Deep Mixing Method: An International Overview of Technology, Testing, and Product

AMELIORATION DES SOLS EN PROFONDEUR PAR LA TECHNIQUE DU "SOIL MIXING": Une revue Internationale de la Technologie, des Tests et Matériaux utilisés.

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ABSTRACT: The Deep Mixing Method is a very valuable tool for combating problems related to in situ soil treatment, improvement, and retention. Many different variations are used throughout the world, and there is a correspondingly rich technical literature on the testing and properties of the treated soil. This paper provides a synopsis of these aspects.

RÉSUMÉ: La technique du "Soil Mixing" est certainement une bonne méthode pour résoudre des problèmes liés à l'amélioration des sols in-situ, et à leur soutènement. De nombreuses variations autour de cette technique sont utilisées à travers le monde, et il existe en conséquence une littérature technique suffisament riche sur les tests et les propriétés charactéristiques du terrain traité. Cet article présente une synopsis de ces aspects, s'appuyant sur une étude Fédérale récente faite aux USA.

1 INTRODUCTION

1.1 *Background*

Following the Tokyo Conference on Deep Mixing and Jet Grouting in May 1996, the Federal Highway Administration (FHWA) commissioned a state of practice review on aspects of the Deep Mixing Method (DMM). The first volume (FHWA, 2000a) dealt with history, application, relative competitiveness, and construction methods. Various commercial issues were also reviewed, with special focus on Scandinavian, Japanese, and U.S. practice. Volume 2 (FHWA, 2000b) provided a great deal of supplementary data in a series of appendices, principally dealing with the details of each of the 24 different DMM techniques described to that point in the technical literature. The third volume (FHWA, 2000c) describes the testing and properties of treated soil, and, reflecting the vast amount of data which have been published in English since 1996, has turned into a voluminous study. It was completed in September 2000, which should lead to availability in the published form in early 2001. Space restrictions clearly prevent this paper being more than a brief synopsis of the findings so far, and the active researcher is referred to the FHWA publications and the hundreds of references they contain. Rather, the goal of this paper is to help establish some basic guidelines and principles for a technology which is enjoying rapid growth and which is at the same time undergoing continuous and often bewildering evolution.

1.2 *Scope and Definition*

DMM is an in situ soil treatment technology whereby the soil is blended with cementitious and or other materials, either in dry or wet (slurry grout) form. The greatest amount of the work conducted globally involves vertical penetration by one or a number of mixing shafts to create discrete columns or panels. Depending on the application, these elements may be constructed to overlap to provide a variety of geometries of treated soil. The FHWA study addresses only these vertical, rotary methods. However, there is an increasing number of methods under development which create either mass treatment by using inclined auger or conveyor technology or by using vertical beams with lateral jetting capabilities to provide thin, but continuous in situ membranes. Such applications mainly serve the environmental market and are typically viable to relatively shallow depths (10 m). Future studies of DMM may well entertain these methods also.

1.3 *Historical Evolution*

The FHWA study listed some 82 events considered significant in the growth of DMM since the original U.S. concept in 1954, and the independent Japanese and Scandinavian initiatives of 1967. Most of these key events have occurred in the last decade, emphasizing the ever-increasing rate of development by contractors, consultants, and owners - including federal agencies in the case of Japan, China, France, Sweden, and Finland. Another mark of the significance of deep mixing as an engineering tool worthy of retrospective study is the series of reviews by Porbaha and coworkers (1998a, 1998b, and 2000), sponsored by the Science and Technology Agency of Japan which closely detail both commercial and research progressions in these last 25 years.

1.4 *Applications and Commercial Viability*

The main groups of applications remain:

- Hydraulic cutoffs (e.g., through dams, levees, and canals)
- Excavation support walls (typically steel reinforced and supported by bracing or anchors)
- Ground treatment (for large scale tunneling or deep foundation projects)
- Liquefaction mitigation (formation of "cells" around individual piles or under the entire structural footprint)
- In situ reinforcement, piles and gravity walls
- Environmental remediation (both by containment and fixation).

Globally, the novelty now arises when local methods are used for new applications, or when established methods are used in new geographic areas, often by contractors who are seeking to develop their own variant of the method in response to a particular project's challenges. Thus one may anticipate in the next decade's technical press a plethora of case histories dealing with environmental and liquefaction mitigation, and in situ earth reinforcement, from practitioners in countries as diverse as the U.K., Indonesia, and Australia, based on the authors' current project awareness.

The viability, both technically and commercially of DMM in its various potential applications and settings, continues to be challenged by solutions based on other technologies and cultural preferences, and rightly so: deep mixing is not the panacea for all specialty geotechnical problems. However, when the goal is ground treatment, improvement or retention, the ground and site are relatively unobstructed, and the depth is limited to about 40 m, then deep mixing will most probably be a viable option in countries with easy commercial access to the technology and the appropriate binder materials.

2. TECHNOLOGICAL ASPECTS OF DMM

2.1 *Classification of Methods*

A total of 24 different methods - mostly fully operational and patented - were identified by the FHWA survey and reflected developments in Japan, Scandinavia, Western Europe, and the U.S. The classification adopted is based on the nature of the "binder" (grout, or dry); the method of soil blending (rotary alone, or rotary with jet assistance); and the location at which most of the soil/binder blending occurs (along the shaft of a long auger, or only at the mixing tool located at the end of a rod). A new "arm" to this classification will be necessary to accommodate the "mass", or "lateral jetting" variants.

Using the classification, of the eight possible combinations of categories, only four are used:

- WRS: wet, rotary, shaft mixing (e.g., Raito Soil Mix Wall).
- WRE: wet, rotary, end mixing (e.g., CDM).
- WJE: wet, jet assisted, end mixing (e.g., GeoJet).
- DRE: dry, rotary, end mixing (e.g., Lime Cement Columns, DJM).

2.2 *Relationship of Technology to Market*

The level of DMM activity in Japan remains by far the highest in the world. Building upon the Government-sponsored research work in 1967, full scale DMM systems have been used commercially since 1974, and appear to have grown especially quickly in annual volume since the early 1980s. The Japanese contractors, in close cooperation with the Federal Government, manufacturers, suppliers and consultants have continued to develop and enhance DMM technology in response to technical and commercial challenges. Trade associations, often comprising dozens of members, serve the technologies of CDM, DJM, SWING, and Mixed Walls, for example. These associations organize annual conferences and collect and publish data on market volume: a service not yet available in the U.S. Data on annual volumes of ground treated were published by Bruce et al. (1998) from which it may be inferred that the annual DMM volume in Japan is valued at $250 to 500 million, most of it related directly to seismic mitigation. Activity is increasing in China, especially for harbor and port development at estuarine cities and for earth retention projects, and has traditionally involved Japanese input. DMM has also been used elsewhere in S.E. Asia, including Taiwan (Liao et al., 1992) and Hong Kong. The total regional market outside of Japan is smaller than in Japan, but exact figures are not readily available.

Like the Japanese, the Swedes began researching in 1967 via a series of laboratory and field tests. The original coworkers included the Swedish Geotechnical Institute, private consultants, and piling companies. This cooperative model has endured, and a wealth of information has been generated about the technical and commercial aspects of the Lime Cement Column method in Sweden, and more recently by similar groups in Finland. Their focus remains on ground improvement and pile/soil interaction solutions for very soft, highly compressible clayey and/or organic soils. Therefore, and again in contrast with typical Japanese and U.S. practice, relatively light and mobile equipment has been developed producing single columns only up to 0.8 m in diameter, to relatively shallow depths (typically not more than 25 m) and with low unconfined compressive strengths. Market growth has been particularly rapid since 1989 in both countries where the combined volume has averaged around $30 to 40 million annually. Contractors from Sweden and Finland are also active in other countries including Norway, the Baltic States, Holland, U.K., and Hong Kong (in addition to two companies in the U.S.) The region's commitment to DMM development is clearly underlined by the formation, in Sweden, of the Deep Stabilization Research Center, and in Finland, a National Structures Research Programme, both in 1995. In each case, national resources have been assembled - similar to the Japanese model - and the findings are to be published in 2000 and 2001, respectively.

Elsewhere in Europe, the main application appears to have been for environmental remediation purposes, while the expansion of DMM into other applications has been somewhat restrained by soil conditions and devotion to other, more traditional techniques (such as a diaphragm walling, tangent or sheet piles).

The U.S. market effectively began in 1987 with the seismic retrofit at Jackson Lake Dam, WY, but it has only been since 1992 that DMM has achieved a national prominence as a geotechnical construction tool. Contractors are divided between a) those who are either wholly-owned subsidiaries of foreign companies or operate only and exclusively under foreign license, and b) those who have developed "native" systems. The bulk of the work remains in the massive projects in the Boston and San Francisco Bay areas where the main applications are for earth retention, ground treatment, and seismic mitigation. National statistics on usage are not maintained, although it may be estimated that the average annual market between 1995 and 2000 was in the range of $50 to 80 million.

2.3 *Construction Parameter Recording and Control*

Process control is a critical element in assuring the quality of the treated soil, and it is possible to determine three broad levels of process control, based on the degree of sophistication.

<u>Level 1</u>: 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.

<u>Level 2</u>: 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 with all salient drilling and injection parameters. Spot checks are made of fluid slurry properties.

<u>Level 3</u>: The highest level of computer control and display is provided. For example, the GeoJet system 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.

2.4 *Future Development Trends*

Throughout the world, similar trends are evident:

- Understanding the factors which control the homogeneity of the mixing process, and thereby improving the quality and properties of the treated soil.

- Experimenting with new binders, especially those which can address technical challenges (e.g., organic soils of low pH), or commercial realities (e.g., cost or availability of certain industrial byproducts).
- Obtaining large diameters of treatment via mechanical or jet means.
- Improving the level of computer monitoring and control to help assure higher and more consistent quality of the treated soil (Yano et al., 1996).

3. THE TESTING OF TREATED SOIL

3.1 *Designing the Properties of Treated Soil*

A common thread in the excellent case histories of Scandinavian and Japanese practice, as illustrated in the Tokyo and Stockholm Conferences (1996 and 1999, respectively) is the logical and systematic approach to determining and achieving target treated soil parameters. Although as illustrated below, there is obviously a large number of properties which may be critical, national practice and application tends to be based on unconfined compressive strength (Japan and U.S.A.), undrained shear strength (Scandinavia), or permeability (U.S.A.).

Regardless of the level of expertise of the Contractor, and/or the level of understanding of the particular site conditions, some 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 are 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.

3.2 *Testing Methodologies*

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

<u>Laboratory-produced samples (before construction)</u>. This is an international practice which is used to confirm design assumptions and to investigate the impacts of the various components. It is, at best, only an "index" of the actual field properties. Laboratory strengths are typically two to five times higher than field values, although the difference (and the scatter) is inversely proportional to the field quality control measures.

<u>Wet grab samples (during column construction)</u>. Especially in the U.S., fluid samples are retrieved from newly treated columns and remolded into cylinders for later testing. The process may experience systematic problems relating to the sampling tool and the homogeneity of the mixed soil. Test results show considerable variability, and strengths are usually intermediate between those from laboratory-produced samples, and those from cores.

<u>Coring (after column construction)</u>. Led by Japanese practice, coring of hardened treated soil, if carefully and responsively conducted, provides representative samples for visual observation of homogeneity and for testing. The quality and accuracy of the data increase with core diameter (in the range of 76 to 150 mm), and a 90% recovery target is a common acceptance criterion. Such strengths may be within 30% of laboratory strengths, but are usually 50% or less.

<u>Exposure, extraction, and block sampling (after construction)</u>. This provides an excellent opportunity to observe column shape, homogeneity, diameter, and overlap, on the full scale, in situ. Due to cost, however, it is typically restricted to preproduction demonstrations on major projects.

<u>Modified geophysical testing (after construction)</u>. Practitioners in Japan especially are researching this concept to assess or predict column properties. Broadly, each technique (including shear wave) is "promising", but none is yet used routinely.

<u>Modified geotechnical testing (after construction)</u>. Especially in the Nordic countries where column strengths are relatively low, it is common to use modified standard geotechnical tests (Table 1). Virtually all routine testing is carried out by some form of penetrometer testing, each with its own advantages and disadvantages.

Table 1. Modified standard geotechnical tests for DM testing.

METHOD	RESEARCHING COUNTRIES	NOTES
Conventional Column Penetration (KPS)	Nordic countries	Used since 1980 in columns of s_u less than 200 to 300 kPa. Depth limit 6 to 8 m, aided by predrilling.
Inverted Column Penetrometer (FOPS)	Nordic countries	Used in Sweden since early 1990s for strengths up to 600 to 800 kPa and to depths of 20 m.
KTH Penetrometer	Sweden	New simple development, of promise.
Pressuremeter	Sweden/U.S.	Accurate test, especially for stronger columns, being promoted.
Dynamic Penetrometer	France/U.K.	Being used commercially in conjunction with Colmix system.
Static/ Dynamic Penetrometer	Finland/Sweden	Developed in 1980s but not as accurate as CPT.
Standard Penetration Test	Japan	Widespread, simple test, well known.
Cone Penetrometer (CPT)	Norway and Finland (since 1970s) less in Sweden	Despite systematic problems, can provide data in columns of c_u up to 1000 kPa, 20 m depth.
Modified Vane Test	Norway	Under development for c_u less than 200 kPa but use decreasing with use of CPT in 1990s.
Tube Sampler	Norway	Promising development but gives low strengths in heterogeneous columns.
Screw Plate Test	Scandinavia	Developed in early 1970s and is a very precise but expensive test.
Measurement While Drilling (MWD)	Japan, Finland	Good experimental results achieved in stronger columns through real time monitoring of drilling parameters.

4. PROPERTIES OF TREATED SOIL

4.1 *Binder Materials*

For wet mix methods, the most common materials used to provide slurries for geotechnical applications are (in addition to water – both fresh and salt), Portland cement, bentonite, slag cement, clay, flyash, lime, gypsum, sand, and kiln dust. Small amounts of additives may be used to enhance fluid and set properties whereas the use of various "industrial byproducts", more common in "dry" methods, is rare in wet mixing. Careful experimentation has been conducted with various proportions of these materials to satisfy economic and technical goals.

Dry mix methods have been used to treat relatively soft, compressible, or liquefiable materials, often with high organic contents, and moisture contents of 60% to over 200%. Dry methods typically use lower cement factors than wet methods (100 to 300 kg/m^3) and naturally produce far less spoil, and so less wasted binder. Ordinary Portland Cement is the most common binder type in Japan and in Sweden, where mixes contain up to 50% quicklime (which promotes pozzolanic reactions). In Finland, increasing use is being made of proprietary binders using slag, gypsum, and other products since importing lime and cement may be unattractive commercially.

4.2 *Treated Soil Properties*

The major controls over treated soil properties appear to be the soil (especially water and organic contents); type, amount and water content of binder; curing temperature; effective in situ stress; age; and mixing efficiency. High soil sulfate contents, and/or high organic contents (and so low pH) inhibit strength development, whereas data indicate that the presence of chloride ions (as in salt water) enhances pozzolanic activity and hence increases strength. In addition, little improvement can be expected in soils with over 1.5% humus content, and the effect of humus content on strength is especially marked in coarser grained materials.

Given the influences that even subtle difference in soil conditions, mixing method, or even testing procedures may exert on the results, one must be very wary when trying to compare, analyze, or use published data. Also, properties can apparently vary considerably over relatively short distances. However, the following generalities may be made (Table 2).

Table 2. Summary of typical properties which may be anticipated.

PROPERTY	WET MIX	DRY MIX
U.C.S. (MPa)	0.5 – 10	0.3 – 10 (DJM) 0.1 – 1.0 (LCC)
k (m/s)	$10^{-7} – 10^{-10}$	Depends on lime content
Tensile strength	8 – 20% U.C.S.	10 – 20% U.C.S.
Undrained shear strength, c_u	20 – 50% U.C.S.	33 – 50% U.C.S.
Elastic modulus, E_{50}	100 – 1000 U.C.S.	100 – 600 U.C.S.
Poisson's ratio	0.19 – 0.45	-

5. FINAL OBSERVATIONS

The various technologies of the DM method are being used with increasing frequency on ground improvement, treatment, and retention projects throughout the world. There is a correspondingly impressive explosion in the number of technical papers being published in the English language in journals and in international conferences. It is hoped that this paper –itself a very brief condensation of a detailed Federal study – will serve as a useful introduction and guide.

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