Basic Aspects of Deep Soil Mixing Technology Control

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Abstract. Improving a soil is a process of increasing its physical/mechanical properties without changing its natural structure. Improvement of soil subbase is reached by means of the knitted materials, or other methods when strong connection between soil particles is established. The method of DSM (Deep Soil Mixing) columns has been invented in Japan in 1970s. The main reason of designing cement-soil columns is to improve properties of local soils (such as strength and stiffness) by mixing them with various cementing materials. Cement and calcium are the most commonly used binders. However new research undertaken worldwide proves that apart from these materials, also gypsum or fly ashes can also be successfully implemented. As the Deep Soil Mixing is still being under development, anticipating mechanical properties of columns in particular soils and the usage of cementing materials in formed columns is very difficult and often inappropriate to predict. That is why a research is carried out in order to find out what binders and mixing technology should be used. The paper presents several remarks on the testing procedures related to quality and capacity control of Deep Soil Mixing columns. Soil improvement methods, their advantages and limitations are briefly described. The authors analyse the suitability of selected testing methods on subsequent stages of design and execution of special foundations works. Chosen examples from engineering practice form the basis for recommendations for the control procedures. Presented case studies concerning testing the on capacity field samples and laboratory procedures on various categories of soil-cement samples were picked from R&D and consulting works offered by Wrocław University of Science and Technology. Special emphasis is paid to climate conditions which may affect the availability of performing and controlling of DSM techniques in polar zones, with a special regard to sample curing.

1. Introduction

The following study is divided into two parts. The first part concerns the methods of soil improvement my means of mixing soil with a binder. The second part is focused on the influence of an application of fly ashes on soil-cement columns. The resistance of DSM columns and its increase in time will be taken into account. The results of laboratory testing include those carried out for samples prepared at laboratory and the ones taken directly at construction site.
It must be underlined that presented work covers just a very small part of technological challenges, widely described in the literature [1-6]. The goal of the authors was to emphasize the variability of factors influencing the final quality and suitability of Deep Soil Mixing materials.

2. Basic aspects of soil mixing, climate conditions and fly ash application

The variety of problems concerning insufficient capacity of soils imposed a wide development of soil improvement technologies. Some of them were never in a common practice however it is worth to juxtapose diverse ideas:

- Filling with bentonite. As opposed to cement grouts, bentonites can be used to bond dry rocks only, which – following the bentonite solution is forced in – absorb water from the solution. For this reason, in case of sealing rocks with cohesive material, the hydraulic pressure of bentonite grout within the zone in question need to be maintained for several days.
- Silicatization is used to bond fine-grained and dusty mineral soils by filling (injecting) them with water-glass. A two-component silicatization composed of water-glass filling followed by chloride calcium application is most often used.
- Asphalt grouting is used for creation of waterproof soil.
- The method of hot asphalt grouting is applied in intensely cracked rocks where high speed of filtering is prevailing. It consists in forcing molten bitumen into injection holes to fill in narrow crevices and to seal them. Since bitumen does not mix with water and because it forms a low thermal conductivity contact layer, so a large spaces fractures can be filled in even at intense flow of water. As bitumen cools down slowly, sealing material can be forced to large distances from injection.
- Tar (pitch) mixing is a use of synthetic pitches which turn out various chemical technologies. These pitches turn soil into rather firm basis.
- The thermal way is applied to fixing of dusty and clay or collapsible soil. A basis of this method is to increase durability of communications by means of high temperature (agglomeration), by burning combustible material in wells. For example: solar oil, fuel oil, natural gas.

The most common and widely used technology is cementation, applied for improving most of the mineral soils. All kinds of injections, jet grouting and mechanical Deep Soli Mixing can be applied depending on required resulting parameters (compressive strength, elastic modulus). Only in the case of high organic content its suitability is limited. When subbase strengthening work is carried out at sub-zero temperatures, cementation mixing installation is warmed and maintains temperature not below plus 10°C. Also the injection lances should be warmed up to initial temperature of 20-40 °C. Solution at the time of forcing shall have temperature plus 15-20 °C. For this purpose, water and the soil are warmed up to the temperatures which values can be approximately determined by the formula (1)

$$t_p = (0.48 + 2.2i_n) \cdot t_n + (0.32 - 2.2i_n) \cdot t_w$$

where: $t_p$ - the required temperature of solution, °C; $i_n$ - mass humidity of sand, %; $t_n$ and $t_w$ - temperature of heating the sand and water, respectively, °C;

Solution forcing should be conducted by a circulating method in the winter that excludes freezing it in the pressure head line. In case of a no-circulation method of forcing it, is necessary to arrange circulation of solution in a land part of system of pipes (between the pump and the mouth of a well). Nowadays, the most common binders which are used are cement and calcium. However new research undertaken in Japan, USA and Scandinavia proves that despite these materials we can also successfully implement gypsum or fly ashes. As the Deep Soil Mixing is still being developed, anticipating mechanical properties of columns in particular soils and the usage of cementations materials in formed columns is very difficult and often inappropriate.
Currently, a research is carried out in order to find out what binders and diameters of columns should be used. Nowadays much of electricity we consume comes from coal-fired power plants. Consumed coal leaves molten particles with alumina, silica and calcium. These tiny portions become solid as microscopic spheres. Subsequently they are collected from power plant’s exhaust until they escape (fly away). The material which is obtained in such a manner is obviously fly ash consisting of non-flammable mineral portion of coal. However, research undertaken during recent years points out that we are able to apply it in variety of concrete products. Having added fly ashes, it was obtained concrete with enhanced properties (better strength, durability and resilience against chemical conditions). Moreover, considered material is perfect for filling voids in concrete structure – it comprises particles usually finer than cement ones. B understanding of the problem should be achieved if we consider the following advantages of using fly ashes in particular areas:

- Environment: Using fly ashes is an environmental-friendly solution. As the material is considered to be industrial waste it can produce dust or cause atmospheric pollution. Moreover, it is harmful to human and other creatures. Applying it as a compound of construction material enables to avoid landfill disposal of ash products.
- Increased volume: A result of relatively low unit weight of fly ash.
- Water savings: Lower quantity of water can be applied to concrete mix in order to obtain a compulsory slump. It is caused by the spherical shape of fly ash particles. Ordinary, water demand in concrete mix comprising fly ashes is reduced from 2 to 10%.
- Durability: Using considered material we obtain less permeable concrete and soil-cement mixture. The fly ashes contribute to filling capillaries as well as bleed water channels.
- Corrosion protection: Using fly ash we significantly improve permeability of soil-cement material. It results in diminished water and chemicals penetration inside columns. Finally, additional reinforcement implemented to enhance bending or tensile strength of column is protected against corrosion.
- Slower hardening process: This aspect can be both taken into account as positive or negative. However, in terms of DSM columns formed in order to strengthen subsoil for erection purposes it is treated as an essential upside. In this case soil-cement material is not sufficiently hardened after few days and still is able to be easily cut on particular level.
- Low costs: There is no established price for fly ash. Nevertheless, this material is usually 3-4 times cheaper than typical cement, so significant savings of money can be generated.

3. Deep Soil Mixing technology specification

The strength properties of the soil are enhanced by mixing it with binders such as cement slurry, bentonite or cement-fly-ash slurry. A special-design rotating auger is introduced into the subsoil. It causes destruction of soil structure and mix it with injected binder. Typical auger consists of drilling rods and cross bars. The whole procedure, from the first injection of auger, till the end of formation is aided by binder which is spread through nozzles installed at the ends of rods. Having reached the designed depth, we start the column formation phase which combines lifting and lowering of auger in order to obtain continuous, well-mixed cement-soil column. In case the considered column is subjected to bending or tension, additional reinforcement can be inserted. Three main methods of performing DSM columns are distinguished: Dry DSM Method, Mass Stabilization, Wet DSM Method.

Dry soil mixing can be used in soils of high moisture. The common equipment consists of station provided with binders and drilling machine, which are adopted to work in adverse soil conditions. Binder is transported thanks to compressed air. Its amount is permanently monitored so as to estimate the total usage per 1 m³. The process of mixing dry binder with surrounding soil takes place when lifting up the auger (rotating in reverse direction than during penetration). The typical diameter of columns is 60-80 cm and maximum depth of implementation is roughly 10m. The most essential advantages of dry methods are:

- possibility to perform columns in low temperatures,
- lack of dredged material,
ability to strengthen very weak soils,
relatively low price.

Another kind of dry soil mixing is mass stabilization. In this method special augers are assembled to arm of excavator. Mixing occurs in both horizontal and vertical direction. Stabilization process is divided into stages covering 8-10 m². Having implemented proper dosage of binder, mixing is continued in order to obtain continuous structure.

Wet soil mixing is a method invented and developed in Japan. The technology and manner of forming columns is very similar to dry DSM method. However, in this case having reached the designed depth we start forming columns by implementing slurry instead of dry binder. The most typical binders are varied cements, especially blast-furnace cement which is less susceptible to be influenced by aggressive environment and the process of hardening develops slower. If there is a need to improve tightness of columns (e.g. when they are performed as water barrier), it is possible to add some quantity of bentonite. Logical effect of appliance of water comprised in slurry is fleeing of dredged material on the surface. However, the total quantity of left material is still much lower in comparison to other methods such as Jet Grouting. The typical diameter of these columns is 60-120 cm, however the technology is still developed and larger diameters reach over 2 m.

![Figure 1. Performing water-tight screen by means of DSM wet method.](image.png)

Construction site in Wrocław (courtesy of KELLER Poland)

When choosing method of performing DSM columns we take into account the following aspects:
preliminary moisture of soil being strengthened: cohesive soils of moisture > 60% would be better mixed with dry method, in terms of \( I_L < 0 \) water is not sufficiently accessible for hydratation process,
quality of mixing: wet method leads to more homogenous structure of soil-cement material, which is caused by longer mixing phase and presence of applied water,
compression resistance of a soil: it is much easier to obtain satisfactory compression strength using wet method (exception are soils of very high moisture),
multi-layered soils: wet mixing gives opportunity to vertical movement of soils at the length of column, which is much more difficult in subsequent method,
dredged material: using dry method we do not gain any left material, in terms of wet method the situation is reverse,
mixing at temperature below 0 degrees: dry method is more efficient here because the binder is transported pneumatically,
putting additional reinforcement: basically it is possible merely in wet method,
• relative cost of stabilization: (dry mixing is usually cheaper).

The process of mixing a soil encompasses:
• positioning of machine and rod beneath previously arranged point,
• penetration phase,
• checking of level of subbase together with simultaneous strengthening layers on contact areas,
• pulling out phase,
• shift of position.

**Figure 2.** Typical cycles of Deep Soil Mixing phases (courtesy of KELLER Poland)

During penetration, rotating auger is aided by compressed air (dry method) or cement slurry (wet method). To restrict the risk of blocking in compact soils, operator can take advantage of partial lifting. Pulling out the auger can be accomplished with several steps or in even flow. Quantity of implemented binder is under control as well. It is spread in the soil usually when penetrating or lifting the auger. The first manner is used in majority for wet-formed columns. It is caused by the fact that presence of slurry diminishes movement resistance. Generally during penetration 80-100% of slurry is transferred into the ground. The degree of homogeneity of cement-soil material depends mainly upon time of mixing, type of rotating auger and properties of soil.

4. Experimental study of applying fly ashes into DSM columns

The work contains two independent groups of analyses. The first one comprises results coming from the laboratory research undertaken by the authors. This is just a small part of huge investigation which is aimed at boosting the knowledge of possible implementation of fly ashes into DSM columns. The second part contains results of specimen provided by Keller Poland company. The soil-cement samples were collected on the building site in Wroclaw, Poland, where a water-tight screen by means of DSM wet method was under construction.
4.1. Preparation of the specimen
In considered case the uniaxial compressive test of soil-cement and soil-cement-ash specimen is taken into account. Thanks to the research we are able to obtain uniaxial compressive strength (UCS) of the material. Moreover, having results of both stress and strain in the material we simply derive the modulus of linear elasticity. In order to obtain satisfactory and comparable results showing the trends of stress-strain curve it is essential to prepare applicable test specimens.

The tested samples should be small enough to be easily handled and simultaneously large enough to make sure that results we obtain reflect somehow the natural situation. That is why the typical specimen for that kind of testing is of size: 15x15x15 cm. The area of the compressed edge is then 0.0225 m². The whole process of forming specimen consists of few steps. Firstly, we have to prepare necessary equipment which is: huge bucket, scales, empty forms and mixing machine. Components of the mixture are: particular soil, cement, water and fly ashes (but only when they are needed). Having scaled the ingredients, we put them into the bucket. All components are to be mixed to provide clear and uniform structure of final soil-cement material. In order to do that, the mixing process is going to take roughly from five up to ten minutes (Figure 3).

It is important that after adding a binder we should finish the whole process within 30 minutes, so not to let the soil-cement to harden too much. Having reached the aimed colour and properties of material we are able to start putting it into previously prepared forms (Figure 4). These are made of plastic forms of internal size 15x15x15 cm. Subsequently, we ought to level the upper surface of the casted material by means of trowel. This activity is needed to ensure that our specimen will not exceed the designed volume and provides flat surface of all sides. When our product is ready it is just the matter of time to use it in uniaxial compressive test. It is essential that every test specimen is prepared in the same way so the final results are reliable and comparable.

![Figure 3. Preparation of DSM samples - mixing](image1)

![Figure 4. Preparation of cubic samples](image2)

4.2. Uniaxial compressive test
In order to obtain a reliable picture of development of compressive strength for test specimen different hardening times are arranged. Within the first group of samples the considered cubes were compressed after 7 and 28 days of casting them into forms. In the second group, all the specimens were examined after 14-days period. It is estimated that the majority of resilience contributed to cement-soil samples is reached until 28 days (as the situation looks like in terms of concrete specimen). The samples containing either cement and fly ash or just cement will be compared in terms of compressive strength and modulus of linear elasticity.

The question could be posed, why is uniaxial compressive test used in order to do research on such samples? The answer is more than simple; DSM columns are mainly subjected to compression, much
more often than to bending or tension (which is more complex problem in terms of laboratory investigation). Using UCT we are able to receive lower strength results than during triaxial test. It means that we keep the safety margin for future design. In order to perform uniaxial compressive test, we put our specimen on a special circular pad and start pressing it by means of a slow movement of the upper part of the machine. Everything is connected to a computer which continuously backs up all the data concerning input stress and strain of the specimen (Figure 5).

Figure 5. Laboratory station, uniaxial compressive test on soil-cement specimen

Figure 6. Destroyed soil-cement sample

Thanks to obtained results we are able to derive the chart of stress $\sigma_i$ [MPa] as a function of strain $\varepsilon_i$ [%]. The test is finished in the moment of noticing a (usually vertical) crack on a surface of investigated sample. Simultaneously, it is easy to observe sharp increase of strains with almost steady stress factor. To paraphrase, deformation rises significantly without changes of force acting on a specimen. The typical view of destroyed sample looks like that in Figure 6. In the first phase of the uniaxial compressive test we witness an almost-linear relation between stress and strain. That enables us to use approximation between two points and obtain linear modulus (also known as a Young’s modulus) $E$ [MPa] by means of the relation:

$$E = \frac{\Delta \sigma_i}{\Delta \varepsilon_i}$$

Where:

- $\Delta \sigma_i$ – difference between stresses for two subsequent points [MPa]
- $\Delta \varepsilon_i$ – associated difference in strains for the same points [%]

In the considered case, the destruction occurred at the stress level 0.951 [MPa] – it is treated as maximum compressive strength of investigated material. That is adequate for force acting on a specimen of value roughly 21.4 [kN]. We calculate it by multiplying the resultant compressive resilience by the area of upper surface of specimen $\pm 0.0225 \text{ m}^2$. Obviously, the area of a side of a sample can differ a little from established one. This is the effect of small imperfections during the process of forming as well as pulling the specimen out of a form. However, that margin is minor in terms of undertaken calculations and do not disturb overall, final results.
As we take a notice on the beginning of stress-strain curve, we observe a straight, red line which is the best approximation of almost-linear part of the chart. Taking into account the values which are embodied there is possibility to obtain linear modulus according to [7]:

\[
E = \frac{(0.51 - 0.09) MPa}{(0.53 - 0.18)\%} \approx 120 MPa = 0.12 GPa
\]  

These results (3) are not even comparable with concrete material when the results are at least dozens times greater. Nevertheless, soil-cement is still very considerable in terms of stabilizing subsoil and many other reasons. In the following chapter, the exact results of strength resilience for specimen with and without fly ash will be presented.

5. Results of laboratory testing

Having completed the tests for investigated samples from the first group prepared in the Lab, it is possible to derive some trends concerning the increment flow of compressive strength and Young’s modulus for particular specimens. To have a better view of collected results the table is presented:

| Groups of samples | Quantity of cement [kg/m³] | Quantity of fly ash [kg/m³] | R_c [MPa] 7 days | R_c [MPa] 28 days | E [MPa] 7 days | E [MPa] 28 days |
|-------------------|---------------------------|-----------------------------|-----------------|-----------------|----------------|----------------|
| 1.1               | 1.2                       | 160                         | 0.91            | 2.40            | 130            | 431            |
| 1.3               | 1.4                       | 200                         | -               | 1.42            | 316            | 993            |
| 2.1               | 2.2                       | 136                         | 0.47            | 1.02            | 82             | 247            |
| 2.3               | 2.4                       | 170                         | 0.73            | 1.65            | 129            | 434            |

In the considered soil the best results of both uniaxial compressive strength and linear modulus (after 28 days of hardening) were obtained for samples containing 200 kg/m³ of cement. The maximum bearing capacity was approximately 4.5 MPa. However, taking into account the shape of rise increment we can assume that it is still going to increase in subsequent days. The highest result performed by specimen with fly ashes is 1.65 MPa which is less than 40% of the best result, despite the fact that the amount of binder implemented clocks up to 260 kg per cubic meter of soil. Nevertheless, according to previous authors’ studies [8] the assumption is that the compressive strength of the material is also going to rise. That leads us to a very important conclusion: application of fly ashes slows down the hardening process in soil-cement material. This fact could turn out to be very meaningful if we do not want or need to receive rapid compressive resistance.
On the basis of the undertaken research one can assume that linear modulus for specimen is related with uniaxial compressive strength. These partial results are in Table 2 comparing compressive resistance with Young’s modulus for samples tested after 28 days: In general, according to the presented table, linear modulus increases with rise of uniaxial compressive strength. It is not noticeable in terms of all samples, because of almost identical values in samples 1.2 and 2.4. However, a relation between linear modulus and amount of cement implemented leads us to the conclusion that: Young’s modulus of soil-cement material increases with quantity of cement.

### Table 2. Comparison of Young’s modulus in accordance with other factors

| Sample | Quantity of cement [kg/m³] | Rc [MPa] | E [MPa] |
|--------|---------------------------|---------|--------|
| 1.2    | 160                       | 2.4     | 431    |
| 1.4    | 200                       | 4.48    | 993    |
| 2.2    | 136                       | 1.02    | 247    |
| 2.4    | 170                       | 1.65    | 434    |

Having successfully examined the second part of samples, we can come up with another fruitful conclusion concerning the influence of fly ash on DSM columns. There are also some evidences proving the influence of methods of compiling samples on final resistance. The Table 3 below presents the juxtaposed results:

### Table 3. Comparison of results for different relations of binders

| Groups of samples | Quantity of cement [kg/m³] | Quantity of fly ash [kg/m³] | Rc [MPa] | E [MPa] |
|-------------------|----------------------------|-----------------------------|---------|--------|
| 3.1               | 174                       | 116                         | 1.71    | 593    |
| 3.2               | 145                       | 145                         | 0.97    | 263    |
| 3.3               | 145                       | 145                         | 1.20    | 293    |
| 3.4               | 116                       | 174                         | 1.78    | 477    |
| 3.5               | 116                       | 174                         | 1.08    | 277    |

### 6. Conclusions and final remarks

Comparing samples without input of fly ash we come up with an obvious conclusion that: the resistance of soil-cement material increases simultaneously with enlarged quantity of cement [8]. It confirms the previous research [3] undertaken by PhD Leśniewska from Gdańsk University of Technology, which provides that in clay the resistance increases almost linearly with the α factor (defined as dry binder mass to volume of soil ratio), whereas in sands it is over-linear. The typical values of resistance depending of quantity of binder and class of soil are as follows in Table 4 [3]. Another matter is the strain analysis. The charts obtained in hydraulic press show that: deformation in the moment of destruction decreases with increase of resilience of investigated sample. In case of sample 1.1. the destruction struck with deformation of 1.6% whereas for specimen 1.3. (with greater amount of cement) it indicates roughly 1.1%. Similar situation takes place in terms of tests after 28 days of hardening. The results are not fully satisfactory in terms of deriving a trend of binder content on fly ash on total resistance dependence. As the samples 3.2 and 3.3 with binder relation 50/50 reach palpably lower values than specimen 3.1 (the uniaxial compressive strength is as follows: 43 and 30% lower), it does not work when we take into account the other samples. The specimen 3.5 (binder relation 40% cement, 60% fly ash) indicates similar values of susceptibility as the ones with binder relation 50/50 (it is roughly in between) whereas the sample 3.4 achieves much higher results (!). The puzzling outcome of the research can be justified simply.
Table 4. Typical values of resistance depending on quantity of binder and class of soil [2]

| Type of soil              | Quantity of cement applied [kg/m³] | 28-day resistance [MPa] |
|---------------------------|------------------------------------|------------------------|
| Aggregate mud/Peat        | 150-350                            | 0.2-1.2                |
| Soft clay                 | 150-300                            | 0.5-1.7                |
| Stiff clay                | 120-300                            | 0.7-2.5                |
| Silt                      | 120-300                            | 1.0-3.0                |
| Fine and medium sands     | 120-300                            | 1.5-5.0                |
| Coarse sands/Gravel       | 120-250                            | 3.0-7.0                |

We have to take a notice of the completely different conditions of forming the samples from group 3 in comparison to the ones from 1 and 2. While the first two were conducted in laboratory, so we can make sure that the soil provided was the same and everything was mixed properly. Meanwhile all the samples from group 3 were conducted when performing DSM columns by wet method on construction site. That is why the final results of resistance reached could have been disturbed by following factors:

- Varied soil and ground water conditions in the points of collecting samples
- Substantial influence of cement slurry as a result of compiling the investigated material from the top of the column (the majority of material there is excessive, dredged cement slurry which provides overestimated results).
- Non-uniform structure of samples and presence of seams of unwanted soil material

Nevertheless, it has to be underlined that there are no samples of very low resistance. It means the DSM column formed by means of these specimens will not crack under the effect of ‘weak link’ but will rather maintain average strength.

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