Deep Mixing: QA/QC and Verification Methods

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ABSTRACT: The Deep Mixing Method (DMM) technologies are finding increasing use in North America, and Western Europe, in addition to their traditional strongholds of Scandinavia and Japan. A series of federally funded studies has recently been completed by the authors, and this paper provides a synopsis of a portion of the third volume. The various methods used for sampling and testing DMM treated soils are reviewed.

1. INTRODUCTION

The first Deep Mixing Method (DMM) studies funded by the Federal Highway Administration (FHWA) concentrated on the history, application, relative competitiveness and construction method (FHWA, 1999). The same state of practice review also discussed various commercial aspects of the technology worldwide, with special focus on Scandinavian, Japanese, and U.S. practice.

The most recently funded study deals with the testing and the properties of soil treated by DMM. Given the vast amount of data generated over the years, this has turned into a monumental task, and a voluminous final report is anticipated. The purpose of this paper is to provide a synopsis of the data on testing procedures, as an introduction to practitioners who may not have the time, resources, or need to pursue in-depth studies. Space restrictions disallow a discussion of soil-cement chemistry, and stress-strain behavior, both of which are very important related topics described in detail in the FHWA Report.

Throughout the paper, the generic classification proposed by the authors (FHWA, 1999) is used to categorize the different types of DMM techniques. Figure 1 shows this classification, based on the distinctions between the use of

- Slurry or "dry binder" as the cementing agent.
- The mixing energy (rotary or jet assisted).
- The location of mixing (along the shaft or at one point).

While most of the DMM terminology is either well known or obvious, two terms in particular are important to define clearly at the onset:

- Cement Factor (also known as the α factor): defined as the weight of dry binder introduced into the ground to be treated, divided by the volume of ground to be treated. The weight can refer to the actual weight of binder used in dry methods, or the actual weight of binder used in the slurry in wet methods. Expressed in units of kg/m^3. Alternatively, the term a_w is also used, and this is the ratio of dry binder to dry weight of soil (expressed as a percentage). This and the natural water content of the soil dictate the actual cement factor.

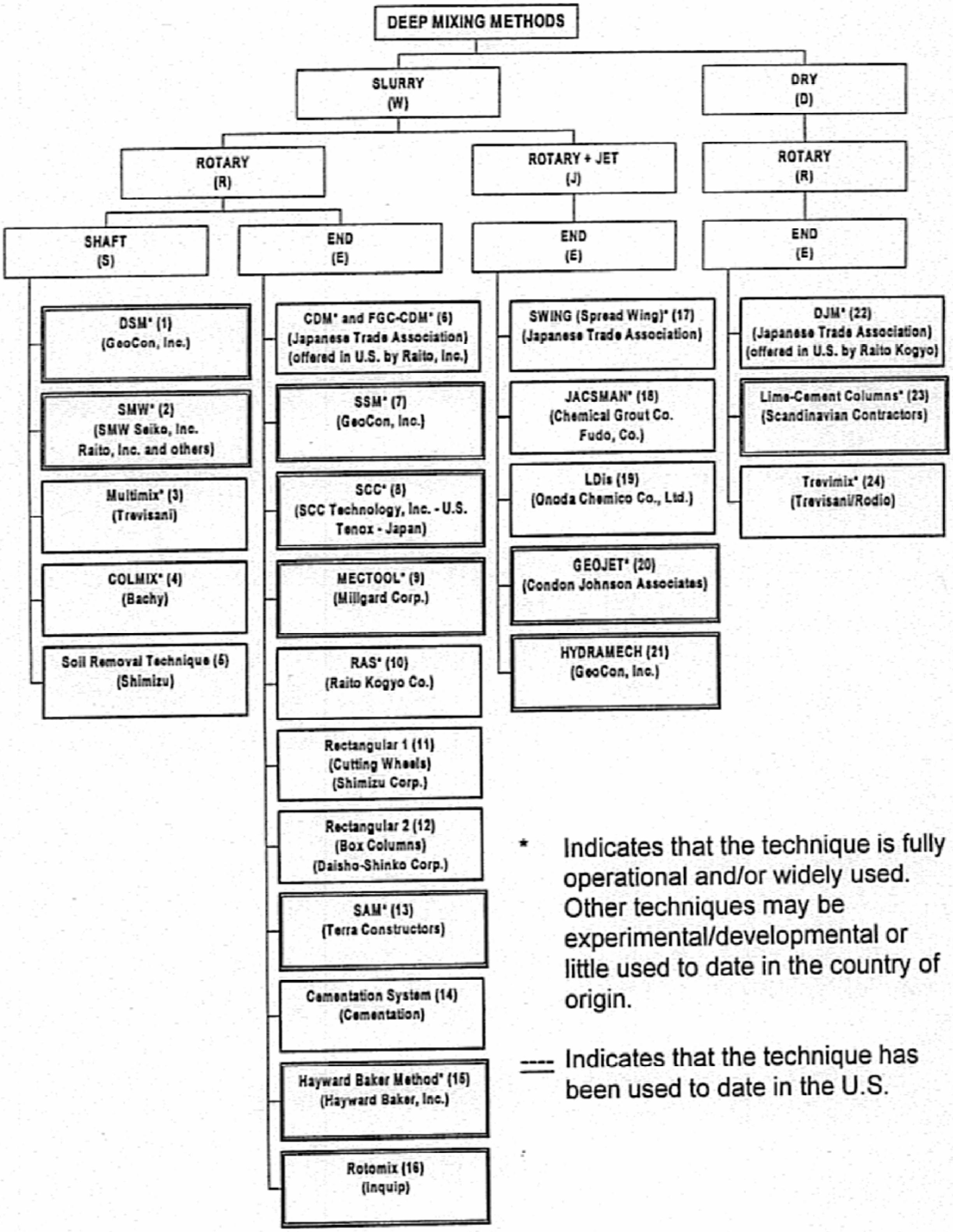

Figure 1. Classification of Deep Mixing Methods based on "binder" (Wet/Dry); penetration/mixing principle (Rotary/Jet); and location of mixing action (Shaft/End) (FHWA, 1999).

- Volume Ratio: defined as the ratio of the volume of slurry injected (in wet method systems) to the volume of ground to be treated. Expressed as a percentage.

2. CONSTRUCTION PROCESS CONTROLS

2.1 Construction Parameter Recording and Control

Process control is a critical element in assuring the quality of the treated soil. By studying the data published on each of the methods shown in Figure 1, it is possible to determine three broad levels of process control, based on the degree of sophistication.

Level 1: Batching and injection parameters for the slurry (or dry binder) are monitored by simple instrumentation and are displayed on digital or analog gages for field personnel to view. Spot checks are made manually on slurry fluid properties, e.g., density (by Baroid Mud Balance), fluidity (by Marsh Cone), and so on.

Basic drilling parameters are displayed in the drill rig cabin and controlled manually by the operator. Typically the operator is in telephonic contact with the batch plant, and/or the batch plant data may be electronically relayed to the cabin. The operator manually determines changes to drilling and grouting parameters based on these inputs and upon general progress observations. Typical examples of this level of instrumentation would appear to be Methods 8 and 15 as they are currently configured.

Level 2: Batching and injection parameters are controlled by computer, and are preset to provide a pre-selected volume ratio and cement factor, which is closely related to shaft penetration rate. In turn, these data are automatically recorded and displayed, with visual confirmation to the rig operator that they are within the pre-selected parametric range. If not, manual corrections may be made. Full construction records are automatically generated for each column for all salient drilling and injection parameters. Spot checks are made of fluid slurry properties.

As illustration, Yano et al. (1996) described details of the "centralized control system of CDM Method", where a computer system is employed in order to guarantee high quality production of columns, and also to control all stages from execution to daily report generation. This centralized control system is composed of a sensor section and an execution management section. The sensor section includes sensor detectors for depth, penetration and withdrawal velocity, volume of slurry discharge, shaft rotation speed, and shaft rotation motor current, and the execution management section consists of processing, monitoring and recording devices. During execution, the centralized control system checks that the real time data measured each second satisfy the quality standard values registered in advance for each depth and that acceptable quality columns are produced. "If the standard values are not satisfied, an alarm is issued" and changes can be made to installation parameters. After the completion of the work, the results of each column can be printed out in tabular form along with the evaluation of the quality standard values. At the end of each working day, the system can also print out a daily report and production total report, which include the numbers of columns, their length, and the amount of cement used. "This centralized control system thus helps produce high quality piles, simplifies the work of preparing various reports and saves time and labor." These efforts are focused on two key quality control aspects, namely

- That the amount of slurry pumped is uniform and in accordance with the specifications.
- That the rpm and penetration/withdrawal velocities are sufficient to blend the soil at a "minimum of 350 blade cuttings/meter."

The authors listed this control method as having been used on 44 projects (988,797 m^3 treated soil) in 1993 and 61 projects (1,371,348 m^3) in 1994. Typical examples would appear to be Methods 1, 2, 3, 4, 6, 7, 9, 21, 22, and 24, as they are currently configured.

Level 3: The highest level of computer control and display is provided. Method 20 (GeoJet) features a microprocessor which senses, every 6 seconds, rpm, penetration rate, torque, thrust, slurry density, pressure, and rate. The computer reacts to changing ground conditions and automatically adjusts injection parameters to maintain specific treated soil parameters for each stratum. Rotation is stopped automatically if these projected treated soil parameters are unlikely to meet preset limits. The drill operator has a touch screen control system. Level 3 is also characterized by full continuous records of each column installed.

Regarding innovations in QA/QC monitoring, Tateyama et al. (1996) described how fuzzy logic was used to evaluate real time construction data, in order to rationalize construction with DJM (Method 22), while Yano et al. (1996) reviewed innovative trends in computer controlled CDM work (Method 6) and summarized these as follows:

"The central control system permits high quality uniform pile placement and simplifies daily report preparation and other administrative tasks. The following studies and development activities are now underway order to make the control systems easier to use and deliver even better quality control.

1. Automatic Control of Slurry Discharge. The system will automatically control the amount of slurry discharged by controlling the rotation of the inverter motor on the slurry pump based on comparisons of the actual measured amount with the design values. For every 25 to 50 centimeters of depth, the set values sent to the pump will be recomputed from the integrated data and controlled so that the design values for every meter of depth are satisfied. The pump discharge volume will also be adjusted in stages in response to changes in the penetration and withdrawal velocity.

   The most serious problem to be resolved in developing this automatic slurry pump control system is to find a way to control the pump's own time lag between the time the discharge amount instruction is sent to the slurry pump and the time the pump actually begins to deliver the required amount.
2. Automatic Confirmation of Bearing Layer. The system will automatically confirm the bearing layer by judging the arrival at the bedrock based on electric current measured as the load on the auger and the penetration and withdrawal speed. Data are now being analyzed to determine what type of operation expression should be incorporated to evaluate the current.
3. Execution Management of the Machine's Operation. With the existing centralized control system, a single operator controls and monitors the execution management unit and the flow volume, but if the amount of slurry discharged can be automatically controlled, this person will no longer be needed, and the execution equipment can be managed from a central operator room for the deep mixing machine. However, this means that the execution equipment operator will have to spend more time operating the control equipment. To minimize the workload on the operators, studies are now in progress to develop easy-to-use system based on the operator's sense of sight and hearing by using one-touch panels, voice synthesizers and so on. Centralized control systems will thus be far easier to operate than those in use today.
4. Pile Track Measurements. To ensure that the strength of the overall improved soil satisfies the design values, the work must be executed in accordance with the pile arrangement and lap width stipulated by the design. To achieve this, it is necessary to confirm the manner in which the piles have been formed under the ground. This requires a technique of monitoring and controlling the track of the mixing bit underground to be developed.

   These technique problems will be resolved and even more accurate execution work will then be possible."

2.2 *Designing the Properties of Treated Ground*

The FHWA report (1999) illustrates the mass of experimental data available on the properties of treated ground. Reinforced by these data, performance prediction models can be established and optimized. Typical of the systematic Japanese approach is the work of Saitoh et al. (1996), colleagues in the Takenaka group of companies. Figure 2 is a standard conceptual flow chart for determining and achieving target treated soil strengths.

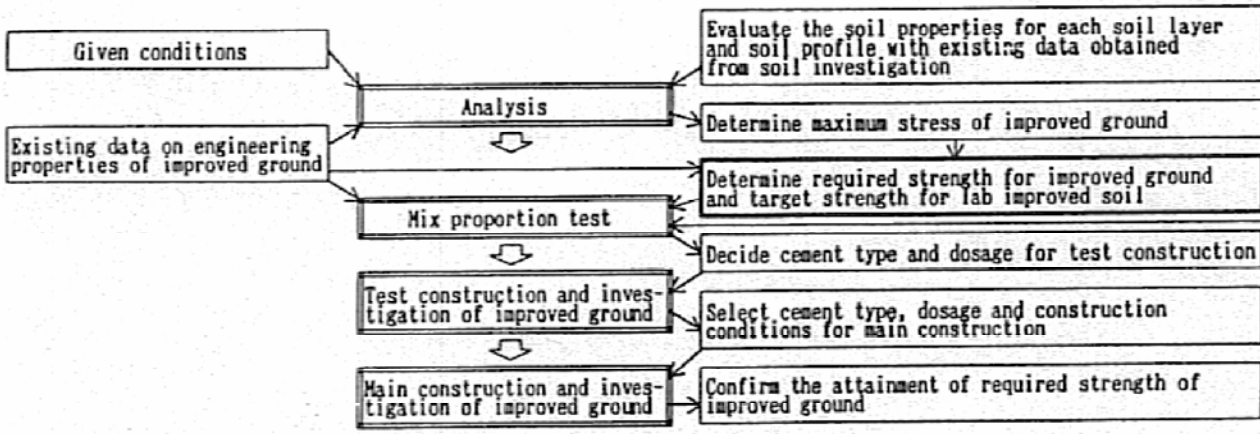

Figure 2. Flow chart of work involved to determine and achieve required strength of improved ground (Saitoh et al., 1996).

2.3 *Pre-Production Field Tests*

Regardless of the level of expertise of the Contractor, and/or the level of understanding of the particular site conditions, same type of pre-production test program is highly advisable, if not essential. Such a program affords the opportunity for the Contractor to demonstrate that the specified performance criteria, tolerances, and engineering properties can be met, even if two or more iterations have to be made. Once these criteria have been achieved, then the production parameters can be selected logically and only modified if there are obvious changes in the soil, or in the project scope.

Such programs require the scope of the testing to be clearly defined, together with the acceptance criteria for every aspect. Testing and sampling is usually more rigorous than in the subsequent production phase. Test programs should also be a demonstration of the efficiency of the quality assurance/quality control and verification processes themselves.

3. VERIFICATION METHODS FOR TREATED GROUND

The properties of treated ground are predicted and/or verified by the following broad groups of tests:

- Laboratory testing of laboratory samples (before construction).
- Wet grab sampling of fluid in situ material (during construction).
- Coring of hardened in situ material (after construction).
- Exposure and cutting of block samples (after construction).
- Miscellaneous, including geophysical testing (during and after construction).

It is reiterated that these properties are influenced in detail by many interactive factors, including soil type, amount and type of binder, water cement ratio, degree of mixing, curing conditions, environment, and age, although the soil characteristics themselves seem to be the most sensitive determinant of variations in strength. Excellent recent overviews of Scandinavian practice have been provided by Halkola (1999); Axelsson and Rehnman, 1999; and Holm et al., 1999).

3.1 Laboratory Testing

Such testing is a valuable basis for confirming basic design assumptions, and for demonstrating the effect and impact of the various materials used (both artificial and natural). It is also clearly useful in establishing base-line parameters, and for investigating in a controlled fashion the relationships between the various strength parameters and construction variables (Table 1). With respect to temperature, this is related to the size of the treated soil mass, as well as the quantity of binder introduced. In laboratory testing, there is no way to reliably vary and simulate factors III and IV

Table 1. Factors affecting the strength increase of treated soil (Terashi, 1997)

I	Characteristics of hardening agent	1. Type of hardening agent 2. Quality 3. Mixing water and additives
II	Characteristics and conditions of soil (especially important for clays)	1. Physical chemical and mineralogical properties of soil 2. Organic content 3. pH of pore water 4. Water content
III	Mixing conditions	1. Degree of mixing 2. Timing of mixing/re-mixing 3. Quality of hardening agent
IV	Curing conditions	1. Temperature 2. Curing time 3. Humidity 4. Wetting and drying/freezing and thawing, etc.

from Table 1, except for the amount of binder and the curing time. Laboratory testing therefore standardizes these factors, with the result that the strength data obtained during such tests are "not a precise prediction" but only an "index" of the actual strength. Likely field strengths can then be estimated using empirical relationships from previous projects, and exercising engineering judgment. However, there is as yet no standard laboratory test procedure (in Japan).

Kamon (1996) summarized that unconfined compressive strength data from field cored samples are 20 to 50% those prepared in the laboratory findings largely supported by Kawasaki (1996). These data were determined from land projects whereas on the massive marine CDM projects, larger field than laboratory values are often obtained due to the "adiabatic temperature rise" in in-situ treated masses.

Mizutani et al. (1996) found that core strengths were 60 to 70% those of laboratory mixed samples and that 60 to 80% of the lab strength can be achieved in the field with "fairly good" quality control.

Taki and Bell (1998) also found a reduction in apparent strengths from laboratory to field, with a wider data scatter in the field data (Figure 3).

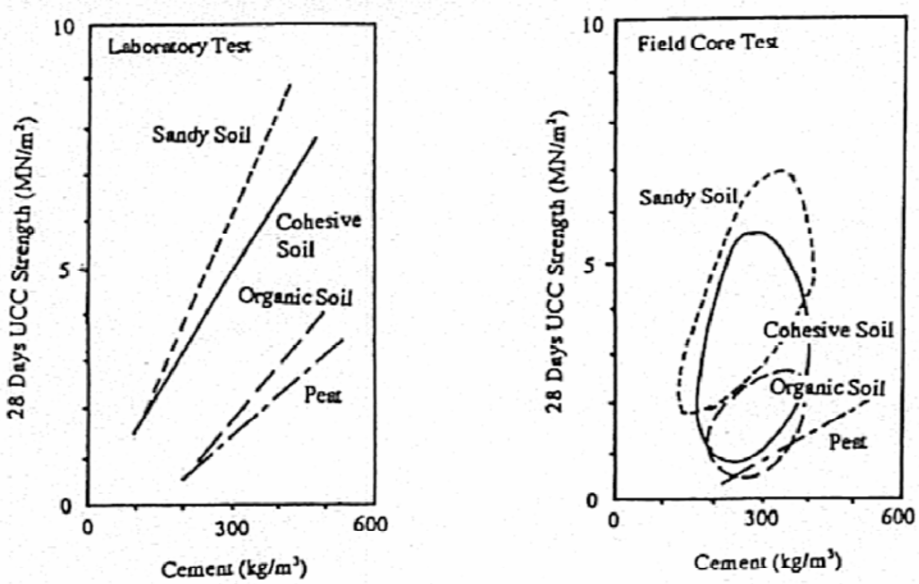

Figure 3. Relationship of unconfined compressive strength, cement factor and soil type (data developed with water/cement ratio of 0.6 to 1.2, and a volume ratio of 23 to 75%) (Taki and Bell, 1998, after Hibino, 1989).

3.2 *Wet Grab Sampling*

The concept simply is to obtain samples from the treated ground before the mix reaches such a strength that a sampler cannot be introduced easily or without causing significant sample disturbance. Such samples are then used to make cubes or cylinders for later laboratory testing. Wet grab sampling may be faced with a number of systematic and logistical problems. For example, the sampling device must be able to reach a prescribed depth, take a representative sample from that depth, and allow it to be retrieved without contamination. This places great emphasis on the efficiency of the sampling tool and how expedient it is to introduce and withdraw. If the deep mixing efficiency has not been high, the presence of unmixed native material may prevent the sampler from functioning correctly, and/or from obtaining a wet sample whose composition is truly representative of the overall mixed volume. In this regard, it is typical to screen wet samples, prior to casting samples for testing, and screens with 6- to12-mm aperture are common.

3.3 *Coring*

Given that coring is an energetic, local and invasive technique, even when conducted with the best equipment, skill, and methods (the triple tube core barrel is widely recommended), it is notable that most contractors cite core samples as their prime source of data on treated ground properties in general, and unconfined compressive strength in particular.

Druss (1998) noted several key elements which promote good and representative core sampling. These include using experienced drillers and logging engineers; taking large diameter cores (greater than 76 mm in diameter); using triple tube methods, coarse diamond bits to minimize sample washout, and appropriate drilling flush; and ensuring that the inside surface of the sample tube is well lubricated. The Japanese Committee on DM strength evaluation (Hosoya, 1996) recommends a minimum core diameter of 150 mm.

Taki and Bell (1998) wrote that core locations can be randomly selected, but additional core drilling and testing should be performed when questionable soil conditions or mix conditions are observed during installation. Uniformity of mixing can be evaluated from the inspection of core samples. The depths of core samples should include intervals containing the weakest soil layers and should be more than 95% in sandy soil and more than 90% in cohesive soil.

There is healthy debate as to the relationship of unconfined compressive strengths measured from cores, and those cast from wet grab samples. It is perceived in some quarters that core samples will provide lower strengths given the distress caused to the core during drilling and extraction. (However, it is typical to select only the "better" core samples for testing and this will automatically provide higher actual test data). Taki and Yang (1991) produced data (Figure 4) from various soil types which show that the core strengths were about twice those obtained by samples made from wet grabs. Their view is supported by Burke (1998), who found that on a DMM project in soft clays the core samples always gave higher strengths than wet grab samples, but were only 50% of laboratory strengths and showed a wider variation. Although pre- and post-construction CPTs are possible for in situ strengths less than 7 MPa, if in situ strength is expected to average over 3.5 MPa, Burke considers coring feasible (minimum diameter 76 mm). Recovery rates can vary from 25 to 100% depending on mixing parameters and soil strengths. They found that, with their particular DMM technique (Method 15), the grout:treated soil strength ratio was about 4.

Taki and Yang (1991) published data illustrating the relationship of unconfined compressive strength, cement factor, and soil type, (Figure 4), which highlighted also the difference in value and quality between laboratory and core data.

Isobe et al. (1996) conducted several field tests using a WRE method in sands and silts at Kunishima, Japan. Cores were taken at various positions across the face of different sized columns. Strengths were higher in centrally cored samples, but decreased by up to 50% toward the perimeters of the DMM columns.

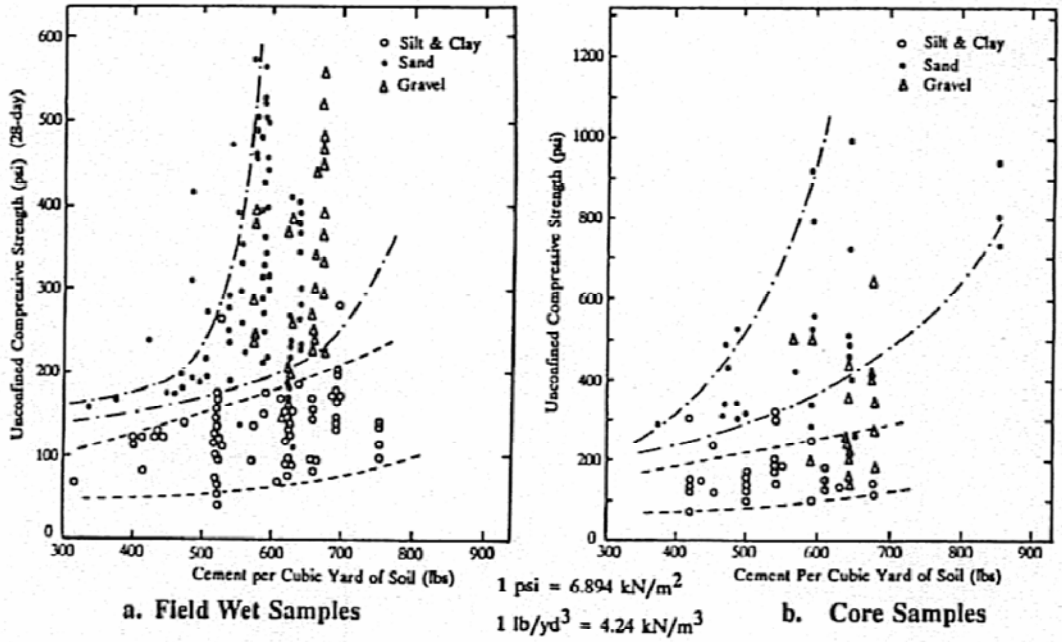

Figure 4. Strength of soils treated by SMW Method (Taki and Yang, 1991).

Okumura (1996) stated that for large DMM projects in Japan, it is typical to core one hole per every 10,000 m^3 of treated soil (marine projects) and 1 per 3,000 m^3 (land projects).

Regarding future developments, Sugawara et al. (1996) produced a most interesting paper on their attempts to produce an improved core sampler. However, even this can only *reduce* disturbance to the core samples, although the use of triaxial as opposed to uniaxial testing will generally give higher and more consistent results.

3.4 Exposure and Block Sampling

The opportunity to expose the treated ground allows all parties to observe column shape, homogeneity, diameter, nature of overlap and so on. It also permits samples to be taken with different shapes, sizes and orientations from those that can be obtained by vertical coring. The value of this kind of testing is underlined when it is recalled that important technical goals of any DMM operation are to provide a uniformly treated mass, with minimal lumps of soil or binder, a uniform moisture content, and a uniform distribution of binder throughout the mass. Exposed treated soil can be sprayed with phenolphthalein solution to indicate the presence of cement in the mass.

Single columns can be fully exposed, and even extracted (e.g., Method 23), while multiple columns can be installed in a circular shaft, or box, arrangement to allow a self-supporting excavation to be completed.

Again, the major drawbacks to such exercises are principally cost, time, and site logistics, but on certain projects of critical size, complexity and significance, exposure is a vital element in verification, both as a pre-production measure, but also as a special demonstration during construction. Burke (1998) is of the opinion that the most efficient method of evaluation is to drill a shaft into overlapping columns to allow visual observation of integrity, homogeneity and sampling of the mixed soils, and therefore to put into perspective any apparent anomalies identified by coring.

3.5 Miscellaneous

Depending on the nature, purpose, and extent of the treatment, a variety of miscellaneous methods have been reported. For example, Methods 11 and 19 both have been developed to reduce adjacent ground and structural movements: inclinometer and borehole extensometer testing results have therefore been reported. Similarly, in those methods (e.g., 15 and 23) focusing on very soft clays and low strength treatment, CPT/SPT testing may be conducted before and after mixing although the Japanese Committee (1996) regards SPT values as "coarse" but of "some merits". Most recently, Esrig (1999) described the value of routine pressuremeter testing to indicate in situ shear strengths. In higher strength materials (e.g., Method 4), "sonic velocity measurements in three dimensions" have been conducted to verify quality of treatment.

Hane and Saito (1996) reported on the use of shear wave seismic tomography to explore a treated sandy soil mass, underwater. In this case, the increase in velocity was from 200 to 500 m/s (untreated) to 950 to 1200 m/s (treated), with a very small velocity contrast indicating homogeneity of treatment. These data were consistent "with other mechanical tests". Similarly, Hiraide et al. (1996) were able to relate shear wave data to unconfined compressive strength and E value.

Regarding other geophysical techniques, Imamura et al. (1996) investigated borehole resistivity for treated soil quality, and Nishikawa et al. (1996) experimented – also successfully – with PS logging and SPT testing for predicting unconfined compressive strength. Tamura et al. (1996) reported on low strain sonic integrity testing, while Barker et al. (1996) illustrated the value of a portable cone resistance testing apparatus. Halkola (1999) noted that CPT methods are used almost exclusively "even for the testing of semi-strong and soft" columns in Helsinki. At the other end of the test scale spectrum, full-scale load testing (vertical or lateral) can be conducted on entire DMM elements (Druss, 1998).

For low strength DMM installations, such as Lime Cement Columns, a range of column vane penetrometers have been designed and tested in Scandinavia (Rathmayer, 1996; Halkola, 1999; Holm et al., 1999). Both push down and inverted versions are available. Significantly Rathmayer stated that "methods applied for integrity testing of concrete piles do not work" (for LCC). Therefore "the only reliable test method today is total sampling, managed by lifting upon the entire column".

Experiments have also been made in Finland and in Japan with, respectively, "measurement while drilling" (MWD) or "factor of drilling energy" tests, which, according to Halkola (1999) relate the records of various drilling parameters to the strength properties of the treated soil. A useful summary of these various methods was provided by Hosoya et al. (1996) (Table 2).

4. FINAL REMARKS

This paper introduces the various methods currently available, and indicates the goals of ongoing research. Obviously the time taken and the cost involved in conducting the various types of tests vary greatly and must be taken into account on each project. Many practitioners still feel (e.g., Rathmayer, 1996) that the available quality control methods do not paint a full or accurate picture of the quality of the work executed.

Equally, there is no doubt that the future growth potential of DMM is linked closely to the ability of the profession to control, assure, and verify its construction. It would seem, however, that the profession is fully aware of this challenge and is responding accordingly.

Table 2. In-situ tests for evaluating treated soil (Hosoya et al., 1996).

Type of test	Method	Test method and results	Comment on quality control method
Sounding test	Standard penetration test	Let 67.5kgf hammer fall free from 75cm height and count the number of strokes (N-value) to penetrate 30 cm.	Most common method on natural soil. However, only a few applications for stabilized soil are available. There is correlation with unconfined compressive strength.
	Dynamic cone penetration test	Let 5kgf hammer fall from 50cm height and count the number of strokes (Nd-value) for cone to penetrate 10cm.	Easy transportation and operation. Practical for unconfined compressive strength of qu=2~5 kgf/cm2. qu=0.29Nd-2.58(kgf/cm2)
	Electric static cone penetration test	Let the cone penetrate at uniform speed and measure the resistance at the end and surrounding surface and pore-water pressure in sequence.	Applicable to measure the improvement of low strength stabilized soil in sequence. However, not applicable for firm stabilized soil.
	Rotary penetrating test	Measure the bit pressure, torque, and muddy water pressure by the sensor at the end of the boring rod to observe the soil strength in sequence.	Greater mobility compared with core sampling and in-situ strength can be measured. However, correlation with the unconfined compressive strength must be compared from site to site.
Test of utilizing bore-hole	PS logging	Measure the velocity of P and S waves. Then calculate rigidity and Poisson's ratio of stabilized soil. There are two testing methods, Down hole method and Suspension method.	There is some correlation with unconfined compressive strength although it is not so uniform. Suspension method is better to evaluate the stabilized soil.
	Electrical logging	Supply electricity to stabilized soil and measure electric current and voltage through an electrode. Then calculate the specific resistance. Lately, analysis is made by tomography in some cases.	The correlation with unconfined compressive strength is low.
	Density log	Measure the gamma rays emitted from a probe inserted into the hole by the detector installed at a certain distance. Then convert the data into density.	Since it is influenced by hole diameter and water inside the hole, calibration is important. There is no correlation with unconfined compressive strength.
Loading test	Bore-hole lateral load test	Press rubber tube toward the bore-hole wall in stages and measure the strength and deformation modulus of stabilized soil. Mesurement apparatus is Pressio metre and LLT	Deformation modulus rather than strength is often the objective of the tests. Vertical measurement is costly so it is used as representative value of stabilized soil.
	Plate loading test	Place a loading plate (round plate of 30cm diameter) on the stabilized soil and put on load in stages. Bearing capacity and deformation characteristics can be obtained directly from the load and settlement curves.	Bearing capacity and deformation characteristics can be obtained directly. However, the evaluation of stabilized soil is possible only down to the depth of 2 to 3 times of(load) plate diameter.
	Stabilized pile loading test	Place the (load) plate of the same diameter as the stabilized pile on the surface of the leveled stabilized pile. Then put on load in stages. This is a sort of vertical load test of a pile where bearing capacity characteristics are obtained from the load and settlement curves.	Bearing capacity characteristics of a stabilized pile can be directly obtained. However,testing equipment is costly and the number of tests available is limited.
Non-destructive test	Integrity test	Safely stroke the surface of a stabilized pile with a hammer and measure the reflected wave of the vibration by the accelerometer installed on top of the pile. Length and discontinuity of the stabilized pile is measured.	Simple method. However, evaluation standard for a stabilized pile has not been established yet.
	Elastic wave exploration	Emit P and S waves to measure the velocity distribution of stabilized soil. In the case of stabilized soil, measurement of S wave is preferred.	Stabilized condition is measured by velocity distribution of the S wave. The measurement is made in the bore-hole and on the ground surface. Tomography is used to improve accuracy of the test.
Other test	Penetration test	Use pocket type pin penetration apparatus and measure the penetration resistance of stabilized soil on the job site. Then estimate the unconfined compressive strength.	Easy and simple method. A lot of tests can be done. However, only the surface of the stabilized soil can be tested.

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