A CASE HISTORY ON THE DESIGN, CONSTRUCTION, AND FIELD QUALITY CONTROL OF CEMENT DEEP SOIL MIXING

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This paper presents a case study of the use of single axis cement deep soil mixing (CDSM) to deal with static settlement and seismic stability of the foundation soils under a reinforced soil slope (RSS) embankment up to 50 feet high. As part of the widening of Interstate 5 (I-5) to allow High Occupancy Vehicle (HOV) lanes in Tacoma, Washington, a new approach and span over the Puyallup River will be constructed. During the soils investigation and design phase of the project, low plasticity silts (ML) inter-bedded with silty sand layers and organic silt where identified as being potentially liquefiable. CDSM was selected to address the embankment foundation concerns and allow for future trenchless installation of utility lines beneath the embankment. The presence of a confined, artesian aquifer within the design depth of the CDSM led to the installation of a depressurization system to avoid an upward gradient through the wet soil-cement. In addition to addressing the design approach, the paper discusses the challenges associated with quality assurance of CDSM within the time constraints of an ongoing project. The limited recovery rate of conventional triple tube coring in the soil-cement and double tube wet sampling led to the use of sonic coring to provide a near continuous core of the soil-cement.

Introduction

Cement deep soil mixing (CDSM) was used as a replacement for stone column ground improvement in a corridor which the owner, the Washington State Department of Transportation (WSDOT) wanted to reserve for future trenchless crossings beneath reinforced soil embankments within a freeway interchange. The work was part of HOV improvements to I-5 in Tacoma, Washington. The CDSM construction occurred in late 2010 and early 2011.

Approximately 14,500 cubic yards of soil cement columns were placed by CDSM. The soil cement improved ground supports permanent geosynthetic reinforced slopes up to 50 feet high. The ground improvement was designed primarily to provide global stability of the reinforced slopes during seismic loading, but it was also utilized to reduce the time and total amount of settlement following construction of the embankments.

This paper presents a discussion of the design approach and challenges associated with quality assurance of a relatively small volume of CDSM within the time constraints of an ongoing project. The challenges associated with attempts at collecting cores of the cured soil-cement mix cured by triple tube coring and pushing a double tube into the wet mix and allowing it to cure in-situ are discussed, along with the eventual adoption of sonic coring combined with reliance on laboratory testing of wet mix samples collected daily.

Subsurface Conditions

The alluvial deposits to be improved were typically soft to firm silt and sandy silt with interbeds of medium dense to dense sand. Stiff clay lenses were also present near the bottom of the deposit. The silt was typically nonplastic with a plasticity index less than 15, but zones in the soil profile included organics (up to about 4% loss upon ignition, AASHTO T267)) and soils with a plasticity index above 20. Composite samples collected for laboratory bench testing contained approximately 20 to 30 percent fine to medium sand, were nonplastic or with plasticity index less than 10, had pH ranging from 3.8 to 5.5 and resistivity between 500 and 900 ohm-cm, and 2 to 3 percent loss upon ignition. The depth of improvement ranged from about 60 to 80 feet. The unconfined groundwater table was typically 5 to 10 feet below the working surface, but a confined aquifer in the dense and very dense glacial deposits at the base of the alluvium had an artesian pressure of several feet above the ground surface. A typical CPT log is attached as Figure 1.

Design

The amount of ground improvement using CDSM was determined based on the required equivalent improved ground strength to provide adequate factors of safety under static and seismic loading conditions. During the initial design, an unconfined compressive strength of 150 psi was assumed for CDSM columns based on published curves of unconfined compressive strength and cement dosage for similar material types (Taki and Yang, 1991). A replacement ratio of 15% was determined based on the assumed CDSM UCS of 150 psi.

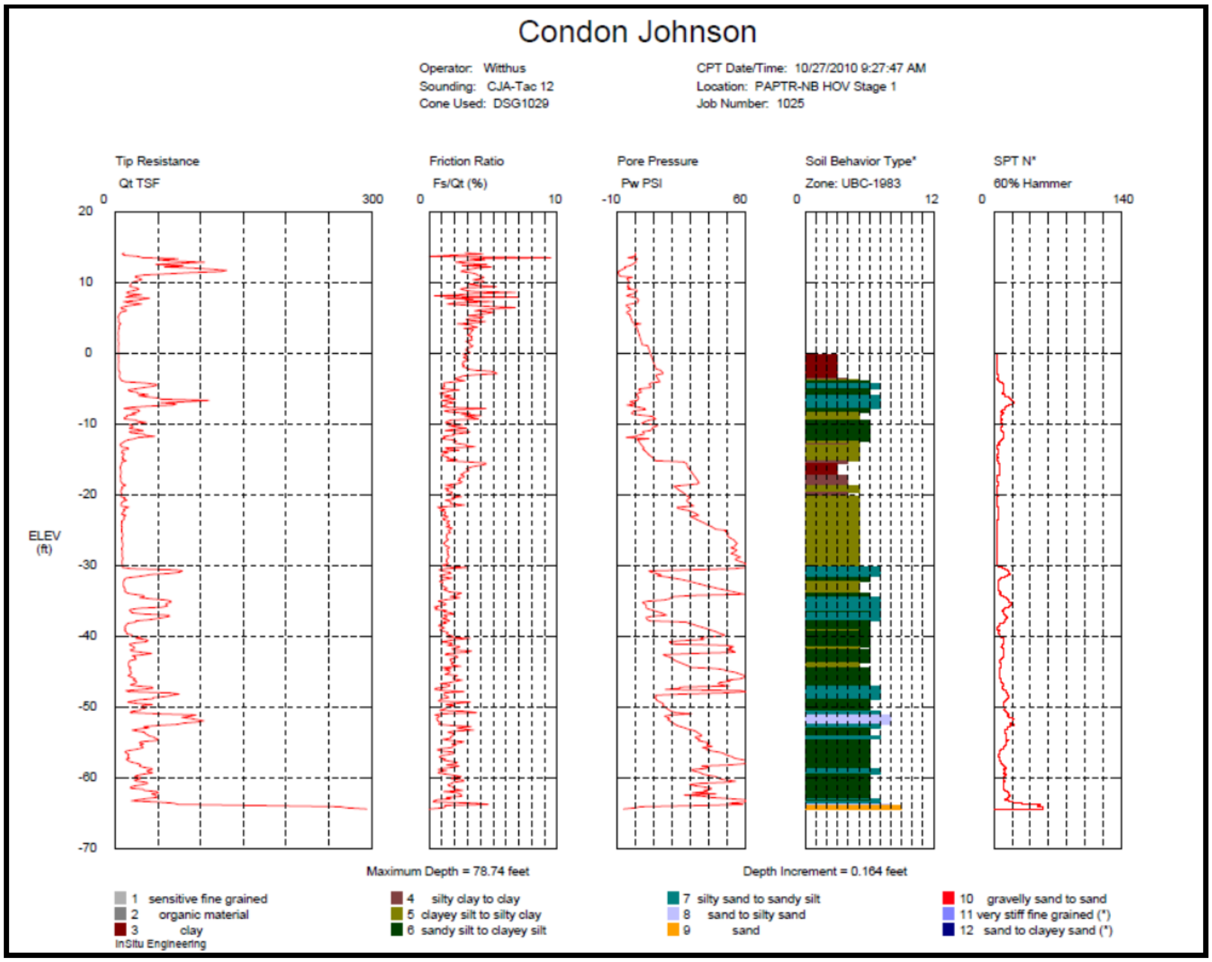

Figure 1. Cone Penetration Log from Test Section

During design development, laboratory bench testing using composite samples collected on-site yielded relatively low unconfined compressive strength results. As a result of the bench testing, the design UCS of the CDSM was reduced to 75 psi. When the design compressive strength of the CDSM was reduced by half, the target replacement ratio was doubled to 30 % to maintain the same composite strength.

Contract Requirements for CDSM Construction

The construction contract provisions required a minimum soil-cement column unconfined compressive strength of 75 psi at 28 days and a replacement ratio of 30 percent. The contractor was allowed to select the column diameter and spacing that would produce the specified replacement ratio. In order to eliminate possible concerns about artesian groundwater affecting the quality of the soil-cement columns, the Contractor was required to lower the groundwater head in the deep aquifer to an elevation 5 feet below the ground surface.

Prior to the start of production CDSM, a test area with four soil-cement columns centered around a cone penetrometer test (CPT) or boring with standard penetration testing (SPT) was required. The test area was required to determine the rpm and torque response of the equipment when the mixing tool reached the bearing layer. This response will then be used during production work to ensure that the CDSM columns reached the bearing layer. In addition to determining the equipment response, the test section was required to verify that the cement content, tool design, and mixing energy selected by the contractor were adequate to meet the specifications. In addition to laboratory tests on cores from the cured columns, several sets of wet mix cylinders were required from each test column to determine correlations with core strength and to develop time vs. strength gain curves to speed production quality assurance testing.

During production CDSM, quality control consisted of verifying the equipment response indicating the column had reached the bearing layer and monitoring the injection quantities and tool rotations to ensure that the mixing energy and cement content was equivalent to the minimums determined in the test section. Quality assurance consisted of daily wet sample collection for UCS testing and strength testing of cores from one of every 50 columns. Coring by triple tube sampling was specified. A minimum waiting period prior to coring was not specified, but the responsibility for collecting quality cores to verify achievement of the specified minimum 28-day strength was placed on the Contractor.

Bearing Layer Profile

The specifications required that the bearing layer be identified at the test section location. This bearing layer was defined as a soil layer providing a CPT tip resistance, q_t, of 110 tons per square foot (tsf) or a standard penetration test (SPT) N_{60} value of 24 blows per foot over a length of 10 feet. This would prevent the termination of the soil-cement columns within dense layers at shallower depths that may be followed by weaker soil layers beneath. Based on the sub-surface geotechnical data available, the depth of the anticipated bearing layer was profiled across the site. The location of the test section and CPT are shown in Figure 1 which also shows layout arrangement. Based on the available sub-surface investigation data, the Contractor developed a profile of the bearing layer. The refined profile of the bearing layer provided additional quality assurance that the CDSM equipment response was indicating that the bearing layer had been reached. Additionally, such accurate profiling enables a more precise valuation of project quantities for costing and material/equipment requirements for the Contractor. The developed bearing layer profile is shown in Figure 3. The bearing layer profile should be viewed in conjunction with Figure 2 which is the layout of the CDSM columns.

De-Pressurization of Confined Aquifer

Geotechnical investigations carried out during the design and planning stage indicated the presence of a confined aquifer with artisan pressures within the dense till material identified as the potential bearing layer. Given that the columns were required to penetrate into this layer, the designer was concerned about the artesian water pressures compromising the quality of the installed CDSM columns prior to initial set of the soil-cement. Depending on the upward pressure gradient of the confined aquifer, it was felt that this could potentially cause deficiency in the column.

The design and installation of the de-pressurization system was entrusted to the Contractor as part of the bid. As per the Contractor’s design, a total of two de-pressurization wells were installed to an average depth of 100 feet below existing ground level. Each was screened over a 35-foot depth within the artesian aquifer, below the bottom of the soil being improved. An additional monitoring well was also installed. The wells were 6 inches in diameter. The locations of the wells with regard to the site and the treatment area are seen in Figure 2. Subsequent to well installation, the static head measured in the wells was found to be approximately 12-ft above ground level.

Submerged pumps installed within the wells were used to lower and maintain the head level approximately 5-feet below the working bench (ground level). The amount by which the head level was reduced was dependent on the total pressure head at the top of the confined aquifer. This pressure head minus the weight of the thus far installed soil-cement column is the pressure differential that the column would encounter as the mixing tool first penetrated into the aquifer. As the tool further penetrates into the aquifer the water pressure head would not increase due to generally constant pressure head within aquifers, while the soil-cement column self-weight would keep increasing. The reduction in the water level from the confined aquifer was measured at the monitoring well location furthest from the de-pressurization wells as seen in Figure 2.

Maintaining the pressure head of the confined aquifer 5-feet below the ground surface also ensured that the site was not engulfed by water from the aquifer during column installation, since such as occurrence would have made it impossible to continue working in the area. The de-pressurization pumps were automatic and set to work at a continuous pumping rate. Initially, water level measurements were taken over a period of several days at both the de-pressurization wells as well as the monitoring wells with the pumping rates varied to finalize the rate required to maintain the 5-ft drop in pressure head. Continuous operation of the pumps throughout the duration of the test sections and production soil mixing ensured that this level was maintained. The water level within the wells was checked frequently to ensure this. Average pumping rates were in the range of 60 – 70 gal/minute.

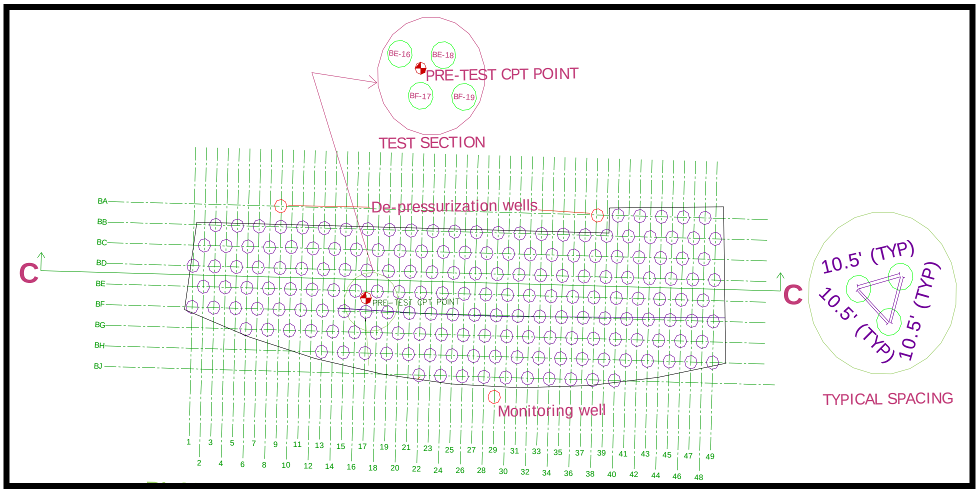

Figure 2. Layout arrangement of soil cement columns

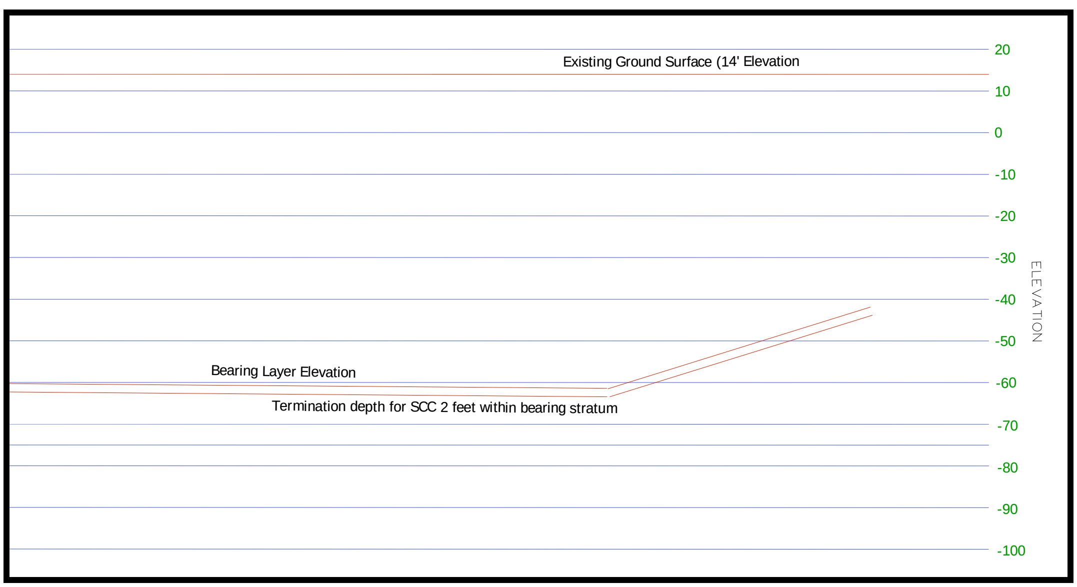

Figure 3. Profile of bearing layer and termination depth (elevation in feet)

Construction Methods

Layout Design

The design required a minimum 30% replacement ratio of treated soil-cement area to gross treatment area. To obtain this ratio, six foot diameter CDSM columns were installed on a 10.5-foot equilateral triangular pattern. General considerations in selecting layout spacing and the size of CDSM columns included anticipated daily production rates, replacement ratios, in-situ soil properties, the ability to mix the cement and soil to obtain a homogenous mass of cement-soil mixed material, anticipated treatment depth, equipment capability and the physical constraints/limitations of the site. Figure 2 shows the layout arrangement of the soil columns within treatment area.

Installation

Based on the available geotechnical information, it was anticipated that the deepest columns would be in the range of about 80 feet to 85 feet below existing ground level. To allow for possible variation in column depths above this range, an auger and mixing tool fixed to the end of a Kelly bar was utilized together with a crane mount drill attachment. Figures 4 and 5 show the equipment used. Based on the available torque and corresponding maximum rotational speeds of the attachment, the speed of penetration was determined in the test section. As the material becomes more dense, this results in difficulty maintaining mixing tool rotation speed, which in turn increases the duration of mixing. The number of revolutions applied on the soil-cement column per foot length of column is an indication of the level of mixing applied.

Based on the required average soil-cement strength of 75 psi and minimum strength of 60 psi, and the nature of the in-situ soils, two different cement contents were initially trialed. The target cement content can generally be varied depending on the specific gravity of the grout prepared as well as the volume of grout pumped into the column per foot depth depending on the diameter of the column.

Figure 4. Soil Mixing Apparatus Used

Data Acquisition System

Ground improvement methods as a whole rely predominantly on improving the properties of the in-situ soil material by modifying their composition. While post improvement testing is necessary for quality control to ensure that project requirements are met, continuous monitoring of installation methods and inputted construction materials (such as grout specific gravity and quantity/volume) are necessary for quality control of the mixing process.

Figure 5. Close-up of the Mixing Tool Arragement

To achieve this, a specialized data acquisition system was installed within the soil mixing rig. Through this, the operator could monitor in real time, the depth of the mixing tool, penetration rates, mixing/rotational rates, grout specific gravity, grout flow rates and pressure as well as verticality of mixing tool. When it was observed that specifications were not being met during the installation, immediate remediation could be carried out because all the data were available instantaneously. Figure 6 shows a view inside of the cab from the operator's perspective.

Figure 6. View Inside the Soil Mixing Cab

Test Sections

A total of eight (8) columns were installed as part of the program to verify construction means and methods. During the test program, various parameters such as penetration/withdrawal speed, auger/mixer rotational speed, cement grout specific gravity, and grout quantity were varied to study their impact and to formulate the optimum method for drilling and mixing.

Initially, four columns were installed within the test program. Wet samples were collected from these columns at three locations along the column depth, within the top one-third, middle one-third and bottom one-third. The samples were tested for unconfined compressive strength at 7, 14 and 28 days using method ASTM 1633 for testing of soil-cement cylinders.

Triple Tube Coring

Core drilling was initially carried out using a triple tube core barrel system. Samples were visually examined to assess uniformity of mixing and to obtain samples for unconfined compressive strength testing. Core drilling was carried out 25 days after column installation so as to obtain testable samples that by specification were required to be tested at 28-days.

Due to the presence of large gravel and cobbles within the native material and the low strength of the cured CDSM material, continuous core recovery was not possible. On several occasions, the core barrels needed to be withdrawn from the core and cobbles and large sized gravel removed. These cores provided a few samples for testing. Given the low design strength of the soil-cement mix, it was observed that the material was not holding together under the abrasive action of the core barrel drill bit and the washing action of the drilling fluid. The highly cemented soil also was typically highly fractured by the drilling action, so that collection of samples for laboratory testing was challenging. There were also a small number of pockets of recovered material which indicated that inconsistent mixing had occurred especially within the peat/highly plastic clay layers.

Conclusions from Initial Test Columns

Subsequent to the results of the initial test program, it was mutually agreed upon that a further set of 4 columns be installed. The additional columns installed used a variety of mixing methods including single pass and double pass mixing. The contractor also modified the mixing tool for the second set of test columns.

On this occasion, it was also determined that a double-tube system with a retrievable PVC pipe would be placed within the soil-mixed material on completion of the column. The inner tube was retrieved upon sufficient strength gain as indicated by the wet sample testing. The double tube sampler is shown in Figure 7. Placement of this double-tube system is shown in Figure 8. A mini vibro hammer was fixed to the top of the sampler and used to aid in placement of the sampler within the column. A representative sample of the retrieved core is shown in Figure 9.

Figure 7. Double Tube Sampler

Figure 8. Placement of the double-tube sampler using a mini vibro hammer

Figure 9. Double-tube core sample

The retrieved core from this method provided continuous, uniformly mixed, high strength material indicating thorough mixing; however, the cores thus obtained were only 20 to 64 percent of the actual installed column length. This shortfall was attributed to the double-tube cores becoming plugged with fibrous organics, unmixed material, cobbles, or large sized gravel while being placed within the columns.

Laboratory testing of wet mix samples and core sections from the triple barrel and double tube sampling generally indicated high strength material, but there was still concern about the incomplete mixing or low strength (Strength testing from the wet grab samples are shown in Figure 14). Therefore, sonic coring of the test columns was also carried out to verify uniformity of mixing. Figure 10 shows a sample sonic core retrieved.

Figure 10. Sonic core sample

<u>Final Selection of Verification Parameters</u>

Based on the results of the test program, the construction methodology to be used was adopted. The sonic cores indicated that the modified mixing tool was producing better quality mixing in the second set of test columns, but there was no appreciable difference between double-pass and single-pass mixing. The number of revolutions of mixing per segment of column, the quantity of cement pumped per cubic foot of column material, specific gravity of the cement grout, penetration rates, and withdrawal rates verified by the test columns were incorporated into the production columns. Figure 11 shows a log of the output obtained from the cab for a production column.

Contractor and owner agreed that production quality assurance would consist of:

1. Previously specified laboratory testing of wet mix samples collected daily for strength verification
2. Sonic coring for consistency verification at the previously designated frequency of once every fifty installed columns.

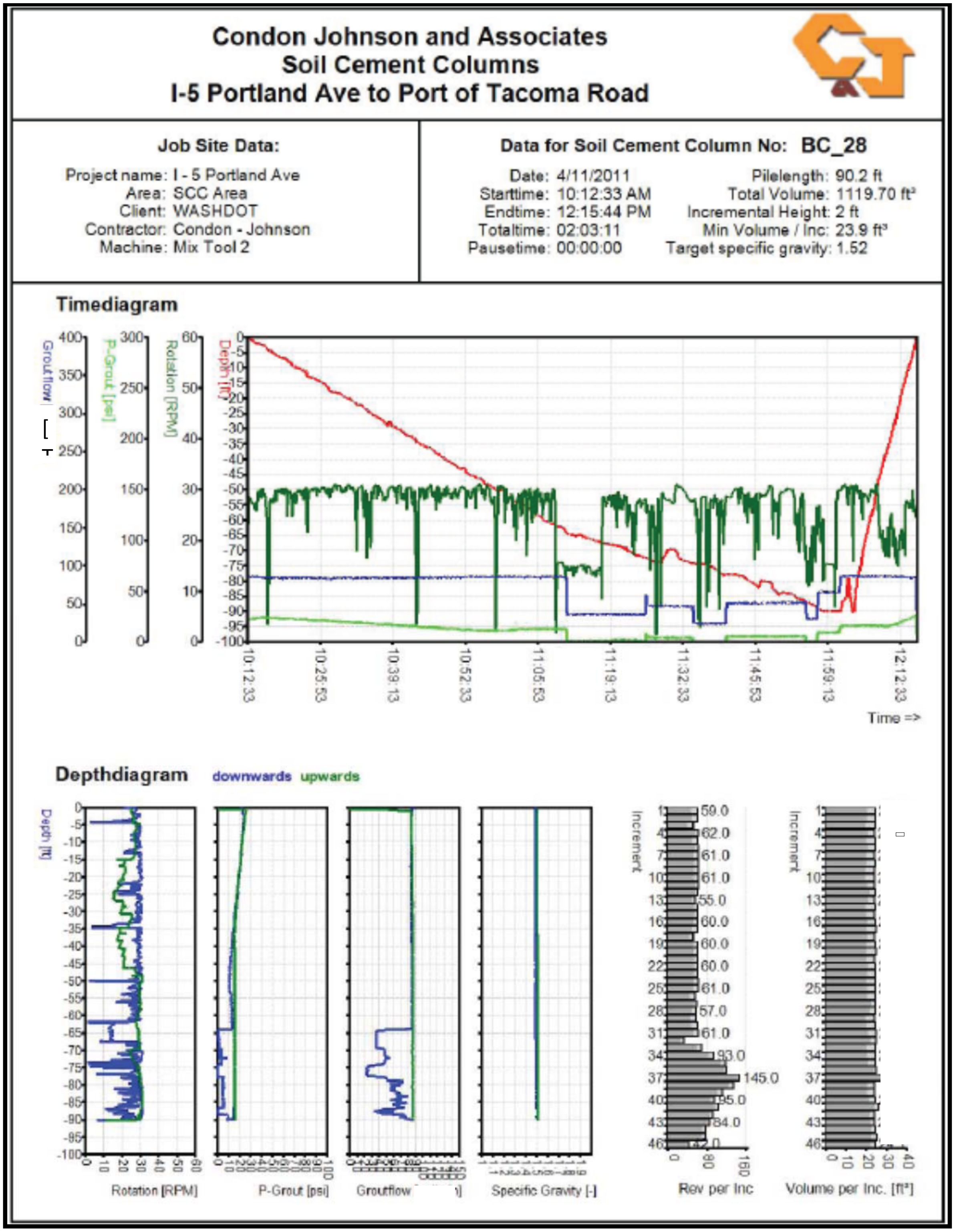

Figure 11. Typical log output from production soil cement columns

Output from Data Acquisition System

The output from the data acquisition system shown in Figure 11 provides the variation in parameters such as mixing tool rotational speed, grout pressure and grout flow with time as well as rotational speed, grout pressure, grout flow and specific gravity with depth.

The quantity of grout flow was maintained near constant value per 2-ft increment. The value of mixing, signified by the revolutions per increment were also maintained near constant value. Dependent on the rpms of the mixing tool penetration/withdrawal rates were either increased or reduced. Grout pumping rates too were varied to keep in line with the penetration/withdrawal rates while maintaining the grout pumped per increment.

Production Strengths

A cumulative distribution of unconfined compressive strength from production wet mix samples is included as Figure 12. The median of all test results was 146 psi and the mean was 169 psi.

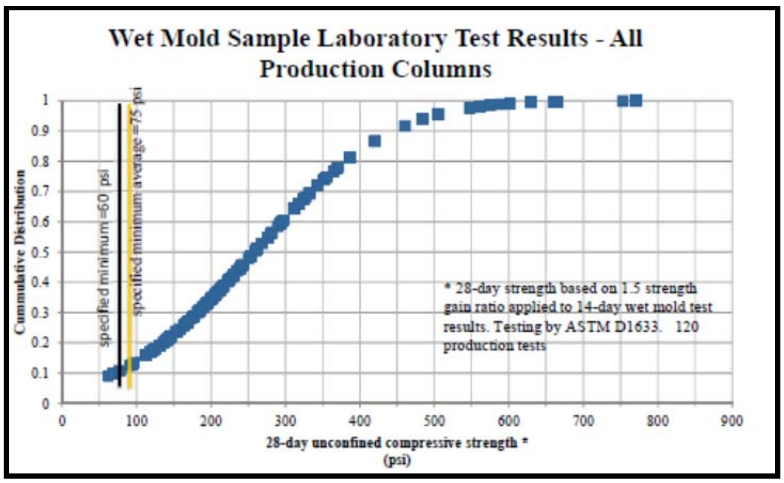

Figure 12. Cumulative distribution of unconfined compressive strength

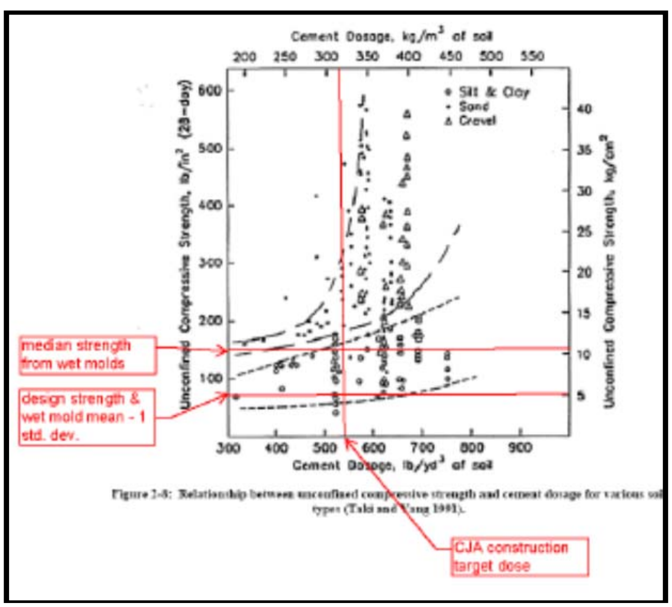

Figure 13. Strength value comparison with published value (Ref 1)

The design minimum and production median strength compared to typical values are shown in Figure 13.

Figure 14 shows strength gain of the samples over the course of 112-days. These samples were obtained from the production columns and results are averaged in the chart. As can be observed, there is significant increase in strength beyond the required 28-day value. This is seen to be up to 2-3 time the 28-days value and 7-8 times the design strength requirement.

Spoils Production

Spoils were temporarily stockpiled onsite and surveyed at the completion of construction. The survey indicated that spoils production was about 50 percent of the neat volume of CDSM installed.

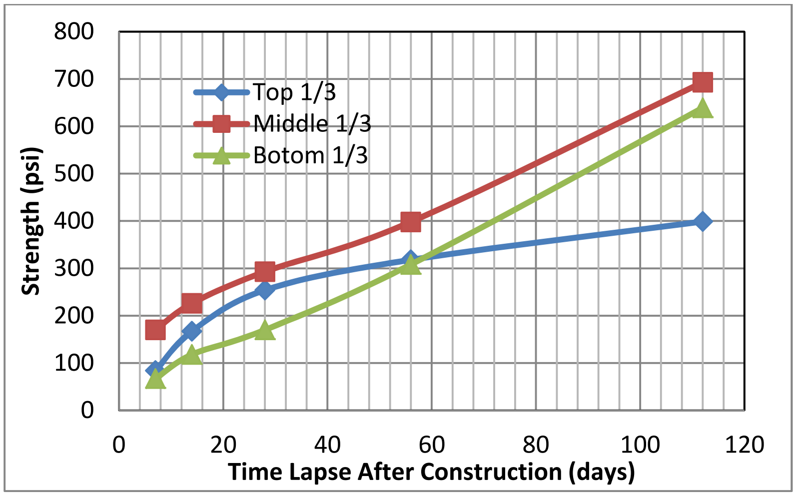

Figure 14. Strength increase with time

Conclusions

Although traditional use of coring after CDSM strength gain, followed by laboratory testing of selected samples of the core can provide undisputable verification of material consistency and strength, in-tact core recovery (for strength testing) can be challenging. The time required for curing before coring can also be problematic. Sonic coring used in combination with laboratory testing of wet mix samples may be an appropriate performance verification alternative in low strength materials, when gravel or larger material is present, or when time is limited.

If sonic coring is to become more widely used as a CDSM quality verification tool in the future, the industry and researchers may want to consider:

1. Repeatable, easily quantifiable methods that can be defined to assess uniformity of mixing within a continuous sonic core.
2. Strength loss induced in soil-cement due to sonic coring.
3. Methods of assessing cement content within a sonic core prior to curing

The cumulative distribution plot of wet mix strength is generally supportive of practical methods being considered by researchers to account for strength variability in deep soil mix design. The comparison of median strength and dosing generally agrees with published values. The strength increase from 28-days to 112- days (and potentially beyond) based on Figure 14 indicates that depending on the time duration post construction, when the columns will be put into service, there is a case for allowing for design strengths at longer durations beyond the standard 28-day strength currently in use.

References

1. Taki, O. and Yang, D.S., 1991. Soil-cement mixed wall technique. American Society of Civil Engineers, Proceedings, Geotechnical Engineering Congress, Denver, Colorado, pp. 298-309.