A Review on Deep mixing method for soil improvement

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Abstract. Deep mixing method, the ideal choice that can be used to treat problems arising from the presence of soft clay soil as a basis for constructing a specific structure. Soft clay soil covers large areas in some countries around the world, making it difficult to find suitable places for construction. Soft clay soil which has a high moisture content that makes it with small shear resistance and high settlement capability is not suitable as a bearing layer under the foundations of the facilities. Therefore, the need arose to either the use of a certain type of foundation, such as deep foundations which are more complicated compared to the second option, or the use a specific treatment technique to improve the properties of the soft clay soil and make it suitable for the construction with the using of a certain type of foundations other than deep foundations. One of the most suitable treatment techniques for soft clay soils in terms of structural purpose, cost and time is the deep mixing process. Deep soil mixing is a complex process in terms of factors that affect the improved soil quality and the processes that causing the improvement. This process has been covered in a lot of books and published researches in many of its aspects, but there is some of that relates to this process has not been significantly highlighted such as improved soil permanence over time, which causes a poor understanding of the behavior of improved soil after the improvement process. In this research paper, everything related to the deep mixing process will be touch upon, starting with the historical development of this process, its beginnings to its types, classifications and applications, and the accompanying chemical and physical processes, in addition to a literary review for what related to this process.

1. Introduction
Soil improvement is an important and large part of soil mechanics and geotechnical engineering, where it includes a wide range of techniques and methods that can be used to address most of the problems that may be encountered when dealing with soil as a structural material. The fact that the market for soil improvement has developed and increased over the past few decades cannot be underestimated, new methods, tools and procedures have been developed and used practically in the field. There is a lot of soil treatment and improvement techniques, many of them are mainly used to treat clay soils as they are structurally weak soils. Clay is a practically important material for geotechnical engineering practices, as it is frequently handled in the field. In general, this type of soil is considered one of the worst problematic soils due to its small shear strength, large compressibility, and great susceptibility to volumetric change. Therefore, it is necessary to treat clay soils before using it for engineering purposes. When one of the soil improvement techniques is used, it causes an improvement by reducing soil plasticity and swelling potential, increasing strength and workability, and thus improving soil stability. Clay is a type of fine soil; clay minerals are very effective electromechanically so they have a great effect on the soil in its microstructure level. In the next section, clay soil will be briefly dealt with, as it is the material that many
methods and techniques have been developed in order to improve it, followed by the deep mixing technique that is most effective in treating this type of soil in several applications.

2. Short view on clay mineral

In general, minerals are naturally inorganic compounds that possess specific physical, chemical, and crystalline properties. These minerals can be classified into primary and secondary, crystalline and non-crystalline, silicate and non-silicate. When rocks are exposed to erosion factors (physical, chemical, biological), the primary minerals that making it up will experience structural and chemical changes. Also, these factors cause a redistribution of the major and minor minerals within the soil profile. Soil minerals can be classified under two main headings, the primary minerals (chemically unaltered) and the secondary minerals (chemically altered). Primary soil minerals are the minerals that have not undergone structural or chemical transformations since their crystallization within the rocks that form it, whether igneous, metamorphic or sedimentary, and are found in sandy and course silty soils. The most common primary soil minerals are silicates, iron oxides (Fe), zircon (Zr), titanium (Ti) and phosphates (P). Secondary minerals are the minerals that are formed by the breaking down or/and transformation of the primary minerals under certain conditions and are found in clay and fine-silt soils. Secondary minerals that exist in soils include alumino-silicates, oxides and hydroxides, carbonates, sulfates, and amorphous minerals [1]. Silicate is the main mineral for most types of soils, they are a product of the weathering processes on the primary minerals which is why the clay minerals are called secondary silicates. Other major soil minerals are sulphides, oxides, hydroxides, halides, sulfates, carbonates and phosphates. The clay minerals are present in a very small size (<0.002 mm) compared to other sizes of other soil components; It is very effective electromechanically because it has a negative charge on its edges and a positive charge on its surface, and this is what distinguishes it from the rest of the components of soils (gravel, sand and silt). Clay minerals are formed from two main structures, the first is the silica oxygen and it results from the bonding of silicon ions with the oxygen atoms from four sides (tetrahedral). As for the second, it results from the bonding of aluminum and magnesium ions from eight sides with oxygen and hydroxide ions (octahedron). All clay minerals are composed of tetrahedra and octahedral plates with specific types of cations that are linked with each other by a certain system, any changes in the structure of the tetrahedral and octahedral sheets result in different clay minerals, [2][3][4]. The most common groups of clay minerals include kaolinite, illite and smectite (montmorillonite). Kaolinite, consisting of alumina and silica sheets, which are linked by very strong bonds and this is what makes this type of clay very stable, figure (1a). Illite, consists of three plates, two silica plates and one alumina plate, it has potassium ions between every two plates and this is what makes it stronger than montmorillonite, figure (1b). Montmorillonite, this type is similar in terms of composition to illite, as it consists of two plates of silica and one of alumina, and due to the weak bonds between these plates, large quantities of water can easily enter within the structure of this type, causing the of the swelling phenomenon, figure(1c) [5].
3. How clay minerals affect soil behavior

Many clays feature greatly affect the properties of the soils that contain it and govern its behavior to a large extent - even if their percentage is less than the rest of the other soil components - like strength, settlement, swelling, and hydraulic conduction. These features include isomorph substitution and surface anion and cation exchange capacity. It can be said that these features control the ability of the soil to interfere with water (the ability to absorb and retain water or excrete it outside the soil body); these details, in particular, give clay its dominance over the behavior of the soil. The presence of water is the cause of many problems encountered in geotechnical engineering practices and this is what was expressed by Karl Terzaghi in 1939, “…In engineering practice, difficulties with soils are almost exclusively due not to soils themselves but water contained in their voids. On a planet without any water, there would have been no need for Soil Mechanics.” but this effect remains to depend on climatic conditions, the topography of the region, and the environment for soil genesis. The structural composition of the clay minerals that make up clay soil takes certain shapes and forms and has a certain degree of electromechanical stability. Any change in this structure such as changing the locations of the tetrahedral and octahedral with other atoms naturally present in the soil environment causes the instability of the electrical load of the particles of these minerals, which leads to a great affinity for water, and that at the molecular and atomic level of the soil. While at the level of the soil body as a whole, these processes lead to an increase in the plasticity of the soil, which in turn affects the structural properties of the soil, and thus the physical behavior of the soil depends to a large degree on the chemical behavior of individual clay mineral particles. The composition of the soil, physically and chemically, can be examined accurately through several tests, the most important of which is an X-ray diffractometer (XRD) and a scanning electron microscope (SEM). [7][8][4][6][9].
4. Methods for soft soil improvement

From an engineering point of view, the term weak soil includes several types of soils, which are soft clay soil - the soil that retains large quantities of water within its structure -, the soil that contains large amounts of fine particles such as silty soil, organic (peat) soil and loose sandy soil near or below water level. For the soft clay soil, its softness is evaluated by the undrained shear strength $S_u$ or unconfined compressive strength $q$, and the spt test is used to evaluate its consistency and density. In order to improve and strengthen the engineering properties of this type of soil to prepare it for construction purposes, many methods have been developed for decades and a lot of researches and books have been published on this topic. Soil improvement techniques aim to improve some of the properties that make the soil weak and unsuitable for construction. Therefore, with regard to clay soil, the goal of improvement is to increase shear strength, reduce or eliminate settlement, and reduce permeability. (Kamon and Bergado 1991) presented Table 1 to help in selecting the appropriate method for treating the soft ground according to soil type and the duration required to accomplish the improvement process and the changes that the improvement method causes to the soil state. According to what is shown and can be deduced from Table 1, soil improvement techniques can be classified into two main classes that include most of the available techniques which are currently used for improvement. The first class includes techniques that mainly deal with the soil without any addition, such as dewatering and compaction. As for the second class, it includes techniques that depend on adding some materials (chemical and physical materials) to the soil in order to improve it [10].

Table 1. Applicability of Ground Improvement for Different Soil Types (Kamon and Bergado, 1991)

| Improvement Mechanism | Reinforcement | Admixtures or grouting | Compaction | Dewatering |
|-----------------------|---------------|------------------------|------------|------------|
| Improving period      |               |                        |            |            |
| Organic soil          | Depending on the life of the inclusion | Relatively short-term | Long-xterm | Long-term |
| Volcanic clay soil    |               |                        |            |            |
| Highly plastic soil   |               |                        |            |            |
| Lowly plastic soil    |               |                        |            |            |
| Silty soil            |               |                        |            |            |
| Sandy soil            |               |                        |            |            |
| Gravel soil           |               |                        |            |            |
| Improved state of     | Interaction between soil and inclusion (No change in soil state) | Cementation (change in soil state) | High density by decreasing void ratio (change in soil state) | High density by decreasing void ratio (change in soil state) |
In general, for the soft cohesive soil in the deep layers, several methods are applicable for the aim of improvement, the first of which is reinforcement (i.e. stone columns pile), the second is the admixtures (i.e. The deep mixing method), and the third is the dewatering (i.e. vertical drains). As for the loose sandy soils, many of the deep compaction methods are available such as dynamic and resonance compaction and vibroflotation. For both soft and loose soils in Superficial layers, several treating methods are available, the most important of which is soil reinforcement or (MSE) mechanically stabilized earth and the use of lightweight synthetic materials. Figures 2 and 3 illustrate a good and nice way to choose the appropriate method for improving soft clay for both shallow and deep foundation respectively depending on answering some questions regarding the soil condition of the construction site, the time available for the improvement process, the cost, and the preferred improvement approach. [10][11][54]

Figure 2. Selection Flow of Deep Ground Improvement Technique (Karnon and Bergado, 1991)
INDEX
SGI: shallow ground improvement
RSS: do you replaced the soft soil?
IPSS: do you improve properties of soft soil
BRM: blasting replacement method
C’: cement and/or lime stabilization method
USM: do you use special materials?
RS: do you reinforce the soils?   L: is it light?
MRM: mechanically replacement method G”: geotextile – sheet net and/or grid reinforcing method
RCM: roller compacted method
Pm: pre-mixed soil method
LWF: light weight fill method
B: do you use blast?

Figure 3. Selection Flow of Shallow Ground Improvement Technique (Karnon and Bergado, 1991)
Kempfert and Gebreselassie (2006) also report a flow chart illustrates a classification for improvement methods that used for soft clay soil, figure 4. In this paper, only appropriate soil improvement techniques used to improve soft clay soils will be covered. The most important and effective methods for improving soft clay soil are replacement and geosynthetic reinforcement for shallow stabilization, lime and/or cement mixing method for both deep and shallow stabilization, preloading, sand drains and preloading, stone or gravel columns for deep stabilization [12].

![Soil Improvement and Stabilization Methods Diagram]

**Figure 4. Soil improvement techniques classification (after Kempfert and Gebreselassie 2006)**

### 4.1 Soil Replacement

This technique is considered one of the easiest methods for treating soft clay soil, as it is characterized by the short implementation time and the low cost compared to other types of treatment methods. This technique includes removing the weak soil to a specific depth determined depending on the type of structure and its loads, i.e. the affected depth under the foundation and replacing it with another material that is more suitable to bear the load of the structure, usually granular materials are used for this purpose. Among the most important defects of this method are the difficulty of disposing of the removed materials and the cost required for that, and the difficulty or inability to implement this method in the case of presence buildings adjacent to the worksite and the fear of the Consequences of removing parts from the retaining or bearing layers of its foundations except by providing support for it and this considered an additional cost. Usually, the entire depth of the layer that affected by the transferred loads is removed or removing only the depth that suffering from great stress which is out of its bearing ability and keeping the other part within the affected depth which they reached stresses percent considered within its bearing ability [13][14][15].
4.2 Preloading / Pre-compression technique with / without Vertical Drains

When soft clay soils are of very large potential compressibility and have a limited depth below the surface then one of the most recommended methods for improvement in this case is preloading or pre-compression method, figure 5, especially if the loads expected from the facility are very large. The use of this technique reduces or eliminates the expected settlement after construction by accelerating its occurrence before construction, this can be done by applying the same expected structure's load or a part of it according to the desired settlement percentage to be reached before the start of the construction process and that is due to reducing the voids ratio and increasing the density which causes an increase in the shear strength. This technique is suitable for soft clay soils with normally or slightly over consolidation where the time and load required completing the process is relatively short and small respectively. Loads are applied using sand, gravel, or water or oil tanks. The used material's height needed to provide the required load to reach the required settlement within a specific time is determined depending on the desired settlement percent and the required time for that, soil permeability coefficient and the density of the used material. Sometimes the needed period to reach the required results is a little long and does not correspond to the time specified for that within the project schedule; the reason for this is the low permeability coefficient of the soil and the long drainage path. Usually, in this case, a specific drainage system is adopted to increase the speed of water exiting from the soil body and that by reducing the length of the drainage path, and so, reducing the needed time to achieve the desired settlement percent, this is what is called the vertical drain. The most popular and efficient vertical drain system that can be trusted in this aspect is the sand and wick (Prefabricated) drains Figures 6 and 7. The basic concept of these techniques is when the soft clay soil is loaded, this leads to an increase in the pore water pressure, the work of the vertical drain causes a reduction in this generated pressure resulting in a movement of the water from all parts of the soil body towards these drains and then it's exiting out of the soil body through certain systems that can be used for this purpose [17] [18] [19] [20].
4.3 Soil reinforcement by geotextile

Geosynthetic was defined by the American society for testing and material ASTM as “A planar product manufactured from polymeric material used with soil, rock, earth or other geotechnical engineering related materials as an integral part of a man-made project structure or system”. This term can also be used to refer to all manufactured synthetics material (usually polymeric once) that are used for the various purposes of geotechnical engineering which may be include drainage, reinforcement, and lightweight fill. Geosynthetic materials include many varieties and types developed by researchers and companies, but they all perform roughly the same function and these types are Geotextiles, Geogrids, Geonets, Geomembranes, Geocomposites, Geosynthetic clay liners (GCLs), Geopipes, Geocells and Geofoams. These materials are often used to treat many conditions through the action of reinforcing Tension parts, confining, lateral, support against spreading and separation, strain reduction, distributing loads over a specific area It is mainly used to increase the shear strength and bearing capacity of the soil under facilities, especially the roads, figure (8). ([14] [15] [21] [22] [23] [24] [25]
4.4 Stone Columns or Granular Piles

The term granular columns include columns composed of sand and/or gravel and crushed stone, i.e. material with a specific particle size that makes it porous, but it does not include cementous like-column element i.e. deep mixing method production or cemented stone column. One of the effective methods for treating soft clay soils with undrained shear strength $cu > 15$ Kpa (as it does not have the lateral support ability) is the granular columns. It also can be used for the improvement of the soft soil with $cu < 15$ kpa by using geosynthetic material as a casing (Geosynthetic Encased Columns (GECs)) to provide additional lateral support for these columns, increase bearing capacity (due to the ringtrac forces action), constructability and to prevent fine clay soil particles from accumulating around the columns thereby reducing the radial drainage capacity of this technique and the defect that it caused to one of the most important functions of this method. Using this technique alone or in combination with another treatment technique address two of the most important problems of soft clay soil which are reduced or eliminate settlement and increase bearing capacity. These columns are implemented in multiple ways according to the degree of soil weakness and the locally available capabilities. The most common of these methods are Vibro-Compaction, Vibro-Compozer and Cased-Borehole Method. Ground improved in this way is called composite ground. These columns are executed with specific surface dimensions and patterns (single or group) and with either fully or partial penetrated depth. When they are loaded they failed individually in one of three mechanisms which are bulging, general shear and sliding, figure (9). [14] [26] [27] [28] [54] [55]

![Figure 8.](image)

**Figure 8.** Spread footing on a reinforced soil with geotextile after Das, B. M. (2015).

![Figure 9.](image)

**Figure 9.** Failure Mechanisms of a Single Granular Pile in a Homogeneous Soft Layer (Barksdale and Bachus, 1983)
4.5 Deep mixing method
4.5.1 General View
Since deep mixing became a part of geotechnical engineering and for decades, this method was used only in soil improvement applications (ground improvement, GI). After that, it was used in environmental and structural functions i.e. earth/water retaining structures, foundations, soil reinforcement, land levees and slope stabilization, in situ remediation and barriers against liquefaction [29]. Deep soil mixing (DSM) or as it has been knowing ground improvement (GI) has been introduced since the 1970s in Japan and the Scandinavian Countries Where this method was used and developed in terms of processes and tools for implementation [30]. This process has been developed a lot by researchers and commercial companies to be suitable for many circumstances and situations. depending on the type of soil that this method is used to improve or the material used in the improvement process or the special equipment used to implement this process it takes its special name, so, according to that we can found lots of names refer to this process each one of them indicates a Specific type of this method Some of them are mentioned in Porbaha (1998) as in Table (2)[30].

| Table 2. Terminology of the deep mixing family, after Porbaha (1998) |
|-------------------------------------------------------------|
| CCP: chemical churning pile                                 |
| CDM cement deep mixing                                      |
| CMC: clay mixing consolidation method                        |
| DCCM: deep cement continuous method                          |
| DCM: deep chemical mixing                                    |
| D.TM: dry jet mixing                                         |
| DLM: deep lime mixing                                        |
| DN!M: deep mixing method                                     |
| DSM: deep soil mixing                                        |
| DeMIC: deep mixing improvement by cement stabilizer in situ  |
| soil mixing                                                 |
| JACSMAN: jet and churning system management                  |
| Lime-cement columns                                          |
| Mixed-in-place piles                                         |
| RM: rectangular mixing method                                |
| Soil-cement columns                                          |
| SMW: soil mix wall                                           |
| SWING: spreadable WING method                                |

Many types of this method have been covered in many books and published research papers, some of them are Terashi (2003), Topolnicki (2004), Larsson (2005), Essler and Kitazume (2008) and Arulrajah et al. (2009), Fattah et al 2015, and Fattah et al 2016. Many standered related to this process were also issued, including European standard “Execution of special geotechnical works – Deep Mixing” (EN 14679) published in 2005. Soil improvement techniques include many types, where deep mixing is classified by the ISSMGE TC 211 Ground Improvement as ground improvement with grouting type admixtures [31], as in Table (3).

| Table 3. Classification of GI methods adopted by TC211, formerly TC 17 (after Chu et al., 2009) |
|-------------------------------------------------------------|
| D. Ground improvement with grouting type admixture          |
| D.I. Particulate grouting                                   |
| Grout granular soil or cavities or fissures in soil or rock by injecting cement or other particulate grouts to either increase the strength or reduce the permeability of soil or around. |
|   |   |
|---|---|
| D2. Chemical grouting | Solutions of two or more chemicals react in soil pores to form a gel or a solid precipitate to either increase the strength or reduce the permeability of soil or around. |
| D3. Mixing methods (including premixing or deep mixing) | Treat the weak soil by mixing it with cement, lime, or other binders in-situ using a mixing machine or before placement. |
| D4. Jet grouting | High speed jets at depth erode the soil and inject grout to form columns or panels. |
| D5. Compaction grouting | Very stiff, mortar-like grout is injected into discrete soil zones and remains in a homogeneous mass so as to densify loose soil or lift settled around. |
| D6. Compensation grouting | Medium to high viscosity particulate suspension is injected into the ground between a subsurface excavation and a structure in order to negate or reduce settlement of the structure due to ongoing excavation. |

The basic principle of the DMM is to strengthen and improve the soil in the site by introducing and mixing cementations materials with the soil. This is done mechanically, hydraulically or pneumatically by specially designed equipment. The deep mixing technique can be divided depending on the transport medium of the additive binder into two main types - from which the other types of this method are branch out - which are the wet and the dry mixing methods. For the deep-wet mixing process which is used more frequently, the binder is mixed with the transport medium (the water) before the injection to make a like mortar admixture, sometimes sand or other additives are added to improve some of the properties of the resulting mixture. This mixture begins with gaining hardening and increasing resistance during and after the hydration process. In the dry deep mixing process, the carrier medium of the binder is air, and the dry binder is mixed directly with the mother soil and the water it contains in its voids to make the like mortar admixture and what Beyond this stage is similar to the deep-wet mixing process [32]. DSM can implement in several patterns according to the purpose for which it is implemented like soil-cement columns, rectangular soil mix panels, continuous barriers or global mass stabilization. It can be said that deep mixing is a highly complex process, with interlocking steps and high sensitivity to conditions changing and processes that accompany its implementation. As any change, no matter how small, in one of the variables that govern this process will have a noticeable effect on the outcome of this process and this effect varies from one variable to another. The type and quantity of the binder and the percentage of water mixed with it in the case of wet mixing have a noticeable effect on the results of this technique, the method of implementation, the type and the configuration of the equipment for the implementation process, and to a large degree the type of soil and its physical and chemical properties and its minerals. Terashi (1997) identified a group of variables that have an impact in this regard, as shown in Table (4), [33].
Table 4. Factors affecting the strength of the DSM material, after Terashi (1997)

| IV. Curing conditions | I. Degree of mixing (Mixing energy) |
|-----------------------|-----------------------------------|
| l. Temperature         | l. Type of hardening agent         |
| 2. Curing time         | 2. Quality                         |
| 3. Humidity            | 3. Mixing water and additives      |
| 4. Wetting and drying/freezing/thawing, etc. | 4. Physical chemical and mineralogical properties of soil |
|                       | 2. Organic content                 |
|                       | 3. pH of pore water                |
|                       | 4. Water content                   |
|                       | I. Physical chemical and mineralogical properties of soil |
|                       | 2. Organic content                 |
|                       | 3. pH of pore water                |
|                       | 4. Water content                   |
|                       | I. Degree of mixing (Mixing energy) |
|                       | 2. Timing of mixing/re-mixing       |
|                       | 3. Quantity of hardening agent     |
|                       | I. Degree of mixing (Mixing energy) |
|                       | 2. Timing of mixing/re-mixing       |
|                       | 3. Quantity of hardening agent     |
|                       | I. Degree of mixing (Mixing energy) |
|                       | 2. Timing of mixing/re-mixing       |
|                       | 3. Quantity of hardening agent     |
|                       | I. Degree of mixing (Mixing energy) |
|                       | 2. Timing of mixing/re-mixing       |
|                       | 3. Quantity of hardening agent     |
|                       | I. Degree of mixing (Mixing energy) |
|                       | 2. Timing of mixing/re-mixing       |
|                       | 3. Quantity of hardening agent     |

4.5.2 Deep mixing method material

Usually, the plasticity index is used to choose the stabilizer to be used in the improvement process. Figure (10) shows the steps followed by the Texas Department of Transportation to choose material for the stabilization process then the dose to be used is determined to achieve the goal of improvement. Reviews of the most important materials used in this process for their effectiveness in achieving the goal of improvement which can be mixed with other materials sometimes will be discussed below.

Figure 10. Typical stabilizer mix design chart used by the Texas Department of Transportation
4.5.2.1 Lime stabilization

The use of lime in soil improvement applications can be traced back to about 5000 years, as it was found in many historical places such as the Appian Way in Rome and the pyramids of Shersi in Tibet, where it was found that these structures were built using a mixture of clay and lime. [34] [35]. There are three forms of lime material according to their chemical compositions. Quicklime which is calcium oxide (CaO), hydrated lime that is calcium hydroxide (Ca(OH)2) and The calcium carbonate (CaCO3) which is used less frequently in soil stabilization. (Sherwood, 1995) report the chemical reactions of these three types as follow (36):

\[
\text{CaCO}_3 + \text{heat} \rightarrow \text{CaO} + \text{CO}_2
\]

\[
\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 + \text{heat}
\]

\[
\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}
\]

The most important aspect in using lime in the improvement process is the provision of calcium which contributes in the ion exchange during the pozzolanic reaction, which in turn depends on the reactive siliceous and alumina available in the soil to be improved. Calcium hydroxide, can be provided by the stabilizer itself and through the hydration reaction. (Ca(OH2) when mixed with water it decomposes and as a result the electrolytic and pH of the soil are increased (34). Dissociation of calcium hydroxide when mixed with water was mentioned (Schoute, 1999). With the following equation:

\[
\text{Ca(OH)}_2 = \text{Ca}^{2+} + 2\text{(OH)}^{-}
\]

The calcium ions released from the dissociation of calcium hydroxide contribute to the cation exchange of the soil, which results in the formation of diffused double layers around the soil particles. This is the first stage of the chemical processes that occur from mixing lime with soil. For soil, the effect of these chemical reactions and exchanges will be noticed in improving the workability of the soil and reducing its plasticity and most importantly the slight improvement in soil strength due to the change of the texture of the improved soil, [37][38]. The second stage of the reactions is that which occurs between siliceous (Si) and alumina(Al) present in the clay on one side and the calcium ions provided by the lime on the other hand, which results in the formation of cementous products that are calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). These reactions are what is called Pozzolanic reactions and occur in a highly alkaline environment, it results in the required increase in soil resistance. These interactions can be represented by what (Nelson and Miller, 1992; Little, 1995) mentioned as following [39] [37].

\[
\text{Ca}^{2+} + 2\text{(OH)}^{-} + \text{SiO}_2 \rightarrow \text{C}_\text{S-H}(\text{gel})
\]

\[
\text{Ca}^{2+} + 2\text{(OH)}^{-} + \text{Al}_2\text{O}_3 \rightarrow \text{C}_\text{A-H}(\text{gel})
\]

Pozzolanic reaction is followed by aggregation and flocculation of soil particles, and this leads to a change in soil texture, increase plasticity limits and soil resistance, decrease plasticity index, shrinkage stresses, compression and permeability [40] [41] [42]. Determining the amount of lime used for improvement depends on the type of soil and the number of its properties, for example, the amount of lime needed to improve soft clay soil is dependent on the pH and UCS properties.

4.5.2.2 Cement stabilization
Shallow and deep soil stabilization using cement has been applied several decades ago and has proven effective in strengthening the soil and enhancing the performance of the structures built on it so that it became expressed by the popular technique. Pozzolanic reactions leading to the improvement are complex chemical activities that result in enhancing soil resistance by increasing cohesion and reducing volumetric changes by reducing its ability to absorb water [39] [43][44]. These interactions are as mentioned (Schoute, 1999) and as follows:

\[
\begin{align*}
2(3\text{CaO} \cdot \text{SiO}_2) + 6\text{H}_2\text{O} & \rightarrow 3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O} + 3\text{Ca(OH)}_2 \\
2(2\text{CaO} \cdot \text{SiO}_2) + 4\text{H}_2\text{O} & \rightarrow 3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O} + \text{Ca(OH)}_2
\end{align*}
\]

(3CaO.Al2O3) + 2H2 O + Ca(OH)2 \rightarrow 3CaO.Al2O3.Ca(OH)2.12H2O

the resulted pozzolanic compounds from the above chemical reactions are caused improvement in the strength and workability of the soil. the grades of cement material available in the market are Type I which is a general-purpose cement, used in ordinary reinforced concrete structures. where Type II and Type V are used for constructing the facility in water or soil containing moderate and high amounts of sulfates respectively. Type III of cement used when there is a need to provides high strength at an early stage, . Type IV is used for the establishment of massive concrete structures due to its low heat generated by its hydration. [45]

4.5.3 Factors Affecting Properties Of Soil Improved By DMM
4.5.3.1 Mixing Degree And Homogeneity Of The DSM Material

According to the great and rapid development of deep mixing technology and its applications, there are many tools and equipment available in the market through which the mixing process can be carried out. The main goal which distinguishes one from another is its ability to produce a homogeneous mixture of the added binder material and the mother soil at the site, thus obtaining the highest level of improvement in the properties of the improved soil with the lowest coefficient of variation of its strength. The number of rotation blades Which expresses the total number of blades passing within 1 meter of the vertical movement of the drilling arm can be used as an indicator to assess the mixing quality, which can be calculated according to the following formula as mentioned in CDIT (2002):

\[
BRN = \sum M \left( \frac{N_d}{V_d} + \frac{N_u}{V_u} \right)
\]

where BRN: is the Blade Rotation Number (num./m), ΣM: the total number of mixing blades, Nd: the rotation speed of the blades during penetration (rpm), Vd: the mixing blade penetration velocity (m/min), Nu: the rotational speed of the blades during withdrawal (rpm) and Vu: the mixing blade withdrawal velocity (m/min). An increase in the value of the BRN lead to a decrease in the value of the coefficient of variation, thus reaching the best degree for improvement. Determining the value of RBN depends on the type of soil, so it should be sufficient to deform the soil and make it loosened appropriately for the process of mixing with the binder material, according to Topolnicki and Pandrea (2012), Clay and loose soils need an RBN value equal to 400 rpm to obtain a value of the coefficient of variation within the acceptable
limits [46]. The formula above from which the RBN value can be calculated for the creating of column-like elements by deep mixing method, Bellato et al. (2012) presented another formula for calculating the “Mixing quality parameter”, μ with which the quality of the mixing output of cutter soil method (CSM) technique can be evaluated. [47]

4.5.3.2 Influence of the cement content
One of the most important goals of the deep mixing process, which is related to several variables, is to increase soil resistance. For example, the degree of mixing is the ruling factor in the homogeneity of the in-situ soil and the added binder, the homogeneity of the mixture resulting from this mixing process is considered one of the important factors affecting the strength of the improved soil. Like what just mentioned before, One of the most important variables associated with the degree of improvement and increasing the strength of the improved soil is the cement content. A way in which a constant amount of cement can be maintained throughout the longitudinal section of a like - column element is to maintain a degree of proportionality between the flow rate of the injected grout and the withdrawal rate of the drilling arm, with that it is possible to achieve the designed amount of cement to be pumped and mixed per cubic meter of soil [48].

4.5.4 Field of applications
Since its inception as a geotechnical application, it has been used for many decades as an effective, fast and economical way to improve and stabilize weak soils, especially soft clays. Later it was used in many important applications in geotechnical engineering, where it is used as a retaining structure for land and water, deep foundations and soil reinforcement, to stabilize slopes and barriers against soil liquefaction and finally as one of the of soil pollution controlling. Below is a presentation of some important applications for this method and some of what is published in this regard.

4.5.4.1 DSM as an excavation support technique
In recent years, the deep mixing method has been widely used for the support function for soil and water when there is a requirement for a difference in the level between two sides of the soil. As a practical fact, the deep mixing method with its both Soil Mix walls and cylindrical columns technique represent an alternative - for the traditional concrete secant pile walls and king post walls retaining systems - that are more economical, faster in term of execution, and have good efficiency in terms of strength and resistance. SMW’s, as it is known, is carried out with special equipment so that it is a continuous wall-like barrier without joints. As for columns -like element with a cylindrical section, they are executed in an overlapping manner that prevents the formation of joints between them, and steel beam with H or I sections are placed in the fresh mixture to resist shear forces and bending moment. SMW is implemented at a depth of about 25 meters, and column-like elements can be executed at greater depths. Many research papers are documenting the use of deep mixing technology to support soil and water permanently or temporarily, Table (5) shows a number of these papers.
### Table 5. Summary of the publications concerning SMW with earth/water retaining functions

| References          | DSM function and duration                        | Type of soil                                      | Details                                                                                                                                 |
|---------------------|--------------------------------------------------|--------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Peixoto et al. (2012a) | Permanent excavation support, permanent foundation and water retaining applications with CSM | Stratified soil: clayey and silty fill, sandy clays and bedrock (sandstone) | Description of the design of the solution and numerical modeling with Finite Element Method FEM (Plaxis®) Execution details, QC aspects (UCS on wet grab samples) and monitoring plan (surveying targets, inclinometers and extensometers in the struts) |
| Peixoto et al. (2012b) | Temporary earth/water retaining wall for excavation with CSM | Sandy fill and calcarenite substratum | Description of the CSM technique, the design and the execution of the solution QC aspects (UCS, modulus of elasticity (E) and tensile splitting strength (T) tests on 36 wet grab samples) and monitoring plan (5 inclinometers, 5 load cells and 17 surveying targets) |
| Peixoto et al. (2012c) | Temporary earth/water retaining wall for excavation with CSM | Clayey fills and fractured dolomitic rock | General description of CSM technique Details of the design and execution of the solution and FEM of the retaining wall with Plaxis® |
| Peixoto et al. (2012d) | Temporary earth/water retaining wall with CSM | Sandy clay overlying substratum of marls | Details of the design and execution process and FEM of the retaining wall with Plaxis® QC aspects (UCS tests on wet grab samples) and monitoring plan (19 survey targets and 3 inclinometers) |
| Pinto et al. (2012) | Temporary circular shaft for excavation below ground water table at Ponte de Lima (Portugal) | Heterogeneous soil: heterogeneous landfills, sandy and gravel soils and weathered schist | General description of CSM technique Different case histories with CSM: design/execution criteria for foundation, slope stabilization |
Permanently earth/water retaining wall and foundation solution in Lisbon (Portugal) with heterogeneous soil: heterogeneous landfills and Miocene medium dense to dense sands and sandstones and temporary or permanent earth retaining structures above and below ground water table QA/QC aspects (UCS and E tests on core samples) and monitoring plan.

Table 6

| Permanent earth retaining wall for excavation in Lisbon (Portugal) with geodrains for the control of the water table | Heterogeneous soil: heterogeneous landfills and Miocene medium dense to dense sands and sandstones | and temporary or permanent earth retaining structures above and below ground water table QA/QC aspects (UCS and E tests on core samples) and monitoring plan |

one can Take what was mentioned by Pinto et al. (2012) as an illustrative example of one of the applications of the deep mixing method, namely CSM, which was used as a support technology (against soil and water) for the construction of two cylindrical pits with a depth of 18 meters and a diameter of 15 meters to be used in the process of laying a water feed pipe under the river bed using micro tunneling technology. CSM panels were implemented with 24m depth and reinforced with vertical IPE300 steel profiles. Through its design, the work of these panels is by preventing water from seeping into the pits by creating a watertight barrier and preventing the collapse of pits sides by transferring the lateral driving load from soil and water to the vertical steel I-beam sections that are supported from the top by reinforced concrete beam and from the bottom at three various levels through annular steel beam as illustrated in Fig. (11).

Figure 11. inside view of the right bank shaft after excavation, after pinto et al (2012)

4.5.4.2 DSM technique for foundation applications and soil reinforcement

In the past decades, there was an urgent and increasing need for the possibility of constructing on soils with weak strength, and this need was lead to a development of a new soil improvement techniques and foundation solutions, taking into account the time of implementation and the cost. Deep mixing is an interesting alternative to foundation solutions and soil improvement methods with some technical, environmental and financial advantages. Some of what was mentioned from the published documentation for the use of DMM as permanent solutions to the foundation problems are shown in Table (6).
Table (6): Summary of the publications concerning DSM for foundation applications and soil reinforcement

| References          | DSM function and type of soil | Details                                                                                                                                 |
|---------------------|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
| Chapman et al. (2012) | GI with CSM for permanent foundation of a liquefied natural gas (LNG) tank in Coast of North Queensland | Details of the design of CSM foundation Description of laboratory UCS tests on wet grab samples and mention of plate load tests 2D plane strain and axisymmetric 2D analyses with Plaxis® |
| Mendes et al. (2012) | CSM panels for permanent foundation of buildings | Laboratory test campaign on mixture specimens (to determine the cement, organic matter and sulphates contents): water content, small strain stiffness (P wave velocity propagation tests), UCS, E, T and shear strength (CU TX) tests Effect of curing (14, 28, 54 and 91 days) Quality index for sample selection |
| Peixoto et al. (2012e) | CSM for permanent GI application: foundation of an industrial building | Description of the design and numerical modeling with FEM (Plaxis® ) Details of the execution process and QA/QC aspects (UCS on wet grab samples) |
| Pinto et al. (2012)  | Permanent foundation solution in Lisbon | Description of the design and execution criteria for foundation below ground water table QA/QC aspects (UCS and E tests on core samples) and monitoring of the building during and after construction |
| Lambert et al. (2012) | Soil reinforcement for railway infrastructure with soil-cement columns performed with the help of the FLAPWINGS® tool (Keller Foundations) | Description of the European Research Project INNOTRACK (2006-2009) Details of the execution, the excavation, the field load tests on 2 columns and the laboratory tests on core samples Comparison with Jet grouting |
Chapman et al. (2012) mentioned the use of CSM, one of the deep mixing method techniques in the construction of a liquefied natural gas reservoir (LNG) on mudflat weak delta, where the dimensions of the tank are 85 meters and 54 meters in height. The traditional solutions for foundations by using piles were very expensive. The decision was to use the CSM, it was carried out with 605 panels with a depth ranging from 13 to 15 meters, then a granular load convey layer was placed on. Figure (12) shows some details about this work.

| Source                        | Description                                                                 |
|-------------------------------|-----------------------------------------------------------------------------|
| Guimond-Barrett et al. (2012a) | Reinforcement and re-use of railway platforms and existing foundations with the help of soil-cement columns executed with the SPRINGSOL® tool (Soletanche-Bachy) |
| Stratified soil: fill, clay/silt and gravelly sand |
| Description of the Rufex project Details of the execution and QC aspects with the excavation of the columns and the laboratory tests on cores |
| Dhaybi et al. (2012)         | Shallow foundations on DSM columns                                           |
| Hostun sand                  | Reduced scale modeling and axisymmetric FEM of shallow foundations on soil-cement columns |
| Suganya et al. (2012)        | Embankments founded on soil-cement columns                                  |
| Soft organic clay            | Parametric study of embankments founded on soil-cement columns for the reinforcement of soft organic clay using FDM with FLAC 2D®: influence of the column properties, spacing, area, mass stabilized zone and pile material modeling |

Figure 12. a) soil layering below the LNG tank and b) CSM panel layout, after champman.et al,(2012)
4.5.4.3 DSM technique for land levee

One of the applications in which DMM can be used is what one can call dams, barrier or levees, which are an embankment built in adjacent of any water body to prevent its overflow. Hurricane Katrina which hit southeast of New Orleans in USA on August 29, 2005 caused a huge damage to the hurricane control and drainage system in this state, it was one of the worst engineering disasters in the history of the United States of America, where the collapse of these barriers caused great losses of lives and property and the reason was that it was established On soft organic clay soil. a plan was decided to remove the old damaged barrier with a length of 8.5 km and replacing it with another one (The LPV111 project (Leoni and Bertero, 2012)) with the same location and length by using the deep mixing method for the constructing of its foundation and as a stabilization method for the barrier material itself. figure (13) shows some detail of this project. Table (7) summarizes several published research papers in this regard.[51]

| References               | DSM function                                                                 | Type of soil                                                                 | Details                                                                                                                                   |
|--------------------------|------------------------------------------------------------------------------|-------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Leoni and Bertero (2012) | DMM applied for permanent foundation and stabilization of a land levee (LPV111 project) with the help of the TTM single, TTM double and CI-CMC double systems | Existing levee fill, soft clay, marsh/peat deposits, fat clay, and Pleistocene soils                                             | General description of the project Preliminary laboratory program: Bench-scale test with the study of the effect of the w/c ratio, the type and the amount of cement on the UCS Field test program (Validation tests) QA/QC testing (5000 cores with UCS tests) and UCS design consideration |
| Mc Guire et al. (2012)   | Dry Deep Mixing method for the permanent stabilization of a section of a land levee and floodwall                        | Clays and cohesionless soils                                                  | Numerical analysis of the stability of a section of a land levee and floodwall with the finite difference method and a limit equilibrium analysis (using Spencer’s method) Study of the influence of vertical joints in the deep-mixed zone and study of the influence of a waterfilled gap on the flood side of the cantilevered floodwall |
4.5.4.4 DSM technique for slope stabilization

Another area of application of the deep mixing method is slope stabilization. As sometimes there is a need for the construction on sloping ground and for this there is a risk of possible sliding of the slope material under the load imposed by the facility and sometimes due to the occurrence of earthquakes. in this case, the DSM is employed as a treatment method for the slope material under the facilities. Pinto et al. (2012) mentioned a case in which the CSM was used to stabilize a slope material under a road. after its implementation there was an intention to make an expansion of the previously implemented road. CSM panels were utilized as a foundation for the self-weight of the retaining wall used to support fill material for the expansion, which reaches a height of 20 meters as a maximum, Figure (14) shows some of the details of this project, (49)

Figure (14): cross section of the geological condition and adopted solution, after pinto et al. (2012)

4.4.4.5 Soil Mix Remediation Technology

in situ treatment of contaminated soil can be done by deep mixing process, where mixing equipment and some chemicals are sometimes used to make either a permeable reactive underground barrier PRB. this barrier is perpendicular to the direction of the contaminated water flow, when the contaminated water passes through the PRD, it will interact with the existing chemicals where pollution is removed by one of
the following mechanisms which are sorption, precipitation, oxidation, biodegradation and encapsulation. Or by creating a containment barrier which is with low permeable or impermeable and in this case the contaminated soil will be isolated from its clean surrounding. In the event that the soil is contaminated with hazardous chemicals or radioactive substances, a deep mixing technique is used to stabilize/solidification (S/S) of the contaminated materials, this is done through chemical fixation or the physical encapsulation of the materials in the same place within the soil. DSM considered one of the very appropriate solutions to the problem of soil pollution in terms of safety, speed of implementation, cost and effectiveness, Al-Tabbaa et al. (2012).(52).

4.5.4.6 DSM barrier against liquefaction

Another important application of deep mixing is to prevent the risk of soil liquefaction and to eliminate the effect of soil flow after the occurrence of soil liquefaction. As a documented and published case what reported by Benhamou and Mathieu (2012). Martinique (France) is a region at great risk of earthquakes, for a safe construction process for two buildings rested on very soft silty/sandy alluvia strata, the principle of deep mixing has been utilized to create a new type of permanent foundation system, where what is called a Geomix caisson in an arrangement of (36*40) m was used and implemented by hydrofraise technology combined with the CSM principle. it was introduced as a liquefaction mitigation technique this method was used previously in Japan under the name of deep mixing method. Executing the foundations in this way makes the soil confined to a box-like structure, and this reduces the risk of soil liquefaction as the stresses will be concentrated on the panels forming the foundations. Figure (15) shows the shape of the foundations executed by the geomix caisson method.[53].

Figure (15): 3D view of the Geomix caisson structure, after Benhamou and Mathieu (2012)

5. Conclusion

Geotechnical engineering is one of the most important branches of civil engineering as it is considered the basis and the first step in any construction project and it has a special and appropriate attention, time and cost in the preparation and design stage, and from here the soil acquires great importance as it is the material that geotechnical engineering specializes in studying. In this paper, two important topics in geotechnical engineering and the practical practice of civil engineering were dealt with, namely, soft clay soil and one of the soil treatment techniques which is the deep mixing method. These two topics gain their importance through the fact that the first of them is often dealt with and is considered one of the worst
problems that can be encountered in practice in terms of the difficulty of dealing with it as a construction material, while the second is considered the most effective and most used method in dealing with such kind of construction problems. In order to understand clay soil in any of its aspects, it is necessary to know its composition at the microscopic level, its chemical composition and the physical forces that bind its molecules. So, it was mentioned that the clay minerals are basically two types and they are primary minerals (chemically unaltered) which are found in sandy and course silty soils and secondary minerals (chemically altered) which are found in clay and fine-silt soils. Clay minerals are exist in two main structures, the silica oxygen and it results from the bonding of silicon ions with the oxygen atoms from four sides (tetrahedral) and the second which results from the bonding of aluminum and magnesium ions from eight sides with oxygen and hydroxide ions (octahedron) and The most common groups of clay minerals are kaolinite, illite and smectite (montmorillonite). It has also been pointed out that the dominate control of clay over the behavior of the soil is due to some properties of clay minerals and their chemical behavior, and that any change in the chemical structure of these minerals causes a strong attraction to water and this results in the great ability of clay soils to absorb and retain water and this is the reason for all the problems associated with clay soil. In another section, the treatment methods used in treating soil problems, whether surface or deep treatment, are covered. What (Karon and Bergado, 1991) mentioned as a way to choose the appropriate treatment method is listed as in figure 2 and3, as well as what (Kempfert and Gebresealsie 2006) mentioned in Figure 4. Also, it was briefly touched upon some of the techniques used in treating soft clay soil, including the method of soil replacement, where it was mentioned that it is an effective and fast implementation method, but it has a limited depth and Problems related to disposing of the replaced soil. Also, some details were mentioned regarding the method of pre-loading with or without sand drains. It is shown that the work of preloading is to increase settlement rate before the start of the construction works by increasing the speed of water exit from the soil body, and for the small permeability coefficient of clay soil, vertical drains are made to reduce the water pressure generated from the preloading process, thus reducing the time needed to reach the required settlement ratio. Among the limitation of this method is the inability to implement it within a populated areas and the difficulty of providing the required load for a certain settlement percentage in some cases. It has also been pointed out that many types of geosynthetic materials are used to stabilize the soil by means of action of reinforcing Tension parts, confining, lateral support against spreading and separation, strain reduction, distributing loads over a specific area and It is mainly used to increase the shear strength and bearing capacity of the soil under facilities, specially the roads. Stone columns or granular piles are used as reinforcement for soft clay soils with undrained shear resistance greater than 15 kPa and it can be used for soils with cu of less than 15 kPa by using casing stone/granular column due to the weak lateral support provided by this soil. Finally, what was mentioned about the deep mixing method, as it was dealt with in more detail in terms of its classifications, its most popular terminology, the materials most used for the stabilization process which are lime and cement, and the chemical processes which ended out with the required improvement, and the most important factors affecting the outcome of the deep mixing process were also identified, namely, The degree of mixing and the amount of cement used, as these two variables are considered one of the most important factors governing the improvement process, also what has been mentioned regarding the applications in which the deep mixing process is used and it is many and has been practically utilized in many sites, including what was mentioned as a case history.
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