Study of the effect of cement amount on the soil-cement sample strength

Izabela Karpisz 1, Jacek Pyda 1, Leszek Cichy 2 and Dariusz Sobala 2

1Wrocław University of Science and Technology, Wyb. Wyspiańskiego, 27, Wrocław, 50-370, Poland
2STRABAG Sp. z o.o., ul. Parzniewska 10, Pruszków, 05-800, Poland

E-mail: jacekpyda@gmail.com

Abstract. This paper presents the results of laboratory tests of low amount organic soil-cement samples. The research program is a continuation of previously reported experience of Wrocław University of Science and Technology (WrUST) with high amount organic soil sample testing. Over 150 of compression and a dozen of tension tests have been carried out altogether so far. Samples were mixed and stored in laboratory conditions. Several samples were waiting for failure test for over one year after they were formed. Several factors were of crucial importance to the scope of this research: a large number of samples under test, a long observation time (3 months), carrying out the tests in complex cycles of loading and the possibility of registering the loads and deformation in the axial direction. All these made it possible to take into consideration numerous interdependencies which have been presented in this work: the increments of compression strength and the stiffness of soil-cement in relation to time and cement amount. Both compressive strength and elastic modulus were examined on cubic samples. Tensile resistance was derived from the testing of tubular samples. The results are generally in accordance with previous research and the results previously obtained in simultaneous tests by other authors.

1. Introduction
The increasing trend of designing structures on “weak soils” is responsible for the growing need for soil improvement and stabilization. This trend required civil engineers to expand their knowledge in terms of technologies which make it possible to achieve desirable level of soil strength. Soil improvement technologies demand various control procedures depending on the expected effect of soil strengthening. The importance of geotechnical monitoring (supervision) was clearly stated in work [1] whose authors referred to various quality testing procedures, and in references [2,3] where dedicated testing technologies were described. The nature of ground parameters is differing and partially unpredictable, similarly to the variability of recycled materials used in geotechnical engineering as described in references [4,5]. The need of standardization of requirements and current progress of soil improvement technologies imposed the involvement of universities – mostly in a way of scientific research [6,7] and also the concern of building industry Research & Development units. The current study joins the scientific potential of the academic world with the potential of a leading construction company, which may implement the obtained results directly in construction business.
1.1. The sense of DSM technology

One of the methods that is increasingly used in geotechnical engineering is Deep Soil Mixing technology, which was invented in Japan merely 40 years ago. At that time, the first full scale application using lime took place. Since then, deep mixing technology has been constantly developing. This method is very useful for strengthening weak cohesive soils (Figure 1.), but there are no counterindications to use it for non-cohesive ones, which is also practised.

![Figure 1. DSM columns for one of pillars of Lublin-Legnica dual clearway, source: http://www.s3-polnoc-nowasol-legnica.pl/galeria-5/2015-11/1004?page=1](image1)

![Figure 2. Securing excavation walls with DSM columns in Wrocław, source: http://www.kataloginzyniera.pl](image2)

1.2. Technology description

There are three methods of strengthening soil by using the DSM technology: dry DSM method, wet DSM method and Mass Stabilization. Dry DSM method involves mechanical mixing of a dry binder with a soil of sufficient moisture (usually greater than 60%, near liquid limit) enabling chemical reactions between soil, binder and groundwater. The transportation of dry binder is provided by compressed air. For the most part, it is used for soft cohesive soils, including organics, since more economical techniques can be used for other types of soil. Typical diameters of formed columns range between 0.6-0.8 m and the treatment is doable up to depth of 25 meters, but usually maximal length of column is about 10 meters. A great advantage of this method is the fact that it creates roughly no spoil for disposal; moreover, forming at low temperatures is possible.

The procedure of wet Deep Soil Mixing is carried out in a way very similar to dry one. Nevertheless, binding slurry is used instead of a dry binder. The range of diameters of a formed column is definitely greater than in the previous case, since it oscillates between 0.4 m and 2.4 m, depending on requirements. If very high quality is required, there is a possibility of mixing inside a tube. Such manner of forming is called Tubular Soil Mixing (TSM). Moreover, one can enhance the tightness by adding some components of slurry, for instance bentonite. The equipment needed for the DSM technology consists of: a binder storage, a special rig equipped with a drilling rod, transverse beams and a drilling auger at the end of the rod.

Mass Stabilization technique is suitable while dealing with significant volumes of weak soils. It is a method of relatively shallow dry mixing, where the drilling element is able to move both in vertical and horizontal direction. Owning to limited reach of the drilling rig, the process of stabilization is divided into sequences. The area of soil stabilized at the same time is usually about 8 to 10 m² and approximately 4 meters deep. After implementing the required volume of binding material, the process of mixing is continued by the time a homogenous structure is obtained. What is more, the Mass Stabilization can be performed not only by adding the material into the soil but also by forming soil-fly-ash mixtures for the already existing structures. An experiment performed by German and Polish engineers in 2013 is a satisfying verification of that thesis [8].
In Deep Soil Mixing technology, the strengthening of the soil is reached by mixing the soil with a binder (for example cement, cement with lime, bentonite or cement with fly ashes [9]). Forming of the columns consists of several stages:

- one has to prepare a solid subbase for the machine (working platform),
- the DSM rig and the rod must be precisely positioned. The axis of the drilling rod should overlap the axis of the designed column,
- drilling is executed until the designed depth is reached,
- the phase of construction begins: the slurry is injected through nozzles located at the end of the rod and mixed with the soil. The direction of the rotation reverse to the one in the penetration phase. The ability of mixing tool to move up and down along the column being formed boosts the homogeneity of the cement-soil mix. The volume of injection depends on properties of the columns that must be obtained. As for the quality of formation, the mixing process is constantly monitored and controlled.
- after forming the column one can improve the bending stiffness by inserting reinforcement into the column. As an example, such need can occur while securing an excavation walls with the DSM columns where high bending forces act on the columns. It can be a dangerous situation since the DSM columns have relatively low tensile strength. This is why they are reinforced with steel sections, pipes or rods.

![Figure 3. Stages of forming DSM columns, source: www.menard.pl](image)

There are many positive aspects of this technology:

- drilling includes very low vibrations and noise,
- it is an environment-friendly solution,
- the DSM method is relatively cheap and quick,
- it is possible in low temperatures,
- the forming of the columns results in nearly no excavated soil,
- it has soil sealing properties,
- the columns can be formed in very problematic and high-moisture soils,
- it is a form of prevention from liquefaction.

That is why the DSM columns are used as:

- the stabilization of the soil,
- the tightening of the soil,
- retaining wall and excavation support,
- support of foundations (slab/strip/pad foundations, foundations under bridges, wind-turbines etc.).
• embankments,
• reduction of the probability of liquefaction.

The works of Topolnicki [10-13] describe at length Polish local experience in implementing the DSM Wet Technology by Keller Polska.

2. Laboratory testing of organic clays – test description

Polish experience with organic soil stabilisation was presented in works by Kumor [14] and Topolifski [15], where stabilised limestone gyttja was under test. The results were rather disappointing. Similar, rather negative experiences with highly organic peat were reported by Leśniewska in work [6]. Previous research conducted at Wrocław University of Science and Technology, described in works of Kanty et al. [16] and Egorova et al. [17], related to highly organic peat, emphasise the necessity of trial testing prior to the execution of geotechnical works. During in situ mixing, the organic material surrounded by sand layers surely mixes with one another in certain areas. However, it has not been examined and it is difficult to assume such mixing already at the designing stage. In case of designing the DSM columns which go through a thick layer of organic soil it is recommended to carry out the core drilling which checks the degree of material mixing and its strength.

2.1. Materials

Similarly to previous studies reported by Kanty et al [16], two types of cement (with the parameters specified below) were used for the tests. Organic clayey soil (brought from the building site in Kraków) with organic particle amount of 5.5% (in the dry mass) and water content equal to 38.5% was used to form trial samples. As it is definitely easier to mix the soil in laboratory conditions (it is possible to crush it into smaller parts) than in situ, it could be concluded that the obtained results present the upper bound of derived parameters (strength, modulus).

As the hydraulic binder for the making of the cement-soil samples two types of cement were used: CEM II/B-S 32.5R-NA and CEM I 42.5R (Górąźdże Cement S.A. [18]). These cement types are characterized by the strength achievable after 28 days: 50.0 MPa and 57.5 MPa, respectively. The WrUST previous experience from the testing of cement-soil pointed to a comparable usefulness of both cement types for the forming of the DSM material in mineral soils (sands, clays).

The cubic samples, with the dimensions of 15×15×15 cm (Figure 4), were prepared by mixing the organic soil together with the cement slurry, the density of which equalled 1.5 g/cm³. The cement was applied in doses of pre-defined values so that the final outcome gave 250, 300, 400 kg/m³ for the tests conducted. It must be highlighted that such an amount of cement is relatively large for deep mixing – most often the amount of cement applied in situ is no more than 200-250 kg/m³.

Figure 4. Cubic and tubular samples of cement-soil in the testing machine PROETI
2.2. Methodology
Similarly to the methodology applied in the test described in references [16] and [17], our tests were conducted for a constant rate of displacement with the velocity equal to 0.01 mm/s and in the controlled temperature of 20°C. The cubic cement-soil samples were tested for uniaxial compression strength and modulus as outlined in the Code of Practice [19]. The PROETI mechanic press shown in Figure 4 was synchronized with a computer recording: time elapsed since the beginning of the test, the axial force loading the sample, the axial displacement of press piston (reduction of the sample’s length in the axial direction). The data were sent continuously to the PC equipped with software for the automatic recording of tests. The modulus of volume elasticity was determined as the mean modulus for an approximately rectilinear fragment of a tension-deformation curve (at 50% of compressive strength) by a linear interpolation by means of the least squares method in Excel software.

The tests for tension strength during the crushing of the samples of cement-soil were carried out in a way similar to compression tests – on tubular samples with the dimensions of D=13.0 cm and H=11.2 cm. The value of the tensile strength while crushed ($f_t$) was obtained from the formula (1):

$$f_t = \frac{2 \cdot F}{\pi \cdot D \cdot H}$$

Where: $F$ is the maximum load applied, $H$ is the height of the sample, and $D$ is the average diameter of the sample (average length of the contact line).

3. Results of laboratory testing
As it was previously mentioned, the results of compressive strength, elastic modulus and tensile strength are gathered for the current study.

3.1. Comparison of compressive strength of CEM II 32.5 and CEM I 42.5 based soil cement samples
Figure 5 shows material strength increments in time after mixing. The amount of cement applied for the tested material was 250, 300, 400 kg/m$^3$ for the tests conducted at WrUST.

![Figure 5. The increment of uniaxial compression strength in time for CEM II and CEM I and various cement content (250, 300, 400 kg/m$^3$)](image)

Some conclusions can be drawn directly on the basis of those results:
- as a rule, in the period between the 4th to 12th week of material curing, an increase in strength is observed for CEM II samples; contrary, in the case of CEM I samples, the capacity tends to stabilize after 4 weeks,
- it is not possible to predict which cement allows the material to reach higher strength values.
Similarly to the previously reported results [16], one may observe on Figure 5 the lack of constant correlation between the strength and the cement type and, what is worse, the lack of a clear relationship between the strength and the amount of the added slurry content. That shows, for every series of tests, the decisive impact on the results relies on the type of the soil used for the subsequent concrete mix. The important finding is that “weaker” samples tend to increase their capacity in time (between 4th and 12th week), while “stronger” samples stabilize after 4 weeks. That brings some questions to the testing procedures that should be applied to the DSM column material testing. Fortunately, no strength decrease (as in reference [16]) was observed in time. Figure 6 presents the same data of compressive strength with regard to the amount of cement applied for each group of samples, grouped for subsequent testing times.

![Graph of compressive strength vs. cement content](image)

**Figure 6.** The increment of uniaxial compression strength of subsequent groups of samples with respect to cement amount and time of curing

3.2. *Stiffness vs. strength of soil-cement samples*

The modulus of volume elasticity ($E$) was determined at 50% of compressive strength. Its value for a given series and particular point in time are presented in Figure 7. One conclusion can be drawn again on the basis of those results. In the period between the 4th to 12th week of material curing, no considerable increase in stiffness is observed for all the samples and it is not possible to predict which cement enables for reaching higher elastic modulus values.

![Graph of elastic modulus vs. time](image)

**Figure 7.** The increment of elastic modulus in time for CEM II and CEM I samples, for various cement content (250, 300, 400 kg/m³)
Elastic modulus values for all given series are shown in Figure 8 in relation to the uniaxial compression strength. It is visible that this dependence is practically linear and it does not really depend on curing time of the test sample, the type of cement used, and the soil applied. The obtained dependence of compression strength on the mean moduli of volume elasticity may be approximated by a straight line. This straight line (Figure 8) shows a good matching independent of the group of samples. It could be compared with the proposed value given in [16] where the modulus was assumed to be 120 times greater than strength.

![Figure 8](image)

**Figure 8.** The dependence of $E$ modulus on $f_c$ for the soil-cement samples under test compared to results obtained in organic clays

According to the equation of the straight line (trend line – linear), the dependence between the $f_c$ vs. $E$ will be formulated as follows (2):

$$E \approx 143 \cdot f_c \text{ [MPa]}$$  \hspace{1cm} (2)

It is necessary to remember that this formula is true for the tested group of organic soil and cement types. Generally, it may give the idea of the rank of the values of these moduli in the cases when the organic soil (containing peat) is mixed with cement.

### 3.3. Tensile strength vs. compression strength of soil cement samples

Tensile strength was determined for the curing time of 28 days, i.e. for the expected time usually needed to complete the curing of the ground-cement material. The obtained results for all groups of samples are presented in Table 1.

| sample     | $f_t$ [MPa] | $f_c$ [MPa] | $f_t/f_c$ |
|------------|-------------|-------------|-----------|
| cem II-250 | 0.19        | 1.58        | 12.0%     |
| cem II-300 | 0.23        | 2.45        | 9.4%      |
| cem II-400 | 0.26        | 3.04        | 8.5%      |
| cem I-250  | 0.17        | 1.94        | 8.7%      |
| cem I-300  | 0.18        | 2.12        | 8.3%      |
| cem I-400  | 0.34        | 4.44        | 7.6%      |
The results obtained in course of testing do not present a considerable amount of trials in the tension test. Only one sample was prepared for each series (8 test results presented on Figure 9). Despite that, the value of the obtained $f_t/f_c$ relations is consistent with previous experience of the authors in the tests of organic soil. By way of generalization, it is possible to assume that the tensile strength of soil-cement $f_t$ equals approximately 8.4% of the compression strength $f_c$. In designing, however, it will be safer and more reasonable to assume that the value of $f_t$ is equal to zero as proposed in work [16].

![Graph](image)

**Figure 9.** The dependence of tensile strength $f_t$ on compressive strength $f_c$ for the soil-cement samples under test compared to results obtained in organic clays

### 4. Summary and basic conclusions

It is necessary to remember that the DSM technology is recommended mainly for the reduction of settlement in the situations when the load-bearing capacity is ensured. Of course, it must be also remembered that a soil-cement material – especially the one obtained in situ – will never be as homogeneous and resistant as the mix prepared in laboratory conditions. Some consolation may be offered by the fact that in the DSM columns with large diameters one can count on the averaging of the values of strength parameters on the possible failure surfaces. In order to confirm that intuition, though, large-scale tests on core samples would be necessary. Interesting developments concerning the micro-scale structure of cement-soil material was given by Piasecki and Stefaniuk in reference [20].

The current study proves that for the grounds where organic content does not exceed 5-6%, the process is relatively easy to control and proper amounts of cement slurry may be given on the basis of the laboratory tests. Some preliminary conclusions may be drawn:

- in most cases of mixing 5.5% organic clay with cement content of 300 kg/m$^3$ and more, the level of strength reached 3.0 MPa;
- the relation between $f_t$ and $E$ in case of mixed 5.5% organic clay is slightly different than it is for peat with resistance lower than 1.0 MPa;
- the values of strength obtained after 28 days are not stable in time and depend on the binder.

It must be noted that the tests proved that after mixing, the soils with the organic content at the level of a few percent may behave in a different (more advantageous) way than the grounds with the content of the organic component of 40-45%. The authors consequently recommend that sample batches of mixture should be made each time an organic ground is being classified, so that it is possible to design the appropriate amount of cement and assess its parameters after mixing.

### Acknowledgements

The authors would like to thank B U G GEOTECH for making available their laboratory for the preparing and storing of soil cement test samples. A special gratitude is expressed to STRABAG for
financing the whole testing program, carried out at WrUST. Our deep gratitude is also addressed to laboratory staff in Chair K1 at Faculty of Civil Engineering and authors’ supervisor: Dr Jarosław Rybak for their assistance and providing references for the current study. This work was partially co-financed from the internal research grant at Wroclaw University of Science and Technology: grant no. 45WB/0001/17 – “Industrialized construction process (construction 4.0)”.

References
[1] Sobala D, Rybak J 2017 Role to Be Played by Independent Geotechnical Supervision in the Foundation for Bridge Construction, IOP Conference Series: Materials Science and Engineering, 245 (2), art. no. 022073
[2] Drusa M, Vlcek J 2016 Importance of Results Obtained from Geotechnical Monitoring for Evaluation of Reinforced Soil Structure – Case Study, Journal of Applied Engineering Sciences, De Gruyter Open, vol. 6. Issue 1/2016
[3] Drusa M, Chebeň V and Bulko R 2014 New technologies implemented in geotechnical monitoring on transport constructions. Int. Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM, 2 (1), pp 651-56
[4] Pilipenko A, Bazhenova S 2017 Usage of crushed concrete fines in decorative concrete, IOP Conference Series - Materials Science and Engineering, vol. 245 (2), art. 032082
[5] Kawalec J, Kwiecień S, Pilipenko A and Rybak J 2017 Application of crushed concrete in geotechnical engineering - selected issues, IOP Conference Series - Earth and Environmental Science, vol. 95 (2), art. 022057
[6] Leśniewska A 2007 Strength and technological issues of soil improvement by means of Deep Soil Mixing Wet technology. Doctor’s Thesis, Gdańsk University of Science and Technology, (in Polish)
[7] Baker S D 2015 Laboratory Evaluation of Organic Soil Mixing”, Graduate Theses and Dissertations, University of South Florida, http://scholarcommons.usf.edu/etd/5640
[8] Duszyński R Duszyńska A and Cantré S 2017 New experiences in dike construction with soil-ash composites and fine-grained dredged materials, Studia Geotechnica et Mechanica, vol. 39 (4), pp 17-24
[9] Stefaniuk D, Zajączkowski P and Rybak J 2016 Methodology of axial testing of cement-fly ash-soil samples. Stroitel’stvo-formirovanie sredy õživneãâtel’nosti. Moskva, 27-29 apríľ 2016 r. : sbornik materialov. Moskva : NIU MGSU, pp 1091-94
[10] Topolnicki M 2006 Soil mixing - challenges of applications ranging from ground improvement to structural elements, XIII. Danube-European Conference on Geotechnical Engineering, Ljubljana, 29-31.05.2006, pp 1-6,
[11] Topolnicki M 2009 Design and execution practice of wet Soil Mixing in Poland, International Symposium on Deep Mixing & Admixture Stabilization, Okinawa, 19-21 May, pp 195-202,
[12] Topolnicki M 2015 Geotechnical design and performance of road and railway viaducts supported on DSM columns – a summary of practice. International Conference on Deep Mixing, June 2-5, 2015, San Francisco, pp 1-20
[13] Topolnicki M 2016 General overview and advances in Deep Soil Mixing, XXIV Geotechnical Conference of Torino Design, Construction and Controls of Soil Improvement Systems, Torino, 25-26.02.2016, pp 1-30
[14] Kumor Ł 2006 Testing of gyttja stabilized by Dry Mixing. Zeszyty Naukowe Politechniki Białostockiej, Budownictwo 9, pp 97-106, (in Polish)
[15] Topolnicki S 2009 Compressive strength of cement stabilized limestone gyttja. Problemy geotechniczne i środowiskowe z uwzględnieniem podłožy ekspansywnych, Uniwersytet Technologiczno-Przyrodniczy w Bydgoszczy, pp 617-23, (in Polish)
[16] Kanty P, Rybak J and Stefaniuk D 2017 Some remarks on practical aspects of laboratory testing of deep soil mixing composites achieved in organic soils, IOP Conference Series - Materials Science and Engineering, vol. 245 (2), art. 022018
[17] Egorova A A, Rybak J, Stefaniuk D and Zajączkowski P 2017 Basic aspects of deep soil mixing technology control, *IOP Conference Series - Materials Science and Engineering*, vol. 245 (2), art. 022019

[18] Declarations of Cement Utility Performance: CEM II/B-S 32.5R-NA and CEM I 32.5R (Górażdże Cement S.A.)

[19] ASTM (D 3148-02) Standard Test Method for Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression.

[20] Piasecki D, Stefaniuk D 2016 Micro-scale laboratory investigation of cement-soils composite, *Stroitel'stvo-formirovanie sredy žiznedeâtel'nosti, Moskva, 27-29 aprilâ 2016*. Moskva: NIU MGSU, pp 1061-65