Dry Mix Methods: A Brief Overview of International Practice

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ABSTRACT: A recent study completed by the authors for the Federal Highway Administration in the United States has identified and classified 24 different types of Deep Mixing Method (DMM) techniques worldwide. Three of these are of the Dry Mix type. This paper describes the evolution of Dry DMM techniques, introduces the global DMM classification, provides general observations on their use, and discusses the international Dry DMM market.

1 INTRODUCTION

Deep Mixing Methods (DMM), as they currently are defined, had been applied in the United States since their first demonstration in 1986. In May of 1996, the so-called "Tokyo Conference" (1996) was held and in attendance at this pivotal event were many representatives of American organizations, including the authors. Given the growing application of DMM on major Federally funded U.S. projects – the largest being 600,000 m^3 of ground treatment in Boston, MA – the Federal Highway Administration (FHWA) commissioned a state of practice review (FHWA, 1999a), with a global scope.

That Report focused on technology, applications, and commercial aspects, and was followed by a later study devoted to the testing and properties of ground treated by DMM (FHWA, 1999b). It is intended that this contribution to knowledge will serve to promote the correct use and execution of DMM in the United States.

These two studies have been prepared only from the limited pool of English language papers readily accessible: the several hundred papers (Terashi, 1998) in Nordic and Oriental languages were not individually scanned, although the major English language overviews were analyzed. These studies revealed a total of 24 significantly distinct DMM techniques of which three groups – Lime Cement Columns (Nordic countries), DJM Association (Japan), and Trevimix (Italy) constituted the three bona fide dry binder methods. Some other methods, e.g., SSM (Shallow Soil Mixing) occasionally utilize dry materials – but these are only sprinkled on the surface and are blended by a large-diameter mixing blade cycled up and down repeatedly.

This paper summarizes data from the FHWA studies (FHWA, 1999a and 1999b) as they pertain to the three methods, each representative of national practice. It is hoped that practitioners in other countries can build on this foundation and so add to the international pool of knowledge with the goal of establishing a more comprehensive review.

There has been a wealth of information generated by Nordic and Japanese specialists in the dry mixing method, and more is to come (e.g., reports from Swedish and Finnish national research projects). The authors trust that individual researchers will not feel slighted that their work may not have been granted appropriate profile in this broad overview: the activities of the true DMM specialists are acknowledged by their peers throughout the world.

2 HISTORICAL PERSPECTIVE

Table 1 provides a summary of the historical evolution of the dry DMM technologies. Outstanding milestones in the maturity of the 21 "wet" methods are also included (in bold) as perspective.

Table 1. Summary of historical evolution of the dry DMM techniques.

1954	Intrusion Prepakt Co. (United States) develops the Mixed in Place (MIP) Piling Technique (single auger), which sees only sporadic use in the United States.
1961	MIP already used under license for more than 300,000 lineal meters of piles in Japan for excavation support and groundwater control. Continued until early 1970s by the Seiko Kogyo Company, to be succeeded by diaphragm walls and DMM (SMW) technologies.
1967	The Port and Harbor Research Institute (PHRI, Ministry of Transportation, Japan) begins laboratory tests, using granular or powdered lime for treating soft marine soils (DLM). Research continues by Okumura, Terashi et al. through early 1970s to: (1) investigate lime-marine clay reaction, and (2) develop appropriate mixing equipment. Unconfined compressive strengths (UCS) of 0.1 to 1 MPa achieved. Early equipment (Mark I-IV) used on first marine trial near Hameda Airport.
1967	Laboratory and field research begins on Swedish Lime Column method for treating soft clays under embankments using unslaked lime (Kjeld Paus, Linden – Alimak AB, in cooperation with Swedish Geotechnical Institute (SGI), Euroc AB, and BPA Byggproduktion AB). This follows observations by Paus on fluid lime column installations in the United States.
1974	PHRI reports that the Deep Lime Mixing (DLM) method has commenced full-scale application in Japan. First applications in reclaimed soft clay at Chiba (June) with a Mark IV machine developed by Fudo Construction Co., Ltd. Applications elsewhere in Southeast Asia follow the same year. (Continues to be popular until 1978 – 21 jobs, including 2 marine applications, when CDM and DJM overtake.
1974	Intensive trials conducted with Lime Columns at Skå Edeby Airport, Sweden: basic tests and assessment of drainage action (columns 15 m long and 0.5 m in diameter).
1974	First detailed description of Lime Column method by Arrason et al. (Linden Alimak AB).
1974	First trial embankment using Swedish Lime Column method in soft clay in Finland (6 m high, 8 m long; using 500-mm-diameter lime cement columns).
1975	Swedish paper on Lime Columns (Broms and Boman), and Japanese paper on DLM (Okumura and Terashi) presented at same conference in Bangalore, India. Both countries had proceeded independently to this point. Limited technical exchanges occur thereafter.
1975	Following their research from 1973 to 1974, PHRI develops the forerunner of the Cement Deep Mixing (CDM) method using fluid cement grout and employing it for the first time in large-scale projects in soft marine soils offshore. (Originally similar methods include DCM, CMC (still in use from 1974), closely followed by DCCM, DECOM, DEMIC, etc., over the next five years).
1975	First commercial use of Lime Column method in Sweden for support of excavation, embankment stabilization, and shallow foundations near Stockholm (by Linden Alimak AB, as contractor and SGI as consultant/researcher).
1976	Public Works Research Institute (PWRI) Ministry of Construction, Japan, in conjunction with Japanese Construction Machine Research Institute begins research on the DJM method using dry powdered cement (or less commonly, quick-lime); first practical stage completed in late 1980. Representatives of PHRI also participate.
1977	First design handbook on Lime Columns (Broms and Boman) published by Swedish Geotechnical Institute (describes unslaked lime applications only).
1977	First practical use in Japan of CDM (marine and land uses).
1980	First commercial use in Japan of DJM, which quickly supersedes DLM thereafter (land-use only).
1981	Prof. Jim Mitchell presents general report at ICSMFE (Stockholm) on Lime and Lime-Cement Columns for treating plastic, cohesive soils, increasing international awareness.
Early 1980s	DJM Association established in Japan.
1983	Eggestad publishes state-of-the-art report in Helsinki dealing with new stabilizing agents for Lime Column method.
1985	First commercial use of Lime Column method in Finland.

Table 1. Summary of historical evolution of the dry DMM techniques (continued).

1985	SGI (Sweden) publishes 10-year progress review (Åhnberg and Holm).
Mid 1980s	First application of Lime Columns in Norway (under Swedish guidance).
1986	SMW Seiko Inc. commences operations in the United States under license from Japanese parent Seiko Kogyo Co. and thus introduces contemporary DMM to U.S. market.
1987	The Bachy Company in France develops "Colmix" in which mixing and compacting the cemented soil is achieved by reverse rotation of the multiple augers during withdrawal. Developed as a result of research sponsored by French national highways and railroads. Appears to be first European development outside Scandinavia.
1987 – 1989	SMW method used in massive, landmark ground treatment program for seismic retrofit at Jackson Lake Dam, WY.
1989	The Trevisani and Rodio Companies in Italy develop their own DMM version, starting with dry mix injection, but also developing a wet mix method.
1989	Start of exponential growth in use of Lime Cement Columns in Sweden.
1990	New mixing equipment developed in Finland using cement and lime (supplied and mixed separately): capable of creating columns greater than 20 m deep, 800 mm in diameter, through denser, surficial layers.
1990	Dr. Terashi, involved in development of DLM, CDM, and DJM since 1970 at Port and Harbor Research Institute, Japan, gives November lectures in Finland. Introduces more than 30 binders commercially available in Japan, some of which contain slag and gypsum as well as cement. Possibly leads to development of "secret reagents" in Nordic Countries thereafter.
1991	Bulgarian Academy of Sciences reports results of local soil-cement research.
1992	New design guide (STO-91) produced in Finland based on experience in 1980s and research by Kujala and Lahtinen (involving 3000 samples from 29 sites).
1993	DJM Association Research Institute publishes updated Design and Construction Manuals (in Japanese).
1994	DJM Association claims 1820 projects completed up to year's end (total volume of 12.6 million m^3).
Mid 1990s	First use of Lime Cement Columns in Poland (Stabilator Company).
1995	Finnish researchers Kukko and Ruohomäki report on intense laboratory research program to analyze factors affecting hardening reactions in stabilized clays. Discusses use of new binders (e.g., slag, pulverized flyash, etc.).
1995	Swedish government sets up new Swedish Deep Stabilization Research Center at SGI (1995 to 2000: $8 to 10 million budget): Svensk Djupstabilisering. Consortium includes owners, government, contractors, universities, consultants, and research organizations co-coordinated by Holm of SGI and Broms as "scientific leader." Research planned: creating an experience database; properties of stabilized soil; modeling of treated soil structures; quality assurance; and work performance. Results to be published in a series of reports.
1995	Finnish government sets up similar new research consortium lasting until 2001 for the ongoing Road Structures Research Programme (TPPT) to improve overall performance of road structures (similar to Swedish program members and scope).
1995	Swedish Geotechnical Society publishes new design guide for Lime and Lime Cement Columns (P. Carlsten) focusing on soft and semi-hard columns. English version released in 1996.
1995	From 1980 to 1996, about 15 million m^3 of DJM treatment reported in Japan.
1996	SGI (Sweden) publishes 21-year experience review.
1996	Conference on Deep Mixing held in Tokyo, Japan in May.
1996	First commercial use of Lime Cement Columns in the United States (Stabilator USA, Inc., New York)

Table 1. Summary of historical evolution of the dry DMM techniques (continued).

1996	More than 5 [illegible] lineal meters of Lime and Lime Cement Columns reportedly installed in Sweden since 1975. Annual production in Sweden and Finland now averages about the same output. Sweden's market is 2 to 3 times larger than Finland's, which in turn far exceeds Norway's.
1997	Major Lime Cement Column application for settlement reduction at I-15, Salt Lake City, UT (proposed by Stabilator USA, Inc.). Followed by seismic retrofit application in California.
1998	Raito, Inc. establishes office in California, offering various DMM technologies under license from Japan (including DJM, CDM, and Raito Soil Mixed Wall), and wins first project in California in early 1999.
1998	First Deep Mixing Short Course presented in the United States (University of Wisconsin – Milwaukee, August).
1998	Formation of Deep Mixing Subcommittee of Deep Foundations Institute during annual meeting in Seattle, WA, October.
1999	Publication of FHWA studies in U.S.
1999	International Conference on Dry Mix Methods held in Stockholm, Sweden, in October.

The authors hope that the enigma of the coincidences of Nordic and Japanese conception (1968 – 1974) can one day be rationalized, if indeed it was something other than coincidence born of common market necessities.

3 GENERIC CLASSIFICATION OF DMM TECHNIQUES

Based on the type of binder (wet or dry), the mechanism of blending (rotary or jet-assisted) and the vertical extent over which blending is accomplished (concurrently over a considerable vertical distance, or, only at the bottom of the mixing tool) the authors developed a generic classification of the 24 different DMM techniques of which they had knowledge. This classification is shown on Figure 1.

The concept of DMM continues to prove attractive to innovative engineers worldwide, and so it is fully anticipated that some of the individual techniques of Figure 1 will be superseded and/or replaced in rapid order. In this case, the progenitors of innovation are invited to challenge the authors as to the tenability of the current classification: in particular, some of those techniques currently identified as "experimental" may be expected to graduate into "fully operational" status, while others may simply disappear.

4 CHARACTERISTICS OF THE VARIOUS DRY METHODS

The three DRE methods, identified in the classification of Figure 1, are all in operational status, although, as described in Section 6 (below) their respective national markets vary presently in value, technique, and application. Table 2 provides *typical* parameters, bearing in mind that specific project requirements often demand atypical approaches. Full descriptions of each of these methods are provided in FHWA, 1999a.

5 GENERAL OBSERVATIONS ON DRY MIX METHODS

The technical goals of any DMM operation include providing a uniformly treated mass, with no lumps of unreacted binder or untreated soil, a uniform moisture content, and a certain target strength criterion. Equipment, methods and materials must therefore be selected or developed accordingly in order to satisfy these goals, given the nature and properties of the soils to be treated.

Thus the Japanese DJM techniques tend to favor large scale equipment and methods intended to give treated soil unconfined compressive strengths in excess of 0.5 MPa (far higher in sands) to depths of over 30 m, whereas Nordic goals are satisfied by smaller, lighter equipment and procedures giving design strengths rarely in excess of 0.2 MPa, even in soils containing high organic contents. Such columns may also be regarded as providing vertical drainage paths.

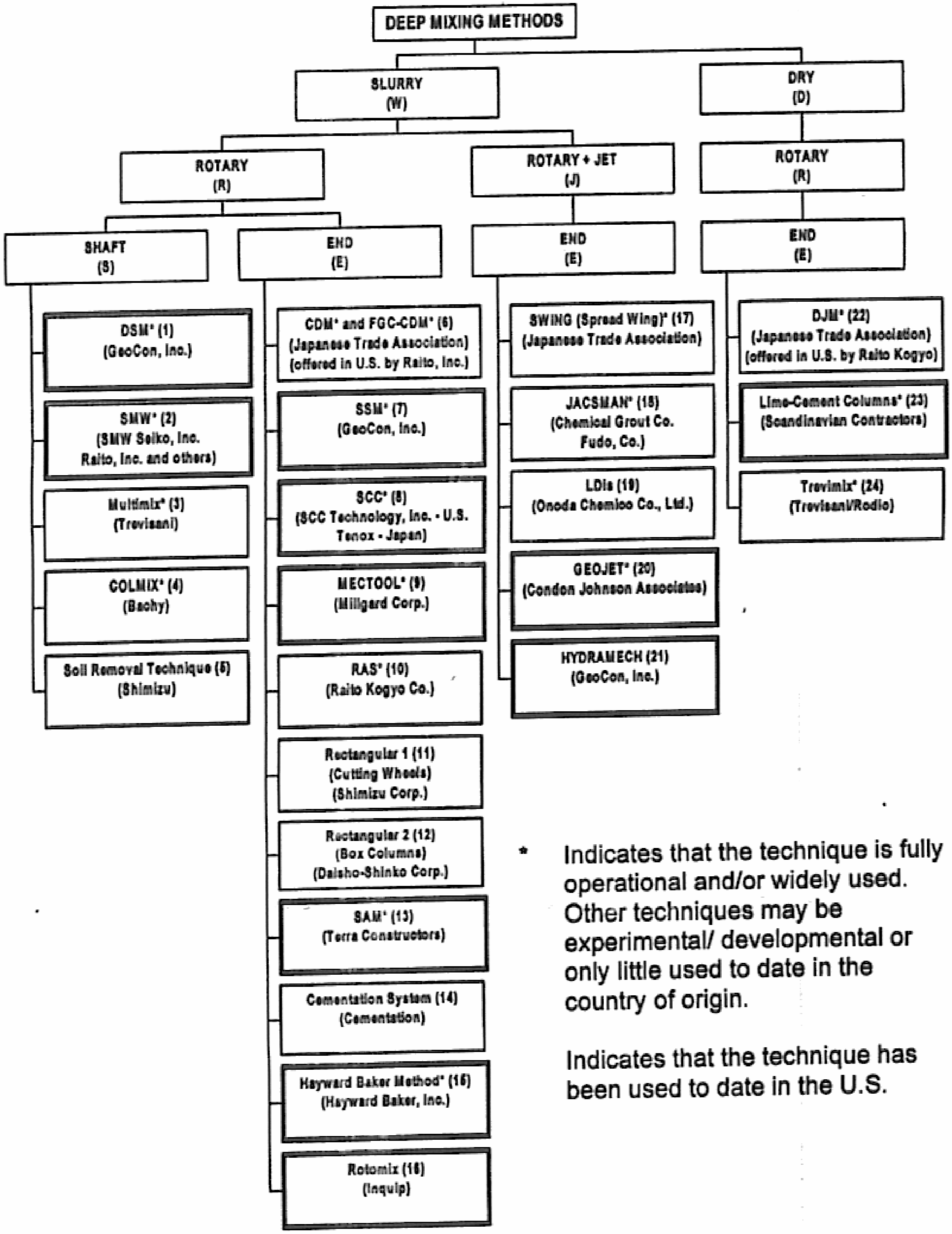

Figure 1. Classification of Deep Mixing Methods based on "binder" (Wet/Dry); penetration/mixing principle (Rotary/Jet); and location of mixing action (Shaft/End).

Table 2. Summary of mixing equipment and pertinent information for each dry DMM technique.

Name		Dry Jet Mixing	Lime Cement Columns
Classification		D-R-E	D-R-E
Company		DJM Association (64 companies)	Various (in Scandinavia/Far East). Stabilator alone in U.S.
Geography		Japan	Scandinavia, Far East, U.S.
General Description of Most Typical Method		Shafts are rotated while injecting compressed air from the lower blades to avoid clogging of jet nozzles. Dry materials are injected during withdrawal via compressed air, and with reverse rotation. Air vents to surface around the square section shafts.	Shaft is rotated while injecting compressed air below mixing tool to keep injection ports clear. Dry materials are injected during withdrawal via compressed air, and reverse rotation. Requires sufficient free water to hydrate binder, e.g., sand >15%; silt >20%; clay >35%.
Special Features / Patented Aspects		System is patented and protected by DJM Association. Two basic patents (blade design and electronic control system). Many supplementary patents.	Very low spoil. High productivity. Efficient mixing. No patents believed current. Strong reliance on computer control. Close involvement by SGI.
Details of Installation	Shafts	1-2 shafts adjustably spaced at 0.8 to ~1.5 m, each with 2-3 pairs of blades	Single shaft, various types of cutting/mixing blades.
	Diameter	1 m	0.5-1.2 m, typically 0.6 or 0.8 m
	Realistic maximum depth	33 m max.	30 m max. (20 m typical)
	RPM	24-32 during penetration. Twice as high during withdrawal.	100-200, usually 130-170
	Productivity/ output	0.5 m/min penetration; 3 m/min withdrawal. 35-45% lower in low-headroom conditions	2-3 m/min (penetration) 0.6-0.9 m/min (withdrawal) 400-1000 lin m/shift (0.6 m diameter)
Mix Design *(depends on soil type and strength requirements)*	Materials	Usually cement, but quicklime is used in clays of very high moisture content	Cement and lime in various percentages (typically 50:50 or 75:25)
	w/c ratio	NA*	NA*
	Cement factor (kg_{cement}/m^3_{soil})	100-400 kg/m^3 (sands and fine grained soil using cement); 200-600 kg/m^3 (peats and organics using cement); 50-300 kg/m^3 (soft marine clays using lime)	23-28 kg/m (0.6m diameter), typically 40 kg/m (0.8 m diameter); overall 20-60 kg/m i.e., 80-150 kg/m^3
	Volume ratio ($Vol_{grout}:Vol_{soil}$)	NA*	NA*
Reported Treated Soil Properties	U.C.S.	Greatly varies depending on soil and binder, 1-10 MPa	Varies, but typically 0.2-0.5 MPa (0.2-2 MPa possible). Shear strength 0.1-0.30 MPa (up to 1 MPa in field)
	k	"Higher than CDM permeabilities"	For lime columns, k = 1000 times higher than the k of the clay; for lime-cement columns, the factor is 400 to 500.
	E	E_{50} = 50 to 200 x U.C.S.	50 to 200 x U.C.S.
Specific Relative Advantages and Disadvantages		Heavy rotary heads remain at bottom of leads, improving mechanical stability of rigs, especially in soft conditions. Very little spoils; efficient mixing. Great deal of R&D experience. Fast production on large jobs.	Same as for DJM. Excellent Swedish/Finnish research continues.
Notes		Sponsored by Japanese Government and fully operational in 1980. (First application in 1981.) Offered in the U.S. by Raito, Inc. since 1998.	Developed by Swedish industry and Government, with first commercial applications in mid 1970s, and first U.S. application in 1996.
Representative References		DJM Brochure (1996); Fujita (1996); Yang et al., 1998	Holm (1994); Rathmeyer (1996)

*ND = No data; NA = Not applicable.

Table 2. Summary of mixing equipment and pertinent information for each dry DMM technique(continued).

Name		Trevimix
Classification		D-R-E
Company		TREVI, Italy
Geography		Italy, Eastern U.S., Far East
General Description of Most Typical Method		Soil structure disintegrated during penetration with air. Augers are then counter-rotated on withdrawal and dry materials are injected via compressed air through nozzles on shaft below mixing paddles. Binder can also be added during penetration.
Special Features / Patented Aspects		Use of "protection bell" at surface to minimize loss of vented dry binder. System is patented by Trevi and also used under license by Rodio. Needs soil with moisture content of 60-145+%, given relatively high cement factor and diameter.
Details of Installation	Shafts	1-2 (more common). Separated by fixed (but variable) distance of 1.5-3.5 m.
	Diameter	0.8-1.0 m (most common)
	Realistic maximum depth	30 m
	RPM	10-40
	Productivity/ output	0.4 m/min penetration 0.6 m/min withdrawal 139 m/8-h shift
Mix Design *(depends on soil type and strength requirements)*	Materials	Dry cement (most common), lime, max. grain size 5 mm
	w/c ratio	NA*
	Cement factor (kg_{cement}/m^3_{soil})	150-300 kg/m^3
	Volume ratio ($Vol_{grout}:Vol_{soil}$)	NA*
Reported Treated Soil Properties	U.C.S.	1.8-4.2 MPa (avg. 2.5 MPa)
	k	ND*
	E	1 to 2.66 x 10^3 MPa (clays) 3.125 x 10^3 MPa (sandy soils)
Specific Relative Advantages and Disadvantages		No spoil, uniform mixing, automatic control of binder quantity. System allows for "possibility of injecting water during penetration."
Notes		Developed by TREVI in Italy in late 1980s. Trevi-ICOS, U.S. licensee, in Boston, MA
Representative References		Pavianni and Pagotto, 1991; Pagliacci and Pagotto, 1994

ND = No data; NA = Not applicable.

Some authors (e.g., Pagliacci and Pagotto, 1994) note that wet DMM techniques are mechanically and logistically simpler to use, especially in "difficult" geographic locations. Such methods will use cement factors in the range of 100 to 500 kg/m^3, and volume ratios of over 50% which thereby generate large volumes of spoil containing waste slurry. Dry mix methods are applicable in soils with moisture contents (natural or induced) of over 60% and values of over 200% have been recorded. Cement factors range from 80 to 150 kg/m^3 (Scandinavia), to 150 to 300 kg/m^3 (Italy), to 100 to 500 kg/m^3 (Japan). Spoil, waste, and heave are typically negligible.

Regarding strength development, Figure 2 shows the benefit of dry cement over slurries and other dry materials. DJM Association (1996) claims that the rate of gain of strength for dry methods is faster than that of wet methods, in all soil types. Generally they find 28-day unconfined compressive strengths 1.5 times those at 7 days, while Stabilator (1997) report a factor of 2.5 times. Although higher cement factors are necessary in soils with higher moisture content and/or organic contents, little improvement may be found in soils with more than 1.5% humic content (Kujala et al., 1996).

6 OBSERVATIONS ON THE INTERNATIONAL DRY MIXING MARKET

United States

Excluding some simple surface mixing of dry materials into sludges for environmental purposes, the only dry mix method used is the Lime Cement Column method of Stabilator. Since 1996, several projects have been conducted in the New York and Salt Lake City areas, and in California. These have covered a wide range of applications, but principally settlement reduction and liquefaction mitigation. Most recently, American arms of foreign companies have been established, having the capacity to offer dry mix methods – Raito, Inc. (DJM) and Trevi-ICOS (Trevimix) – although no applications have so far been reported.

The annual U.S. market is probably around $5 million, or about 10 percent of the total DMM market value.

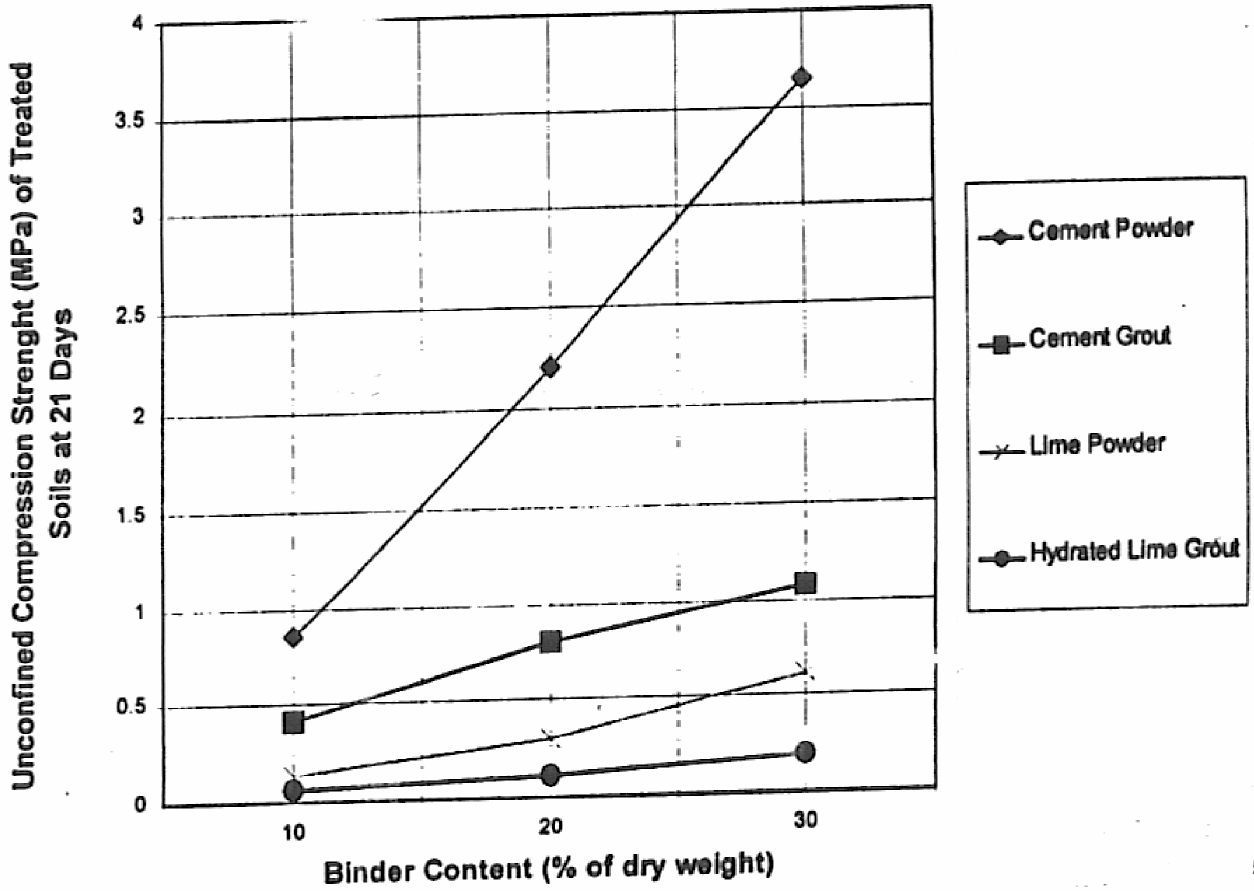

Figure 2. The effect of wet vs. dry binders on unconfined compressive strength of treated soils (Catalano, 1998).

Japan

Data recorded by the DJM Association (1996), which has 64 members, are shown in Figures 3 and 4. They report about 16 million cubic meters of soil treated from 1980 to 1996 in 2,345 separate projects, with an average annual volume of about 2 million cubic meters. There are about 60 to 70 rigs active. Soils to be treated are on average coarser and deeper than in Scandinavia, although the marine clays are highly plastic and the natural moisture content is at or above the liquid limit. Cement factors tend to be higher, especially in peats and organics (to provide higher strengths), but field data do tend to show a wider scatter than the Scandinavian information. Most applications are for slope stabilization and settlement control in both static and seismic scenarios.

The value of the Japanese DJM market annually is believed to be around $150 million.

Although CDM and SMW applications have been reported elsewhere in S.E. Asia, no DJM projects have been recorded outside of Japan in the literature seen by the authors to date, although such activity is highly likely.

Scandinavia

A wealth of data is available from Swedish and Finnish sources in particular (e.g., Figures 5 and 6). Annual outputs are very sensitive to national economic trends. As much as 90 percent of the applications are for settlement reduction and about 80 percent of the work is for roads and railways (Åhnberg et al., 1995). Other papers in this conference provide more details, but it would seem that there are four major Swedish contractors (owning about 20 machines), and they operate in many countries outside Sweden, including the U.K., the Baltic countries, U.S.A., and the Far East. Finland has three major competitors with a total of about 10 machines. Binder materials constitute 35 to 60 percent of installation costs, and this ratio varies between countries, depending on material availability and cost. Thus Swedish practice utilizes lime and cement exclusively, whereas the Finns are increasingly using alternative materials, often byproducts of the steel industry.

Data indicate Swedish output to be about 4 million lineal meters per year, with a further 1.5

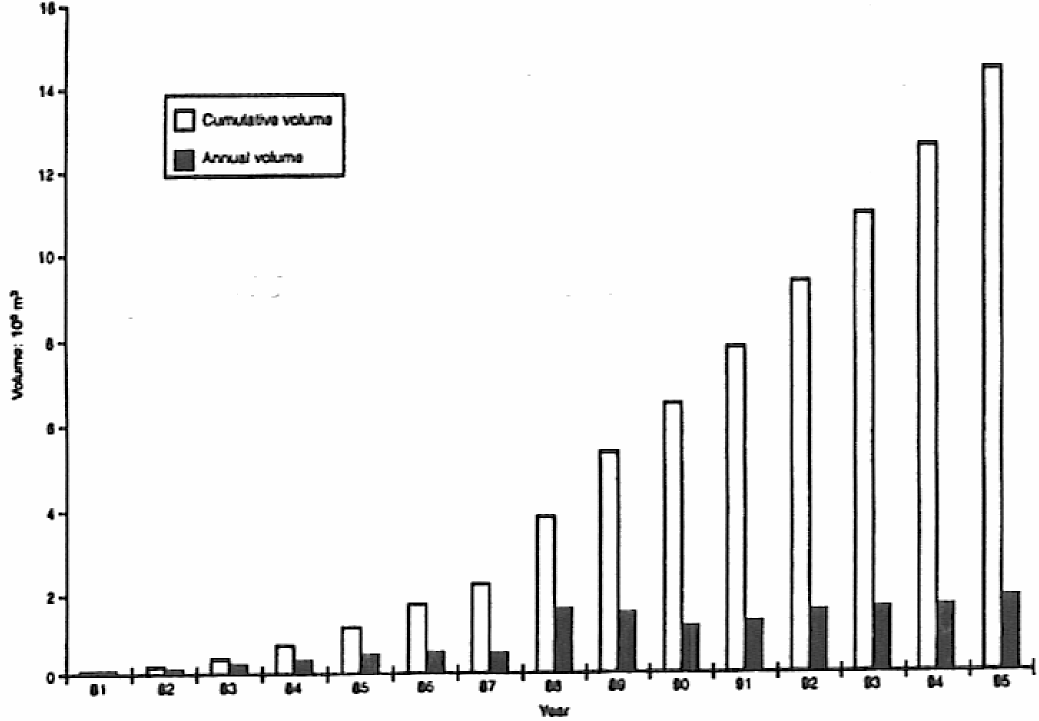

Figure 3. Volume of soils treated by the DJM method in Japan (1981-1995) (data from Okumura, 1996).

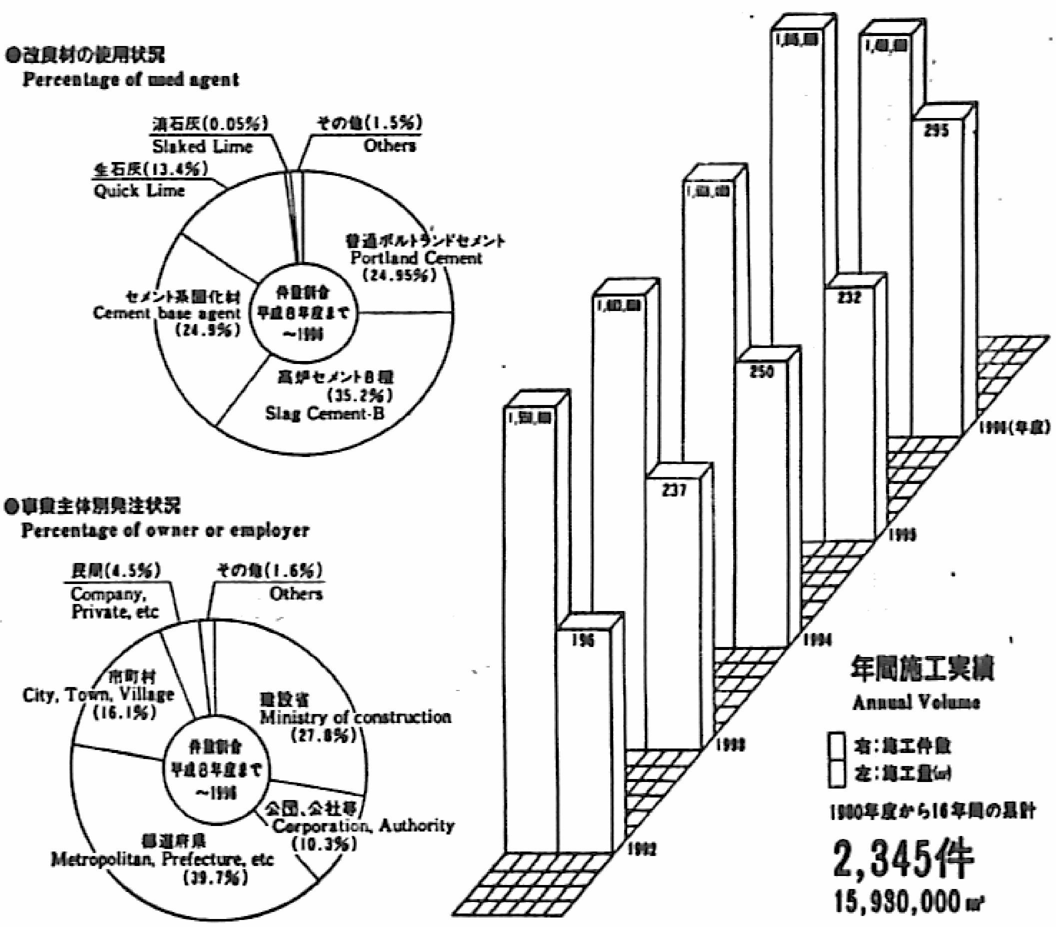

Figure 4. Data on DJM usage in Japan (1992-1996) (DJM, 1996).

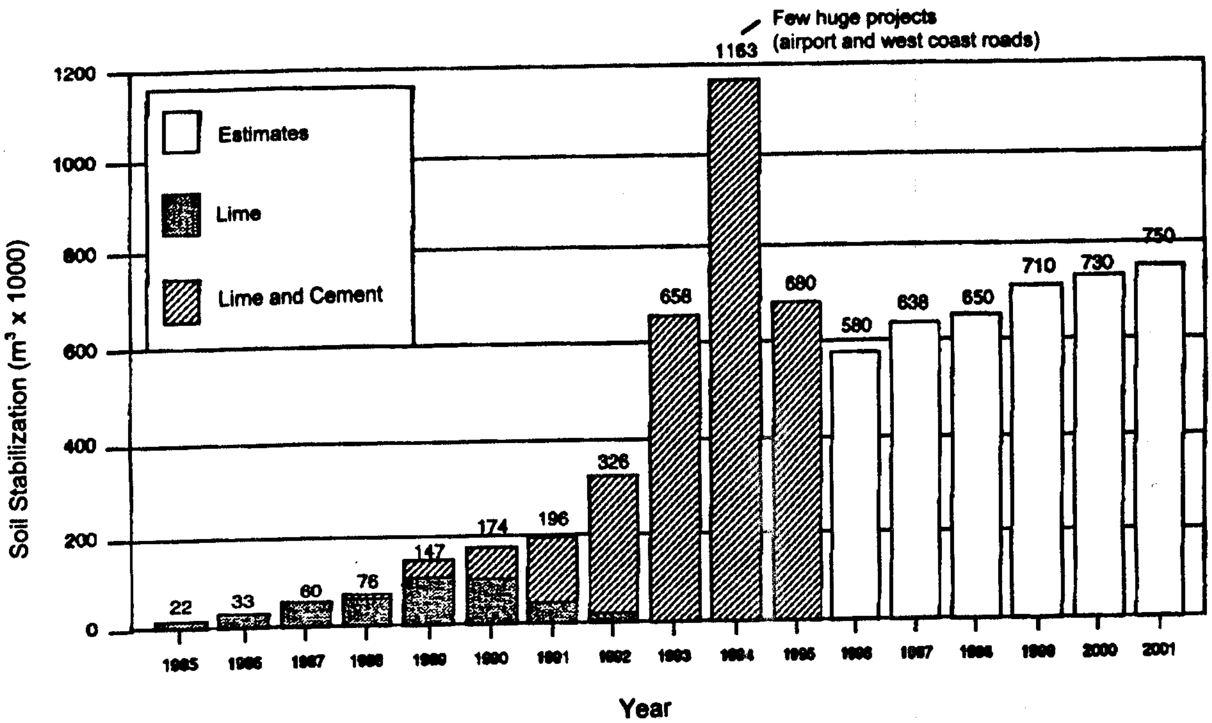

Figure 5. Details of Lime Cement Column production in Sweden (Finnish Technical Development Center, 1996).

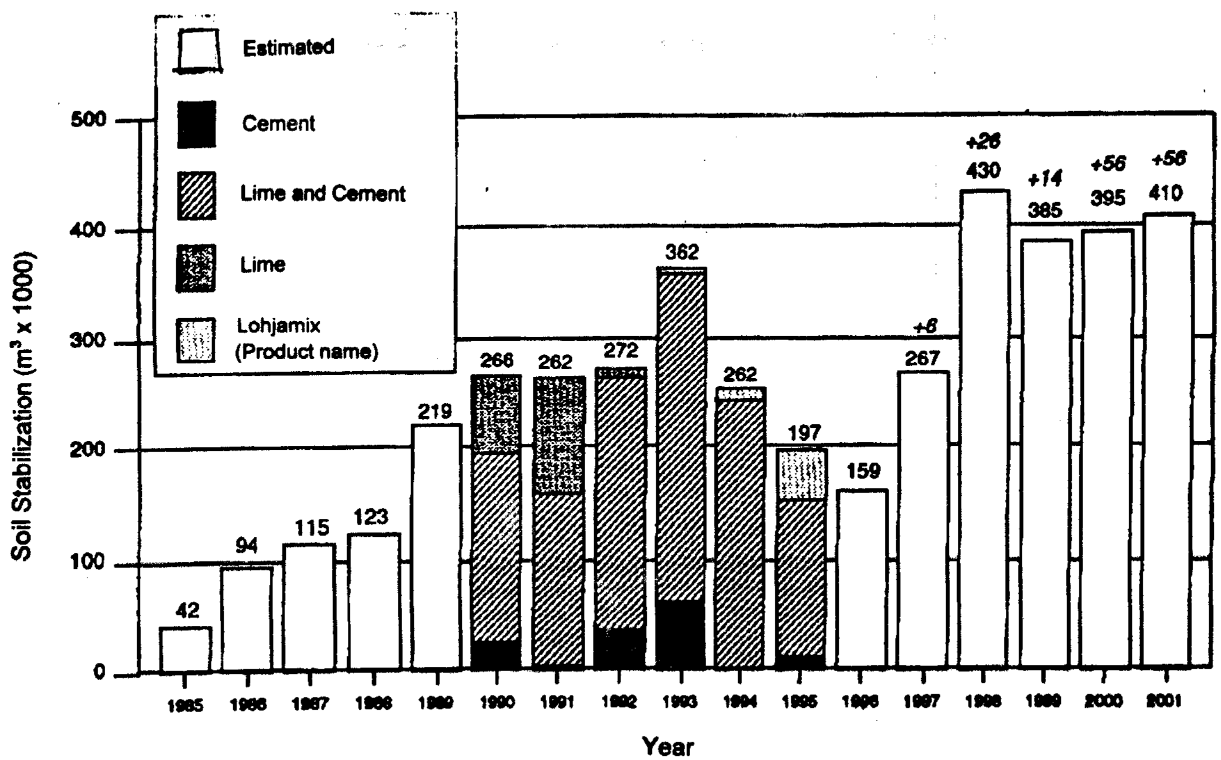

Figure 6. Details of Lime Cement Column production in Finland (Finnish Technical Development Center, 1996).

million lineal meters in Finland, and about a third of that in Norway. This may be worth about $45 to 60 million per year in total. As in Japan, intense research efforts, led by government agencies, but including all aspects of industry, continue to be made to better understand the execution, control, and performance of the techniques, and the properties of the treated soils.

Trevisani's late 1980's initiative saw a limited number of projects conducted by them in Italy and Thailand. Since then, however, very little, if any activity appears to have occurred, possibly due to the difficulties of the national economy and competition from other "more conventional" technologies.

7 FINAL REMARKS

The advantages of dry DMM methods are being exploited in three continents in a wide variety of soils and applications. Not surprisingly there are major differences between the various methods themselves, the most fundamental being the contrast between Nordic and Japanese practice. Research and development continue apace and increasingly large amounts of work are being conducted - a trend stretching back to the late 1980s. The authors have every reason to suggest that this growth pattern will continue.

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