MODIFIED DRY MIXING (MDM) – A NEW POSSIBILITY IN DEEP MIXING

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ABSTRACT

A Modified Dry Mixing (MDM) method has been developed. By an innovative modification to the existing dry mixing process and equipment, water can be injected into the soil during the installation process. By adjusting the water content of the soil, columns of significant strength can be produced even in various soils of very low water content, where the regular dry method normally could not be used. The MDM process also yields improvements in mixing efficiency resulting in more homogenous columns of high quality. During the development, a feasibility full-scale field test was performed showing promising results and improvements compared to the regular dry mixing method. This paper presents the possibilities of the MDM method and the field test results.

Modified Dry Mixing (MDM) - New Possibilities

The new technology, MDM (Modified Dry Mixing) has been developed based on initiatives by Johan Gunther and Benny Lindström at LCTechnology, LLC. Hercules Grundläggning AB has incorporated the technology on existing dry mixing equipment. The Swedish Geotechnical Institute (SGI) has performed laboratory tests and compiled data.

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The MDM technology is suited to a wide variety of soils and applications and can be used to:

1. Treat soils with insufficient water content for standard dry mixing to achieve proper hydration of the binder, i.e. install high strength columns in dense sandy and dry soils
2. Treat soils and/or soils with embedded layers too hard for standard dry mixing equipment to penetrate
3. Treat layered soil profiles comprising different relative density, consistency and moisture content
4. Create treated soil profiles with high homogeneity in cross section as well as vertically in the column
5. Create complete columns (to the surface) through the dry crust

The MDM method spans a large spectrum ranging from typical dry mixing applications to truly wet mix installations, using modified dry mixing equipment. The conversion from dry to wet system takes place seamlessly from station to station (one depth to another) throughout the installation of the column. Some further advantages are:

- No surface spoil created
- No mixing plant required
- Small and mobile equipment
- Can be installed in wet as well as dry soils with no downtime to reconfigure equipment

By utilizing dry mixing equipment with some modifications, a cost-effective deep mixing system is realized. The MDM method enables modification of the existing soil parameters in that the liquidity index and water content of the soils can be adjusted to better suit the installation, creating a custom tailored column. With these new capabilities, the MDM method will expand the market for dry mixing to a wider range of applications. The cost-effectiveness of the MDM method offers an attractive over-all economy for deep mixing projects.

Modified Dry Mixing (MDM) – The System

The MDM Process

In the MDM system, water, in addition to the binder, is added during the installation process. This affords control over the liquidity index (for clays) and water content (for sand) in the soils treated. By modifying the liquidity index in clay to a desired (even) level throughout the installation, i.e. raising the amount of available water, the sensitivity of the clay is increased, making mixing more efficient. An increase in water/binder (cement) ratio will decrease the strength of the mix but the increase in mixing efficiency results in a better, more homogeneous column. In dense sandy soils the addition of water enables penetration and provides the necessary water for hydration of the binder injected, resulting in columns of significant strength.

Liquidity index (LI) is the relative consistency (of the clay). It is defined as the difference between the natural water content (Wn) and plastic limit (PL) normalized with plasticity index (PI), (Wn-PL)/PI, Das, B.J. (1983). This index is modified (raised) using the MDM process thus increasing the sensitivity of the clay.

MDM Equipment

The MDM equipment consists of a specially equipped mixing tool and appropriate valves for water, in addition to a pump and control means for the water to be injected. Water and binder is fed through individual conduits to the mixing tool and is injected into the soil through separate nozzles to prevent clogging. An example of a mixing tool is shown in Figure 1.

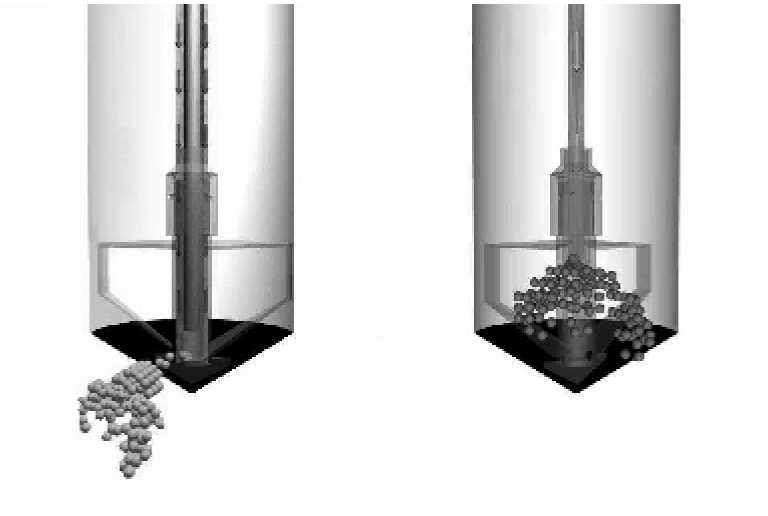

Figure 1. Principle of the MDM process. Example of mixing tool. (Left) A predetermined amount of water is added through conduits to alter liquidity index, water content or water/binder ratio. (Right) Binder is added through separate conduits, in amounts corresponding to modified amounts of available water.

Feasibility Study through Full Scale Field Tests

Full-scale field tests were performed in Bro and Tullinge, one clayey and one sandy site respectively. Both sites situated in the suburbs of Stockholm, Sweden. The Swedish contractor Hercules Grundläggning AB installed the MDM columns for the test. In Bro, the functionality of the equipment was evaluated. The test in Tullinge was a production trial run. The purpose of the latter test was to evaluate the application of the process and the products produced. The specially equipped mixing tool developed by LCTechnology, LLC replaced the standard dry mixing tool and a few modifications to the installation rig were made. Thirty days after the installation, the columns were tested. All columns were excavated to a depth of approximately 4.5

meters and visually inspected. Core sampling was performed on three of the columns at half the radius plus a complementary core in center of column A. Unconfined compression tests were conducted on the specimens. Permeability tests were also performed in conjunction with the coring process.

Description of Test Site - Tullinge

The Tullinge site was situated within a sand quarry of fluvial deposits. The soil profile, according to Swedish Weight Sounding, consisted of medium dense to dense, slightly silty sand. The sand was semi-dry and had occasional horizontal layers of fine silt. During excavation, a 0.5 meters layer of wet silt with minor constituents of fine sand was observed at 3.5 meters depth. Figure 2 shows the results of the Swedish Weight Sounding, Smoltczyk (2002). Based on the unit weight and friction angle of the sand, an estimation of the standard penetration number ranged from 25 to 50. Auger sampling indicates higher natural water content around 1.5 meters depth.

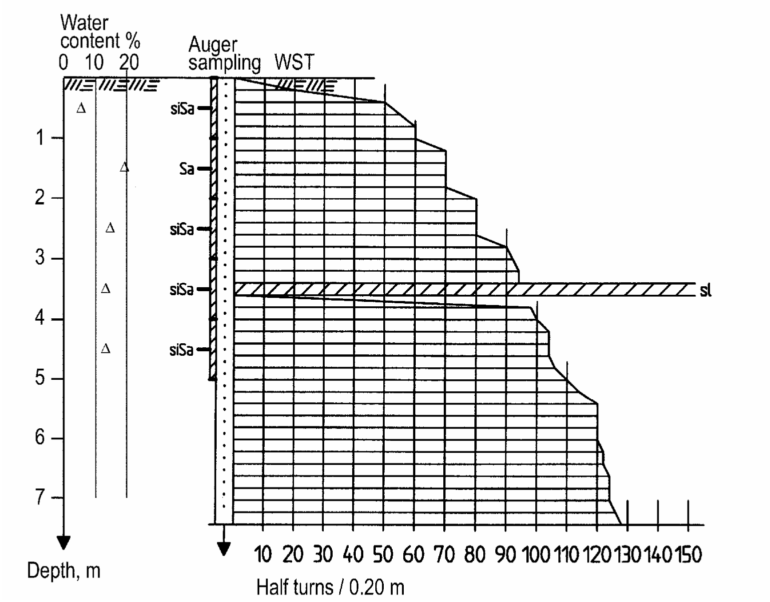

Figure 2. Swedish Weight Sounding test at Tullinge (lower plateau)

Installation - Tullinge

The Tullinge test site consisted of an upper and lower plateau. An initial installation was performed at the upper plateau comprising nine columns. The mixing tool used had a diameter of 820 mm. The initial rate of penetration was 150 mm/rev, but it produced an uneven descent. After some modifications the rate was set at 25 mm/rev. The rig was then moved to the lower plateau. As a reference, one trial installation of a standard dry mix column was performed. The same mixing tool and equipment was used but without the water. The tool became lodged a few meters down due to the resistance of the soil and retrieval was impossible without excavation. Four MDM columns were installed at the lower plateau ranging in depth from 5.0 to 9.3 meters. All columns were fully visible at the surface after installation. These MDM columns were produced with 100 % cement (CEM II/A-LL 42.5) at an amount of 450 kg/m^3. Water was added during penetration at a constant rate throughout the columns with some variations between columns. The resulting water/cement ratio ranged from 0.4 to 1.2. See Figure 3. Under the prevailing circumstances, the installation of a 7.5 meters deep column with 450 kg/m^3 of binder was completed in approximately seven minutes.

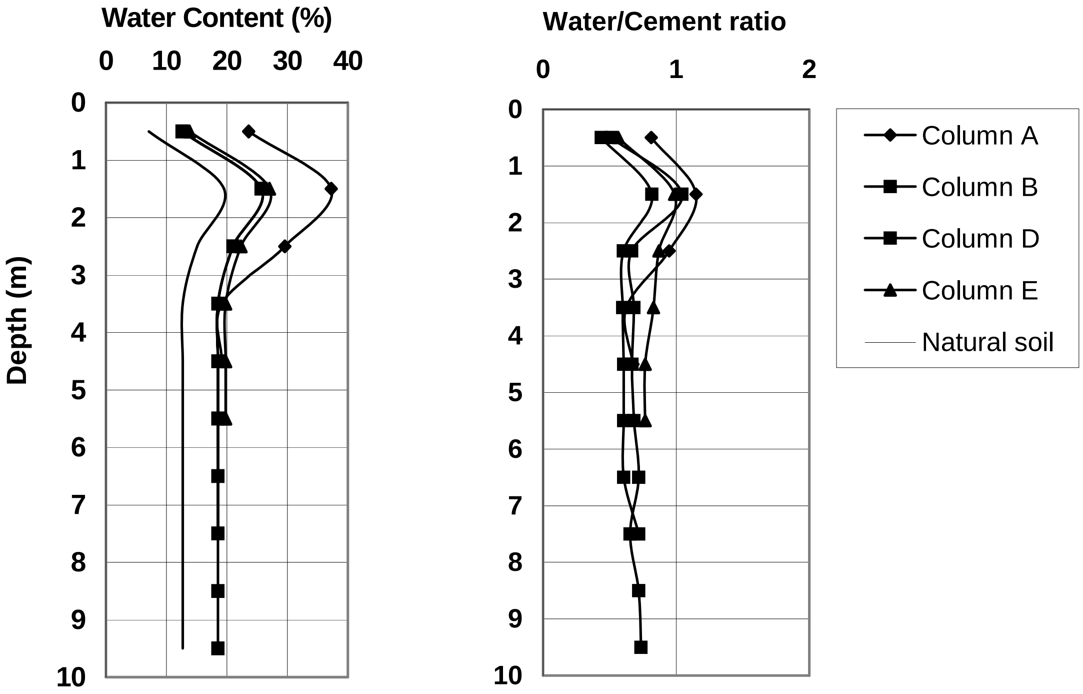

Figure 3. Water content and water/cement ratio for installed columns at the lower plateau

Visual Examination of Columns and Cores

Immediately after each column was installed, the diameter was measured at the surface to 0.5 meter down proving the columns to have a diameter of 0.85 meter and to be round.

After thirty days, excavations at both the upper and lower plateaus were completed to a depth of approximately 4.5 meters. All columns had a diameter of 0.03 meter greater than the mixing tool and appeared to be even and solid from the surface to the bottom of the excavation. However, in the silt layer prevailing in the location of the lower plateau, most likely very local and not detected by the soil investigation, the columns had an increased diameter of 0.1 - 0.3 meter. This is not fully explained, but is probably due to a combination of factors, including ground water pressure and variations of the soil permeability. At the lower plateau the mixed material at the exposed surface of the columns appeared like freshly poured concrete of a uniform consistency. At the upper plateau, with a higher rate of descent during installation, the centers of the columns were wetter than the edges. Excavated columns at the lower plateau are shown in Figure 4.

Figure 4. (Left) “Live load” test at Tullinge site. (Right) Cross-section of MDM column, lower plateau.

Visual inspection of the cores indicated an even mixing of the binder with the soil. Small voids, fairly uniformly distributed, could be observed in some parts of the cores. Their presence was probably due to the air injection of the binder. Nevertheless, high strength was obtained.

Figure 5. (Left) Coring: lower plateau, Tullinge. (Right) Box with core from column B.

Tests and Test Results

Tullinge Field Test

Coring in three columns (A, B, and E) was performed at half the radius. In column A, a complementary coring at centre was performed. During coring, water was used as a cooling agent and the core recovery was approximately 100 percent. Specimens were taken from the cores for unconfined compression tests in the laboratory.

The unconfined compression strength and the elastic modulus evaluated from the compression tests are presented in Figures 6 and 7. The tests were performed 40 to 80 days after installation of the columns. The unit weight of the core specimens was approximately 20 kN/m³ (127 pcf) while the unit weight of the untreated sand was about 18 kN/m³ (115 pcf). Samples to measure the calciumoxide (CaO) content were taken in order to study the distribution of binder across, and vertically in the column. The results are presented in Figures 8 and 9. The distribution of the binder, examined as the calciumoxide content indicate only a small variation in cross-section. However, it should be stressed that the content is derived from very small samples, and of insufficient numbers for reliable conclusions.

Constant head permeability tests with single side top packers were performed during coring in the shaft of column B. The shaft was tested twice, first from ground surface to 3 meters depth and then from 3 meters to the bottom at 6.5 meters. At the equipment's maximum pressure of 4 bar (58 psi), no water flow was registered in the first test. In the second test, a flow of 0.8 liters/min. at 4 bar was observed, resulting in a permeability of approximately 10^{-7} m/s. Based on sieve curves, permeability of the virgin soil can be assumed to be 10^{-3} to 10^{-5} m/s.

The test results show that high strength can be achieved by the MDM method when installed in semi dry sandy soils. In column B, three out of eight specimens had such a high strength that they could not be loaded to failure, due to the limitations of the loading equipment. (Maximum capacity was 11.5 MPa (1700 psi).)

The E-modulus of the tested specimens varied between 700 to 4000 MPa (102000 to 580000 psi). The majority of all tested specimens had an E-modulus from 1200 to 2400 MPa (145000 to 290000 psi). The E-modulus over compressive strength ratios was approximately 200. The modulus used herein is the E_{50}-modulus, which is the secant modulus derived at 50 percent of the maximum deviator stress.

It should be noted that these "sand" columns were installed with a standard tool developed for clay installations. A purpose designed tool for drier/harder soil conditions will likely reduce the variations in strength seen in areas of these initial test columns. No "double packing" was performed at the bottom of the columns and while this task slows the production rate somewhat it also brings up the strength in the very beginning of the column making for more uniform strength throughout.

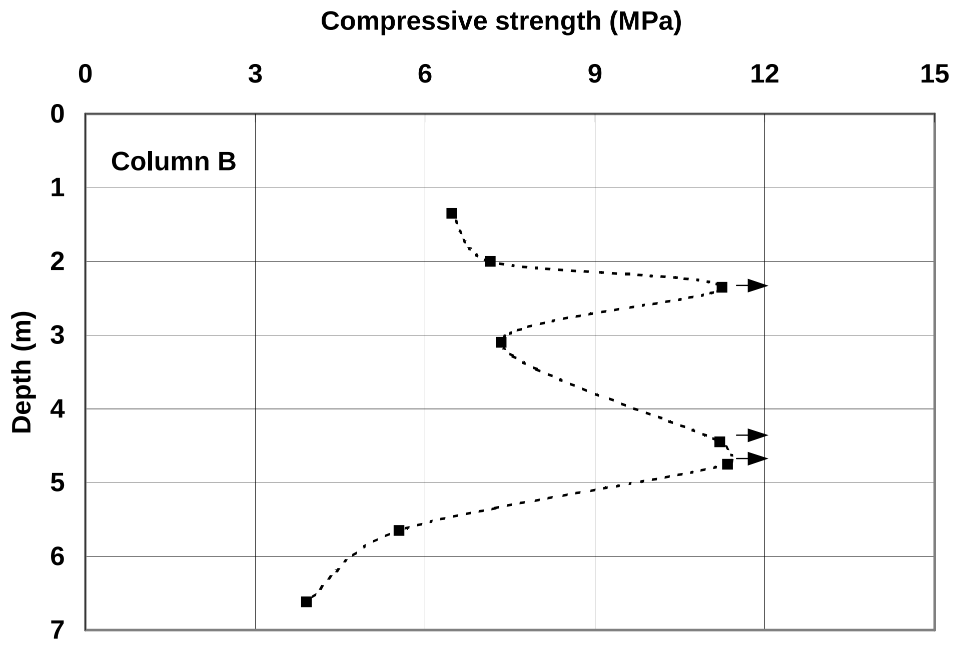

Figure. 6 Unconfined compressive strength in MDM column B, Tullinge.

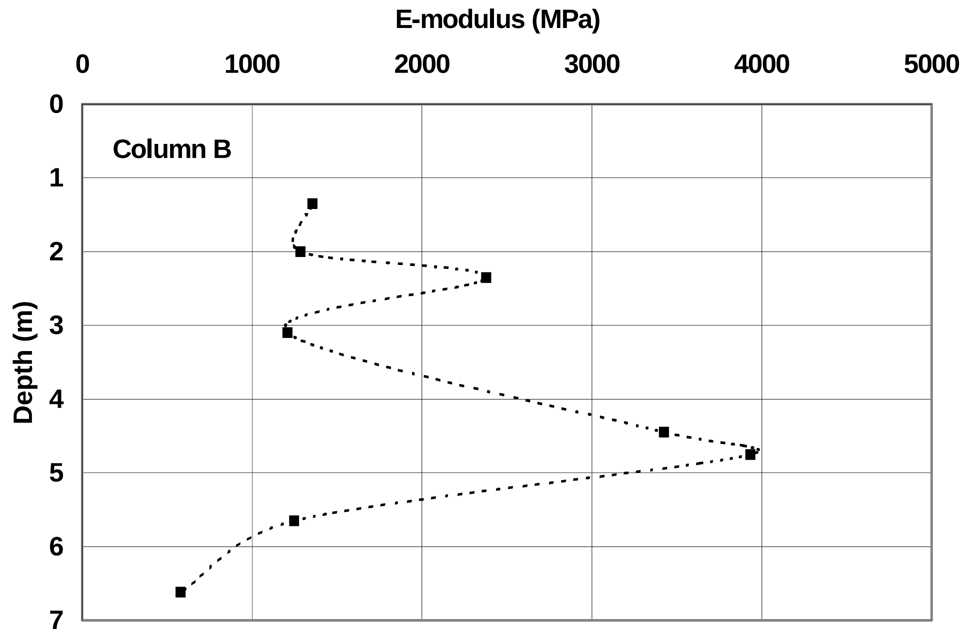

Figure 7. E50-modulus in MDM column B, Tullinge.

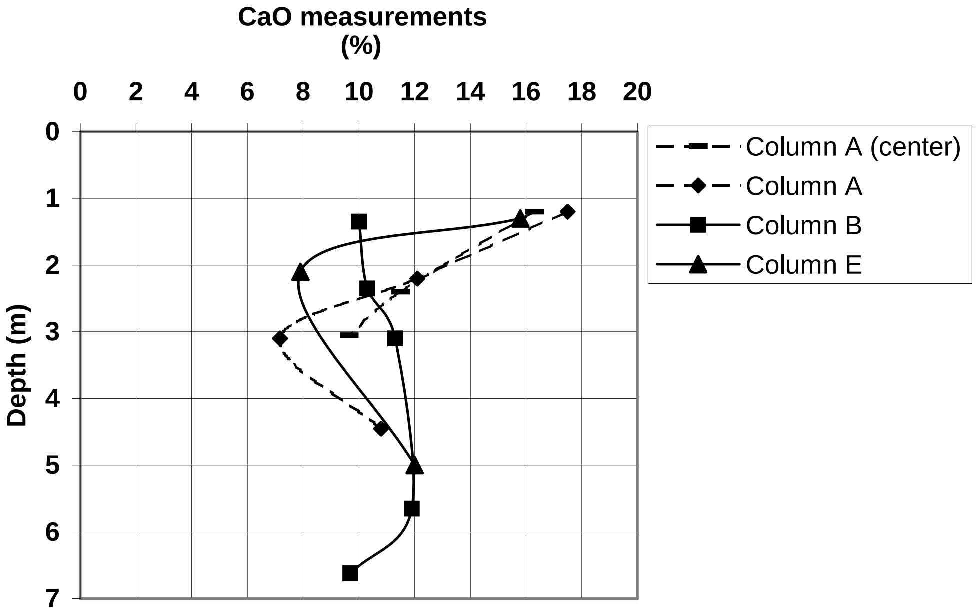

Figure 8. Calciumoxide content as a percentage of dry weight material for MDM columns in Tullinge.

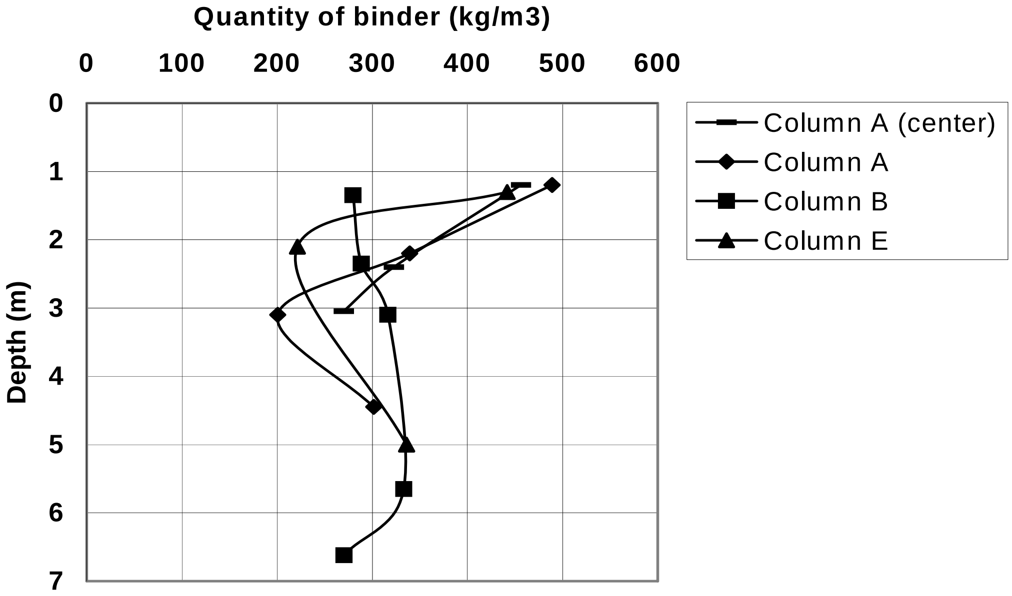

Figure 9. Evaluated binder content per cubic meter of treated soil for MDM columns in Tullinge.

Additional Comments Regarding Bro

At this site, the soil consisted of normally consolidated soft clay to a depth of 10.5 meter, with a dry crust approximately 2 meters thickness, overlaying the clay. Atterberg limits at a depth of 2.5 and 4 meters were PI 25%, PL 36% with shear strength of 19 kpa and PI 35%, PL 50% and 18 kpa respectively. The natural liquidity index ranged from –0.5 to 1.1. This was modified in increments from 0.1 to 3.5, showing the variation capacity of the equipment. The MDM columns were created all the way through the dry crust to the surface. No dry binder was spread into the air. A number of columns were excavated and comparing the mixing efficiency of MDM versus dry mixing, the MDM appears to be more even. The dry mixing columns showed streaks of cement, which the MDM columns were lacking. In comparison, material feed for the MDM columns was smoother than for their dry mixing counterparts. The dry mixing method encountered clogging problems whereas the MDM experienced none.

Conclusions

The full-scale field test conducted at the Tullinge test site with sand and silt has verified that

- The MDM method can produce high quality/strength columns in sandy soils with insufficient natural water content for proper hydration of the binder
- The MDM columns achieved high strengths and high E-modulus
- The MDM columns had low permeability
- By adding water during the process, the MDM equipment can penetrate soils not penetrable by ordinary dry mixing equipment

The initial testing of the equipment itself at Bro proved that the MDM method can produce columns all the way through the dry crust to ground surface without any (dry) binder spread into the air, nor any spoil deposited on the surface.

The overall project cost can be reduced using the MDM process compared to soil improvement performed with standard dry mixing.

Reference

Smoltczyk, U., (2002) "Geotechnical Engineering Handbook" Volume 1: Fundamentals, Böblingen, Germany, pages 93-96.

Das, B.J. (1983). Advanced soil mechanics, Hemisphere Publishing Co., Washington.