

Optimal control time evaluation for “dry DSM” soil-cement composites

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Abstract. Soil improvements with hydraulic binders are a widespread practice in foundation works. They vary depending on the mixing method (jet grouting - hydraulic, deep soil mixing -mechanical), medium type (wet/water, dry/air) and binder type (cement, lime, fly ash or mixtures). The produced component’s strength changes in time thus its control should change in time as well. The paper presents the results of laboratory testing of an organic soil component mixed in dry method. The process of samples preparation and testing methodology of compressive strength and stiffness is described. Volatility of the parameters in time is considered. On the basis of the results, recommendation for optimal quality control time and its methodology for soil-cement components might be proposed.

1 Introduction to dry Deep Soil Mixing

Deep soil mixing is a ground improvement method which leads to enhancing a number of soil geotechnical properties. Cement, blast furnace slag, quick lime, fly ash or gypsum are additives used in this method. Binder is mixed with a soil at least several meters into the ground. Deep soil mixing technologies have been developed all over the world since 1970s. Polish experience [1], [2], [3] is linked mainly with the DSM wet technology. Due to popularization of the DSM technology, researches on limitation in its use for organic soil [4], [5], [6], [7] have been conducted. Interesting remarks on dry soil mixing in highly organic soils can be found in reference [8]. Special equipment is used for this purpose, depending on soil mixing type: columns installation (columns are formed one by one in different patterns and mutual position), mass stabilization (mixing unit with a mixing drum) (Fig. 1). Deep Soil Mixing is commonly used as an enhancement for embankment, excavations, foundation of houses and light warehouses, but also as geohydrological barrier or land reclamation/remediation of contaminated areas [9], [10], [11], [12]. There are no restrictions about the depth of treatment in this type of strengthening. For mass soil stabilization (Fig. 1), either wet mixing method or dry mixing method is used. Therefore, the binder can be delivered as slurry or in a dry form with compressed air as a medium. In both methods water plays the key role in binder hydration. In the wet method, water is delivered as a grout component and in the dry method – binder is mixed with high-water content soil to obtain necessary parameters.

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Due to the use of special equipped excavator the depth of treatment is limited to about 6 m.



Fig. 1. Mass mixing scheme (<https://www.menard.pl>)

Dry deep soil mixing was invented in Sweden in 1960s and became a very popular method of soil stabilization in Scandinavian countries, as well as in Japan. It is applicable in organic soils with water content exceeding 60% [8] and commonly accepted that lower water content does not allow carrying successful hydration process of binder.

For dry soil mixing, a number of binders are used. Cement is in general used as a binder for most soil conditions. Lime is suitable for inorganic soil, as is clay and slit clay. Lime provides initial dewatering effect and the increase of PH, but stabilization effect can be poor, as humic acids inhibit strengthening reaction [8]. Slag and ashes are used as secondary products in the binder. They need to be mixed with cement or lime. With their use the significant improvement of permeability is observed which results in decrease of water and chemicals penetration inside the stabilized mass [8]. Moreover it is an environmental friendly solution as both materials are an industrial waste and can be reused for a good purpose. The mixture of slag and cement is suitable (with some restrictions) for peats and organic soils.

2 Laboratory test

Initial laboratory tests are almost mandatory in case of dry mixing. This is due to high sensitivity of the mix parameter to various parameters described in the next section.

2.1 Objectives and scope of the research

The objectives of the research were to investigate:

- the optimal time of improved soil Quality Control after its implementation [13],
- the influence of cement amount on compression strength in a function of curing time [14],
- the relation between strain changes and time of curing,
- time influence on the accuracy of the archived results,
- profitability of deep soil mixing in soils with water content below 60%.

The research was conducted according to recommendations given in [15], [16] on the population of 148 samples with amount of cement – CEM IIIA 32,5 – vary between 120 kg/m³ - 230 kg/m³. The peats for laboratory test come from Oława – city in Lower Silesia province, Poland. Peats were characterized by the content of organic component between 5.80% - 8.28% - measured in combustion process. The natural moisture varied from 37.4% up to 56.2 %. The uniaxial compressive test of the samples was carried out at Wrocław University of Science and Technology and was a base for further considerations.

2.2 Samples preparation

The samples were prepared as a mixture of peat and cement in various proportions. The mixing process was carried out with an electric stirrer under constant rotational speed. Mixing process lasted around eight minutes. Placing soil-cement mixture into the cubic forms was divided into four layers under constant pressure of 18 kPa. The free surface was carefully flattened to obtain an even surface for uniaxial test. The cubic forms of internal dimensions 150×150×150 mm were used. First, they were cleaned and covered with a thin layer of oil to guarantee easiness of samples removal. The samples were stored in laboratory conditions – constant temperature 18-20°C. They were unformed 5 days after the preparation and stored in special containers.

Table 1. Breakdown by unit weight of samples and by cement amount

Unit weight of the samples [kN/m ³]	Number of samples in the range	Cement amount [kg/m ³]	Number of samples in the range
13,0 – 13,6	5	120	17
13,6 – 14,2	17	130	35
14,2 – 14,8	17	140	19
14,8 – 15,4	17	170	17
15,4 – 16,0	17	180	34
16,0 – 16,6	44	200	18
16,6 – 17,20	29	230	8



Fig. 3. Preparation of sample - mixing process



Fig. 4. Sample in the form



Fig. 5. Samples storage, right after preparation



Fig. 6. Unformed samples

The weight of the cubic samples varied from 4.46 kg to 5.80 kg depending on cement amount and compression. The samples were tested after 7, 14, 28, 56 and 84 days of preparation.

2.3 Uniaxial compression test

The uniaxial compression test was chosen, because in most of cases the DSM columns are designed and created under compression rather than by way of bending or tension. The test was conducted at Wroclaw University of Science and Technology using Compression Test Machine. During the investigation, the sample was under compressive force – linearly increasing as a result of upper pad constant movement in the lower pad direction – until the moment of the sample's destruction. During the test, several parameters were registered on the basis of the type of the chart of stress in a function of strain which was proposed.



Fig. 7. Compression Test Machine



Fig. 8. Samples after compression test

As the basis for stress/strain calculation, the following equations (1) and (2) were used:

$$\varepsilon = \frac{\Delta u}{h} \left[\frac{\text{linear deformation}}{\text{sample height}} = \% \right] \quad (1)$$

$$\sigma = \frac{F}{A} \left[\frac{\text{applied force}}{\text{compressed area}} = \text{MPa} \right] \quad (2)$$

It is easily observed that the column sample failure shape corresponds to columnar failure model rather than cone failure model, as it was for soil-cement samples tested at Wroclaw University of Science and Technology by Karpisz and Jaworski [13]. The elastic modulus E_l was determined for a linear part of stress-strain curve – at approximately 50% of compressive strength f_c .

The slope of the diagram varies at the initial fragment due to the fact that pads did not fit the samples precisely, and thus the compressive force was not transferred through the whole accessible area.

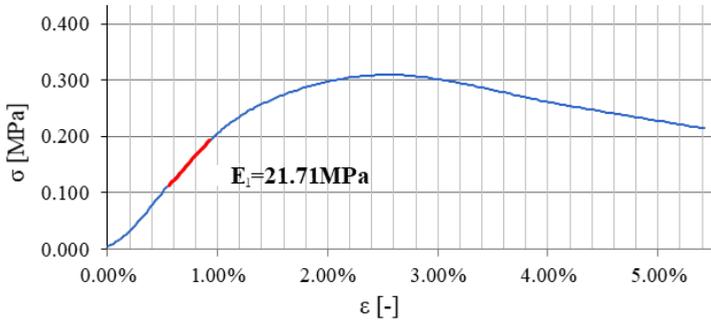


Fig. 9. Marking of the elastic modulus E_i at 50% of f_c .

3 Research program results

Figure 10. presents the changes in the compressive strength f_c in time for various cement contents (120-230 kg/m³). The increase of the uniaxial compressive strength in time varies, depending on cement amount. That might have a great influence for Quality Control methodology. Precise classification based on empirical studies should be proposed to obtain reliable results of QC. According to the obtained results – the samples with cement content between 120 kg/m³ – 180 kg/m³ should be tested after 28 days, since the observed value of compressive strength does not change in time in a significant way.

The samples with cement content exceeding 200 kg/m³ should be tested after 28, 56 and 84 days, because in the period between 56th and 84th day, approximately 50% increase of f_c is observed comparing to 56th day. Density of samples causes results fluctuations. 4% reduction of mass (in the constant volume) compared to mean value for a given series causes decrease of compressive strength despite the passage of time. For a series with cement content 200 kg/m³, the compressive strength after 56 days does not exceed the value observed in the samples with cement content of 170 kg/m³. For peats characterized by the natural moisture content in the range of 37% - 56% – stabilization with binder amount lower than 200-230 kg/m³ is uneconomical. After 84 days of curing, the observed strength is up to three times higher than for smaller cement content.

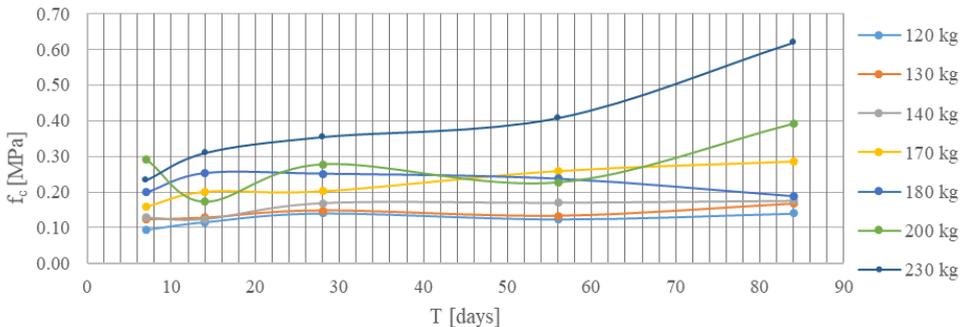


Fig. 10. Compressive strength in time for different amount of cement

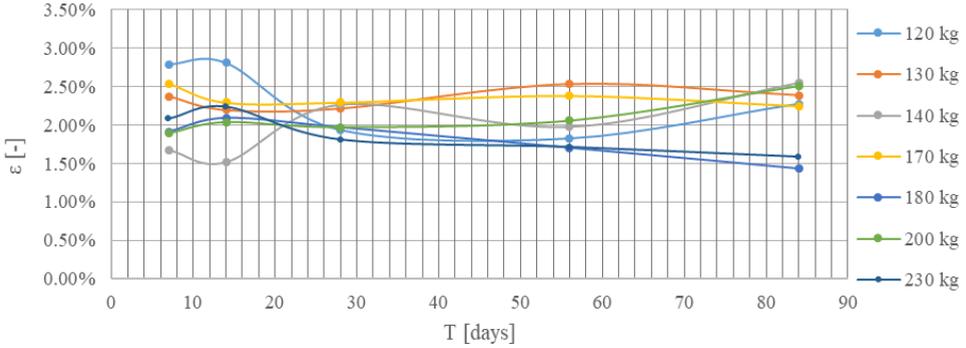


Fig. 11. Strain under breaking load in time

The diagram of strain under breaking load in function of time has a horizontal trend. Within a series (constant amount of cement), the value of strain almost does not change between 28th – 84th day of curing. It might be observed that for higher cement content, lower values of strain were registered. That leads to a straightforward conclusion: the main aspect that affects strain values is cement amount. Besides its influence on strain value, the decrease of strain volatility is noticeable. The results are ambiguous. Hence, the proposed conclusions are not fully objective.

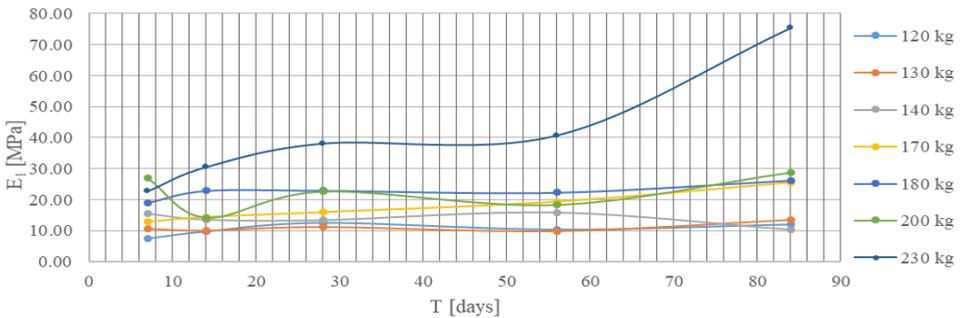


Fig. 12. Elastic modulus E_1 in time for various amount of cement

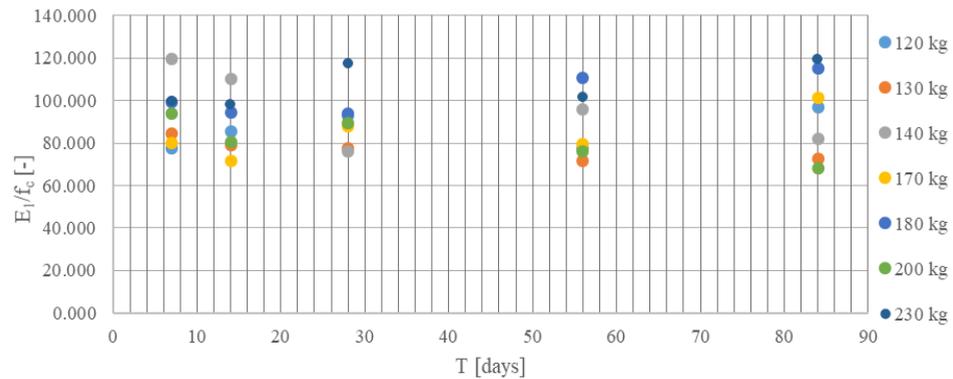


Figure 13. The dependence of E_1 modulus on f_c for the soil-cement samples under test in time

Moreover, the rise of cement amount causes non-linear growth of strength and thus additional tests should be conducted to determine if this trend continues for higher cement content. In Figure 12, variations of elastic modulus in time are presented.

Neither for cement amount of 120– 140 kg/m³, nor for cement amount of 170 – 200 kg/m³, significant increase of the elastic modulus in time is observed. The values of the elastic modulus in these ranges are as follows:

- $E_t = 7 - 15$ MPa for 120 – 140 kg/m³ of binder
- $E_t = 14 - 28$ MPa for 170 – 200 kg/m³ of binder

The change is observed for 230 kg/m³ of binder. The great increase of the elastic modulus appears after 56th day of curing. From 40.7 MPa in 56th day up to 75.4 MPa in 84th day. The results of the elastic modulus changes correspond to the results of the compressive stress changes in time, therefore the same recommendation for QC time should be given.

The diagram (Fig. 13) has a horizontal trend. The dependence of elastic modulus on strength in time varies from 70 to 120. The formula given in work [4] for DSM laboratory test is as follows:

$$E_t \approx 120 \cdot f_c \text{ [MPa]} \quad (3)$$

Theroposed value exceeds the values obtained in this research. The given formula was accurate for the tested group of samples of organic soil mixed by the wet method and for certain cement types. For current research (peats, CEM III, dry mixing), the dependence between elastic modulus and compressive strength can be formulated as:

$$E_t \approx 90 \cdot f_c \text{ [MPa]} \quad (4)$$

4 Conclusions

Control of soil improvement works quality is a basic factor for the reliability of foundations. Both, implemented testing technologies [17] and supervision quality (human factor) [18] play a decisive role, especially when the product (soil cement composite) is not uniform and the variability of parameters may be time dependent due to internal corrosion process. The two main factors that affect the results are cement amount and soil compaction. Cement content below 200kg/m³ should be taken out of consideration for DSM Dry technology in case of soils which were considered ($I_{om} \sim 6-8\%$, $w_n = 38-56\%$). None significant growth of the compressive strength in time appeared. Higher amount of binder influences the strain decrease; it improves column stiffens, but still to the lower level than in the case of wet mixing. Even local changes of soil compaction can highly affect soil-cement composite's properties, thus precise geological studies should be carried on. During the stabilization process, the mixing and compression parameters should be carefully observed. They vary depending on the rotation speed, feed speed, blades number and compressed air stream. It is a common practice to enhance compressive strength by overloading the stabilized area with additional surcharge right after mixing. Laboratory tests confirm the impact of pre-compression on the achieved results in a time scale. It also speeds up the settlement process which is the main issue in organic, highly compressible soils. The research indicates that in order to capture all of the changes of soil-cement composite, optimal time for quality control is around 28th, 56th and 84th day of curing. Finally, despite the general perception, in the DSM Dry technology it is possible to considerably improve parameters of soil with the natural moisture content around 40%.

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