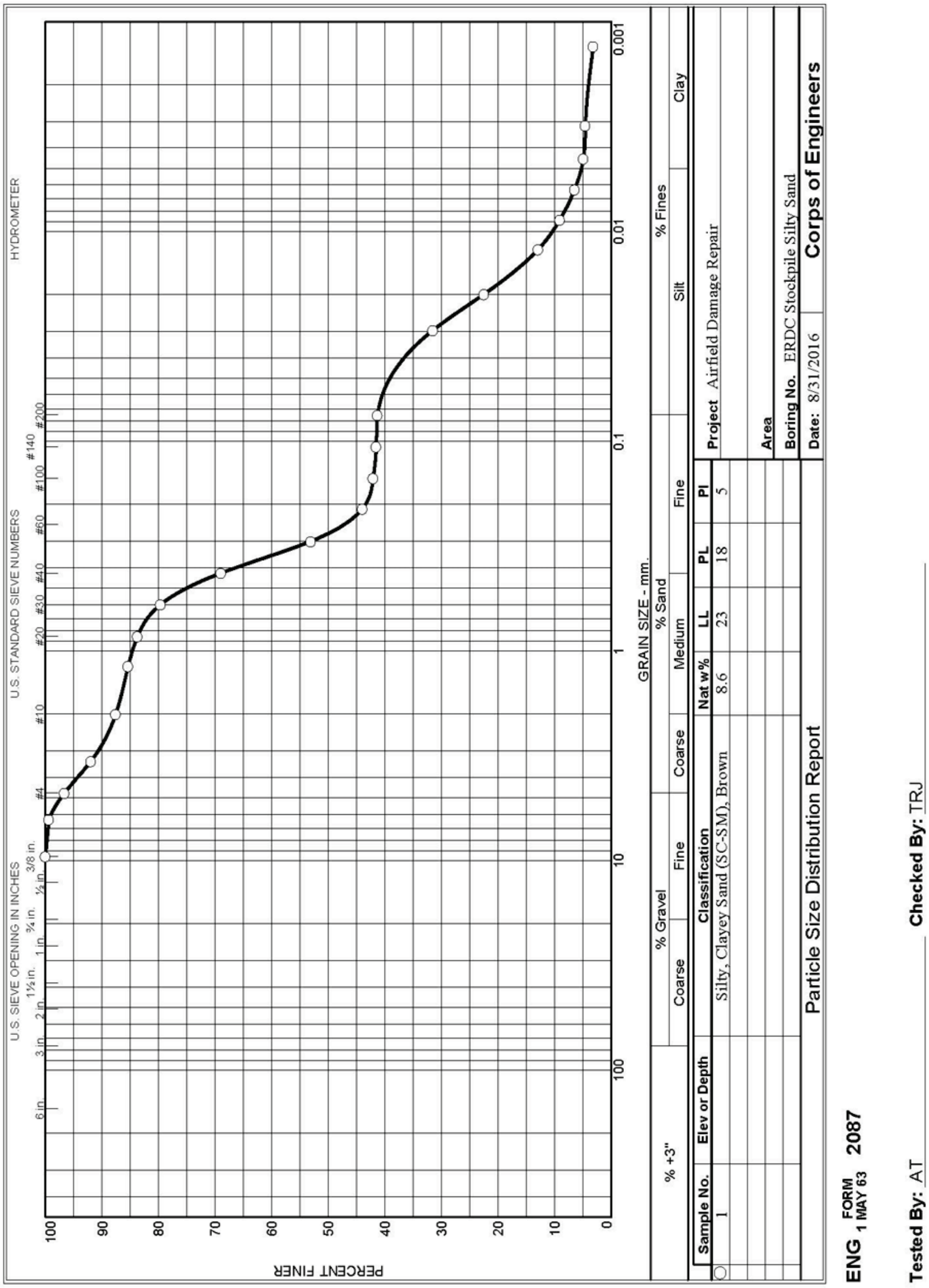


Figure 2. Grain size and hydrometer distribution of silty, clayey sand (SC-SM).

GRAIN SIZE DISTRIBUTION TEST DATA 8/31/2016

Project: Airfield Damage Repair
Location: ERDC Stockpile Silty Sand
Sample Number: 1
Material Description: Silty, Clayey Sand (SC-SM), Brown
PL: 18 **LL:** 23
PI: 5 **Nat W.%:** 8.6
Tested by: AT **Checked by:** TRJ

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
1018.30	0.00	0.00	3/8 IN	0.00	100.0
			1/4 IN	6.40	99.4
			#4	34.40	96.6
			#6	82.10	91.9
			#10	126.60	87.6
79.50	0.00	0.00	#16	2.00	85.4
			#20	3.50	83.7
			#30	7.20	79.6
			#40	16.90	69.0
			#50	31.30	53.1
			#70	39.60	43.9
			#100	41.30	42.1
			#140	41.80	41.5
			#200	42.00	41.3

Hydrometer Test Data

Hydrometer test uses material passing #10
Percent passing #10 based upon complete sample = 87.6
Weight of hydrometer sample =79.5
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -4.7
Meniscus correction only = -0.5
Specific gravity of solids = 2.73
Hydrometer type = 151H
Hydrometer effective depth equation: L = 16.294964 - 0.2645 x Rm

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
2.00	22.5	1.0225	1.0181	0.0129	22.0	10.5	0.0296	31.5
5.00	22.5	1.0173	1.0129	0.0129	16.8	11.9	0.0199	22.5
15.00	22.5	1.0118	1.0074	0.0129	11.3	13.3	0.0122	12.9
30.00	22.5	1.0096	1.0052	0.0129	9.1	13.9	0.0088	9.1
60.00	22.5	1.0081	1.0037	0.0129	7.6	14.3	0.0063	6.5
120.00	22.5	1.0072	1.0028	0.0129	6.7	14.5	0.0045	4.9
250.00	22.5	1.0070	1.0026	0.0129	6.5	14.6	0.0031	4.6
1440.00	22.5	1.0062	1.0018	0.0129	5.7	14.8	0.0013	3.2

CEERD-GEGB

Figure 3. Grain size and hydrometer distribution of silty, clayey sand (SC-SM).

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	3.4	3.4	9.0	18.6	27.7	55.3	36.0	5.3	41.3

D_5	D_{10}	D_{15}	D_{20}	D_{30}	D_{40}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
0.0046	0.0096	0.0138	0.0178	0.0275	0.0558	0.2753	0.3504	0.6115	1.0812	2.7992	4.2047

Fineness Modulus	C_u	C_c
1.55	36.36	0.22

CEERD-GEGB

Figure 4. Atterberg limits of material passing the No. 40 sieve.

LIQUID LIMIT, PLASTIC LIMIT, AND PLASTICITY INDEX OF SOILS

ASTM D 4318

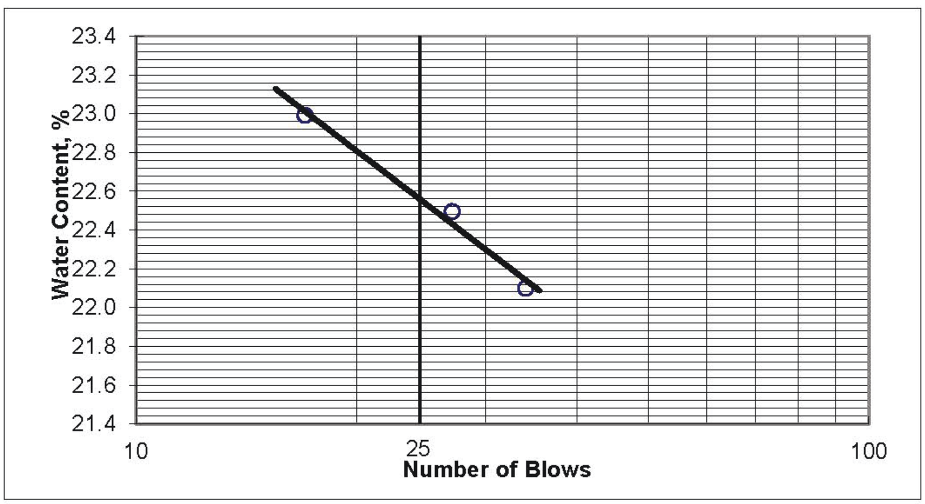
WORK ORDER NO. MD1116 DATE 4/26/2016

PROJECT Airfield Damage Repair

BORING NO. Silty Clay (CL-ML) with Sand SAMPLE NO. 1

LIQUID LIMIT

Run No.	1	2	3	4	5	6	7
Tare No.	135C	110	15A	94			
Tare Plus Wet Soil, g	55.90	37.83	36.89	38.32			
Tare Plus Dry Soil, g	52.28	34.26	33.07	34.60			
Water, g	3.62	3.57	3.82	3.72			
Tare, g	35.90	18.39	15.30	18.42			
Dry Soil, g	16.38	15.87	17.77	16.18			
Water content, %	22.1	22.5	21.5	23.0			
Number of Blows	34	27		17			



LL	23
PL	18
PI	5

Symbol from plasticity chart: CL-ML

Plastic LIMIT

Run No.	1	2	3	4	5	6	7
Tare No.	A20	481					
Tare Plus Wet Soil, g	29.44	27.00					
Tare Plus Dry Soil, g	27.28	25.31					
Water, g	2.16	1.69					
Tare, g	15.52	16.03					
Dry Soil, g	11.76	9.28					
Water content, %	18.4	18.2					
Plastic Limit	18.3						

Remarks Silty Clay (CL-ML) with Sand

Technician AT Computed By AT Checked By TRJ

Revised 5/21/09

2.2.3 Unified Soil Classification System (USCS) ASTM D 2487

Common engineering practice entails that engineers group soils into classification types based on the soils' characteristics. The USCS provides a convenient procedure for grouping materials that is both systematic and repeatable. Each material was classified according to the USCS as required in ASTM D 2487 (ASTM 2014a) by using the results of the grain-size distribution and Atterberg limits analyses. The classification for the material is defined as a silty, clayey sand.

2.2.4 Specific gravity (G_s) ASTM D 854

Specific gravity (G_s) is defined as the ratio of the weight in air of a given volume of soil to the weight in air of an equal volume of distilled water at a given temperature. Typical values for specific gravity of solids are 2.65 for sands and 2.70 for clays. The specific gravity of clay materials can typically range from 2.50 to 2.90. The specific gravity of a soil is useful in characterizing the material's weight-volume relationships. The specific gravity values for the material used in this study were determined in accordance with ASTM C 128 (ASTM 2015) and D 854 (ASTM 2014b) (Figure 5). The specific gravity of the silty, clayey sand was determined to be 2.73.

Figure 5. Specific gravity of silty, clayey sand.

SPECIFIC GRAVITY OF SOILS
ASTM D 854
FLASK SET # 1

WORK ORDER NO. MD1116 Date: 2/27/16

Project: Airfield Damage Repair

Method A: Method B: X

Boring:	Silty Clay (CL-ML)			
Location:	with Sand			
Sample No.:	1			
Flask No.:	40	53		
Weight dry soil after test, g, (M_s) :	80.14	84.59		
Test temp., °C:	21.2	21.2		
Average calibrated weight of flask, g, (M_p):	174.27	168.37		
Average calibrated volume of flask, ml, (Vp):	499.44	499.45		
Weight of flask, water, & soil @ test temp., g, ($M_{pws,t}$):	723.60	720.30		
Density of water @ test temp., g/ml, (Table 1, ($P_{w,t}$)):	0.99795	0.99795		
Temp. coefficient, (Table 1 (K)) :	0.99974	0.99974		
$M_{pw,t}$ =	672.69	666.80		
G_t =	2.74	2.72		
$G_{20^\circ C}$ =	**2.74**	**2.72**		
Average $G_{20^\circ C}$ =	**2.73**			

Formulas: Weight of flask & water @ test temp., g = $M_{pw,t} = M_p + (V_p \times P_{w,t})$

Specific gravity of soil @ test temp. = Gt = $M_s/(M_{pw,t} - (M_{pws,t} - M_s))$

Specific gravity of soil @ 20°C = $K \times G_t$

Visual Classification: Silty, Clayey Sand (SC-SM), Brown

Percent passing No. 4 sieve: 96.6

Was any soil or material excluded from the specimen? Yes No X

Description of soil or material excluded:

Remarks: Changed from Sandy Silt (ML).

Technician: AT Computed by: AT Checked by: TRJ

Revised 8/8/11

2.2.5 Modified compaction ASTM D 1557

Compaction is the process of mechanically densifying a soil or aggregate (Figure 6). It is often done to define the relationship between moisture and density for a given material at a given compaction effort designed to simulate field conditions. In these experiments, the moisture-density relationships were defined by using a modified Proctor compaction effort according to ASTM D 1557 (ASTM 2012). Method A of ASTM D 1557 was used for the fine-grained soils and consisted of a 4-in. (101.6-mm) soil mold, a 10-lb (4.536-kg) hammer weight, a 1.5-ft (0.46-m) drop height, five soil layers, and 25 blows per layer. The H-4169 Automatic Mechanical Soil Compactor (Figure 7) was used to compact soil specimens according to Modified Proctor Compaction, ASTM D 1557 (ASTM 2012), Laboratory CBR (ASTM 2016), and Unconfined Compression Test (ASTM 2007c). Prior to the project, the Automatic Mechanical Soil Compactor was calibrated according to the requirements within the referenced standards. An example of a compacted specimen is shown in Figure 9.

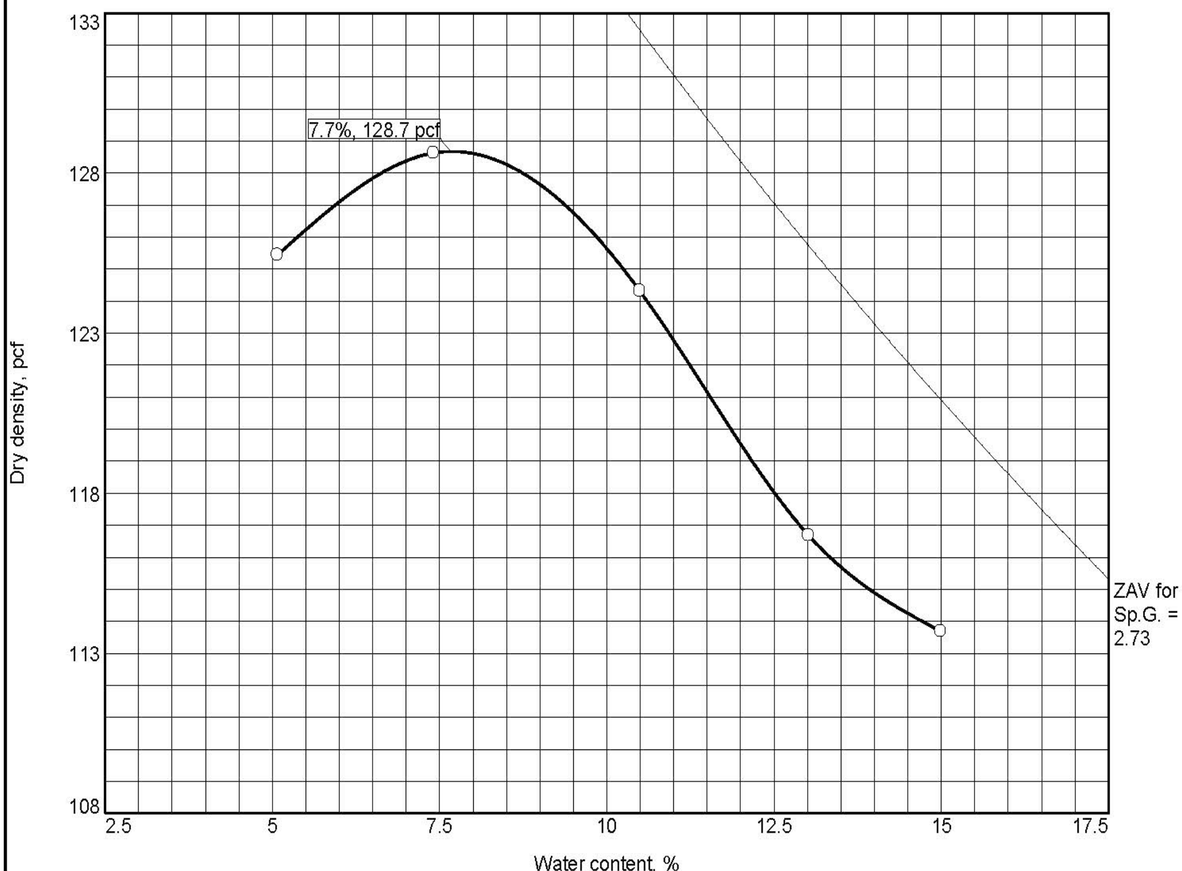
The modified Proctor compaction curve for the material in Figure 8 shows that optimum moisture content for silty, clayey sand is 7.7% and max dry density is 128.7 pcf.

Figure 6. Modified compaction of specimen.

Figure 7. Humboldt H-4169 automatic mechanical soil compactor.

Figure 8. Modified Proctor compaction curve of silty, clayey sand.

COMPACTION TEST REPORT



ASTM D 1557-12 Method A Modified

25 blows per each of 5 layers, with 10 lb. rammer and 18 in. drop. 0.03333 cu. ft. mold.

Elev/ Depth	Classification		Nat. Moist.	Est. Sp.G.	LL	PL	% > #4	% < No.200
	USCS	AASHTO						
Surface	SC-SM		8.6	2.73	23	18	3.4	41.3

TEST RESULTS	MATERIAL DESCRIPTION
Optimum moisture = 7.7 % Maximum dry density = 128.7 pcf	Control Silty, Clayey Sand (SC-SM),Brown

Project: ADR, Target CBR 40

Boring No:

Location: ERDC

Depth or Elevation: Surface

Date: 13 May 2016

Remarks:

40 % Silt (ML) 60 % Sand (SP)

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Figure 1

Figure 9. Compacted soil specimen for 2-hr UC testing.

2.2.6 Unconfined compression test ASTM D 1633

The unconfined compression test (ASTM 2007c) is frequently used to approximate the compressive strength of a molded stabilized soil. A cylindrical specimen is placed vertically in the test device, and a gradually increasing axial load is applied with no lateral support (unconfined), as shown in Figure 10. Figure 11 shows the specimen after testing. Unconfined compressive strength (UCS) is defined as either the maximum load sustained by the specimen divided by the specimen's loaded area or the load per unit area at a specified axial strain. The UCS is frequently assumed to be twice the undrained shear strength, s_u, of the material. Prior to the start of the experiment, soil compaction curves were developed for 4-in. (101.6-mm)-diam by 4.58-in. (116.43-mm)-high cylindrical specimens of each material by using a Humboldt H-4169 automatic mechanical soil compactor. Compaction energies for unconfined compression testing followed laboratory compaction characteristics of soil using modified effort (56,000 ft.-lbf/ft^3) (ASTM 2012) moisture-density compaction for the materials.

Specimen preparation consisted of four steps: preparing, molding, compacting, and curing the soil. The soil was prepared by air-drying the material to a moisture content of 0.5 to 4%, pulverizing large clods of fines to pass the No. 4 sieve, determining the free water requirements to obtain the desired moisture, and mixing the soil-water to obtain the desired moisture content. Each material was placed in a sealed plastic container overnight to achieve equilibrium of the free moisture.

A sample of the material was taken to determine the initial moisture content prior to each mix of the material according to ASTM D2216 (2010a). An initial quantity of loose material was measured for each specimen that would produce a 117 mm-high compacted specimen. The quantity of material used to mold each specimen was altered slightly after compacting the previous specimen to improve the accuracy of the compacted specimen height. The material was molded using a 4-in.-diam by 4.58-in.-high Proctor mold. The material was placed in five lifts, and each layer was compacted with 25 blows. Once placed in the mold, the specimens were inserted into the H-4169 automatic mechanical soil compactor and compacted by using the procedures described previously. The compacted specimens were extruded from the Proctor mold by using the Humboldt hydraulic extrusion device mounted in the lab. The height of the compacted sample was recorded, and the compacted sample was weighed to calculate the as-molded wet and dry densities. The compacted specimen was then placed in a temperature-controlled room where it was allowed to cure at 21.0 +/-2°C and 50-55% relative humidity for 2 hr or 7 days (see Figure 9). The curing process could be considered as air-dried rather than a moist curing process. This method of curing was selected to represent field conditions during ADR construction operations. The curing process primarily consisted of the evaporation of moisture from the specimens over time.

Figure 10. Two-hr UC testing.

Figure 11. Two-hr UC specimen.

2.2.7 California Bearing Ratio (CBR) ASTM D 1883

This test method is used to determine the CBR (ASTM 2016) of a pavement subgrade, subbase, and base course material on a laboratory compacted specimen. The CBR test is both a laboratory and a field test designed to provide an index of strength. The test involves pushing a 1.954-in. (49.63-mm) piston into a soil specimen at a constant rate of

0.05 in./min. The unit load is recorded at 0.1-in. intervals up to a deformation of 0.5 in. (1.27 cm). The loads at 0.1 in. or 0.254 cm and 0.5 in. or 1.27 cm of deformation are compared to loads required to cause equal penetrations in a standard well-graded crushed-limestone specimen. Thus, the CBR values represent a percentage of the standard material's strength and typically range from 0.1 to 100. Characterization of materials by using the CBR test is typically accomplished according to ASTM D1883 (2016) with a modified compaction effort. The modified Proctor and data developed for the silty, clayey sand soil specimen used in this experiment are given in Figures 8, 12, and 13. In the development of alternative backfill materials for rapid ADR, a non-soaked CBR of 40 or greater was targeted.

2.2.8 Soil analysis

The silty, clayey sand contained approximately 3.4% gravel, 55.3% sand, and 41.3% fines. The material had a G_s of 2.73, a LL of 23, a PL of 18, and a computed PI of 5. As such, the material was classified according to the USCS classification system as a silty, clayey sand, denoted by silty, clayey sand. The material's moisture-density relationship was defined for a modified Proctor compaction effort resulting in an optimum moisture content for compaction of 7.7% and an optimum dry density of 2,203 kg/m^3 (128.7 pcf). Measurement of the CBR at the material's optimum moisture content (7.7%) was approximately 97, which indicates excellent potential for use as a base layer. Typical design requirements for CBR values for materials to be used in a subgrade beneath CTS Rapid Set Concrete Mix® range from 10 to 40. The unconfined compressive strength of the material when molded and cured for 2 hr was 80 psi at 4% water content, 70 psi for 6% water content, 40 psi for 8% water content, 14 psi for 10% water content, and 10 psi for 12% water content. The compressive strength value could not be obtained for specimens with a water content of 2% or less due to specimen failure during extrusion.

2.2.9 Durability testing

The durability testing made use of the extruded 7-day cured CBR specimen. While the durability test is not a standard testing method, it correlates to the performance of soil additives and the permeability of the soil. If the soil is highly permeable with the stabilization additive, it is more likely that the soil structure will decompose, resulting in lower performance in the field. The method for sample preparation followed ASTM D 1883 (2016; see Figures 6 and 7). Durability testing used an extruded CBR tested soil specimen that was cured at 21.0 +/-2°C and 50-55% relative humidity for 7 days. The specimens were placed into a 10½ in. (W) x 12½ in. (L) x 5½ in. (D) stainless steel soil moisture pan and exposed to a half height (1/2 H) water depth. Any changes that were observed in the CBR soil specimen were noted through images and notation daily within a consistent time interval of +/- 30 min. For durability results see section 3.2.5.

Figure 12. Modified Proctor compaction data of silty, clayey sand.

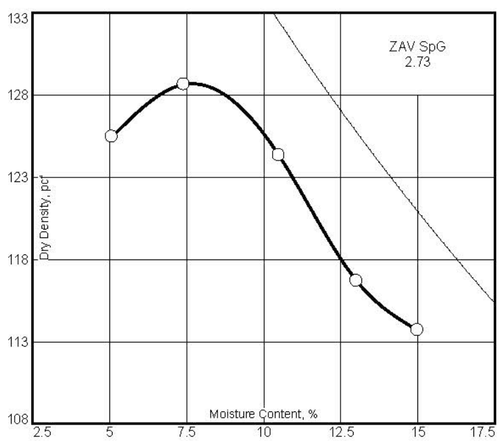
MOISTURE DENSITY TEST DATA **9/7/2016**

Client: Johnson, Tyler; Edwards, Lulu
Project: ADR, Target CBR 40
Project Number: MD 1116
Location: ERDC
Depth: Surface **Sample Number:** 1
Description: Control Silty, Clayey Sand (SC-SM),Brown
USCS Classification: SC-SM
Natural Moisture: 8.6 **Liquid Limit:** 23 **Plastic Limit:** 18
Sample Date: 13 May 2016
Testing Remarks: 40 % Silt (ML) 60 % Sand (SP)
Percent passing #4 sieve: 96.6

Test Data and Results For Curve 1

Test Specification:

Type of Test: ASTM D 1557-12 Method A Modified
Mold Dia: 4.00 **Hammer Wt.:** 10 lb. **Drop:** 18 in. **Layers:** 25 **Blows per Layer:** 5



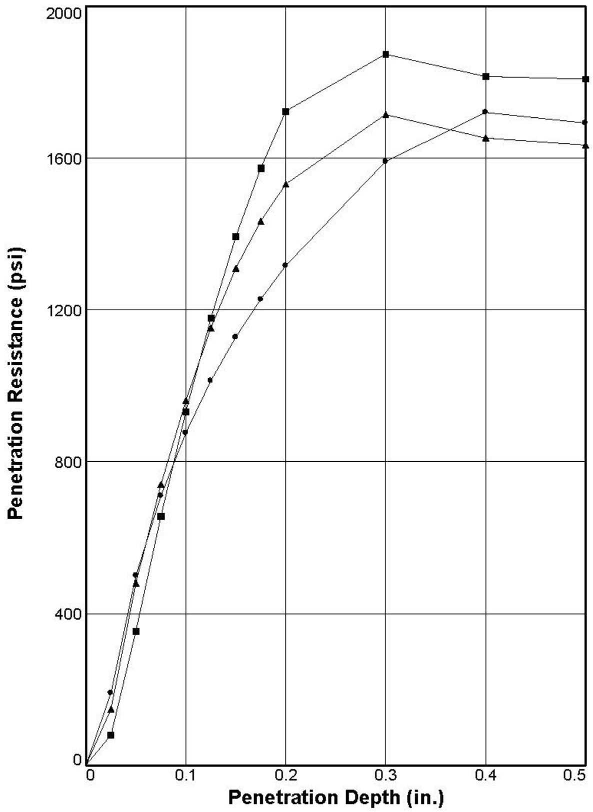
Point No.	1	2	3	4	5
Wt. M+S	4092.0	4009.0	4104.0	4008.0	3991.7
Wt. M	2015.3	2015.3	2015.3	2015.3	2015.3
Wt. W+T	377.2	493.2	468.1	470.1	663.2
Wt. D+T	361.0	460.3	449.4	456.9	598.2
Tare	206.6	207.5	197.0	196.8	164.6
Moist.	10.5	13.0	7.4	5.1	15.0
Dry Den.	124.3	116.7	128.6	125.4	113.7

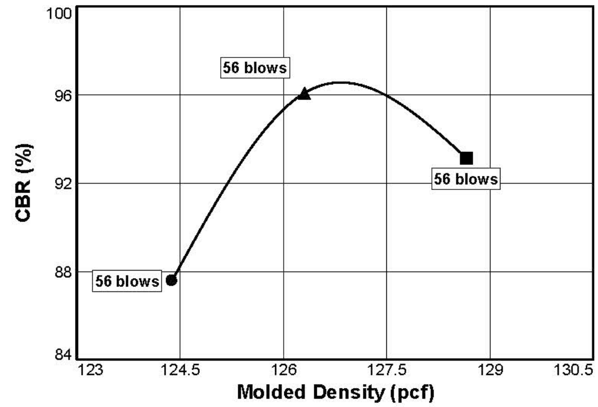
Test Results: **Max. Dry Den.=** 128.7 pcf **Opt. Moist.=** 7.7%

CEERD-GEGB

Figure 13. California Bearing Ratio vs. density for silty, clayey sand.

BEARING RATIO TEST REPORT
ASTM D 1883-07





	Molded			Soaked			CBR (%)		Linearity Correction (in.)	Surcharge (lbs.)	Max. Swell (%)
	Density (pcf)	Percent of Max. Dens.	Moisture (%)	Density (pcf)	Percent of Max. Dens.	Moisture (%)	0.10 in.	0.20 in.			
1 ○	124.4	96.7	4.1				87.6	87.8	0.000	10	
2 △	126.3	98.1	6.1				96.1	102.1	0.000	10	
3 □	128.7	100	8.0				93.1	114.9	0.000	10	

Material Description	USCS	Max. Dens. (pcf)	Optimum Moisture (%)	LL	PI
Control Silty, Clayey Sand (SC-SM),Brown	SC-SM	128.7	7.7	23	5

Project No: MD 1116

Project: ADR, Target CBR 40

Location: ERDC

Sample Number: 1 **Depth:** Surface

Date: 13 May 2016

BEARING RATIO TEST REPORT
Corps of Engineers
Engineer Research Development Center

Test Description/Remarks:

Figure 1

3 Laboratory Results

3.1 Soil stabilization and mixing analysis

The performances of a variety of additives, which included 15 traditional and non-traditional materials, and of a control were tested. A control and 15 additives were mixed at three different water contents in batches of triplicates to produce hundreds of specimens for testing UCS, CBR, and durability. Specimen preparation consisted of six steps: preparing the soil, measuring additives, blending with a Hobart 12-qt mixer, molding, compacting, and curing. Table 3 provides the target values for the engineering properties of the additive-soil mixture. A list of all the additives used in this study including the type of material and color are given in Table 4. The soil was prepared by air-drying the material to a moisture content of 1 to 4%, pulverizing large clods to allow fines to pass the No. 4 sieve, determining the free water requirements to obtain the desired moisture, and mixing the soil-water to obtain the desired moisture content. Each material was sealed in an air-tight plastic container overnight to achieve equilibrium of the free moisture. A flowchart of the process can be found in Appendix A, Figure A2.

Additives can alter the soil's performance by both changing the particles' in-place properties and improving or decreasing the effectiveness of compaction. The compaction curve is a result of the relationship between water content and the resistance to compaction (Holtz and Kovacs 1981). On the dry side, compaction is resisted by the increase in grain-to-grain forces created by tension of water menisci that form between grains. These forces enhance the frictional resistance across the interparticle contact, creating an apparent cohesion. At very low water contents, menisci play a small role because most of the moisture adheres to the grain surfaces. As water content is increased, more water is available for meniscus formation and intergranular forces are increased. Reduced density or bulking is the result of the increased intergranular resistance. As the water content is increased, the menisci between soil grains increase in quantity; they also increase in size, reducing the effect of the surface tension in creating intergranular stress, which causes a resistance to compaction. As more water is added, significant pore space becomes filled with water, virtually eliminating the effect of surface tension leading to an optimum state in which to induce compaction (i.e., maximum dry density). At higher water contents, nothing more can be gained from reduced capillary tension, as the bulk pore water itself creates compaction resistance through excess pore pressure, leading to a reduction in dry density on the wet side of the optimum moisture content. Therefore, the mechanism that imparts greater in-place strength also resists efforts to obtain target compaction densities. The ideal additive would reduce resistance to compaction then increase resistance in place.

With mix variants, 15 soil additives plus one control were chosen to initiate testing at cure times of 2 hr and 7 days for alternative backfill materials used in the subgrade. The additives can impact the cation exchange ability of fine grain particles primarily clays and silts. The pH of the soil additive and the classification as silt or clay can dramatically change how each of the additives work in the system. The sodium silicate, potassium silicate, and other inorganic additives caused reaction of the fine grained material due to high pH. This is why it is imperative to have clay mineralogy and bulk X-ray diffraction completed. With clay-rich soils, the plasticity and water content influence the performance of the stabilizer. While it would be very beneficial to compare moisture-density relationship changes induced by each of the additives, it was beyond the scope of this study.

Stabilization with traditional additives, cement and lime, showed that 5% by weight of “traditional additives” provided significant strength increase compared to the control tests. This was expected and is consistent with current guidance published in UFC 3-250-11 (UFC 2004) for a silty, clayey sand material. These results indicate that stabilization additives, which provide significant physical bonding, will be successful in modifying the properties of the silty, clayey sand material. Additives that rely on chemical reaction mechanisms may not be as successful due to the lack of adequate exchangeable cations or bound water due to the small percentage of clay in the specimen. In summary, mechanical bonding will likely be more important for this material type than known chemical bonding processes. Additional laboratory testing data and procedures can be found in Appendix A.

Table 3. ADR test matrix.

ASTM	Analysis	Properties Measured	Targeted Values
D422	Grain Size Distribution	Gradation	40 % (+/-)
D4318	Atterberg Limits	PL, LL, and PI	PL:18, LL:23, PI:4 (+/-)
D2487	Unified Soils Classification	Soil Type	Silty Sand (SM)
D854	Specific Gravity	Weight Volume Relation	Gs: 2.70 (+/-)
D1557	Modified Compaction	MDD	MDD: 125-130 (lb.ft3)
D1883	California Bearing Ratio	CBR	CBR: ≤ 40
D1633	Unconfined Compressive Strength	UCS, Bearing Capacity	50 PSI increase
D421	Dry Preparation of Soils	Soil Constant	*N/A
D75	Sampling Aggregates	Sampling	*N/A
N/A	Durability Testing	Moisture Degradation	No loss/ color change

Table 4. ADR soil testing materials list.

Soil Additive Matrix		
Additive	Material Identity	Color
Base-Seal	Inorganic chemical	White
Sodium Silicate W/ Fly Ash (C)	Chemical powder	Gray
1:1 PLC and Fly Ash (C)	Cement	White
Dirt Glue, Terra Dry	Polymer	Light Gray
Flowable Fill	Cement W/ CA and FA	Amber
RR 600 Soil Stabilizer	Urethane foam resin	Light Gray
PLC	Fine particles	Light Gray
Rapid Set	CSA Cement W/ CA and FA	White
Potassium Silicate	Chemical powder	White
Soil Sement Engineered-Ecopave	Enhanced polymer	White
Soil Sement Engineered Formula	Polymer emulsion	White
EMC^2 (EMC^2 2000 & EMS)	Organic Poly Emulsion	Amber

3.1.1 Soil and additive mixing

Specimen preparation consisted of six steps: preparing dry soil (ASTM 2007a), measuring additives, blending with a Hobart 12-qt mixer (Figure 14), molding, compacting, and curing. The soil was prepared by air-drying the material to a moisture content of 1 to 4%, pulverizing large clods to allow fines to pass the No. 4 sieve, determining the free water requirements to obtain the desired moisture, and mixing the soil-water to obtain the desired moisture content. Each material was sealed in an air-tight plastic container overnight to achieve equilibrium of the free moisture.

Figure 14. Soil additive paddle mixer.

Specimens were prepared for the unconfined compressive strength testing using the 0.033-ft^3 Proctor mold, and for the California Bearing Ratio and durability testing, the 0.075-ft^3 CBR mold was used; for the compaction effort, the Humboldt H4169 Automatic Mechanical Soil Compactor was used to compact the specimens. The specimens were mixed in a 12-qt Hobart mixer for two min at low speed and compacted following ASTM D 1557 method A (ASTM 2012). Method A used a 4-in.-diameter Proctor mold, five layers, and 25 blows per layer with a 10-lb rammer and a drop height of 18 in.

Preparation of the CBR and durability test specimens followed the process of mixing on low speed for two min. The CBR specimen were compacted in a 6-in.-diam CBR mold in five layers with 56 blows per layer.

Table 5 lists the additive mix rate and the volume requirements for this study.

Table 5. ADR soil testing lab additive mix rate.

Mold	Diameter	Volume	Unit
Proctor	4	0.0333	ft^3
CBR	6	0.0750	ft^3
Proctor	4	0.0403	ft^3 (Vol. increase)
CBR	6	0.0898	ft^3 (Vol. increase)
*Vol. increase accounts for additional material needed for mixing and data collection			

Soil Additive Lab Mix			
Additive	4 in. Mold	6 in. Mold	Unit
Base-Seal without and with lime	1	2	grams,*add 3% Lime by weight
Sodium Silicate W/ Fly Ash (C)	125	275	grams
1:1 PLC Cement I/II / Fly Ash (C)	125	275	grams
Dirt Glue, Terra Dry	75	180	grams, two part system
Flowable Fill	125	275	grams
RR 600 Soil Stabilizer	9	9	lb./ft^3,*moisture adjusted
PLC Cement Type I/II	125	275	grams
Rapid Set	125	275	grams
Potassium Silicate	250	550	grams
Soil Sement Engineered-Ecopave	1.00	1.50	milliliters
Soil Sement Engineered Formula	9.33	21.20	milliliters
EMC^2 (EMC^2 2000 & EMS)	1	2	milliliters, two part system

3.1.2 Control material

The control material soil type was a silty, clayey sand. The silty sand was chosen because it represents the predominant surface soil type in the world. The soil was stock piled in a controlled environment where it was air dried to a water content between 1 and 4%. Based on compaction data and water contents often found in the field, it was determined to use three water contents that defined the compaction curve and represent the moisture at which the additives were applied. The three water contents were 4, 6, and 8%, as shown in Tables 1 and 2 ADR soil testing matrix.

3.1.3 Base-Seal with lime

Base-Seal is a proprietary soil additive manufactured by Base Seal International Inc. The vendor recommends the additive is mixed with soil at a rate of 14.5 fluid ounces per cubic yard to improve the wearing surface and bearing capacity of roadways. Traditionally, Base-Seal is supplemented with lime to increase the pH and enhance the chemical reaction. The lime used is a hydrated type-s lime which is used in mortar and mixes and other cementitious material applications. Base-Seal was supplemented with lime powder at 3% by weight of soil of optimum dry density (128.7 lb/ft^3 at 7.7% moisture) for the silty, clayey sand. Base-Seal is noted for working well with bound moisture in soil or when needed, due to the lack of moisture it can be amalgamated at a rate of 1:32 parts water by use of a reclaimer.

3.1.4 Sodium silicate with Class C fly ash

Sodium meta-silicate and Class C fly ash are mixed as an additive with soil at a rate of 2.5% by dry weight each for the silty, clayey sand. Sodium meta-silicates are known for reacting with silty clayey materials and improving the strength while reducing the permeability and stabilizing the swelling potential of the soil.

3.1.5 Portland limestone cement with Class C fly ash

Portland limestone cement (PLC) and Class C fly ash are mixed as an additive with soil at a rate of 2.5% by weight each for the silty, clayey sand. PLC and Class C fly ash are commonly used to improve the bearing capacity and wearing surface of roadways. These materials have great performance when abundant moisture is bound within the soil structure. Cement and fly ash are also known for being readily available.

3.1.6 Dirt Glue with Terra Dry

Dirt Glue polymer emulsion with Terra Dry is a proprietary soil additive that is non-hazardous and water-soluble prior to curing. Dirt Glue manufactured by Dirt Glue Enterprises. It is mixed as a stabilization additive with soil at a rate of 3% by weight of dry soil for the silty, clayey sand. The Terra Dry is added to the mixture at 9% by weight of the Dirt Glue additive when clays are present in the soil.

3.1.7 Flowable fill

Buzzi Unicem Utility Fill 1-Step 750 is a rapid-setting flowable fill material that has been selected for rapid ADR operations when mixed as an additive with soil at a rate of 5% by dry weight for each moisture point of the silty, clayey sand. Flowable fill is currently used as a fill material beneath Rapid Set concrete caps for ADR repairs. Flowable fill is a low strength material that the construction industry uses to backfill utility trenches and around box culverts and can also be used as a substitute fill material in situations when poor soil conditions are present.

3.1.8 HMI RR-600 Soil Stabilizer with HMI Catalyst

HMI RR-600 a polyurethane Soil Stabilizer is mixed into the silty, clayey sand at a variety of rates (4 lb/ft^3 to 9 lb/ft^3) and soil moisture contents of 2 to 12%. This additive is provided in a two-part system. Initial testing concluded that, with the silty, clayey sand, it is better to use only the RR-600 Soil Stabilizer. Lab testing also noted that, as water content within soils increases, the reaction is more unsTable for methods followed for this study; better results were obtained when reducing HMI RR-600 stabilizer to 4 lb/ft^3 and eliminating the catalyst. This allowed for more workability and field adjustments.

3.1.9 Portland limestone cement

Portland limestone cement (PLC) is mixed as an additive with soil at a rate of 5% by weight for the silty, clayey sand. PLC and other cement materials are commonly used to improve the bearing capacity and wearing surface of roadways. These materials have great performances when abundant moisture is bound within the soil structure. Cementitious materials are also known for being readily available.

3.1.10 Class (C) fly ash

Class (C) fly ash is mixed as an additive with soil at a rate of 5% by dry weight of the silty, clayey sand. Fly ash is not as commonly used in soil stabilization as PLC or ordinary portland cement (OPC) due to the reactivity and ability to decrease permeability of Class (C) ash.

3.1.11 Rapid Set

Rapid Set Concrete Mix® concrete is mixed as an additive with soil at a rate of 5% by weight for the silty, clayey sand. The main cementitious component in the mix is Rapid Set Cement, a proprietary calcium-sulfoaluminate-based material. The cement component differentiates the product from traditional high early strength concrete, which is typically composed of Type III portland cement and has a set time of several hours compared to 30 min with Rapid Set.

3.1.12 Potassium silicate

Potassium silicate is mixed as an additive with soil at a rate of 5% by dry weight for the silty, clayey sand. Potassium silicates react with clays and silts. This material was selected to see how pH changes affect the soil blends. When higher moisture contents and clay materials are present, potassium silicates have the ability to react and stabilize the fine grain soil particles.

3.1.13 Soil Sement Engineering Ecopave soil stabilizer

Soil Sement Engineering Ecopave® is mixed as an additive with soil; the Ecopave product is recommended for soils that contain higher plasticity indexes (PI) than 6. The product is mixed with the soil at a rate of 1 gal per 25 ft^2 per 8-in. lift for the silty, clayey sand. In a surface application, the product application rate is in gallons per 25 ft^2.

3.1.14 Soil Sement Engineering soil stabilizer

Soil Sement® Engineering soil stabilizer is mixed as an additive with soil at a rate of 4.25 gal per 15 ft^2 per 8-in. lift for the silty, clayey sand. In a surface application, the product application rate is in gallons per 15 ft^2.

3.1.15 EMC^2

EMC^2 by Soil Stabilization Products is mixed as an additive with soil at a rate of 1 gal per 15 yd^3 after diluting with water at a rate of 112 to 139 parts water for the silty, clayey sand. This product is typically applied in 6- to 8-in. spoil lifts.

3.2 Strength, CBR, and durability analyses

3.2.1 Strength testing (UCS) - two hr

Results of the 2-hr unconfined compressive strength for 144 specimen are shown in Figure 15. For each of the additive mix, specimens were prepared in triplicates at moisture contents of 4, 6, and 8% then tested following ASTM D 1557 and D 1633 (ASTM 2012 and 2007c). Specimen preparation consisted of four steps, i.e., soil preparation, molding, compaction, and curing. The soil was prepared by air-drying the material to a moisture content of 1 to 4%, pulverizing large clods of fines to pass the No. 4 sieve, determining the free water requirements to obtain the desired moisture, and mixing the soil and water to obtain the desired moisture content. Each material was sealed in a plastic container overnight to achieve equilibrium of the free moisture.

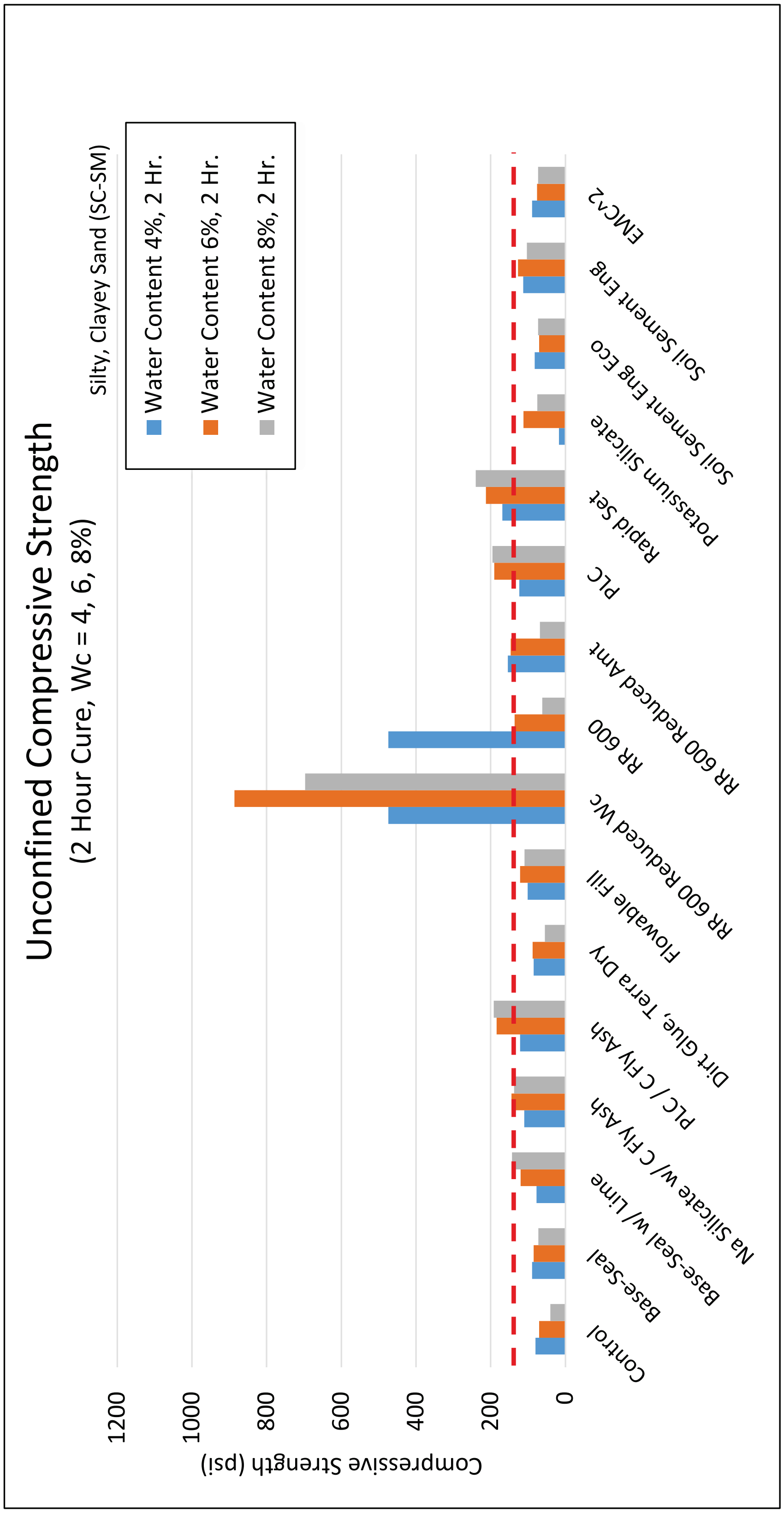
Once the soil was prepared, the specimen were compacted following ASTM D 1557 at each of the three moisture points, extruded from the mold, and then cured in a controlled environment (21.0 +/-2°C and 50-55% relative humidity) for 2 hr. Methods for mixing and curing were held constant; the only changing variable was the additive type and the application rate. It was important to mix and compact the specimen at three moisture points that define the moisture density curve for the silty, clayey sand in order to allow for a better understanding of how moisture affects the specimen's compressive strength.

This testing targeted a strength improvement of 50 psi at a 2-hr cure time, see Figure 15 red line. The highest compressive strength of 886 psi with a 2-hr cure time was the result of the RR 600 Soil Stabilizer with the soil at a 6% moisture content. The lowest compressive strength was 17 psi with potassium silicate at a 4% moisture content.

The reason for the lowest compressive strength of 17 psi for potassium silicate at a 4% moisture content was due to the potassium silicate wicking the moisture from the soil specimen. Increasing the soil's moisture content by 2% from 4% to 6% allowed the potassium silicate to hydrate, which increased the soil specimen strength by over 100%. A significant decrease in strength occurred with a moisture content increase from 6% to 8%.

Two-hour cure data are listed in Table 6. The most substantial strengths with the 2-hr cures were obtained with the Base-Seal with lime kiln dust, PLC with Class C fly ash, RR 600 Soil Stabilizer, RR 600 reduced concentration, PLC, and Rapid Set®.

Figure 15. Unconfined compressive strength (2-hr cure).



3.2.2 Strength testing (UCS) - 7 day

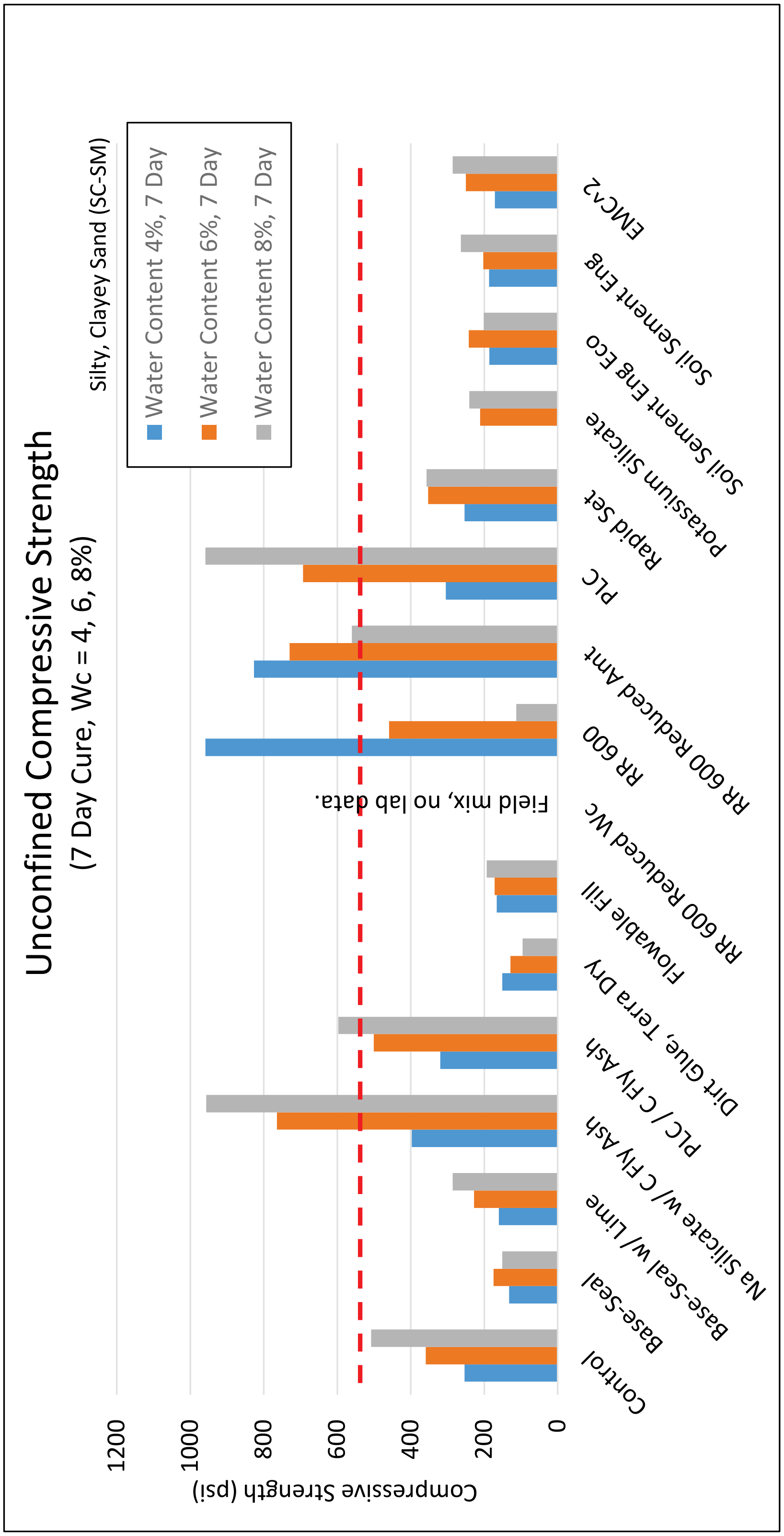
Results of the 7-day UCS (ASTM D 1633) unconfined compressive strength for over 144 specimen are shown in Figure 16. For each of the additive mix, specimens were prepared in triplicates at moisture contents of 4, 6, and 8%, then tested following ASTM D 1557 and D 1633 (ASTM 2012 and 2007c). Specimen preparation consisted of four steps, i.e., soil preparation, molding, compaction, and curing as followed in specimen preparation for the 2-hr cure rate.

Once the soil was prepared, the specimens were compacted following ASTM D 1557 at each of the three moisture levels, extruded, and then cured in a controlled environment (21.0 +/-2°C and 50-55% relative humidity) for 7 days. Methods for mixing and curing were held constant; the only changing variable was the additive type and the application rate. It was important to mix and compact the specimens at three moisture contents that define the moisture density curve for the silty, clayey sand and to allow for a better understanding of how moisture affects the specimen strength.

This testing targeted a strength improvement of 50 psi at a 2-hr cure time, see Figure 16 red line. The highest compressive strength of 959 psi was reached with a 7-day cure rate and was the result of the additive RR 600 Soil Stabilizer with the soil at a 4% moisture content. The authors of the report found that the PLC provided about the same strength with a higher moisture content in the soil. With a longer cure time, the strength did increase. However, the lowest compression strength was also recorded at 0 psi with potassium silicate at a 4% moisture content; the cause of the lost strength is due to the potassium silicate wicking the moisture from the soil specimen. It was found that increasing the soil's moisture content by 2% from 4% to 6% allowed the potassium silicate to hydrate to increase the soil specimen strength by over 200 psi. There was not a significant increase in strength from increasing moisture content from 6% to 8% for any of the additives except for samples containing cement and fly ash. It was found that increased moisture content reduced the effectiveness of many of the polymers.

The 7-day cure results are listed in Table 7. The most substantial strengths noted at 7 days included the following additives, i.e., sodium silicate with Class C Fly Ash, PLC with Class C Fly Ash, RR 600 Soil Stabilizer, RR 600 reduced concentration, PLC, and Rapid Set. The average compressive strength doubled from the 2-hr cure to the 7-day cure.

Figure 16. Unconfined compressive strength (7-day cure).



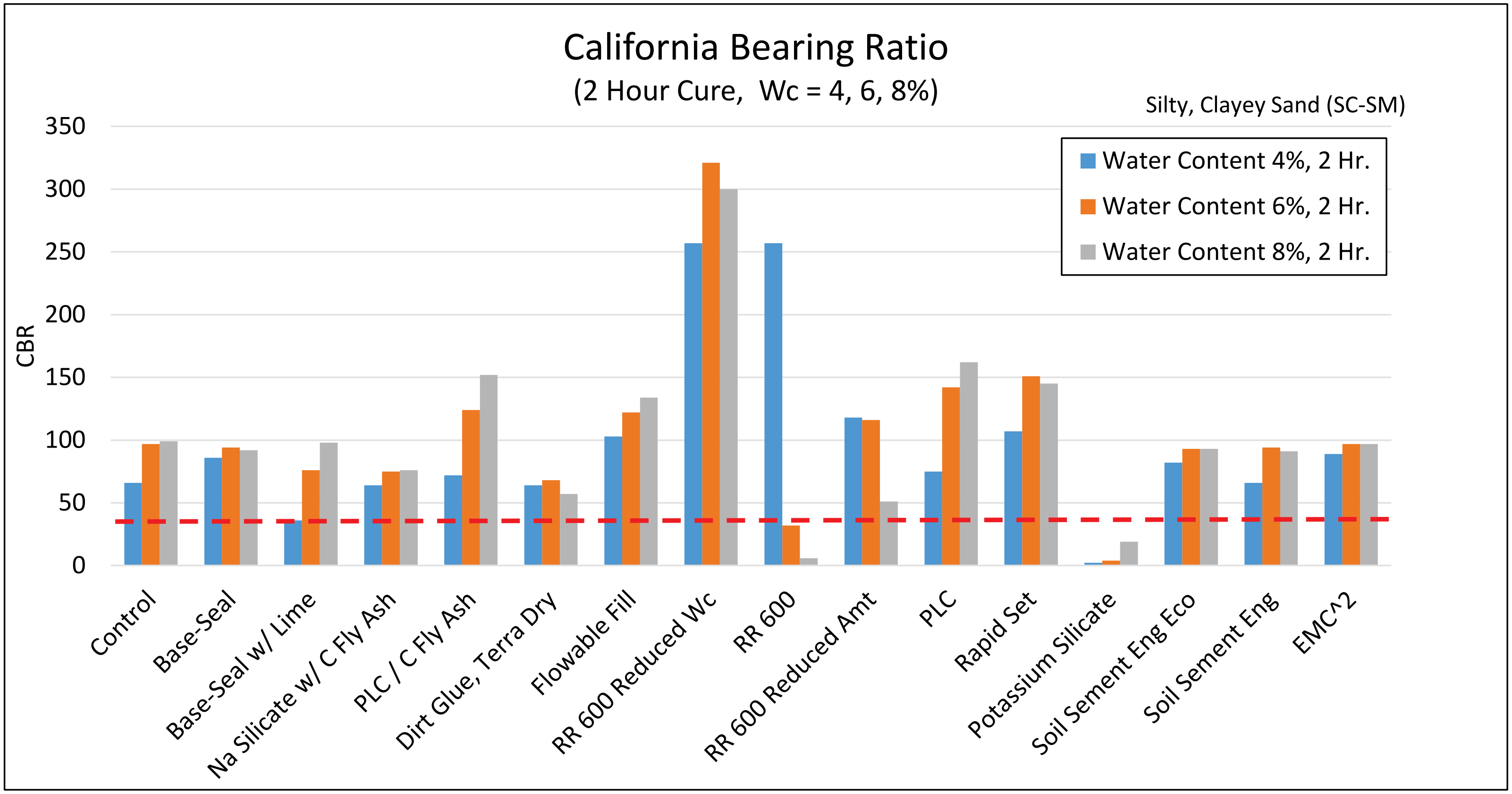
3.2.3 California Bearing Ratio (CBR) - 2-hr cure

Results of the 2-hr cure of the specimens for California Bearing Ratio (CBR; ASTM D 1883; ASTM 2016) tests are shown in Figure 17. The CBR test is both a laboratory and field test that is designed to provide an index of strength. The method used in this study deviated from the standard in the process of allowing the specimens to cure for two hr. It was important to understand exactly how the material properties improved or declined over a 2-hr time frame. Figure 13 shows the CBR relationships developed for each of the silty, clayey sand specimens used in this experiment. In the development of alternative backfill materials for rapid ADRs, an un-soaked CBR of 40 or greater was targeted, see Figure 17 red line.

Testing identified that many of the materials had recorded CBR values much greater than 40, see Figure 17. The additive that did not meet the targeted CBR of 40 within two hr was the potassium silicate; it was also recorded that others dropped below the target as a result of changes in moisture content. The material RR 600 performed extremely well with low moisture contents at all three of the mix variations. The greatest CBR values were achieved with the PLC with Class C fly ash, flowable fill, RR 600 with a reduced water content, RR 600, RR 600 reduced additive concentration, PLC, and Rapid Set ®.

Two-hour cure data are listed in Table 6. The highest recorded CBR value was 321, at two hr, and the lowest was 2.2 at 2-hr cure time. A majority of the additives outperformed the target CBR of 40, with an average CBR value of slightly under 100. On average, the additives performed the best at a moisture content of 6%, returning an average CBR value of over 100. The average performance of the additives in the silty, clayey sand dropped when increasing the moisture 2% and curing for two hr.

Figure 17. California bearing ratio (2-hr cure).



3.2.4 California Bearing Ratio (CBR) – 7-day cure

The results of the 7-day cure CBR specimens (ASTM D 1883) for the 144 specimens are in Figure 18. The curing method deviated from the standard in the process of allowing the specimens to cure for seven days. It was important to understand how the material properties improve or decline over a 7-day time frame, which can also be compared with the 2-hr cure data. Figure 18 shows the CBR relationships developed for each of the silty, clayey sand soil specimens used in this experiment. In the development of alternative backfill materials for rapid airfield damage repairs, an un-soaked CBR greater than 40 was targeted (see Figure 18 red line).

Seven-day cure time testing identified that many of the materials had recorded CBR values much greater than 40 (see Figure 18), outperforming the target CBR with an average CBR value of slightly over 150, which was more than triple the target. The bulk of the additives increased in strength with regards to the CBR value from the 2-hr cure to the 7-day cure. One additive, potassium silicate, did not meet the targeted CBR of 40 within seven days; more of a reaction with the clay particles present was expected. It was noted that many additives did well, outperforming the target CBR value of 40 as a result of changes in cure time from two hr to seven days. The moisture contents and additive contents were held constant; the only change was cure time. The material RR 600 performed extremely well; the data showed that the CBR value increased with a 4% moisture content at all three of the mix variations. Some of the greatest CBR values were achieved with Base-Seal with lime, sodium silicate with Class C fly ash, PLC with Class C fly ash, RR 600 reduced water content, RR 600, RR600 reduced concentration, PLC, Rapid Set ®, and Soil Sement® Engineered (original formula).

The 7-day cure results are listed in Table 7. The largest recorded CBR value over a 7-day cure regimen was 315 with the additive PLC, followed by sodium silicate with a CBR value of 314; the lowest value was 0 with the additive potassium silicate. On average, the additives performed the best at a moisture content of 6% and returned an average CBR value of over 160. The average performance of the additives in the silty, clayey sand dropped when adding 2% more moisture and curing for seven days.

Figure 18. California bearing ratio (7-day cure).

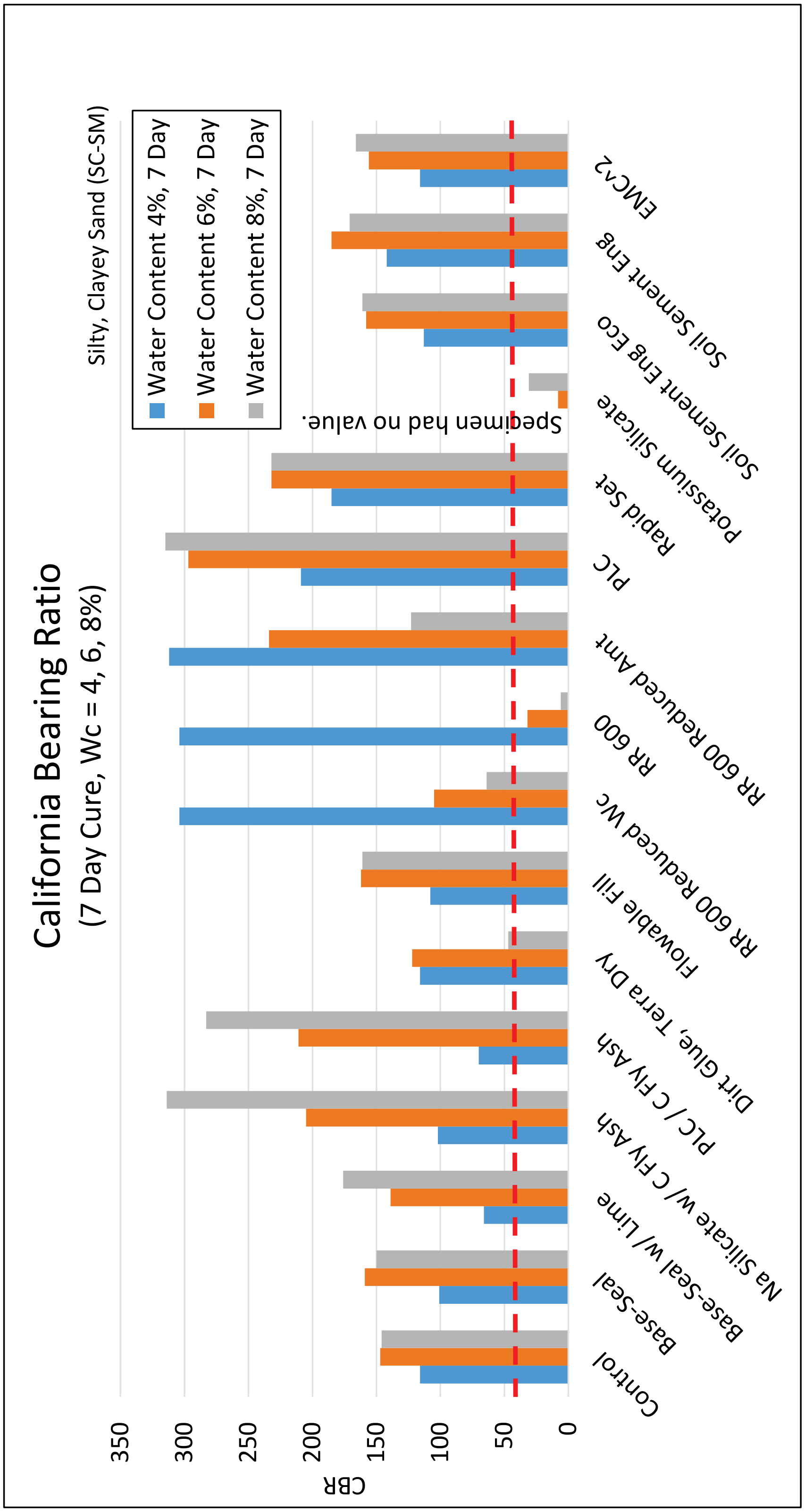


Table 6. ADR soil testing matrix. (2-hr cure).

ADR Soil Testing Matrix 2-Hr Cure																		
Material	Additives	Moisture Contents (%)					Proctor (lb/ft³) Modified 10 (lb)					Compressive Strength at 2hrs (psi)			CBR at 2 hrs			
		M1	M2*	M3*	M4*	M5	5%	7%	10%	13%	15%	4%	6%	8%	4%	6%	8%
(SC-SM)	Control		7	10	13		125.4	128.6	124.3	116.7	113.7	80	70	40	66	97	99
			Targeted Moisture (%)					4%	6%	8%		4%	6%	8%	4%	6%	8%
1	Base-Seal		4	6	8			121.6	125.4	127.0		89	85	72	86	94	92
2	Base-Seal W/ Lime		4	6	8			115.4	118.7	121.9		77	120	143	36	76	98
3	Sodium Silicate W/ Fly Ash (C)		4	6	8			121.4	127.3	131.5		110	144	137	64	75	76
4	1:1 PLC and Fly Ash (C)		4	6	8			117.0	121.5	124.0		120	184	192	72	124	152
5	Dirt Glue, Terra Dry		4	6	8			124.5	127.5	99.9		85	88	55	64	68	57
6	Flowable Fill		4	6	8			124.3	126.6	128.6		101	121	109	103	122	134
7	RR 600 reduced Wc		4	6	8			131.2	129.2	121.7		474	886	697	257	321	300
8	RR 600		4	6	8			127.0	132.0	131.0		474	136	62	257	32	6
9	RR 600 Reduced Amt		4	6	8			126.8	129.4	127.3		154	146	68	118	116	51
10	PLC		4	6	8			119.7	123.4	126.4		123	190	195	75	142	162
11	Rapid Set		4	6	8			120.8	125.0	127.0		169	213	240	107	151	145
12	Potassium Silicate		4	6	8			101.7	105.8	122.3		17	112	75	2	4	19
13	Soil Cement Engineered-Ecopave		4	6	8			122.3	127.5	127.5		82	70	73	82	93	93
14	Soil Sement Engineered Formula		4	6	8			121.2	125.0	126.9		113	127	103	66	94	91
15	EMC^2		4	6	8			123.5	126.4	128.8		89	76	73	89	97	97

Table 7. ADR soil testing matrix. (7-day cure).

ADR Soil Testing Matrix, 7-Day Cure																	
Material	Additives	Moisture Contents (%)					Proctor (lb/ft^3) Modified 10 (lb)					Compressive Strength at Day 7 (psi)			CBR at Day 7		
		M1	M2*	M3*	M4*	M5	5%	7%	10%	13%	15%	4%	6%	8%	4%	6%	8%
(SC-SM)	Control		7	10	13		125.4	128.6	124.3	116.7	113.7	254.0	359.0	508.0	116	147	146
			Targeted Moisture (%)					4%	6%	8%		4%	6%	8%	4%	6%	8%
1	Base-Seal		4	6	8			121.6	125.4	127.0		132	175	151	101	159	150
2	Base-Seal W/ Lime		4	6	8			115.4	118.7	121.9		160	228	286	66	139	176
3	Sodium Silicate W/ Fly Ash (C)		4	6	8			121.4	127.3	131.5		397	764	957	102	205	314
4	1:1 PLC and Fly Ash (C)		4	6	8			117.0	121.5	124.0		320	501	597	70	211	283
5	Dirt Glue, Terra Dry		4	6	8			124.5	127.5	99.9		151	129	96	116	122	47
6	Flowable Fill		4	6	8			124.3	126.6	128.6		166	172	193	108	162	161
7	RR 600 reduced Wc		4	6	8			131.2	129.2	121.7		x	x	x	304	105	64
8	RR 600		4	6	8			127.0	132.0	131.0		959	459	113	304	32	6
9	RR 600 Reduced Amt		4	6	8			126.8	129.4	127.3		827	730	560	312	234	123
10	PLC		4	6	8			119.7	123.4	126.4		304	693	959	209	297	315
11	Rapid Set		4	6	8			120.8	125.0	127.0		254	353	357	185	232	232
12	Potassium Silicate		4	6	8			101.7	105.8	122.3		x	212	241	x	8	31
13	Soil Cement Engineered-Ecopave		4	6	8			122.3	127.5	127.5		186	242	201	113	158	161
14	Soil Sement Engineered Formula		4	6	8			121.2	125.0	126.9		187	203	264	142	185	171
15	EMC^2		4	6	8			126.1	128.5	129.9		171	250	286	116	156	166

* x denotes where data could not be recorded

3.2.5 Durability evaluation

A durability analysis was employed on the 7-day cure CBR specimens. This analysis was conducted in a stainless steel laboratory water content pan that induced the specimen to partial saturation depth of one half the specimen height (h/2). The soaking process was completed in the same laboratory space in which the specimen were cured. The specimens are shown in Figures 19 through 22 at soaking times of zero and after 7 full days. See Appendix A, Figure A3 for the full durability Table.

Figure 19 shows that a total loss of the control silty, clayey sand specimen occurred after two days of partial saturation. The loss of the specimen in two days provided a baseline to judge how effective the soil additives would be.

Figure 19. Control soil (SC-SM) initial sample (left) and after 2 days soaking (right).

Figure 20 shows that the RR600 stabilized silty, clayey sand specimen performed very well while when exposed to partially saturated conditions over 7 days.

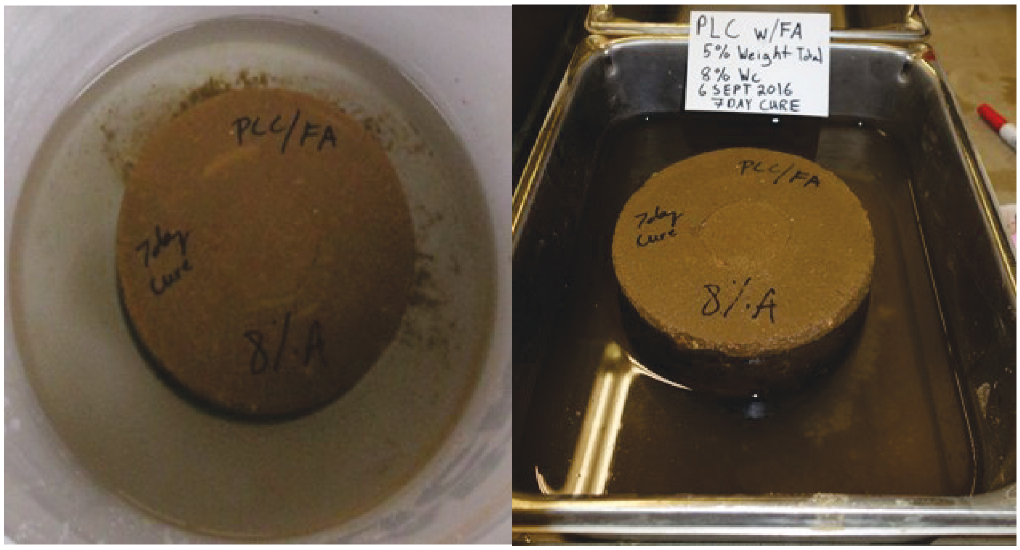
Figure 20. Soil sample with Dirt Glue additive initial sample (left) and after 7 days of soaking (right).

Figure 21 shows that the RR600 with reduced amount of additive stabilized silty, clayey sand specimen performed better than expected. The full additive application did not perform as well as evidenced in the pictures found in Figures 16 and 17 while exposed to partially saturated conditions over 7 days. Possible explanations can relate to mixing and curing.

Figure 21. Soil sample with RR 600 (reduced amount) additive initial sample (left) and after 7 days of soaking (right).

Figure 22 shows that the PLC and Class C fly ash stabilized silty, clayey sand specimen performed well while exposed to partially saturated conditions over 7 days. The images in the Figure below show the color changes and soil particle suspension.

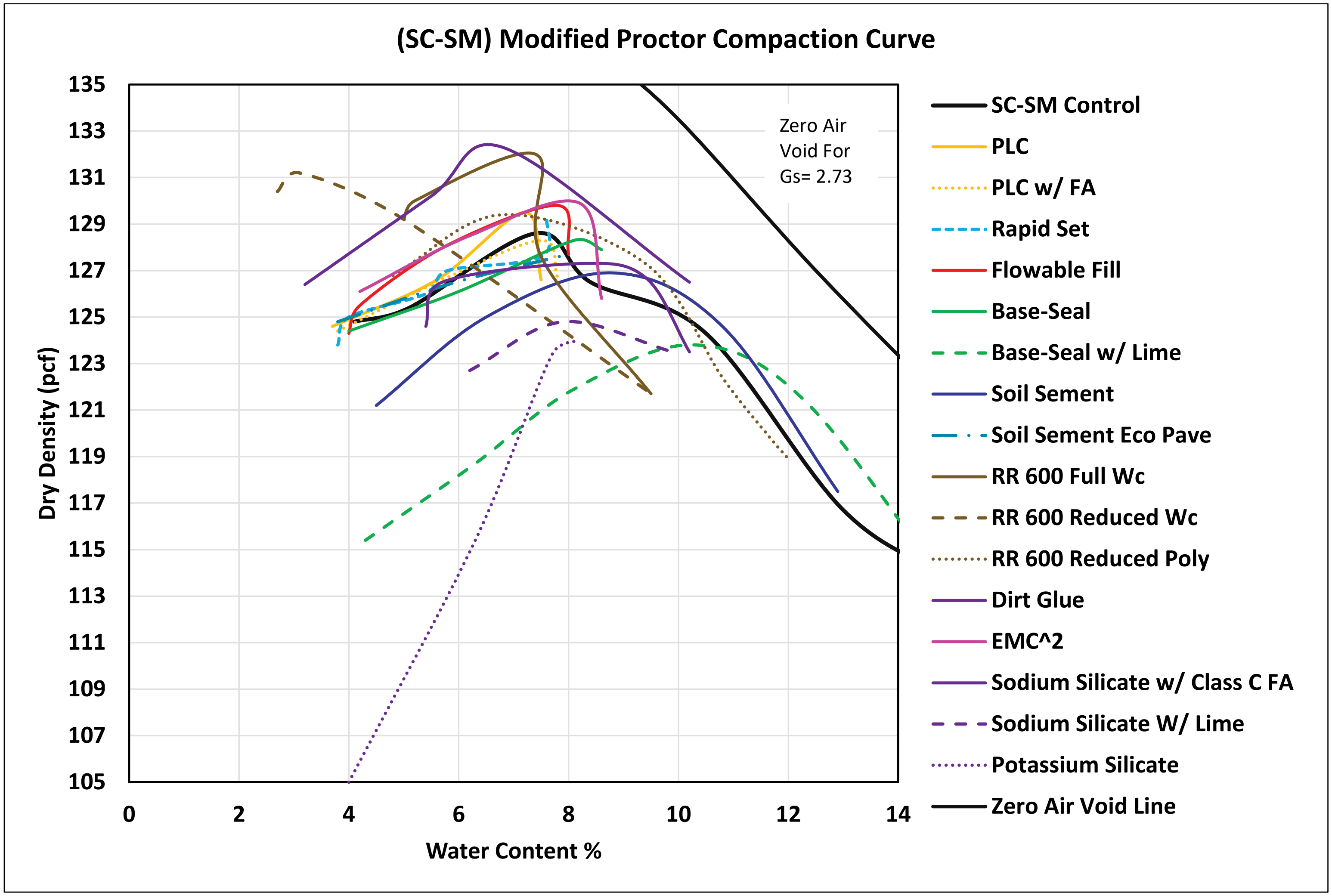
Figure 22. Soil sample with PLC with fly ash additive initial sample (left) and after 7 days of soaking (right).



3.3 Combined modified Proctor curves

A visual representation of the modified Proctor dry density versus water content for the silty, clayey sand with each of the additives analyzed in the study are shown in Figure 23. Throughout the lab analysis, the silty, clayey sand soil was sampled from the same ERDC stockpile. The stockpile was sheltered from the weather and kept free of organic matter and other contaminants. The silty, clayey sand soil for the lab and field analyses was excavated from the same borrow source in a north-central location of Warren County, MS. Identical procedures for obtaining the soil, air-drying, bringing soil material to desired water content, processing over the #4 screen, and mixing were followed throughout laboratory testing for the project.

Figure 23. Modified Proctor compaction curves for all materials used in the laboratory study.



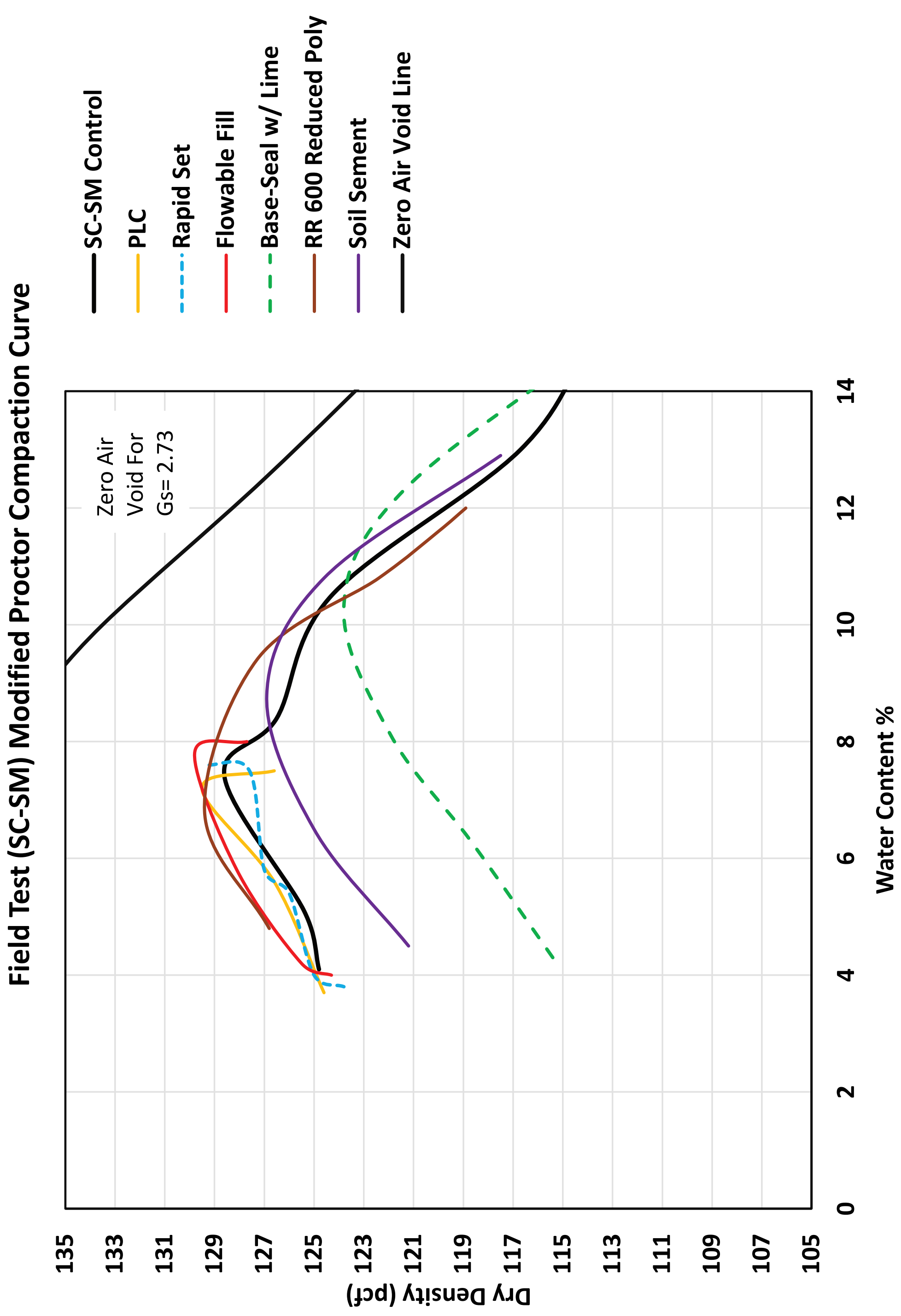
The soil was pre-mixed at the moisture contents of 4, 6, and 8% and allowed to achieve equilibrium. The Proctor curves in Figure 23 indicate that moisture shifts occurred. The moisture shifts were due to the varying chemical and physical natures of the soil additives analyzed. To ensure that each of the additives was analyzed under the same conditions, the silty, clayey sand soil and initial compacted moisture points were held constant throughout the study.

The bulk of the additives shifted the optimum moisture relationship to the left favoring a dryer environment. Over half of the additives recorded improvements in density from the base material silty, clayey sand of 128.7 pounds per cubic foot. The cements, fly ash, urethane, and inorganics with the exception of Dirt Glue and Base-Seal additives increased the density of the soil with varying moisture contents. The silicate and emulsion additives favored a higher moisture content while decreasing the dry density.

3.4 Modified Proctor curves - field tested additives

A visual representation of the modified Proctor dry density versus water content curves for each of the additives selected to be analyzed in the field testing of the study are shown in Figure 24. Throughout the field test activities and analyses, the silty, clayey sand soil was obtained, stockpiled, and processed the same as the soils for the lab tests.

Figure 24. Modified Proctor compaction curves for all materials used in the field study.



Specimen preparation consisted of four steps, i.e., soil preparation, molding, compaction, and curing. The soil was prepared by air-drying the material to a moisture content of 1 to 4%, pulverizing large clods of fines to pass the No. 4 sieve, determining the free water requirements to obtain the desired moisture, and mixing the soil-water to obtain the desired moisture content. Each material was sealed in a plastic container overnight to achieve equilibrium of the free moisture.

The soil was pre-mixed at the moisture points 4, 6, and 8% and allowed to achieve equilibrium. The Proctor curves in Figure 24 identify that moisture shifts occurred in the additives used for field testing. The moisture shifts occurred due to the varying chemical makeup and nature of the soil additives analyzed. To ensure that each of the additives was analyzed under the same conditions, the silty, clayey sand and initial moisture points were constant throughout the study.

The bulk of the additives shifted the optimum moisture relationship to the left, favoring a dryer environment. Over half of the additives recorded improvements in density from the base material of 128.7 pounds per cubic foot. The cements and urethane materials increased the density of the soil with a lower moisture content. The silicate, lime kiln dust, and emulsion additives favored a higher moisture content while decreasing the dry density.

3.5 Scanning electron microscope analysis

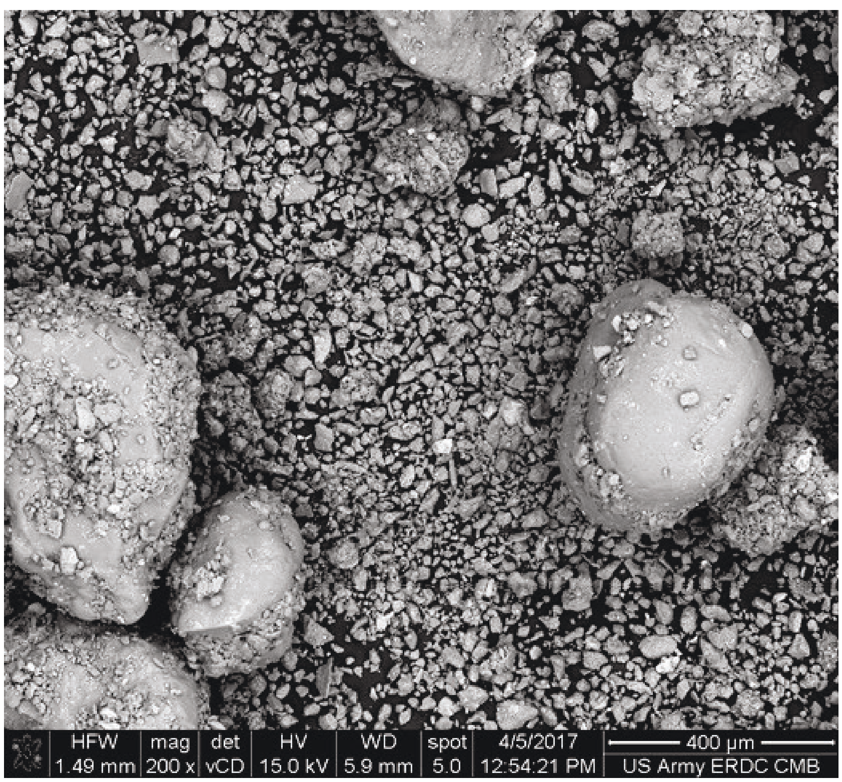
Characterization of the microstructure present in samples obtained from the field was performed using a scanning electron microscopy (SEM). Samples were imaged after at least 3 days of hydration. Specimens for SEM imaging were freshly fractured and affixed to SEM stubs with the exposed fracture surface facing up for imaging. Specimens were imaged using an FEI Nova NanoSEM 630 variable pressure field emission SEM. Imaging was performed at an accelerating voltage of 5 to 15 kV using a backscattered electron (BSE) detector to reveal changes in microstructure and the distribution of phases according to their respective densities. Low-vacuum environmental mode (pressure of 0.1 mbar) was utilized to minimize charging and dehydration of the samples.

The photomicrograph provided from the SEM analysis provides a better understanding of grain size, material angularity, and evidence of chemical and/or mechanical bonding of the soil particles that is occurring.

The SEM analyses (Figures 25-30) were obtained to analyze the mechanical and chemical bonding taking place during the compaction and curing process. Of particular interest is the particle size, shape, distribution, and bonding. The materials imaged within these Figures represent the mixes selected for field testing. The soil in these images is from the same stockpile and classification presented throughout the report, i.e., a silty, clayey sand (SC-SM). It is apparent in the images that there are particles that represent clays, silts, and sands. The fine sand particles represent the fraction sizes of 300-400 μm, the silts represent the fraction sizes of 10 to 100 μm, and the clays fraction sizes are typically 1 to 5 μm. It is evident while studying the SEM images chemical and mechanical bonding is proceeding, at this scale it better rely on the engineering data to define how effective these additives are.

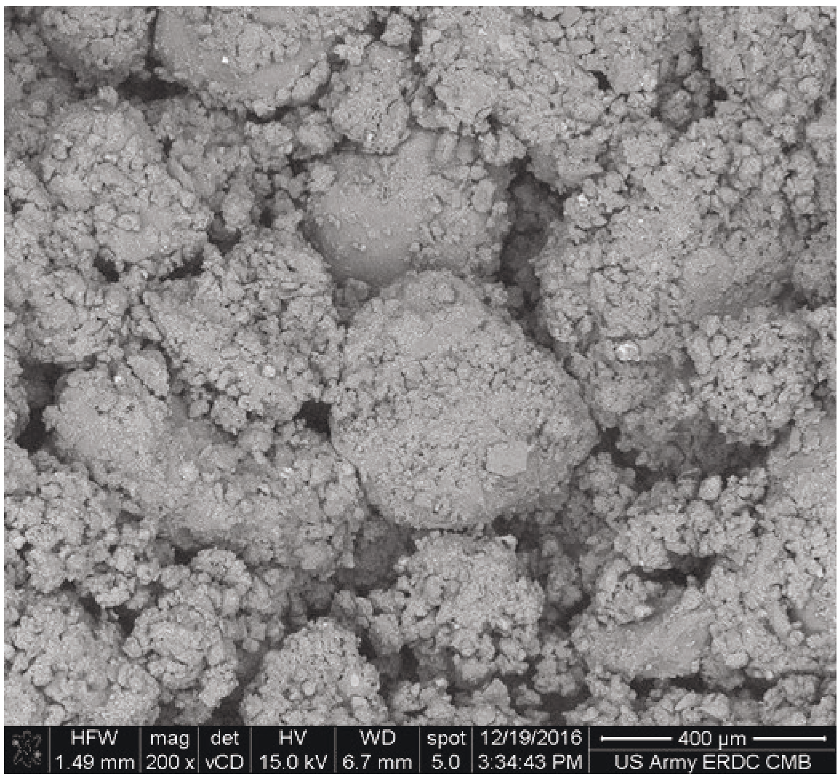
A SEM photomicrograph of the unstabilized soil is in Figure 25. The material is comprised of subrounded larger particles approximately 0.25 to 0.75 mm in size and abundant finer-sized (silty) material.

Figure 25. Scanning electron photomicrograph of silty, clayey sand.



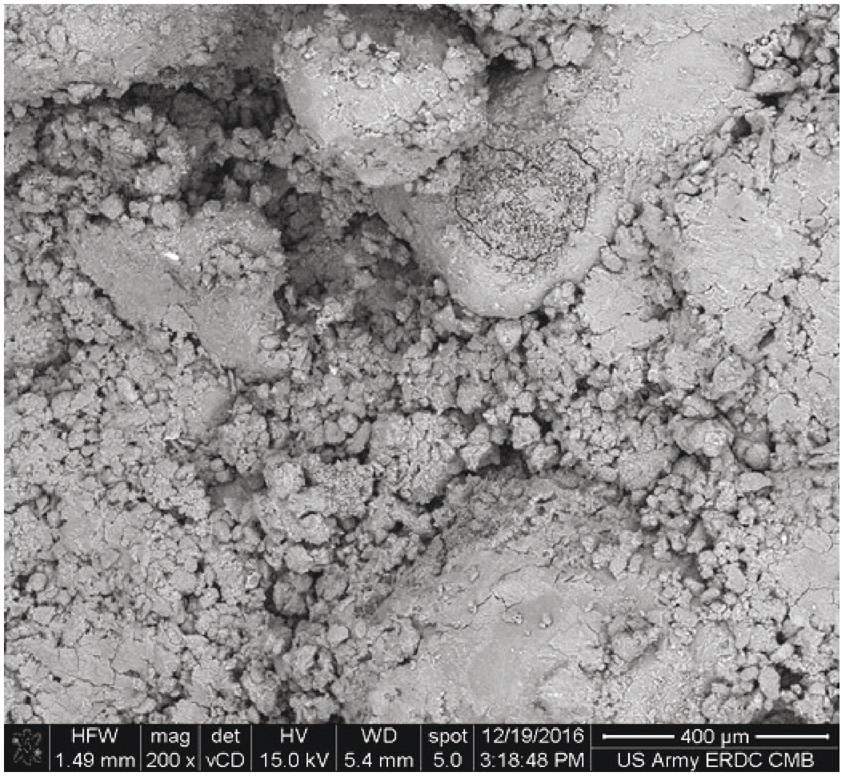
The stabilized and compacted material (Figure 26) is blended with a 5% by weight PLC. The soil fraction present in the photomicrograph is representative of sands, silts, clays, and cement. It is evident that the small soil fractions are compacted and cemented to the larger sand fractions. The coarse material is subangular to subrounded, with finer angular material.

Figure 26. Scanning electron photomicrograph of silty, clayey sand with PLC, 6% moisture content (2-hr cure).



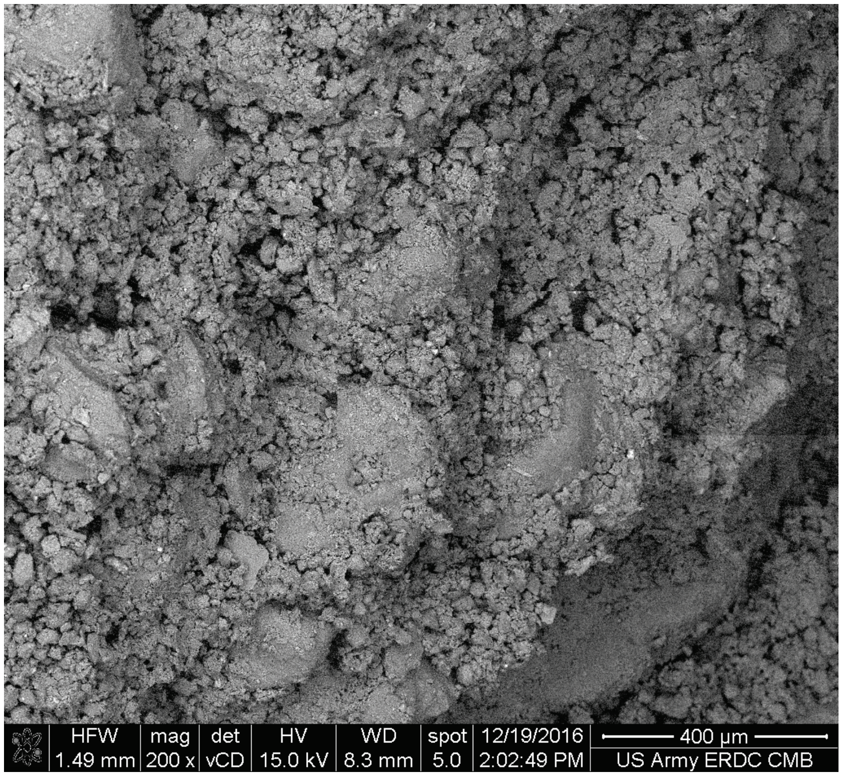
The stabilized and compacted material in Figure 27 is blended with a 5% by weight of Rapid Set Concrete. The soil fraction present in the photomicrograph is representative of gravel, PLC, sands, silts, and clays. It is evident that the small soil fractions are compacted and cemented to the larger agglomerates. The coarse material is subangular to subrounded with finer angular material.

Figure 27. Scanning electron photomicrograph of silty, clayey sand with Rapid Set (2-hr cure).



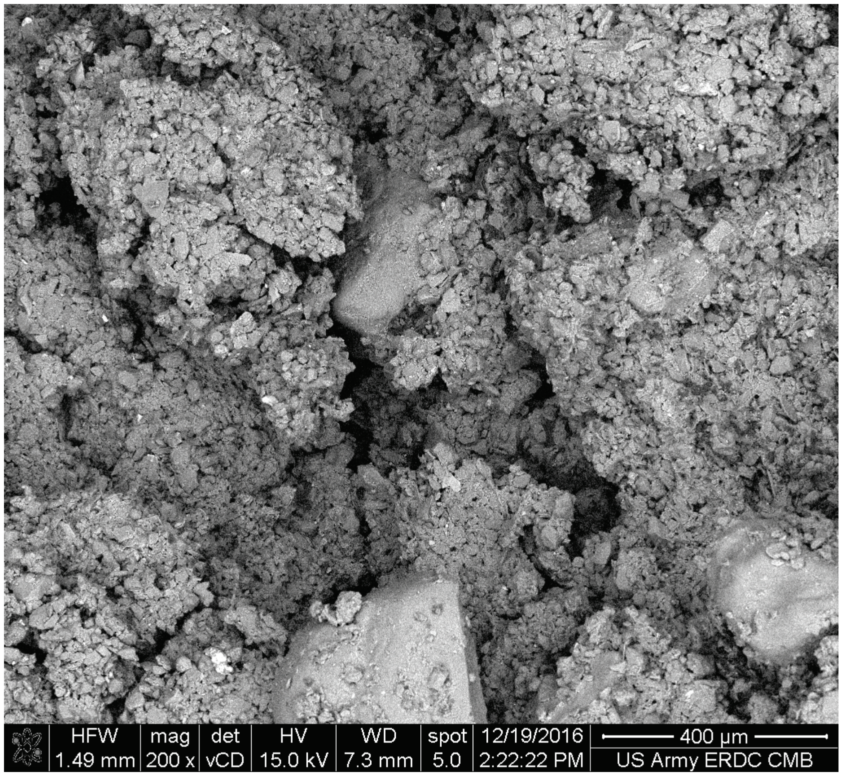
The stabilized and compacted material in Figure 28 is blended with Base Seal at 14.5 fluid oz per cubic yard and 3% lime by mass of soil. The soil fraction in the photomicrograph is representative of gravel, Base-Seal, lime powder, sands, silts, and clays. It is evident that the small soil fractions are compacted and bonded to the larger sand fractions. The coarse material is subangular to subrounded, with angular finer material.

Figure 28. Scanning electron photomicrograph of silty, clayey sand with Base Seal with lime (2-hr cure).



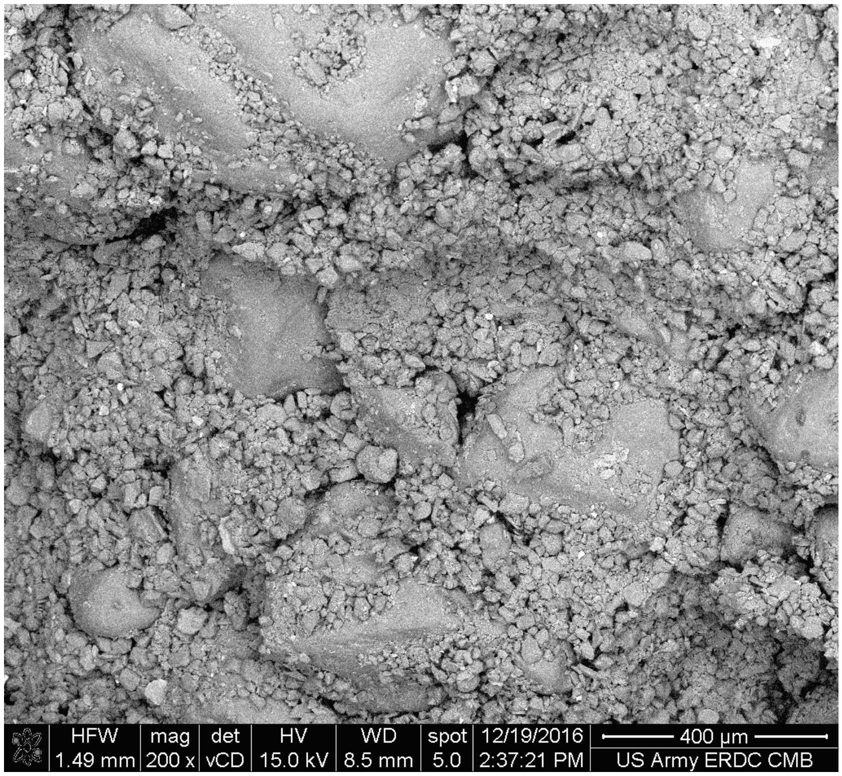
The stabilized and compacted material in Figure 29 is blended with HMI RR 600 soil stabilizer at a rate of 4 lb/ft^3 of soil. The stabilized soil fraction present in the photomicrograph is representative of HMI's RR 600 soil stabilizer, sand, silt, and clay. It is evident that the small soil fractions are compacted and bonded to the larger sand fractions. HMI's RR 600 is a single component polyurethane foam resin that is highly reactive with moisture. The coarse material is subangular to subrounded with the angular finer material.

Figure 29. Scanning electron photomicrograph of silty, clayey sand with RR 600 (2-hr cure).



The stabilized and compacted material in Figure 30 is blended with Soil Sement, the original formula soil stabilizer at a rate of 1 gal/25 ft^2 of soil surface area, 4.25 gal/15 ft^2 at an 8-in. lift, or 9.33 ml per 4-in. compaction mold, or 21.2 ml per 6-in. CBR mold. The stabilized soil fraction in the photomicrograph is representative of Soil Sement's original formula soil stabilizer, sand, silt, and clay. It is evident that the small soil fractions are compacted and bonded to the larger sand fractions. The coarse material is subangular to subrounded, with angular finer material.

Figure 30. Scanning electron photomicrograph of silty, clayey sand with Soil Sement (2-hr cure).



3.6 X-ray diffraction analysis

X-ray diffraction analysis of the soil and a few of the binders used in this study was conducted to ascertain the phases present in each. Various stabilizers work differently depending on the phases present in the soil. In particular, clay-rich samples that are more plastic and contain high water contents need to be considered due to their potential impact on the control specimens and stabilized specimens.

The mineralogy of the soil used in this study and a few of the binders were determined using X-ray diffraction (XRD) analysis. Bulk XRD tests were conducted on each of the samples using the material obtained from splitting sample according to ASTM C 702 (ASTM 2014c). In preparation for XRD analysis, the split portion of the sample was dried in an oven at 50°C and then ground in a Pulverisette (Fritsch Co., Idar-Oberstein, Germany) and passed through a 45-µm (No. 325) sieve. Random orientation powder mounts of bulk samples were analyzed using XRD to determine the mineral constituents present in each sample. XRD patterns were gathered from an X-Pert Pro Multipurpose Powder Diffractometer system that used standard techniques for phase identification (Malvern

Panalytical, Inc., Westborough, MA). The run conditions included Co-Kα radiation and scanning from 2 to 70°2θ with collection of the diffraction patterns accomplished using the PC-based Windows version of X-Pert Pro Data Collector and analysis of the patterns using the Jade2010 program (Materials Data, Inc., Livermore, CA).

The mineralogy of the soil (Figure 31) is comprised principally of 64% SiO2 with minor amounts of feldspars (microcline and albite), dolomites, and clays (montmorillonite, muscovite, and kaolinite). It should be noted that there is 5% expandable clay (montmorillonite) in the soils.

X-ray diffraction patterns were collected for a few of the binders used in this study to determine the material responsible for cementation (Table 8). X-ray diffraction pattern for the PLC (Figure 32) was comprised of limestone ($CaCO_3$) as well as common phases found in portland cement, $Ca_{54}MgAl_2Si_{16}O_{90}$, Ca_2SiO_4, $Ca_2Fe_2O_5$, $Ca_3Al_2O_6$, as well as $CaSO_4 \cdot 0.5\ H_2O$, and $CaSO_4 \cdot 2\ H_2O$ added to prevent flash setting of the calcium aluminates. A small amount of SiO_2 was also observed.

The X-ray diffraction pattern for the flowable fill (without aggregate) (Figure 33) is principally comprised of $Ca_4Al_6O_{12}(SO_4)$, $CaSO_4$, and Ca_2SiO_4. Additional phases in the material include $CaSO_4 \cdot 0.5\ H_2O$, SiO_2, $Ca_{54}MgAl_2Si_{16}O_{90}$, and $Ca(OH)_2$.

The X-ray diffraction pattern of the Rapid Set material (Figure 34) was comprised of phases very similar to the flowable fill, including the principal phase of $Ca_4Al_6O_{12}(SO_4)$, but also had a greater amount of $Ca_{54}MgAl_2Si_{16}O_{90}$ and less of both Ca_2SiO_4 and CaSO4. The material also contained $CaSO_4 \cdot 0.5\ H_2O$ and $Ca(OH)_2$.

Table 8. Phases found in binders used in this study as determined by X-ray diffraction analysis.

Binder	Portland-Limestone Cement	Flowable Fill	Rapid Set
C_3S ($Ca_{54}MgAl_2Si_{16}O_{90}$)	Major	Minor	Minor
C_2S (Ca_2SiO_4)	Major	Major	Minor
C_4AF ($Ca_2Fe_2O_5$)	Minor		
C_3A ($Ca_3Al_2O_6$)	Minor		
Gypsum (CaSO4·2 H_2O)	Minor		
Bassanite ($CaSO_4$·0.5 H_2O)	Minor	Minor	Minor
Calcite (CaCO3)	Minor		

Binder	Portland-Limestone Cement	Flowable Fill	Rapid Set
Ye'elimite ($Ca_4Al_6O_{12}(SO_4)$)		Major	Major
Anhydrite (CaSO4)		Major	Minor
Quartz (SiO2)		Minor	
Portlandite ($Ca(OH)_{2)}$		Minor	Minor

*Major phase is >20%, minor < 20%.

Figure 31. Bulk X-ray diffraction of silty, clayey sand (SC-SM).

WPF Report

Scan ID: MD 1116 - SC-SM.xrdml

Scan Parameters: 2.511°/69.99°/0.01671°/219.71(s), ω=1.255678°/34.99573°, φ=0.0°, I(p)=44643/372, Co(45kV,40mA), Wednesday, Sept

Configuration=Sample Spinner Reflection-Transmission, Owner=User-1, Creation date=12/23/2009 3:41:59 PM
Goniometer=PW3050/60 (Theta/Theta); Minimum step size 2Theta:0.001; Minimum step size Omega:0.001
Sample stage=Reflection-Transmission Spinner PW3064/60; Minimum step size Phi:0.1
Diffractometer system=XPERT-PRO
Measurement program=Chris 2-70 scan time 2h, Owner=User-1, Creation date=6/23/2011 8:43:04 AM

- [x] Kα2 Peaks Present
- [x] Zero Offset = -0.02388 (0.00102)
- [ ] X-Ray Polarization = 1.0
- [ ] Variable-Slit Pattern
- [ ] Displacement = 0.0
- [ ] Kα2/Kα1 Ratio = 0.5

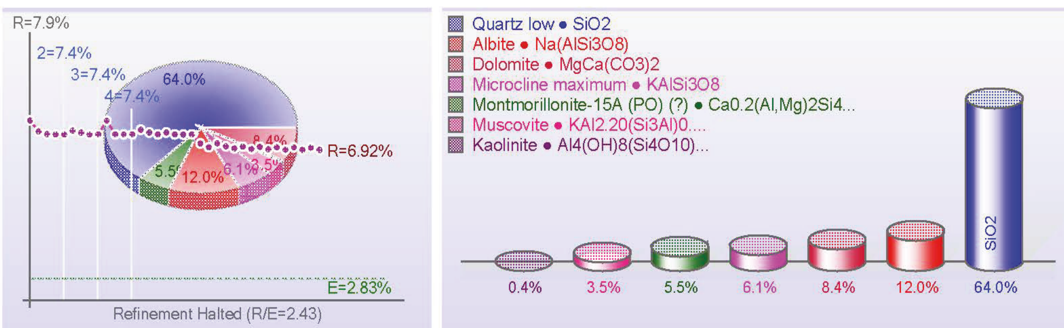
Geometry: Diffractometer Lp Fitted-Range: 2.5 - 63.0° BG-Model: Spline-Curve (19) λ: 1.78899 Å (Co)

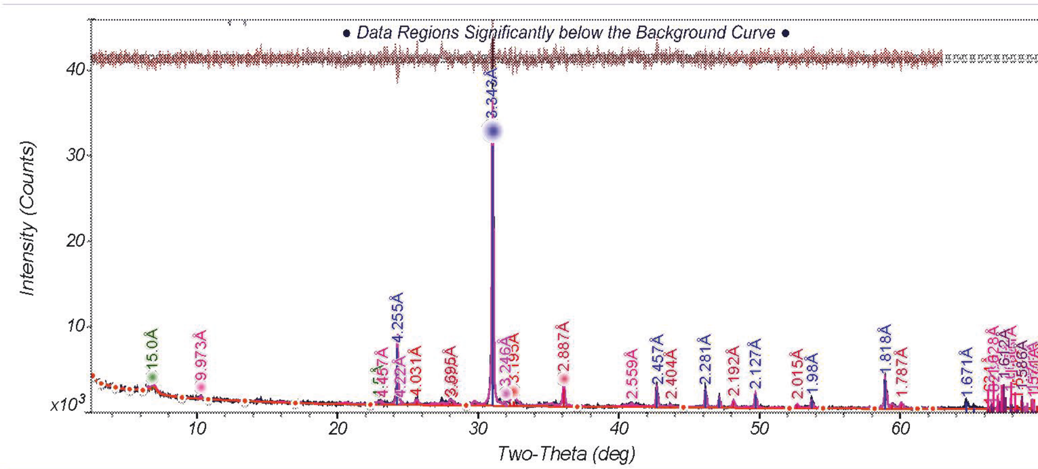
PSF: pseudo-Voigt Broadening: Crystallite Size & Strain Instrument: Constant FWHM = 0.1°

Phase ID (7)	Chemical Formula	PDF-#	Wt% (esd)	RIR	μ
Quartz low	SiO2	01-078-1253	64.0 (0.7)	3.03	140.6
Montmorillonite-15A (PO) (?)	Ca0.2(Al,Mg)2Si4O10(OH)2!4H2O	00-013-0135	5.5 (0.4)	1.50	97.7
Albite	Na(AlSi3O8)	01-089-6423	12.0 (0.5)	0.64	132.0
Microcline maximum	KAlSi3O8	01-076-0918	6.1 (0.6)	0.60	189.5
Muscovite	KAl2.20(Si3Al)0.975O10((OH)1.72O0.28)	01-089-5401	3.5 (0.2)	0.43	184.2
Kaolinite	Al4(OH)8(Si4O10)	01-078-2109	0.4 (0.1)	0.82	120.0
Dolomite	MgCa(CO3)2	98-000-0200	8.4 (0.3)	2.26	202.9

XRF(Wt%): CaO=2.7%, K2O=1.4%, SiO2=81.0%, Al2O3=5.7%, MgO=2.4%, Na2O=1.4%, CO2=4.0%

Refinement Halted (R/E=2.43), ♣ Round=4, Iter=6, P=44, R=6.86% (E=2.83%, EPS=0.5)





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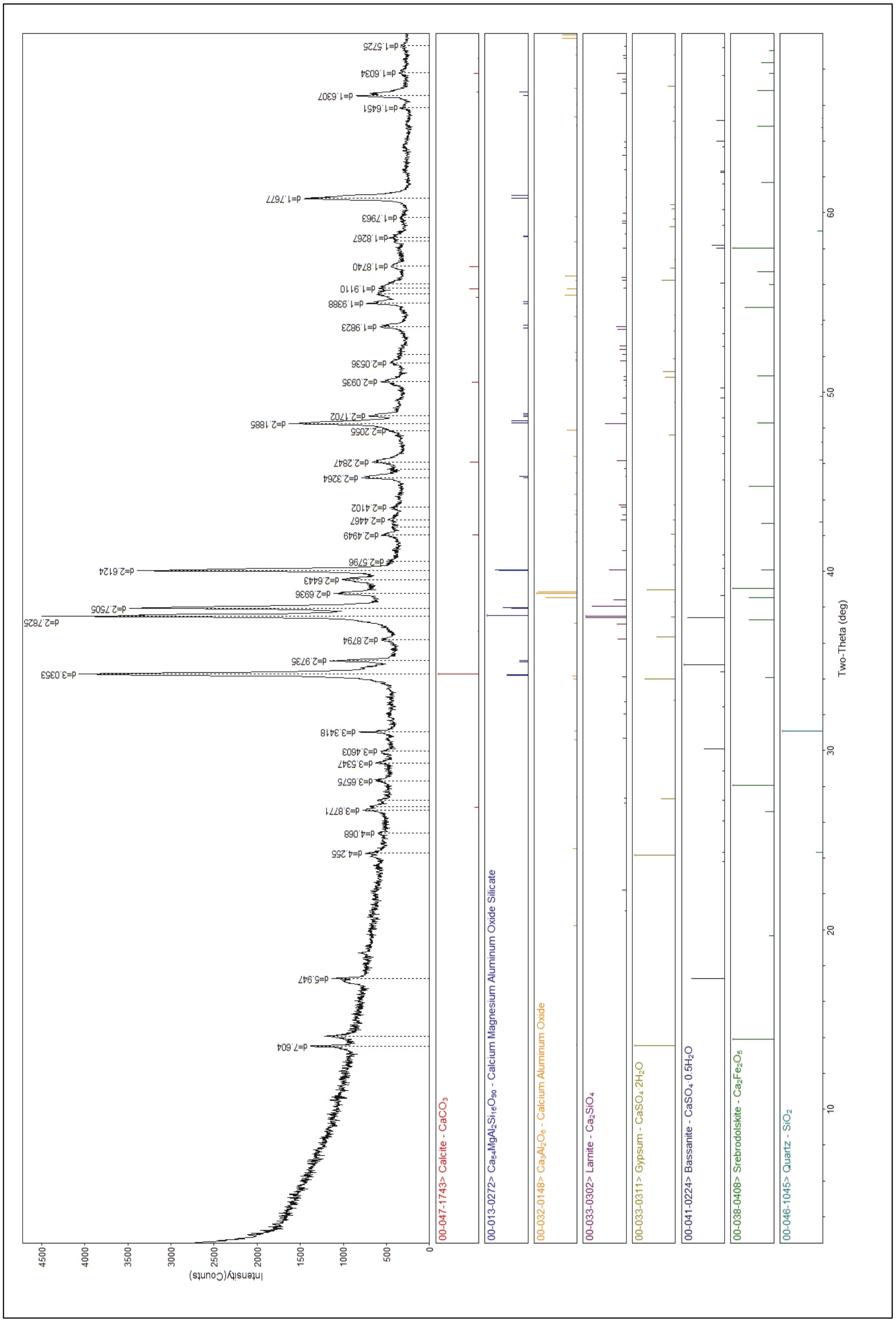


Figure 32. X-ray diffraction pattern of PLC.

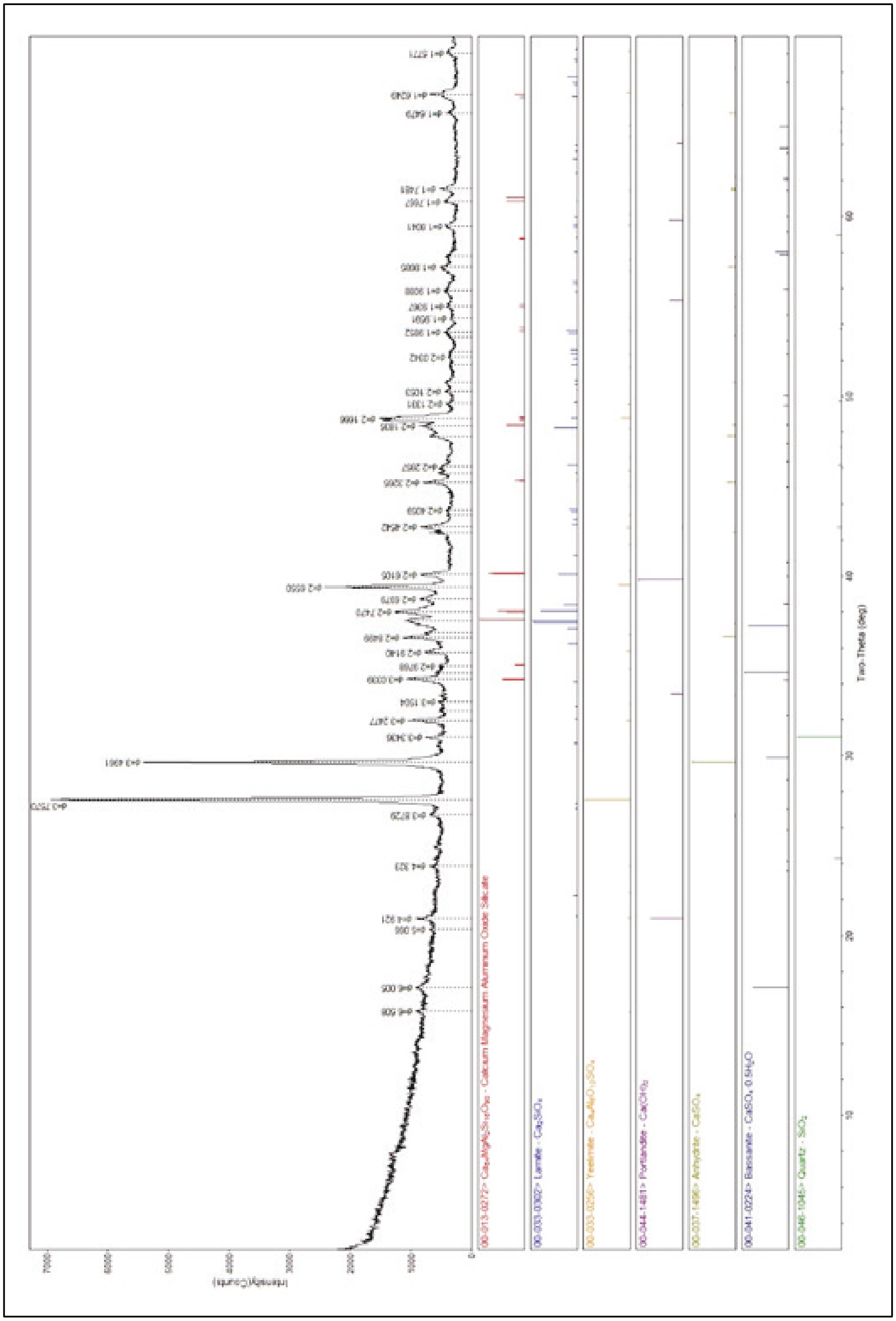
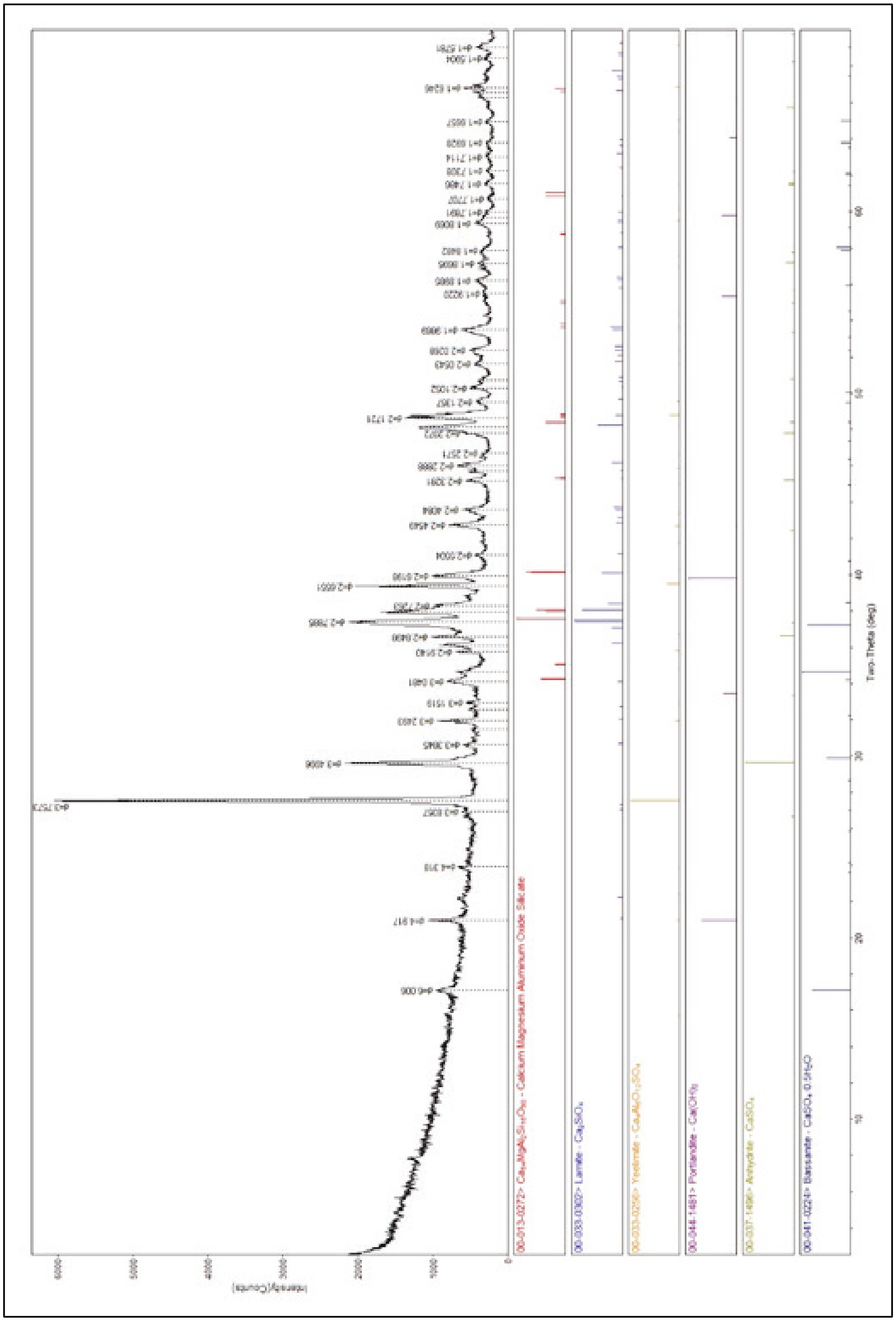


Figure 33. X-ray diffraction pattern of flowable fill with aggregate removed.

Figure 34. X-ray diffraction pattern of Rapid Set with aggregate removed.



4 Conclusions and Recommendations

This report does not justify, recommend, and/or advocate any products used in the testing. The goal of the testing was to gain a better understanding of the materials used and how they perform under rapid exposure and curing. The testing regimen may not have followed manufacturer's specifications for mixing, curing, testing, and/or evaluation.

4.1 Conclusions

The results of this study indicated that each of the proprietary mixes had substantial effects on the soil. This study focused on short-term (2 hr) performance of materials for stabilization of soils. In addition, tests were performed after 7 days of curing to determine materials' improvements. Due to rapid curing requirements, some products outperformed others in rapid short-term testing but may not have yielded the same results in the 7-day analysis. While some materials did not show improvements in strength, each of the materials has the ability to increase the backfill performance of the silty clayey, sand (SC-SM) material. Moisture and curing time were shown to have a large impact on the stabilization ability of the additives.

Due to the rapid trafficability requirements of the Rapid Airfield Damage Recovery Evaluation of Next-Generation Backfill Materials study, a field evaluation was completed with the top five of the additives based on the laboratory study. The additives selected to be mixed with the silty clayey, sand for field evaluation included PLC, Rapid Set, Base-Seal with lime, RR 600 Soil Stabilizer Polymer (reduced concentration), and Soil Sement Engineered Formula (original formula). The control was a full-depth placement of flowable fill.

- Due to high variability in polymer and chemical soil additives, it is hard to predict which product will work best for rapid stabilization. The data presented will help with making the decision for soils that contain silt, clay, and sand.
- When using polymer and inorganic additives, it is important to account for bound moisture in the soil and the moisture that suspends the solids in the additive.
- If the soil has a high water content, the amount of polymer and/or chemical additive must be reduced, or the soil must be mechanically

mixed to evaporate moisture. Water content in the soil induces high variability in strength at both a 2-hr and 7-day cure time.
- This study found that using 5% PLC by dry weight of soil is highly effective in soil stabilization, when water content in the soil is high.
- All additives but the potassium silicate increase the CBR value at both two hr and seven days of curing.

4.2 Recommendations

It is recommended that the study be continued with larger concentrations of the liquid additives to gain a better understanding of their performance. Due to time constraints, a more complex analysis of the additives performances was not feasible. These laboratory analyses allowed for a better understanding of which additives will perform well in the field under a rapid timeline.

- As expected the PLC had the best performance when high water contents were present in the soils for rapid stabilization.
- A mixture of the dry additives proved to be effective at water contents above 6% in the silty clayey sand (SC-SM). The authors would recommend additional studies be conducted.
- Further evaluation of the use of the additives with the SC-SM at longer curing regimes (28 days) as well as other soil types such as sands, clays, and silts may provide additional information when long-term stabilization is desired. Since only one soil was used in this study, performance of other soils using the additives in this study may provide different results.

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Appendix A: Lab Testing Charts

Figure A1. Soil-blending chart.

Material Blending: **Silty Sand Blend**

Materials Information:

Enter material gradations for each soil in columns D-F.

Enter Percentage of Each Material:

Results:

Aggregate 1:	60
Aggregate 2:	40
Aggregate 3:	0

Sieve Sizes		Percent Passing by Weight					
WES Grain Size	**Metric mm**	**Concrete Sand (SP)**	**Loess Silt (ML)**	**X**	**WES Grain Size**	**Blend % Passing**	**Desired Gradation**
1.5	**38.1**	100	100	0	**1.5**	100	100
1	**25.4**	100	100	0	**1**	100	100
0.75	**19.05**	100	100	0	**0.75**	100	100
0.5	**12.7**	99	100	0	**0.5**	99.4	99
0.375	**9.525**	96.2	100	0	**0.375**	97.72	60-100
4	**4.75**	92.9	100	0	**4**	95.74	50-98
6	**3.35**	85.4	99.8	0	**6**	91.16	40-95
10	**2**	79.1	99.5	0	**10**	87.26	
16	**1.2**	76.2	99.3	0	**16**	85.44	40-85
20	**0.5**	74.2	99.3	0	**20**	84.24	25-85
30	**0.3**	69.6	99.3	0	**30**	81.48	25-80
40	**0.15**	56	99.0	0	**40**	73.2	
50	**0.075**	24.4	98.6	0	**50**	54.08	
70	**0.05**	5.5	98.3	0	**70**	42.62	
100	**0.01**	1.3	98.1	0	**100**	40.02	40
140	**0.005**	0.6	97.9	0	**140**	39.52	
200	**0.001**	0.4	97.6	0	**200**	39.28	25-40
D10		0.205	0.0032				
D30		0.31	0.0114				
D60		0.41	0.0204				
Cu		2.00	6.38				
Cc		1.14	1.99				
Classification:		SP	ML				
Failure:		Cu	Cu				

MIX → Input WC% → Input desired Dry wt for 125# mix

SM Silty Sand Blend (mixer load lbs)		WC %	Dry wt. Lbs	% Material
Sandy Gravel (wet)	**0.0**		0	0.0
Concrete Sand (wet)	**80.6**	7.4	75	60.0
Silt (wet)	**58.3**	16.6	50	40.0
			125	100

Figure A2. Flowchart of laboratory testing process

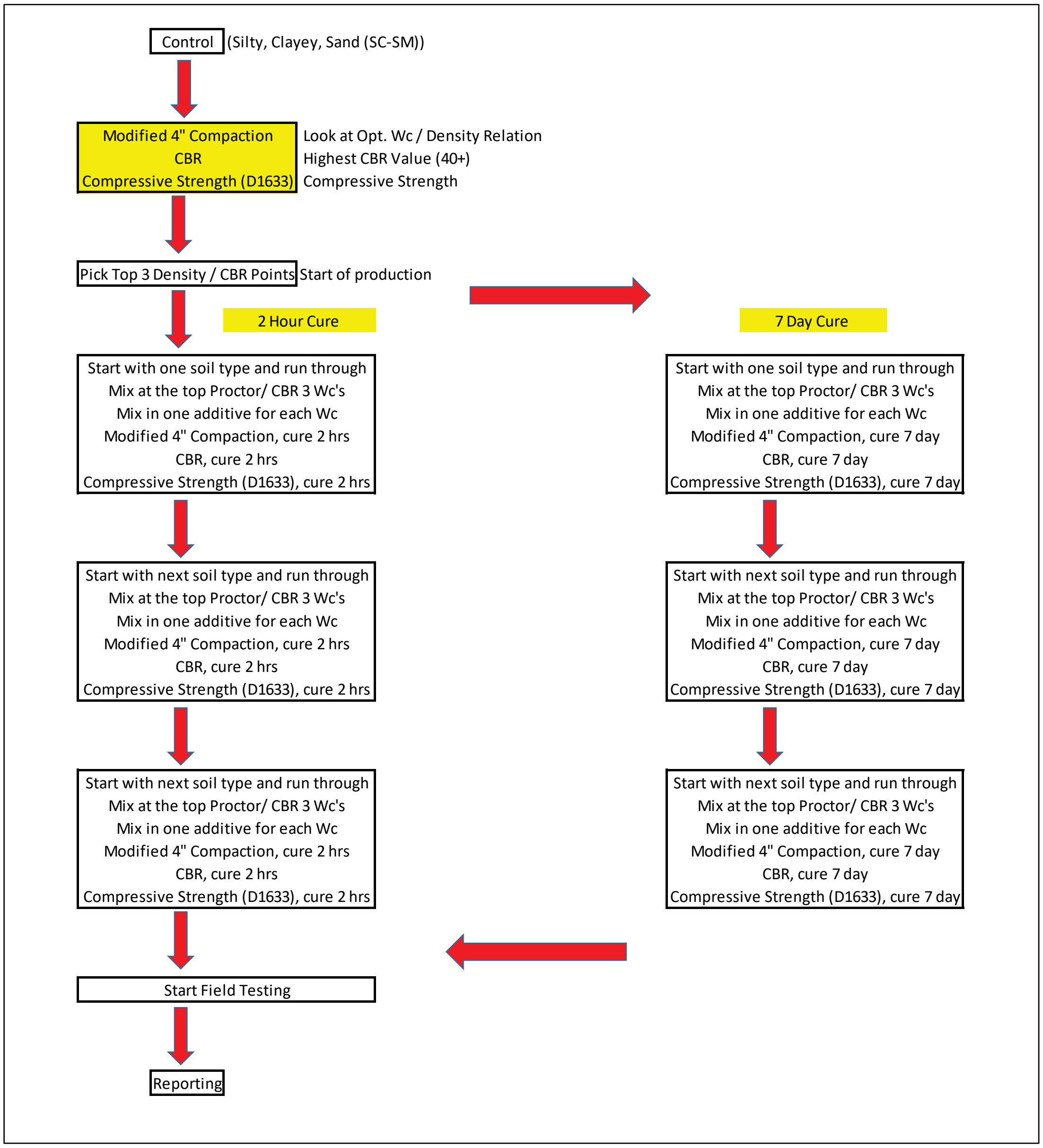

Figure A3. Durability testing results

	Loss of Material			Softening of Sides			Color	Turbidity			
	Minimal	Moderate	Substantial	Minimal	Moderate	Substantial		No Noticeable	Minimal	Moderate	Substantial
Base Seal with Lime (Initial Water Content: 8%, 1 Week Cure)		X				X	Tan		X		
Base Seal with Lime (Initial Water Content: 8%, 2 Hour Cure)		X			X		Tan			X	
Control (Initial Water Content: 8%, 2 Hour Cure)			X			X	Tan				X
Control (Initial Water Content: 8%, 1 Week Cure)			X			X	Tan				X
Dirt Glue (3% Weight Total, Initial Water Content: 8%, 1 Week Cure)		X		X			Tan			X	
Eco Pave (2mL, Initial Water Content: 8%, 1 Week Cure)			X			X	Brown				X
EMC² (0.7mL EMC² 2000 and 1.4mL EMS, Initial Water Content: 8%, 1 Week Cure)			X			X	Brown			X	
Flowable Fill (Initial Water Content: 4%, 2 Hour Cure)		X			X		Brown			X	
PLC (CH) (Initial Water Content: 15%, 2 Hour Cure)			X			X	Gray			X	
PLC (CH) (Initial Water Content: 15%, 1 Week Cure)		X		X			Gray		X		
PLC (Initial Water Content: 8%, 2 Hour Cure)	X			X			Light Tan	X			
PLC with Fly Ash (5% Weight Total – 2.5% PLC/2.5% Fly Ash, Initial Water Content: 8%, 1 Week Cure)	X			X			Light Brown			X	
RR600 Full (354g of RR600, Initial Water Content: 8%, 1 Week Cure)	X			X			None	X			
RR600 Full (354g of RR600, Initial Water Content: 8%, 2 Hour Cure)	X			X			None	X			
RR600 Reduced (131mL, Initial Water Content: 8%, 1 Week Cure)	X			X			None	X			
RR600 Reduced (131mL, Initial Water Content: 8%, 2 Hour Cure)	X			X			None	X			
Sodium Silicate with Fly Ash (10% Weight Total – 5% Sodium Silicate/5% Fly Ash, Initial Water Content: 6%, 1 Week Cure)	X			X			Copper	X			
Soil Sement (Initial Water Content: 8%, 1 Week Cure)		X				X	Tan		X		
Soil Sement (Initial Water Content: 8%, 2 Hour Cure)			X			X	Tan			X	
Potassium Silicate (2 Hour Cure)	X				X		Tan				X

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14. ABSTRACT
During the period March through October 2016, research was conducted at the U.S. Army Engineer Research and Development Center in Vicksburg, MS, to develop alternative backfill materials for rapid airfield damage repairs using a variety of commercially available products. The performance of a variety of additives, including 15 traditional and non-traditional materials, and a control comprised the test matrix of stabilization additives. The types of additives included cement, polymer, polyurethane, petroleum emulsion, and silicates. This report presents the technical evaluation of the laboratory and field performance of alternative backfill materials used in the subgrade of concrete repairs using Rapid Set Concrete Mix®. The additive performance criteria focused on bearing capacity, unconfined compressive strength at 2 hr and at 7 days, and durability of the specimen when partially submerged in water. Laboratory testing included mixing silty, clayey sand soil with each of the additives at specified application rates; compacting; curing; and conducting unconfined compressive strength and California Bearing Ratio testing. For the field evaluation, a repair consisted of preparing the subgrade with a selected additive and overlaying it with Rapid Set Concrete Mix®. Passes-to-failure rates for each repair were determined by using an F-15E load cart at a maximum of 3,500 passes.

15. SUBJECT TERMS
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Fills (Earthwork)
Soil stabilization
Crater repair
Next-generation backfill
Polymer
Cement
Cratering
Materials – Evaluation

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