Some remarks on statistic approach to strength testing of soil-cement composites

Piotr Kanty[1], *Monika* Kiecana[1] and *Piotr* Prokopowicz[2,*]

[1] MENARD Polska Sp. z o.o., ul. Powązkowska 44c, 01-797 Warsaw, Poland
[2] Wroclaw University of Science and Technology, Wyb. Wyspiańskiego 27, 50-370 Wrocław, Poland

Abstract. Results of laboratory testing of organic soil-cement samples are presented in the paper. The research program continues on the authors previously reported experiences with cement - organic soil sample testing. Over 150 compression tests have been carried out altogether. Several samples were cured for over 3 months before they were tested. Several factors, such as: the large amount of the pieces under test, long observation time, carrying out the tests in complex cycles of loading and the possibility of continuous registering the loads and deformation in the axial direction – made it possible to control numerous interdependencies, some of which have been presented in this work. Compressive strength and elastic modulus of cubic samples were examined. Samples were mixed and stored in laboratory conditions. The results clearly point to the fact that designing the DSM dry columns in the organic soil may be linked with a considerable risk and needs special precautions. 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.

1. Introduction – some remarks on Deep Soil Mixing (DSM)

Various technologies of Deep Soil Mixing are implemented mainly in the foundation of bridges and other engineering structures [1-3]. Dry soil mixing can be used in soft soils of high moisture [4-7]. The typical DSM equipment consists of a binder injectors and a drilling machine, which are adopted to work in adverse soil conditions. The binder is transported using compressed air. Its amount is permanently monitored in order to estimate the total usage per 1 m^3. The process of mixing dry binder with surrounding soil takes place when lifting up the auger (rotating in a direction reverse to the one at the stage of penetration). The typical diameter of columns is 60-80 cm and maximum depth of implementation is roughly 10m. Control procedures are generally similar to those designed for the DSM wet version, where the binder is injected in a liquid form [8-12]. The most essential advantages of dry methods are:

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

* Corresponding author: 225326@student.pwr.edu.pl

Another kind of dry soil mixing is mass stabilization. In this method special augers are assembled to the arm of the excavator. Mixing occurs in both horizontal and vertical direction. Stabilization process is divided into stages covering 8-10 m^2. Providing proper dosage of binder and/or fly ash [13,14], mixing is continued in order to obtain homogenous structure. The current study concerns an influence of the dry binder application on soil-cement composite.

The resistance of the DSM columns formed by means of mixing the organic soil with a dry cement binder and its increase in time will be taken into account. The obtained results enabling to carry out this study were taken from laboratory tests performed at the Faculty of Civil Engineering at Wroclaw University of Science and Technology. The tests and a sample design calculation for strip foundation formed the basis of Piotr Prokopowicz's master thesis. This is just a small part of a larger investigation of various composite materials (including soil-cement composites for various binders and modes of mixing), which is aimed at boosting the knowledge of their possible implementation in the building industry. MENARD Polska Sp. z o.o. was a partner of the research, providing all the organic soil from their building sites. Testing of compressive strength of those composite materials, with varying cement amount in the composite, is presented in the paper.

In order to derive satisfactory and comparable results and obtain a reliable picture of development of compressive strength for test specimen, six subgroups of specimens will be presented based on cement amount [15,16] and different hardening times are arranged. Each subgroup consists of many samples tested after different times throughout the duration of the research program. For each group there were some specimens tested and the average value of both uniaxial compressive strength and Young modulus were derived. Selected samples were tested in unloading-reloading mode to evaluate its stiffness in pre-consolidated phase. Moreover, each category is divided into subcategories concerning the time of hardening of the specimen (from 7 to 84 days). Finally, we obtain thirty subcategories of samples. The whole classification is presented in the following Table 1

Table 1. Classification of performed tests.

Time of maturing (days)		7	14	28	56	84
Series number	Cement amount (kg/m^3)	Number of tested samples				
Group 1	123	5	4	6	5	5
Group 2	130	6	3	6	6	5
Group 3	141	4	2	4	4	3
Group 4	170	8	4	8	8	6
Group 5	180	4	2	4	3	3
Group 6	200	6	3	6	6	4

2. Laboratory research program methodology

As the DSM columns are mainly subject to compression, much more often than to bending or tension (which is more complex problem in terms of laboratory investigation). Using the uniaxial compressive test (UCT) we are able to observe lower strength results than during triaxial test. It means that we keep the safety margin for future design. In order to perform UCT, 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.

Using the obtained results we are able to derive the chart of stress σ_1 [MPa] as a function of strain ε_1 [%]. Maximum stress was measured at approximately ε=2%, while the test was finished in the moment when total strain exceeded 5%. Simultaneously, it was 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. In the first phase of the uniaxial compressive test we can 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 (1):

$$E = \frac{\Delta\sigma_1}{\Delta\varepsilon_1} \quad (1)$$

where: $\Delta\sigma_1$ – difference between stresses for two subsequent points [MPa]

$\Delta\varepsilon_1$ – associated difference in strains for the same points [%]

2.1 Succession of soil and soil-cement composite testing procedures

Preliminary tests were focused on proper control of soil parameters before its mixing with cement binder. The water content (Figure 1) and amount of organic parts in dry mass (Figure 2) were examined for proper classification of soil.

Fig. 1. Control of sample moisture content

Fig. 2. Testing of organic parts amount

The results of soil testing were juxtaposed in Table 2.

Table 2. Basic geotechnical information about the ground under study.

Soil Type	Natural Peat
Amount of organic parts in dry mass [%]	5.5% – 8.3% Average: 6,5%
Water content [%]	37.4% – 56.2 % Average: 47,7 %

A typical specimen for that kind of testing is cubic: 15×15×15 cm. The area of the compressed edge is then 0,0225 m^2. The whole process of forming a specimen consists of several steps. We have to prepare necessary equipment which is: a large bucket, scales, empty forms and a mixing machine. Components of the mixture are: mixed soil and cement. Having scaled the ingredients, we put them into the bucket. All components are to be mechanically mixed to ensure a clear and uniform structure of final soil-cement material. According to former experience [6,7], the mixing process should take roughly from five up to ten minutes.

It is important that after adding the binder we must finish the whole process within 20-30 minutes, so as not to let the soil-cement mixture to harden too much. Having reached the aimed uniform structure and properties of the material, we start filling the previously prepared standard forms. These are made of plastic forms of internal size 15×15×15 cm. The upper surface of the material is leveled by means of a trowel. This activity is needed to ensure a flat surface of all sides. It is essential that every test specimen is prepared in the same way (with regard to the expected cement content) so the final results are reliable and comparable. Over 150 cubic samples were prepared altogether for UCT procedures, 148 samples were successfully tested. The binder used for the production of all DSM dry composite was standard cement CEM IIIA 32.5 N/LH/HSR/NA that exhibits the strength circa 22.0 MPa only after 7 days. After completion of sample preparation it is just the matter of time to use them in the uniaxial compressive test.

2.2 Methodology of uniaxial compression test (UCT)

The tests were conducted for a constant displacement with the velocity of 0.01 mm/s, in a controlled temperature of 20°C ± 3°C. The uniaxial compression strength tests of the cubic cement-soil samples were carried out in the PROETI mechanic press Figure 3 and Figure 4, synchronized with a computer recording: the time elapsed since test beginning, the axial force loading the sample, the axial displacement of the press piston (the reduction of the sample's length in the axial direction). Strain-stress charts for exemplary samples with determining compression strength and elastic modulus, are given on Figure 5 and Figure 6.


Fig. 3. and **Fig. 4.** Observed modes of failure mechanism in compression testing

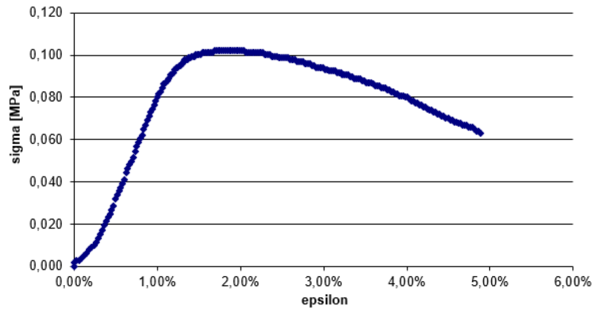

Fig. 5. Strain-stress chart. Sample from group 1, stored for 7 days. Derived uniaxial compression strength is, $R_c = 0{,}102$ MPa.

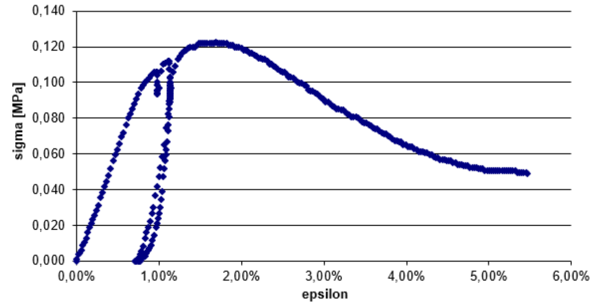

Fig.6. Strain-stress chart Sample from group 1, stored for 14 days. Derived uniaxial compression strength is, $R_c = 0{,}122$ MPa. Derived elastic modulus is,

$E_2 = 30{,}08$ MPa.

3. Uniaxial compression testing results on cubic samples for subsequent groups of samples

Low strength measurements of soil-cement formed in peats confirms the tests previously conducted by Jendrysik [4] and Kiecana [5]. The long time necessary to attain the maximum strength proves that it is desirable to take into consideration the plan of quality control of the material from which the columns are formed. The test carried out after 28 days may be unreliable (the results may be significantly underrated). The observed decreases in the samples' strength examined after 3 months are also alarming. They point to the degradation of the cement-organic material even if there are no external corrosive factors. The test samples were stored in a humid environment, humus-acid free, which would be the situation of an actual column formed in hydrated peats.

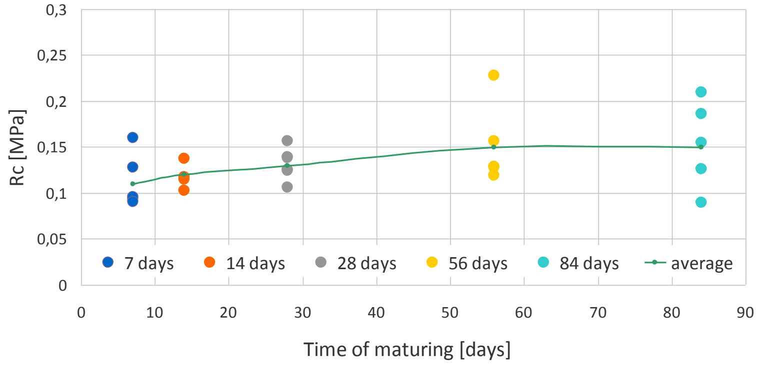

Fig. 7. Increase of measured compressive strength in time throughout testing program – group 1

https://doi.org/10.1051/e3sconf/20199704045

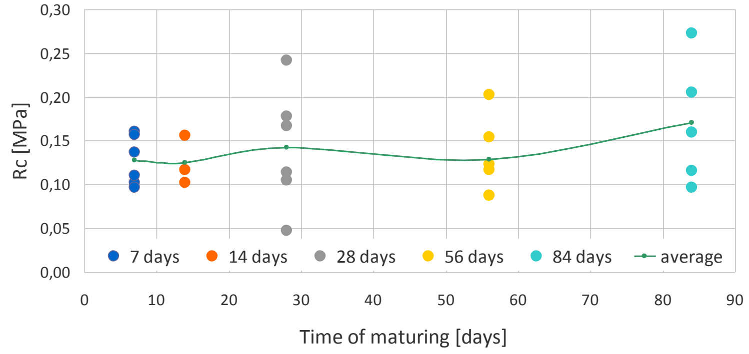

Fig. 8. Increase of measured compressive strength in time throughout testing program – group 2

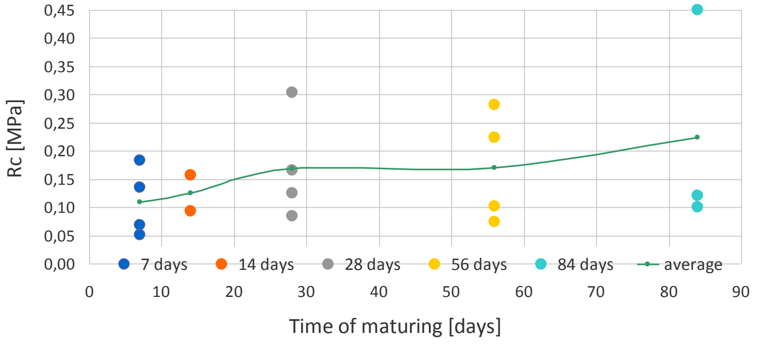

Fig. 9. Increase of measured compressive strength in time throughout testing program – group 3

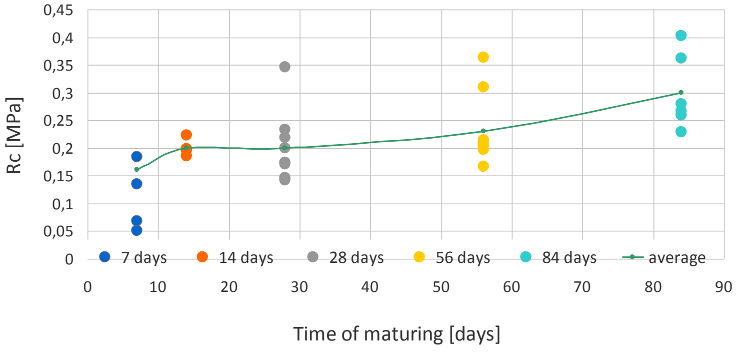

Fig. 10. Increase of measured compressive strength in time throughout testing program – group 4

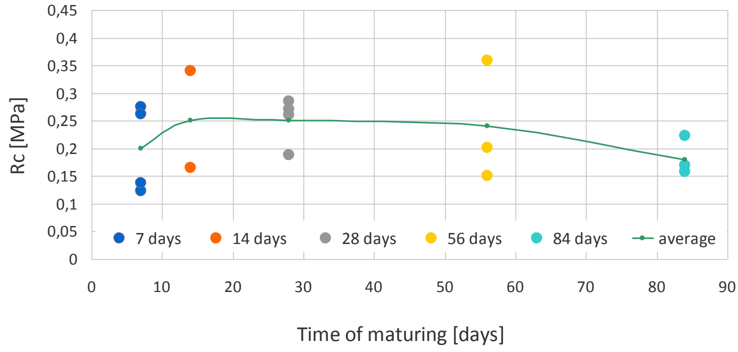

Fig. 11. Increase of measured compressive strength in time throughout testing program – group 5

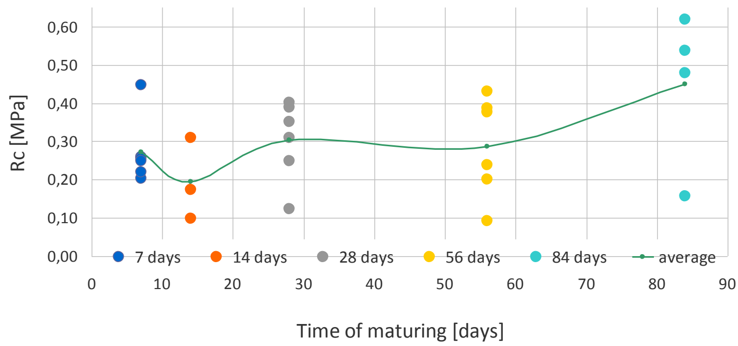

Fig. 12. Increase of measured compressive strength in time throughout testing program – group 6

4. Statistic analyses of obtained results

As the numbers of samples were similar for all the groups, it was possible to check whether the histogram of the obtained compressive strength results would fit into the well-known shape of normal (Gaussian) distribution. Standard deviation of results σ for each group was computed. On the basis of those results it was possible to state that 64% of the results are within $\pm 1\sigma$ margin around the mean value. No less than 87% is fitted within $\pm 2\sigma$ margin around the mean value. Theoretical values are 66% and 95%, respectively.

Histogram of compressive strength distribution is given on Figure 13 below.

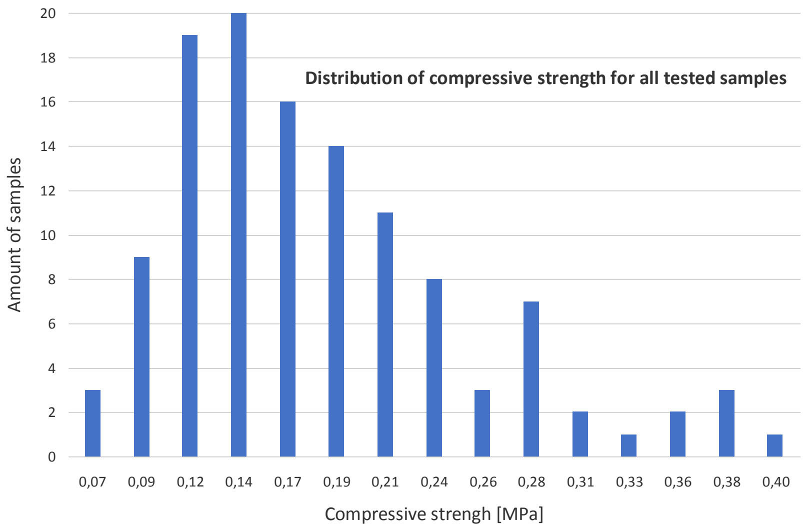

Fig. 13. Histogram of compressive strength distribution for the tested samples

The above presented analysis confirms that, at least for the range of performed test, the results should not be represented by means of normal distribution. Topolnicki in work [2] suggests to use the lognormal distribution. Previous studies with the DSM wet methods confirmed relatively uniform structure of samples and very law number of outliers between results. Large diversity of current study results was probably caused by a relatively law uniformity of manufactured samples due to their various weight – the average weight of the samples was 5kg ± 0,7kg. The weight of the samples varied 14% from the mean value. The heavier samples tend to be stronger and provide higher stiffness for all of performed test.

The values of the mode of destruction, presented on Figure 3 and Figure 4, do not differ much from each other and from the ones found in formerly reported studies [8-13].

5. Conclusions and final remarks

Maximum capacities in most of the cases were gained after 56 days since the composite production. The strength gain should be tested for a longer time period, because the impact of environmental conditions might be diminishing for the composite capacity. The optimal way of improving the reliability of DSM dry method would be the compaction at early stage of setting (increasing density), early over-consolidation and possible inclusions of granular mineral material – preferably sand, gravel or thin particles from demolition works [17].

The increasing amount of cementitious binder may also solve the problem; however current need for sustainable constructions [18] poses serious questions over that solution due to high carbon dioxide footprint.

Results of the current study formed the basis for Eng. diploma thesis of the author - special thanks are addressed to dr Jarosław Rybak who supervised it. The current study is a part of research grant no. 45WB/0001/17 – “Industrialized construction process (construction 4.0)”

References

1. M. Topolnicki, Design and execution practice of wet Soil Mixing in Poland,

International Symposium on Deep Mixing & Admixture Stabilization, Okinawa, 19-21 May, pp 195-202 (2009)
2. M. Topolnicki, Geotechnical design and performance of road and railway viaducts supported on DSM columns – a summary of practice, *Int. Conf. on Deep Mixing, June 2-5, 2015, San Francisco*, 1-20 (2015)
3. P. Rychlewski, Wzmacnianie podłoża gruntowego pod inwestycje infrastrukturalne, Materiały budowlane, **547** (3/2018), 6-8, [in Polish] (2018)
4. J. Forsman H. Jyrävä P. Lahtinen T. Niemelin I. Hyvönen. Mass stabilization manual. http://projektit.ramboll.fi/massastabilointi/materials/mass_stabilization_manual_2015.pdf
5. Design Guide: Soft Soil Stabilisation: EuroSoilStab: Development of Design and Construction Methods to Stabilise Soft Organic Soils, IHS BRE Press, ISBN-1860815995 (2010)
6. K. Jendrysik, M. Kiecana, H. Szabowicz, Preliminary results of dry Deep Soil Mixing soil-cement composite testing, MATEC Web Conf., **251**, 01025 (2018)
7. M. Kiecana, P. Kanty, K. Łużyńska, Optimal control time evaluation for "dry DSM" soil-cement composites, MATEC Web Conf., **251**, 01023 (2018)
8. A. Leśniewska, 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] (2007)
9. A.A. Egorova, J. Rybak, D. Stefaniuk, P. Zajączkowski, Basic aspects of deep soil mixing technology control, IOP Conf. Ser.: Mater. Sci. Eng.,**245** (2), 022019 (2017)
10. D. Stefaniuk, P. Zajączkowski, J. Rybak, Methodology of axial testing of cement-fly ash-soil samples. *Stroitel'stvo-formirovanie sredy žiznedeâtel'nosti*. Moskva, 27-29 aprilâ 2016 r. : sbornik materialov. Moskva : NIU MGSU, 1091-1094 (2016)
11. P. Kanty, J. Rybak, D. Stefaniuk, Some remarks on practical aspects of laboratory testing of deep soil mixing composites achieved in organic soils, IOP Conf. Ser.: Mater. Sci. Eng., **245** (2), 022018 (2017)
12. J. L. Chaumeny, P. Kanty, T. Reitmeier, Remarks on wet deep soil mixing quality control, *XVI Danube - European Conf. on Geotechnical Engineering*, 07-09 June 2018, Skopje, R. Macedonia, Paper No. 039 (2018)
13. R. Duszyński, A. Duszyńska, S. Cantré, New experiences in dike construction with soil-ash composites and fine-grained dredged materials, Studia Geotechnica et Mechanica, **39 (4)**, 17-24 (2017)
14. I. Karpisz, K. Jaworski, Study of compressive strength evolution in soil cement samples with fly-ash admixtures, IOP Conf. Ser.: Mater. Sci. Eng., **365**, 032049 (2018)
15. I. Karpisz, J. Pyda, L. Cichy, D. Sobala, Study of the effect of cement amount on the soil-cement sample strength, IOP Conf. Ser.: Mater. Sci. Eng., **365**, 042061 (2018)
16. K. Brasse, T. Tracz, T. Zdeb, P. Rychlewski, Influence of Soil-Cement Composition on its Selected Properties. MATEC Web Conf., **163**, 06006 (2018)
17. J. Kawalec, S. Kwiecień, A. Pilipenko, J. Rybak, Application of crushed concrete in geotechnical engineering - selected issues, Conf. Ser.: Earth Environ. Sci., **95** (2), 022057 (2017)
18. O. Lohunova, M. Wyjadłowski, Modification of vibratory driving technology for sustainable construction works, MATEC Web Conf., **151**, 03063 (2018)