Note# 0001

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In Situ Soil-Cement Mixtures: definitions, properties, and design considerations

By: Dan Ruffing, P.E.[1] and Tony Moran, P.E.[2]

[1]Engineering Manager, Geo-Solutions, Inc., New Kensington, PA, 724-335-7273, druffing@geo-solutions.com
[2]Project Director, Geo-Solutions, Inc., New Kensington, PA, 724-335-7273, tmoran@geo-solutions.com

PRELUDE

Much of the information presented in this paper should be considered common knowledge by those who regularly encounter soil-cement mixtures. This paper was developed to provide the reader a comprehensive understanding of what soil-cement mixtures are and what physical properties to expect. The target audience is civil or geotechnical engineers that are not commonly engaged in work involving shallow or deep soil mixing or other applications in which soil is mixed with cementitious reagents *in situ*. However, even readers with knowledge of these topics may benefit from the information included in the tables and figures and commentary presented throughout.

The term soil-cement is self-explanatory, but will herein also be used to describe any mixture of soil and reagents containing some cementitious component installed *in situ*. Other common terms used to describe mixtures like this are soil-grout and soilcrete. Applications in which soil or sediment is mixed with cementitious reagents *ex situ* are not addressed here.

INTRODUCTION

Soil mixing is commonly used to improve the strength and/or permeability of contaminated or marginal soils. Over the last few decades, the use of this technology has rapidly expanded in both the geotechnical and environmental markets. Expansion in the geotechnical market is largely due to improvements in soil mixing installation methods and monitoring equipment. Expansion in the environmental market is largely due to the difficult nature of remediating some contaminant matrices (e.g. manufactured gas plant (MGP) waste, wood treating waste), soil mixing's sustainability and cost effectiveness compared to alternative remedies (e.g. vs. dig and haul), and the novel application of existing treatment methodologies to improve efficacy. For these reasons, soil mixing has become a common choice for the immobilization or fixation of contaminants in soil and groundwater. This has, in turn, created an increased interest in understanding and monitoring the properties of soil-cement mixtures including the leachability characteristics of the improved soil masses.

MIXTURE COMPOSITION

Soil-cement mixtures are simply mixtures of soil and cementitious reagents. These mixtures often have a similar overall structure to concrete in that both are aggregate materials mixed with Portland cement, alone or in combination with inert or other cementitious reagents. However, soil-cement mixtures are unlike concrete in two key ways 1) the mixtures contain a much smaller amount of cementitious reagent(s) and 2) the "aggregate" proportion is made up of a variety of different soil types with varying particle sizes, ranging from plastic clays to clean gravels. Concrete aggregate is made up of clean, strong particles of sand and gravel. Standard mix ratios for soil-cement mixes are shown below alongside those of concrete.

Table 1. Concrete versus Soil-Cement Mix Composition

	Concrete (%[1])	Soil-Cement (%[1])
Cement	10 – 30	5 – 15
Water	5 – 15	5 – 45
Coarse Aggregate	30 – 50	40 – 90[2]
Fine Aggregate	20 – 40	
Ultrafine Aggregate	0	

[1]Component % of the total mix, by weight
[2]The "aggregate" of soil cement is predominately clays, silts and sands with little gravel

As with concrete, the cementitious component of a soil-cement mixture can contain other additives to assist in achieving specific property objectives, for cost reduction, or for sustainability metric improvement. Common additives include blast furnace slag, lime, limestone dust, silica fume dust, cement kiln dust, and flyash. However, unlike concrete, soil-cement mixtures may also contain alternate additives including activated carbon, bentonite, organophillic clay, granular iron, etc. These alternate additives are generally for improving the leaching characteristics of the soil-cement monolith or for contaminant reduction, but some can also improve hydraulic or physical performance.

APPLICATIONS

Soil-cement is used in a number of applications ranging from near surface subgrade improvement to barrier wall installation to mass solidification and/or stabilization. Although the Romans and Greeks used cementitious reagents mixed with soils and aggregates to create roads and other structures, the literature indicates that the earliest uses of soil-cement installed *in situ* using soil mixing were in the US in the 1950s. Since this initial application, soil mixing for soil-cement installation has been used widely for both geotechnical and environmental applications around the US and internationally. The widest application of soil-cement in the environmental industry is for the mass stabilization / solidification (S/S) of contaminated soils and groundwater. Soil-cement has also been used in the installation of vertical cutoff walls. In this application soil-cement has been installed using soil mixing, e.g. jet grouting, multi-auger (commonly known as DSM), or single auger, and slurry trenching. In cutoff wall applications, the goal is always the creation of a composite soil-cement monolith with a lower permeability than the *in situ* soils alone.

For clarity purposes, the authors are not intimately familiar with the application of soil-cement for near surface subgrade improvement (for road subgrade or for remote road installations), but are aware that this practice has seen significant growth over the last decade with further growth expected.

PROPERTIES

Soil-cement mixture properties vary widely and depend on many variables including the soil type, soil grain-size distribution, soil plasticity, soil organic content, cementitious reagent source, cementitious reagent quantity, water content, both pore water and water added in conjunction with the reagent(s), and contaminant concentration and type. The addition of cementitious reagents to soil can cost effectively create soil-cement mixtures with hydraulic conductivity values that are 1 or more orders of magnitude lower and strengths that are 30 to 500 times greater than the soils alone.

Strength and Permeability

As with concrete, the strength of soil-cement mixtures tends to increase and the permeability tends to decrease over time. Performance objectives for environmental applications for unconfined compressive strength (UCS) and permeability are commonly set at > 50 pounds per square inch (psi) and < 1×10^{-6} centimeters per second (cm/s), respectively.

For geotechnical applications, performance objectives vary significantly by project. UCS strength targets can range from 20 to 500 psi with permeability less commonly targeted.

For both types of applications, the target UCS and permeability is to be achieved after 28 days of cure. Additional tests, such as further UCS testing or the use of a pocket penetrometer, are commonly performed after 3, 7, and 14 days of cure to assess whether the soil-cement mixture may achieve the ultimate performance objective after 28 days.

The most accurate way to predict property improvement of soil-cement combinations over time is to use a site specific study to assess property changes with time. However, soil-cement mixtures can have substantial property variability across individual specimens and most individual project studies cannot or do not cover statistically significant specimen variation. In order to account for the limitations of individual studies, it’s also useful to use general trends developed from data collected on multiple projects. Relationships between early test results and ultimate (after 28 days of curing) test results for strength and permeability are shown in Figures 1 and 2 respectively. The trends presented in Figures 1 and 2 may be used to predict 28 day mix performance using results of tests conducted at earlier curing ages. Figures 1 and 2 are a presentation of information collected from the author’s experience on over 30 projects involving soil-cement mixtures.

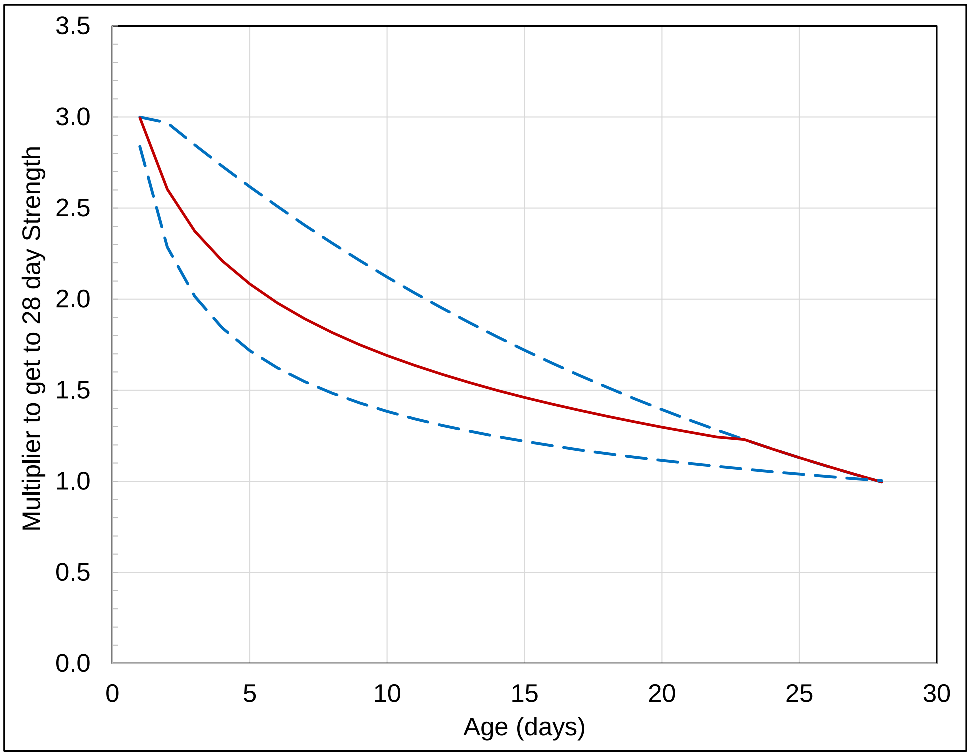

Figure 1. 28 day Strength Predictor

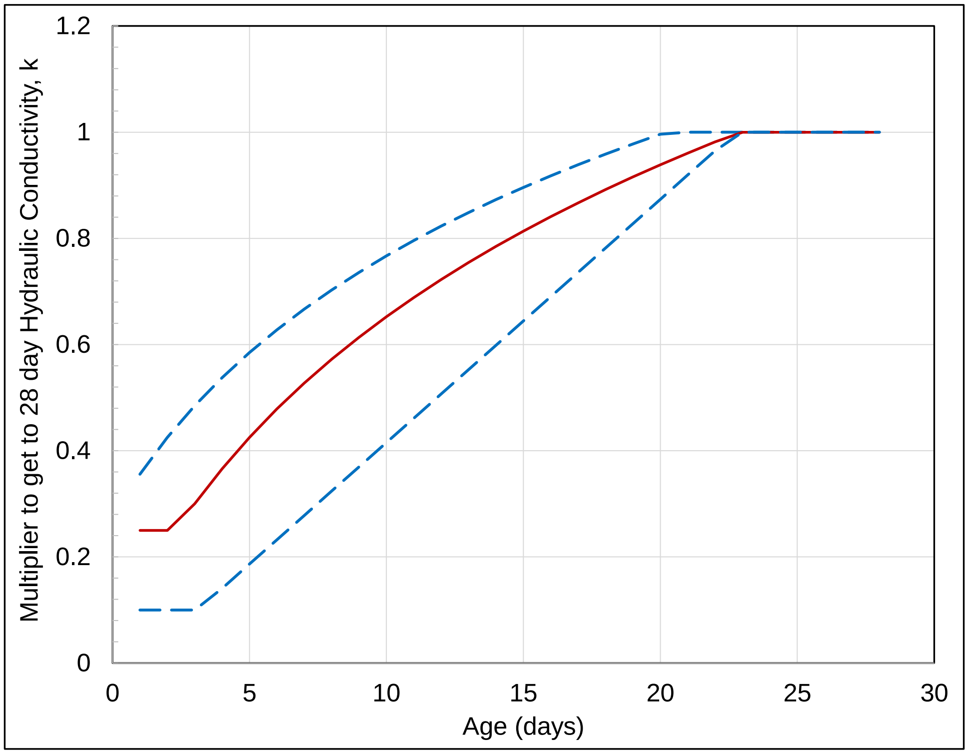

Figure 2. 28 day Permeability Predictor

As should be immediately clear from a review of Figures 1 and 2, the information has been idealized. A simplified version of the information presented in Figures 1 and 2 is also presented on Table 2 for common early test result ages.

Table 2. UCS and Permeability Predictor Plot Interpretation

Property	Test Result After x days of Curing	Multiply Test Result by predictor to get 28 day Estimation
UCS	3	2.4
	7	1.9
	14	1.5
Permeability, k	3	0.3
	7	0.5
	14	0.8

Based on the information presented in Figures 1 and 2 and in Table 2, it is not unreasonable to expect a 100% to 200% increase in UCS and a ½ to 1 order of magnitude decrease in permeability as soil-cement mixtures cure from day 1 to day 28. Mixtures created with contaminants in the soil or groundwater, or mixes containing alternative cementitious reagents or less common reagents, may not follow these relationships. For instance, replacing more than 50% of the Portland cement component with blast furnace slag usually results in greater strength and lower permeability properties after 28 or more days of curing, but the mix may exhibit lower strength and higher permeability than comparable mixes containing only Portland cement in tests conducted at shorter cure times.

The dashed lines in Figures 1 and 2 provide some indication of expected variability. If the property improvement of a given soil-cement mixture follows the general trends in Figures 1 and 2, then approximately 68% (+/- approximately one standard deviation) of the results from tests conducted on soil-cement mixtures can be expected to fall within the bounds of the dashed lines. However, it is not uncommon to see individual UCS test results that deviate by 50% - 200% and permeability test results that deviate by 10% - 100% for tests performed on conceptually "identical" specimens. For the purposes of this discussion, identical means the specimens were cast at the same time, from roughly the same soil source, using the same reagents, and using very similar casting methods. Proper casting procedures (e.g. see Andromalos et al 2014 and the description below) can eliminate some of this variability, but the variable nature of the "aggregate" material in soil-cement mixtures makes some of this variability inherent. Engineers and contractors engaged in the design or oversight of projects involving soil-cement mixtures should take this inherent variability into account when developing performance objectives or determining if existing objectives have been achieved.

Leachability

A growing concern in environmental applications of soil-cement is the ability of the soil-cement matrix to reduce or prevent leaching of contaminants into the surrounding subsurface. This follows with the main objective of soil-cement installations on environmental projects being a reduced impact of contaminated soils and groundwater on the surrounding environment. Historically the tests, e.g. TCLP, SPLP, ANS 16.1, used to assess leachability characteristics were limited for assessing soil-cement mixtures for various reasons. Because of the limitations many projects either did not include a leachability assessment component or only included leachability testing for observational purposes. However, the recently developed LEAF testing protocols, EPA Methods 1313 through 1316, have addressed many of the concerns related to applicability of leachability results to soil-cement mixtures. Performing a full LEAF testing suite can be expensive and therefore cost prohibitive for many projects. A number of modified, primarily shorter and less expensive, versions of these test methods are used and are recommended for most applications. The authors also note the existence of a less known test, EPA Method 1310B: “Extraction Procedure (EP) Toxicity Test Method and Structural Integrity Test”. This method can be used to cost effectively assess both expected structural integrity of the monolith as well as the resulting leaching characteristics of the mixture in a semi-monolithic form (monolith size depends on relative strength). The authors expect that leachability will be an increasingly important consideration in environmental applications moving forward.

BENCH SCALE STUDY CONSIDERATIONS

Given the variability of soils used for soil-cement creation, site specific bench scale studies, a.k.a mix design studies, are extremely important to ensure, with a reasonable factor of safety, that property improvement objectives are feasible on a given project site. Studies in this application should be conducted using means and methods that mimic the full scale application to the extent practical so that results of the bench scale study are suitable for predicting full scale performance. An engineer and/or contractor that is actively engaged in the design and construction of *in situ* soil-cement should be engaged to perform or oversee this work. In the absence of standards, and really the ability to develop standards for a process that varies so widely, experience is critical for ensuring a successful study.

QUALITY CONTROL

Detailed specifications or contract documents outlining specific work related requirements are common for soil-cement applications. These documents will outline the minimum requirements for performance of soil-cement at a given project site. The authors urge designers engaged in soil-cement project specification development to incorporate known variability of soil-cement properties into the specified requirements and relatedly account for this variability in the design. Procedures for doing so are available in published resources, e.g. see FHWA Manual (2013). For example, the strength of soil-cement mixtures is known to vary substantially with an observed coefficient of variation (the ratio of the standard deviation to the mean) of approximately 0.3 to 0.7 with an average around 0.5. In general terms, this means that most of a given data set will fall within a range of +/- 30% to 70% of the mean, but there will be significant portions of the data set, around 16% on each side, that fall well below and well above the mean. It is also impossible to determine what the minimum observed strength will be and therefore specifying a minimum strength is not recommended.

An important component of the overall QC plan on a soil-cement project will be what the authors refer to as “process controls”. These controls include the procedures utilized by the construction team to monitor the process from grout formation to delivery of the grout to the soil mass. These controls may include methods to monitor and document the weight of reagent per unit of grout, the volume of grout added to a unit volume of soil, and the distribution of the grout within a mixed column or cell. Process controls provide real time information that can help identify issues early in the construction process, long before compliance testing (primarily offsite strength or permeability) has been completed.

The ultimate performance of soil-cement mixtures is generally assessed using offsite testing performed by a qualified, third party geotechnical laboratory. The primary objectives for soil-cement applications are typically strength and permeability. On most projects, these properties are measured using cylinders cast from "grab" samples. Grab samples are collected from the soil-cement mixture while the mixture is in its semi-fluid condition. The collected sample is cast in cylinders and allowed to cure prior to being shipped and tested. Collection, preparation and casting, storage, shipping, and testing procedures can all influence the results so it's important to utilize published methodologies when possible and experience when not.

Coring is also performed for visual inspection of the mixed mass and for collecting specimens for laboratory testing. Coring should not be used for the collection of permeability specimens as the coring process imparts micro-fractures to the same that will make permeability assessment unrepresentative. Coring is most commonly used on geotechnical improvement projects where the soil-cement target strength is comparatively high. Coring is not recommended for collecting samples of low strength, e.g. < 100 psi, soil-cement mixtures and the authors caution against putting too much weight on the results of tests conducted on cores, from even higher strength mixtures, e.g. > 250 psi. Although conceptually one would expect the strength of tests conducted on cored specimens to be more representative of the in situ condition, the actual results are influenced by a number of factors including coring methodology, variability of grain size, presence of uncharacteristically influential inclusions, coring subcontractor experience, stress relief, and other phenomena that are not fully understood (e.g. coring induced micro-fractures). If coring is utilized for collection of specimens for strength testing, the designer must understand that the measured results will likely represent a lower strength material than the in situ composite, significant variability will be expected, and some results will need to be discarded because of uncharacteristic inclusions. Specifications should include flexibility to account for these known issues.

In addition to laboratory testing of specimens collected via grab sampling or coring, direct measurement of properties *in situ* is also sometimes performed. Testing in situ is not widely used, but can be a valuable assessment tool if utilized properly. In situ testing that has been used in assessing soil-cement includes CPT, SPT, DCPT, borehole permeability, column penetration, pressuremeter, vane pull-out, and vane shear. Users of any of these methodologies must understand the inherent properties of soil-cement to properly apply and analyze the results of any *in situ* testing approach.

Finally, in addition to the direct assessment methodologies described above, there are also qualitative approaches to assess soil-cement. These approaches include corehole video logging, down-the-hole geophysics, and visual observation of collected specimens (via coring or utilizing other similar approaches, e.g. pitcher sampling). These indirect assessment approaches are generally used as a supplement to one or more direct assessments to help identify issues or to supplement the project team's overall understanding of the installed material.

USEFUL INFORMATION

A companion paper, expected for publication in the proceedings of a TBD upcoming and relevant conference, will highlight the points made above and will also include discussions and interpretations, plots, and tables that the authors have found useful or developed over years of experience with soil-cement in soil mixing applications. In the meantime, the authors recommend the following references for additional information on soil-cement and/or soil mixing. This list is not meant to be exhaustive as there are certainly many other useful resources addressing aspects of this topic.

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23. OTHER RESOURCES: LINK

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