DEEP MIXING CORE DATA FROM LPV 111

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ABSTRACT

One million seven-hundred thousand cubic yards of deep mixing were installed to support an elevation raise of an earthen levee known as LPV 111, which is located in east New Orleans. The deep mixing was done by two contractors using somewhat different technologies, but producing elements of the same size. As part of the quality control and quality assurance program, 507 deep-mixed elements were cored and 5,082 specimens were strength tested in unconfined compression. This paper presents data from the coring and testing program. Very high percentages of the core run lengths were recovered, except during one period for one mixing technology. The coring methods are described, and reasons for the isolated episode of low recovery are discussed. The strength data show that the specification acceptance criteria were satisfied. Statistical parameters of the strength data are provided, and trends between strength and the following factors are discussed: depth, soil type, binder factor, and project-specific experience. Photographs of longitudinal cuts of core specimens are presented. Important lessons learned from this unusually large project are described.

Keywords: deep mixing, coring, unconfined compressive strength, New Orleans, levee, ground improvement

INTRODUCTION

The Lake Pontchartrain and Vicinity Hurricane Protection system included a project known as LPV 111, which is an approximately 5-mile long segment of levee and floodwall located in east New Orleans along the Gulf Intracoastal Waterway and adjacent to Bayou Sauvage National Wildlife Refuge (Cali et al. 2012). The majority of the project consisted of a raise of an existing earthen levee from an existing crest elevation of about 18 ft to a new crest elevation of about 28 ft. The underlying soils were weak and compressible, providing inadequate support for the raised levee. Ground improvement in the form of deep mixing was selected to provide the necessary stability and settlement control for the raised levee.

The US Army Corps of Engineers (USACE), New Orleans District, was the governmental agency in responsible charge of the project, including approval of design, construction, and payment. The lead designer was URS Corporation, and the general contractor was Archer-Western-Alberici (AWA), working in alliance with TREVIICOS South (Trevi), who, together with Fudo Construction (Fudo), performed the deep mixing.

As part of the quality control and quality assurance program, over 500 production deep-mixed elements were cored, the cores were carefully logged, and over 5,000 unconfined compression tests were performed. In addition, selected specimens were carefully photographed before and after longitudinal saw cuts to expose the interior of the specimens. This paper provides a summary of the coring and testing performed on the production deep-mixed elements.

BACKGROUND INFORMATION

Most of the deep mixing completed on the LPV 111 project was done to form shear walls (buttresses) that were oriented perpendicular to the levee alignment. Some additional deep mixing was installed between the shear walls to provide an extra margin of protection against differential settlement along the levee crest. The total volume of deep mixing was about 1.7 million cubic yards, which is the largest deep mixing project ever completed in the Western Hemisphere.

Trevi and Fudo both employed the wet mixing method using double-axis mixing equipment with 5.25-ft-diameter columns, and Trevi also used single-axis equipment to construct 5.25-ft-diameter columns. To supplement mechanical mixing from the rotating mixing blades, Trevi's mixing technology employed medium pressure jets to deliver the binder-water slurry at the level of the mixing blades, whereas Fudo used air pressure to create a slurry emulsion. Trevi generally used a water-to-binder ratio of 1.25, and Fudo generally used a water-to-binder ratio of 0.8. The contractors' equipment employed somewhat different mixing blade arrangements. Thus, there were some differences in the mixing technologies, but both produced very good results, as described in this paper.

The construction was conducted under a procurement technique known as Early Contractor Involvement (ECI), in which the contractor was selected and participated while the project was still in the design phase. This allowed for contractor involvement in design details, which took advantage of the contractor's knowledge of construction means and methods, helped optimize use of the contractor's equipment, and accelerated the construction schedule, while still achieving the project's design goals. This procurement method also allowed for evolution of the design and specification details as more became known about the subsurface conditions and equipment effectiveness as the project progressed.

The deep mixing was installed from a platform elevation established by either cutting into the existing levee or placing imported fill to the platform elevation. Due to variations in levee cross-section and location of deep mixing shear walls along different reaches of the LPV 111 levee alignment, the platform elevation varied from +4 to +12 ft.

For the purposes of managing the deep mixing, the soil to be mixed was described in terms of five layers, which are listed in Table 1, along with the average elevation ranges for each layer. Borings disclosed substantial variations in elevations of these layers across the project site. Deep mixing extended from the platform elevation to a depth of several feet into the Pleistocene soil. The peat was anticipated to require relatively high binder factors because of its high organic content and high water content. The fat clay was anticipated to be somewhat difficult to mix because of its relatively high plasticity and stiffer consistency compared to the soft clay. The Pleistocene soils included lean clays, fat clays, and sandy soils. The Pleistocene soils generally appeared less plastic and easier to mix than the overlying fat clay.

Table 1. Five main soil layers for deep mixing at LPV 111

Soil Layer	Approximate Elevation Range (ft)
Borrow/Soft Clay	-5 to +10
Peat	-15 to -5
Upper Fat Clay	-38 to -15
Lower Fat Clay	-49 to -38
Pleistocene	below -49

A bench-scale testing program was performed on the different soil layers, and binder factors were determined that generally produced an unconfined compressive strength (UCS) of about 240 psi for laboratory mixed and cured specimens (Bertero et al. 2012). The laboratory target value of 240 psi was twice the originally specified value of 120 psi for production elements. The factor of two was introduced to account for the more thorough and consistent mixing that often occurs in the laboratory compared to the field, thereby providing a margin of safety to address field variability, which was an important consideration because the specifications required that 90% of all tested specimens from each cored production element should equal or exceed the specified value.

During the bench-scale testing program, it was also found that a binder blend of 25% Portland cement with 75% ground blast furnace slag produced the best results, particularly for the peat deposits. This binder blend was adopted for field mixing. Five phases of field validation testing were performed to fine-tune the field mixing parameter values of blade rotation number (BRN), which is the number of individual blade passes per meter of depth, binder factor, and equipment configuration, to reliably produce core samples that satisfied the specifications (Bertero et al. 2012). The mixing parameter values were also adjusted as the project progressed based on results from production elements.

SPECIFICATION REQUIREMENTS

As implemented at LPV 111, the project specifications included three primary requirements related to coring and core testing:

1. Three percent of production deep-mixed elements must be cored, where an element is either a single deep-mixed column constructed by a single-axis rig or two overlapping columns constructed by a single set-up of a twin-axis rig. USACE personnel selected the elements to be cored. Coring extended from the top to the bottom of the deep-mixed elements.
2. The length of core recovery minus the sum of the lengths of any zones of unimproved soil that completely cross the core must be at least 80% of each 5-ft core run. Said differently, this requires that 80% of each 5-ft core run length must recover treated ground for at least some portion of the core cross section.
3. Nine out of ten specimens from each cored element must have a UCS at least equal to the specified UCS. At the beginning of the project, the specified 28-day UCS was 120 psi. This value was established from a statistical analysis during the design phase based on an assumed coefficient of variation of 0.6 for the deep-mixed ground strength. As the project progressed, data showed that the actual coefficient of variation was much smaller, i.e., about 0.4, which justified using a lower value of UCS equal to 90 psi. Based on this analysis, and employing some conservatism, the URS Corporation and USACE agreed to reduce the specified strength from 120 psi to 100 psi. Following this reduction, additional trial columns were constructed, and binder factors were reduced, primarily in the peat deposit. USACE personnel selected the UCS test specimens. Specimens that contained obvious large inclusions of unmixed soil were not selected for testing because they were not judged to be representative of an entire deep-mixed element. For example, a 3-in.-diameter specimen with a gravel-sized piece of unmixed soil would not be selected for testing because it would correspond proportionately to a 5.25-ft-diameter column with a boulder-sized piece of unmixed soil in the column, and there was no indication from the core drilling or the spoils that such large clumps of unmixed soil existed in the mixed elements. Instead, samples with and without occasional small pieces of unmixed soil were selected for testing, with the pieces of unmixed soil typically not larger than about ½-inch diameter. If a specimen had a UCS value less than the specified value, and if the failure was obviously due to an inclusion of unmixed soil, the USACE allowed for testing another specimen from the same 5-ft core run, and the result from the second test could replace the first test when determining satisfaction of the requirement that nine out of ten specimens have a UCS at least equal to the specified value. The retest specimen was also selected by USACE personnel. Only one such retest was allowed per 5-ft core run.

CORING AND TESTING PROCEDURES

Coring was typically done about 26 days after mixing. The coring was performed using rigs that employed triple-tube wire-line coring systems to recover approximately 3-in.-diameter (PQ3) or 4-in.-diameter (S Geobor) core. Typically, the core run length was 5 ft. The recovered core was logged, photographed, stored in wood boxes, and transported to a humid room. The core holes were backfilled with grout, as specified.

For specification acceptance purposes, UCS testing was typically performed 28 days after mixing, although some specimens were tested at 27, 29, and 30 days after mixing.

CORE RECOVERY

This section describes core recovery quantity and photographs of core specimens, including photographs of longitudinal cuts along the coring axis.

Core recovery quantity

Over 6,000 core runs were made in the 507 production deep-mixed elements that were cored from top to bottom, with most core runs being 5 ft long. Overall, core recovery on this project was excellent, with core recovery near or equal to 100% in almost all core runs. Core recovery in the uppermost core run of a cored element was sometimes less than the typical core recovery of nearly 100%, but even in the uppermost core run, recovery was still not less than 80%.

One exception to the otherwise excellent core recovery occurred during the summer of 2010 for six twin-axis elements installed by Fudo. Most of these were isolated elements installed at locations between buttresses for controlling settlement of the embankment crest. These elements, which were installed using the air-slurry emulsion mixing process, contained substantial voids, as disclosed by core recovery in the range from 0% to 62% for six core runs. For these cases, the core holes were backfilled with grout, and the grout takes were several times larger than the theoretical volumes of the core holes. As an emergency measure immediately following discovery of the voids, Fudo injected extra grout during withdrawal of the mixing tools, which solved the problem until a long-term approach could be established. For the two cases in which coring indicated that voids occurred in elements installed as part of shear walls, coring in adjacent elements in the same shear walls exhibited core recovery that fully satisfied the specification requirements, which showed that this was not a pervasive problem.

Fudo investigated the problem, and determined that air injected in the air-slurry emulsion mixing process was becoming trapped along the center portion of the columns where the mixing shafts were withdrawn from the fat clay. The following principal causes for the voids were suspected:

- The relatively high temperature of the grout during the summer produced accelerated setting of the mixture, particularly in the fat clay, which was relatively stiff to begin with, thereby trapping the injected air.
- There was a high ion concentration in the site soils, as indicated by high conductivity. High ion concentration may have contributed to accelerated setting of the mixture.
- Laboratory tests showed that the fat clay at this site contains the clay mineral montmorillonite, which is a highly plastic clay mineral that can absorb water and produce viscous mixtures.

To address the issue, the amount of air injected during the withdrawal stage of mixing was reduced, while a low rate of grout injection during withdrawal was maintained. At the same time this countermeasure was implemented, there was a drop in ambient temperature and no additional large voids were encountered during coring.

The USACE accepted the deep-mixed elements that contained voids but were backfilled with grout. The USACE's decision considered that (1) the voids were backfilled with grout upon completion of coring, (2) a rational understanding of the mechanism for void formation was developed, and (3) most of these elements were for settlement control, which was judged to be less critical than stability provided by the buttresses. When voids were detected in elements installed in shear walls, core results from adjacent elements in the same shear walls fully satisfied specification requirements.

The Contractor's Geotechnical Review Board reviewed documentation of the core logs and observed core recovered from several deep-mixed elements during multiple visits to the project site. The cores were generally very well mixed, with occasional pieces of unmixed soil ranging in size up to about 3 inches. Very rarely, a larger pocket of unmixed soil was recovered. Occasionally, the Fudo soil-cement also included small air pockets from the air-slurry emulsion that was used. Overall, the Geotechnical Review Board found that the core recovery on the LPV 111 project was excellent. The large voids that occurred in a few Fudo elements, primarily in settlement control elements, were addressed in a systematic manner.

Core photographs

All of the core runs were photographed immediately after extraction from the core barrels. For 30 core specimens, detailed photographs were also taken in the laboratory. In addition to photographing both ends and the exterior surfaces, a longitudinal cut was made along the coring axis of each specimen and the exposed interior surfaces were photographed.

Overall, the photographs showed good mixing quality. In many cases, oxidation appeared to have produced a brown color on the surface of the specimens, while the freshly cut interior surfaces were more grey. The specimens exhibited frequent angled striations and lumps of apparently treated soil from different horizons, as evidenced by different mixture colors within a single specimen, which indicated vertical blending. The specimens also included occasional lumps or bands of relatively unmixed soil or slurry, and occasional small voids. Perfect homogeneity cannot be expected from deep mixing construction, and the quality of mixing on this project was very good. Photographs from two representative core specimens are shown in Fig. 1.

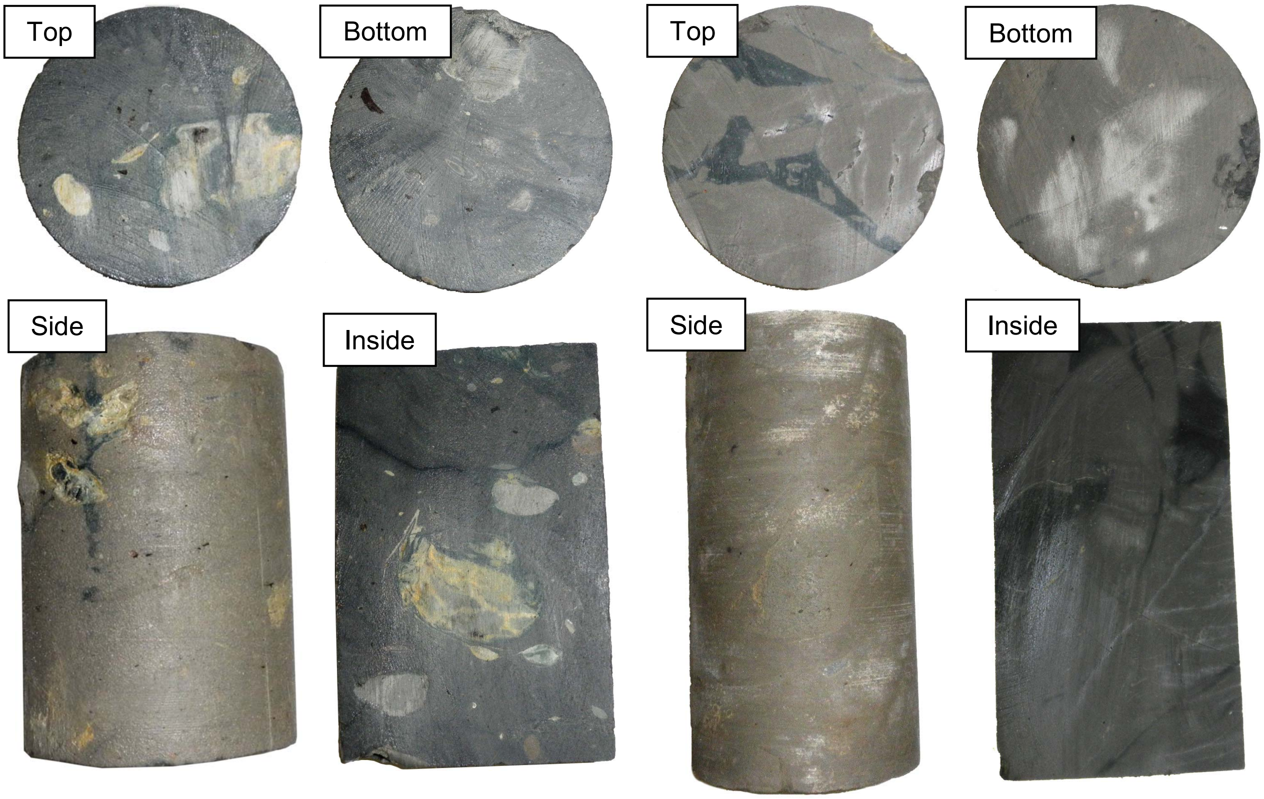

Fig. 1. Photographs of two different core samples; Core A on left and Core B on right.

UNCONFINED COMPRESSIVE STRENGTH

Review of the UCS data did not indicate significant correlation between UCS and station or UCS and mixing date. The mixing was well done along the project alignment and no location stood out as being particularly better or worse than other locations. In addition, no ranges of mixing dates appear to be particularly problematic with respect to the specified strengths. Even during the summer of 2010, when poor recovery occurred in the fat clay layer for some of the elements installed by Fudo, the core that was recovered exhibited good UCS test results.

The UCS results are discussed in the following subsections: overall UCS results, UCS versus elevation, and UCS versus binder factor and soil type.

Overall UCS results

In total, 5,082 UCS tests were performed on production columns. All of the elements subject to coring satisfied the specification requirement that nine out of ten specimens have a 28-day UCS value that equals or exceeds the specified value.

The key statistics for the overall test results for both contractors, as well as for Trevi and Fudo separately, are listed in Table 2. For all three data sets, the average values of UCS are much higher than the specified strengths, and the percentages falling below the initial specified strength of 120 psi range from 2.4% to 5.0%, while the percentages falling below the subsequent specified strength of 100 psi range from 1.0% to 1.5%. Plots of the cumulative distribution of 28-day UCS test results for both contractors, and for Trevi and Fudo separately, are shown in Fig. 2, which also shows the specified strengths.

Table 2. Overall statistics for 28-day UCS test results

Contractor	Number of Tests	Average (psi)	Standard Deviation (psi)	Coefficient of Variation	Less Than 120 psi (%)	Less Than 100 psi (%)
Both	5082	292	126	0.43	3.9	1.3
Trevi	2926	259	103	0.40	5.0	1.5
Fudo	2156	335	141	0.42	2.4	1.0

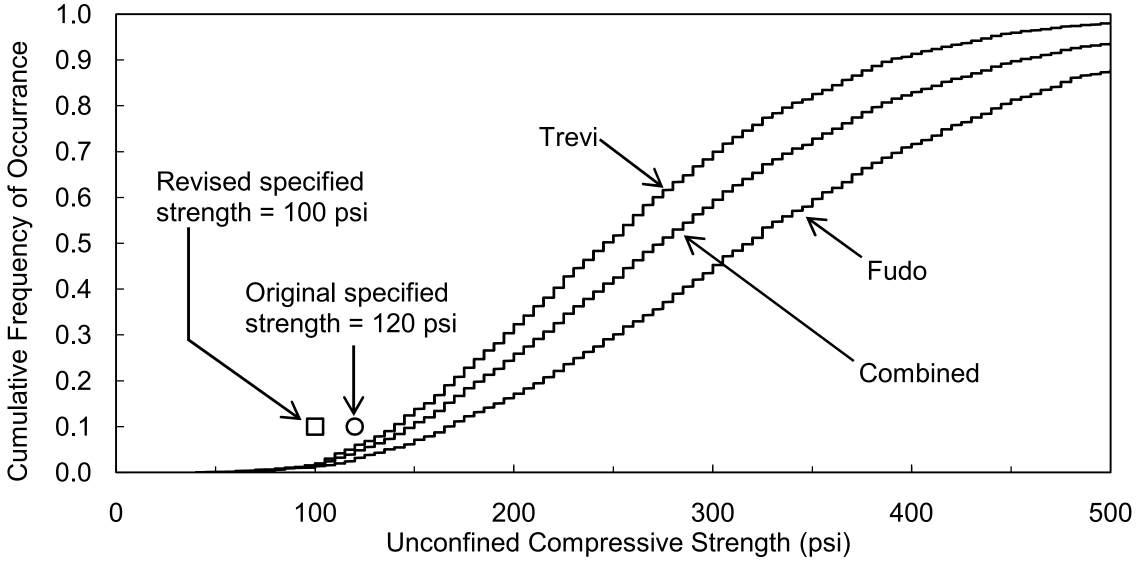

Fig. 2. Cumulative distribution plots of 28-day UCS for all production column data

UCS versus Elevation

Figure 3 shows a plot of 28-day UCS versus elevation for both contractors combined. Consistent with the summary in Table 2, the plot shows only small percentages below the initial specified strength of 120 psi or the subsequent specified strength of 100 psi. In addition, the plot shows a slight trend for decreasing strength with depth. This trend appears to be due to the somewhat greater difficulty mixing the fat clay than the other materials in the profile. The fat clay generally extends from about Elevation –15 to –49 ft, and it is overlain by the peat deposits and underlain by the Pleistocene soils. The high plasticity and the somewhat lower water content of the fat clay made it more cohesive than the overlying materials in the profile, correspondingly harder to blend with the water-binder slurry, and consequently more erratic in UCS.

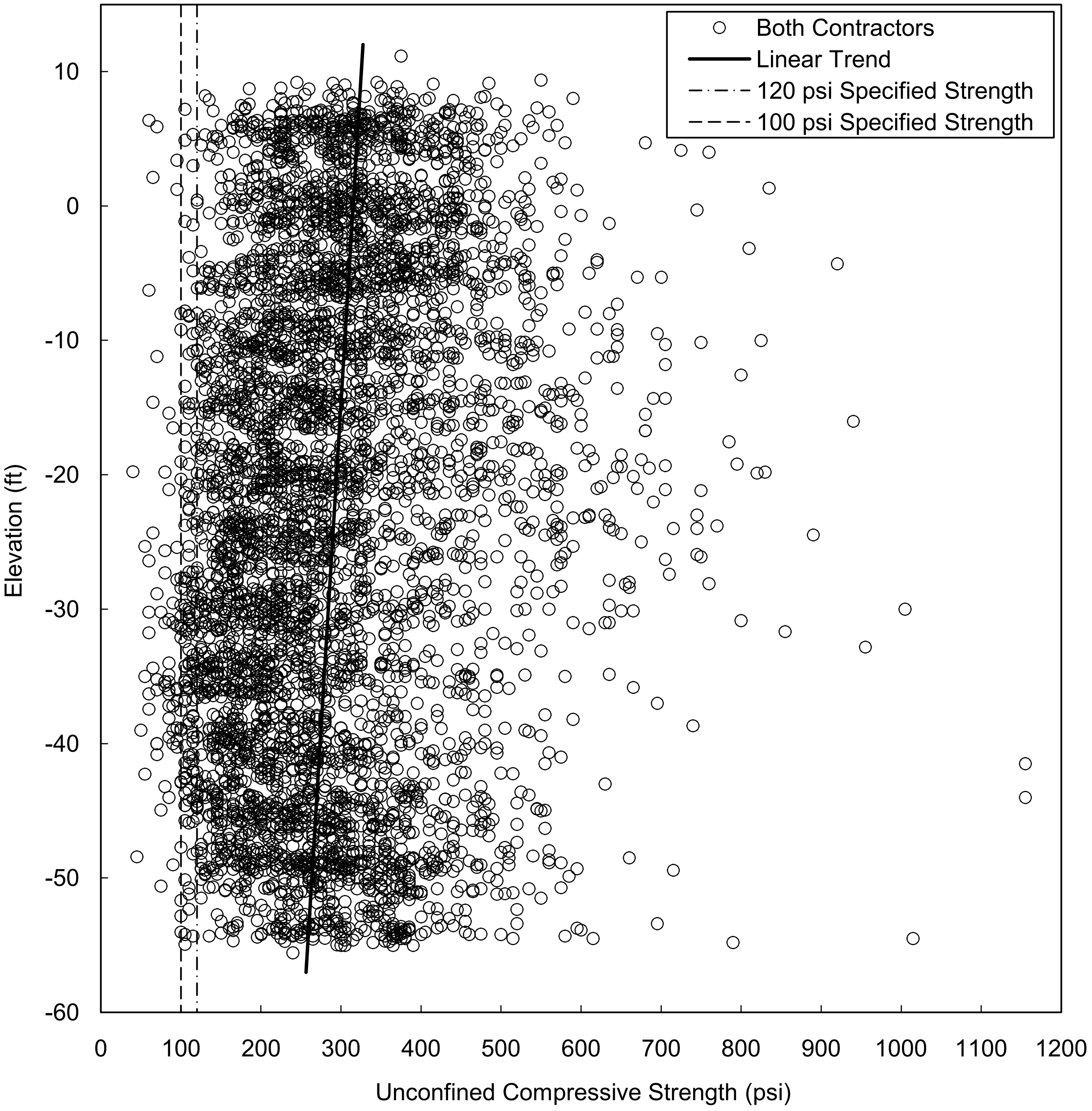

Fig. 3. Comparison of 28-day UCS versus elevation for all production columns

When interpreting Fig. 3, it is important to recognize that injection of slurry tends to move the soil-binder mixture upwards in the element. Thus, the soil that was initially at mid-elevation tends to move upwards in the element, and the soil that was initially near the top tends to be pushed out of the element as spoils. Furthermore, the action of the mixing blades combined with the general trend for upwards movement of the mixture tends to produce a degree of vertical blending of the mixture. In addition, both contractors used a double stroking procedure near the bottom of the element to promote thorough mixing at the bottom. Consequently, there is not a strict correlation between the soil type initially present at a given elevation and the predominant soil type present in the mixture at that same elevation after completion of the mixing process. Nevertheless, it remains true that the concentration of the lowest strengths shown in Fig. 3 is in the zone initially occupied by the relatively difficult-to-mix fat clay.

UCS versus Binder Factor and Soil Type

Based on laboratory bench-scale tests and field trials, both deep mixing contractors established mixing parameters tailored to the site soils and their own mixing technologies. The mixing parameters included water-to-binder ratio of the slurry, binder factor, and BRN. The deep mixing equipment of both contractors was capable of varying the penetration rate as a function of depth. By holding the water-to-binder ratio and the rotation rate constant, this permitted varying the binder factor and the BRN. Both contractors used the boring log information to conservatively vary the mixing parameters as a function of position and elevation to appropriately treat the site soils as they varied along the levee alignment. For example, the peat deposit received the highest binder factor and BRN, and the soft clay received a lower binder factor and BRN. Table 3 provides the binder factors used by each contractor for the main soil groups encountered at the project site. On this project, binder factor was defined as the dry weight of binder divided by the volume of soil to be mixed.

Table 3. Ranges of binder factor applied to production columns for different soil types

	Binder Factor (kg/m^3)	
Soil Type	Trevi	Fudo
Borrow/Soft Clay	170 to 230	210 to 230
Peat	375 to 480	330 to 480
Upper Fat Clay	230 to 260	230 to 330
Lower Fat Clay	230	210 to 230
Pleistocene	200 to 230	210

Table 4 provides a summary of the statistical data from UCS tests for each soil type for each contractor. The average UCS values were relatively consistent for each contractor from one soil type to the next, although slightly lower average UCS values were obtained for specimens from the elevations of either the upper fat clay or the lower fat clay, depending on the contractor. The coefficient of variation values were highest for specimens from the elevations of the upper fat clay. These results again highlight the more difficult mixing conditions for the fat clay. Nevertheless, the specimens from the elevation ranges for all soil types satisfied the intent of the specifications, with less than 10% of the measured UCS values falling below the specified strengths of 120 and 100 psi.

Table 4. Statistics for 28-day UCS test results for different soil types

	Soil Type	Number of Tests	Ave. (psi)	Standard Deviation (psi)	Coeff. of Variation	Less Than 120 psi (%)	Less Than 100 psi (%)
Trevi	Borrow / Soft Clay	643	297	99	0.33	1.6	0.6
	Peat	591	262	99	0.38	3.0	0.8
	Upper Fat Clay	1356	232	96	0.42	8.3	2.6
	Lower Fat Clay	85	277	97	0.35	1.2	0.0
	Pleistocene	251	302	113	0.37	1.2	0.4
Fudo	Borrow / Soft Clay	523	352	118	0.34	0.8	0.2
	Peat	356	360	136	0.38	1.1	0.3
	Upper Fat Clay	760	340	160	0.47	3.3	1.6
	Lower Fat Clay	359	292	134	0.46	4.5	1.9
	Pleistocene	158	302	109	0.36	1.9	0.0

By tailoring the mixing parameters to the soil type, and considering the degree of vertical blending that occurs due to the inclined mixing blade orientations combined with the general upward movement of mixture due to slurry injection, both contractors were able to achieve relatively uniform mixing for all soil types because higher binder factors and higher blade rotation numbers were used for the peat and, to a lesser extent, for the fat clay. As a result, the UCS values overall are approximately independent of binder factor, as shown in Fig. 4. When interpreting Fig. 4, it is important to remember the qualifications that (1) there is a general upwards movement of the mixture during mixing, such that the cored specimens tend to represent mixtures from lower elevations than the range of elevations corresponding to their assigned binder factors, (2) the binder factors were tailored to achieve the desired UCS even as soil type changed, and (3) adjustments to other mixing details, such as BRN and equipment details were made to improve mixing efficiency as the project progressed. Thus, the apparent independence of UCS from binder factor shown in Fig. 4 is a testament to the attention to detail employed by the deep mixing contractors, and it is not an indication that UCS is independent of binder factor for a given soil type.

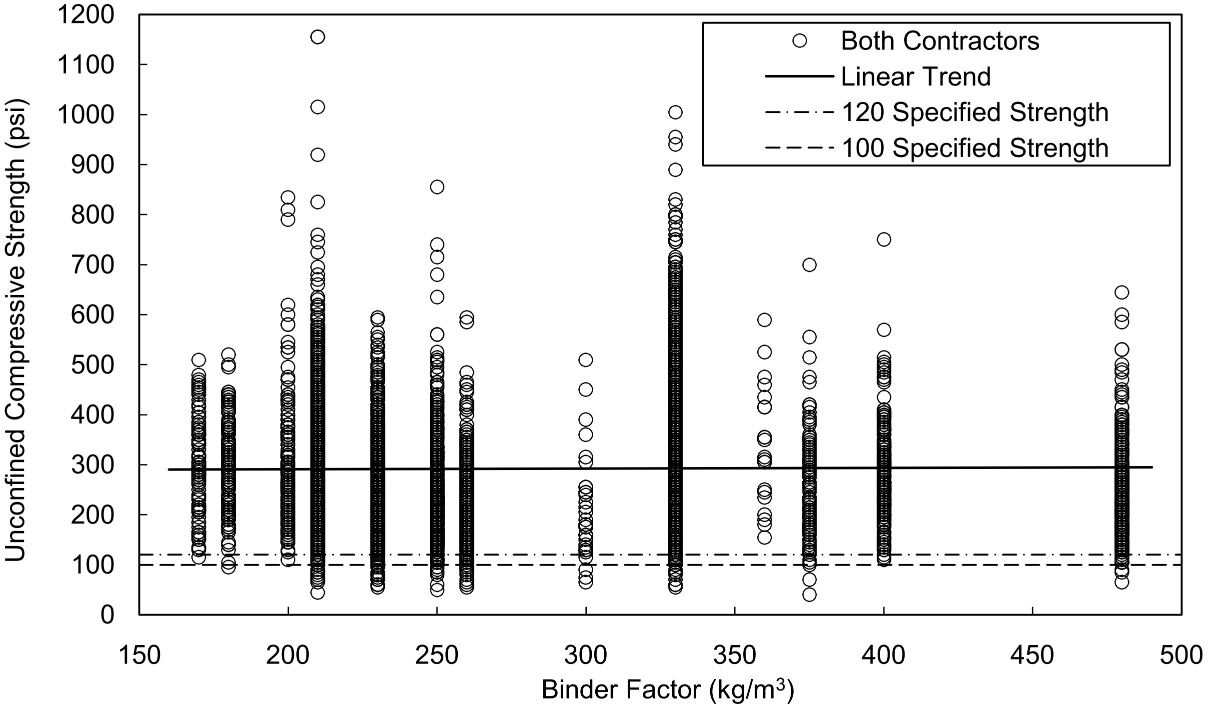

Fig. 4. Comparison of 28-day UCS versus binder factor for all soil types

SUMMARY AND CONCLUSIONS

The following summary and conclusion statements are based on the coring and testing performed at the LPV 111 project:

- Over 6,000 core runs, most of them approximately 5 ft long, were made during the process of coring 507 deep-mixed elements. Core recovery was generally excellent, equal to or nearly 100% for almost all core runs, with a few of the core runs from depth 0 to 5 ft having recovery as low as 80%. The only exceptions to the otherwise excellent core recovery was for six core runs, which is less than 0.1% of the core run attempts, where recoveries ranged from 0% to 62%. However, the occurrence of these six cases was explained, the encountered voids were backfilled with grout and the columns accepted by the USACE, and the formation of subsequent large voids was prevented by adjusting the deep mixing construction procedures.
- Detailed photographs of 30 core specimens, which include photographs of saw-cut surfaces along the long axis of the specimens, indicated very good mixing quality as shown in Fig. 1 for two representative core specimens.
- All of the elements subjected to coring satisfied the specification requirement that nine out of ten specimens have a 28-day UCS value that equals or exceeds the specified value.
- The key statistics for UCS values are summarized in Table 2, which shows that the average strengths were at least twice the design strengths, the coefficient of variation values were about 0.4, and far fewer than 10% of measured UCS values were less than the specified UCS values.
- There was a slight trend for decreasing UCS with depth as shown in Fig. 3. The zone of lowest strength for both contractors was in the upper or lower fat clay layers. For each contractor, even the specimens from the elevation ranges corresponding to the fat clay layers had far less than 10% of the measured UCS values below the 100 psi specified strength.
- Each contractor used different sets of mixing parameters that varied with depth and station along the levee alignment. Because the binder factors were designed to treat the various soil types encountered, and because vertical blending occurs during mixing as a result of the general upwards movement of the mixture and the action of the inclined mixing blades during the downstroke and upstroke, the measured UCS values were relatively independent of the binder factor. This is due to the deep mixing contractors' careful execution of the work, and not because UCS is independent of binder factor for a given soil type.
- Based on the core recovery rates, observation of the recovered core, and the UCS test results, the Geotechnical Review Board considers that the deep mixing at LPV 111 was very well done and serves as a very good example of high-level deep mixing practice.
- Two of the factors that contributed to the project success were: (1) a multi-phase bench-scale testing program to investigate the impacts of different binder types, binder factors, and water-to-binder ratios on the mixture strengths for different soil types and (2) a multi-phase field validation program to investigate and demonstrate the effectiveness of field mixing using different mixing tool configurations and mixing parameters, including variations with depth to achieve optimal treatment of different soil types, at several test locations along the project alignment.

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