Unconfined Compressive Strength Properties of a Cement-Organic Soil Composite

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Abstract. Laboratory strength testing of the mixtures is a necessary stage of soil stabilisation. They enable assessment of the impact of binders on the improvement of the properties of stabilised organic soil, which is extremely useful for the development and verification of the correct composition of the soil-binder composite used in situ. The paper presents selected results of unconfined compressive strength tests of a cement-organic composite depending on the quantity of the cement binder and the different organic matter content. The laboratory testing comprised 20 different mixture designs in which the independent variables were the organic matter content (Iom) and the ratio of added cement to the dry weight of soil (mc/ms): the Iom ranged from 20% to 84.40% and the mc/ms from 0.75 to 2.75. Measurements of the unconfined compressive strength were conducted on more than 150 cylindrical specimens after 7 and 28 days of curing. Analysis of the obtained strength test results shows that there is a close physical relationship between the geotechnical properties of the components and the parameter of unconfined compressive strength of organic soil-cement binder mixtures.

1. Introduction

Cement is the most popular and common hydraulic binder used to stabilise organic soil. It can be applied in essentially all kinds of soil, significantly improving their geotechnical properties. Research shows that cement itself, and if mixed with granulated blast furnace slag, yields the best stabilisation results in a weak-bearing soil with a high organic content [1].

The higher the content of organic matter the lower the efficiency of cement stabilisation. This has a negative impact on the process of setting and hardening of the cement grout, delaying it and permanently compromising the strength. In the case of concrete, as little as 0.05% of humic acid with respect to the aggregate content will decrease the ultimate strength by approx. 20%. In extreme cases, the process of cement hydration can even be stopped [2]. The setting can be accelerated using other admixtures, such as lime, but this means that the resulting strength will be reduced [3].

Unconfined compressive strength testing is a method of testing the effects of in situ mixing of soil with stabilisers. It enables selection of the kind, quantity and ratio of specific binders and finding out whether or not the w/c ratio is suitable for the expected soil stabilisation results. Although the values of compressive strength obtained in laboratory conditions differ from those verified in field tests, they are still an essential element in the design of soil stabilisation mixtures [4].
This paper presents selected results of laboratory tests of the unconfined compressive strength of a mixture of organic soil and cement binder with a variable content of the binder and the organic matter. The results were used in a dissertation [5].

2. Laboratory testing of component strength

There is a number of standards and specifications, mainly used in road construction, with regard to subgrade stabilisation [6-8], the design of mixtures with hydraulic binders [9,10] and the determination of their compressive strength properties [11]. Unfortunately, they are not applicable to the stabilisation of soil with a high organic-matter content, where specific formulation and curing conditions must be observed. In such cases, it is best to use the current standard for deep soil mixing [4]. The European Standard refers to the method of preparation of specimens for laboratory testing according to the EuroSoilStab guide [12]. The design guide specifies the methods of specimen preparation and curing which reproduce the conditions of both shallow and deep stabilisation.

In organic soils, whose natural moisture content is usually high and exceeds 60%, dry mixing of the soil with binders is used. Depending on the soil type, its natural properties and the expected effects of stabilisation, the composition of the mixture is designed according to the intended parameter values. Table 1 presents the recommended binders used in the method of in situ dry mixing of soil and concrete.

Cement, lime and – to a lesser extent – gypsum is the most frequently used mineral binders. Besides typical mineral materials, other substances are used as secondary ingredients to modify specific parameters of the composite, reduce the costs or re-use industrial waste. These materials include reactive fly ash and blast furnace slag or aggregate fillers. Properly applied hydraulic and pozzolanic components can partially replace mineral binders [2].

In soils with a high content of organic substances, plain cement, cement mixed with granulated blast furnace slag [1, 12] or mixed with gypsum [12] are the best. For soil stabilisation, common grades of cement: 32.5 or 32.5 R should be used [7]. For acidic soil with pH < 5 and sulphate content \( \text{SO}_4 > 1\% \), blast furnace cement (CEM III) is recommended [13]. On the other hand, some research indicates that the best stabilisation effects in organic soil are achieved using Portland slag cement (CEM II) [14].

In order to identify the share of the stabiliser in the mixture designed according to the EuroSoilStab guide, the soil bulk density must be determined. The binder is introduced in kg/m\(^3\) related to the wet mass of the stabilised organic soil. The water-cement ratio (w/c) can also be used as the primary parameter, as it is when designing a concrete mix. In organic soils, the quantity and type of binder (usually cement) mainly depends on the percentage content of organic substances, their composition and natural moisture content of the soil.

There is a special method of laboratory testing of stabilised organic soil, determined by the content of organic substances. EuroSoilStab [12] specifies a method of specimen preparation and curing in different conditions for shallow and deep stabilisation. In the case of the shallow stabilisation, the mixed specimens are loaded and a free flow of water is allowed. Thus, actual conditions are reproduced in a laboratory setting. The produced composite is loaded for further consolidation. This is because in real-life stabilisation by shallow soil mixing once the binder is injected and mixed with the soil the ground is usually loaded with a layer of sand on geotextiles.

The EuroSoilStab approach [12] recommends using cylindrical specimens with a diameter of 50 mm and a height of 100 mm for deep-soil stabilisation and 200-300 mm high for shallow-soil stabilisation. On the other hand, the standard [15] recommends using specimens with a round or square cross section of at least 1000 mm\(^2\) for unconfined compression tests. The height-to-diameter ratio of a specimen should fall within a range of 1.8-2.5 for cylindrical specimens and 2.0-2.8 for cuboid. The shape and size of the specimen have a significant influence on the strength of the tested composite. Research shows that the greater the specimen diameter the smaller the dispersion of the compressive strength results [16]. It has also been observed that in the case of smaller diameters lower values are obtained, which may result from a greater impact of the inhomogeneity of the organic soil.
Cube-shaped specimens yield similar results to those obtained using cylindrical specimens of greater diameters [14].

In the case of organic soil, a correct homogenisation of the soil to be tested is crucial. According to the standard [15], the largest particle of the specimen must not exceed a sixth of the specimen diameter (cylindrical shape) or a sixth of the side edge length (cube shape). The time of mixing the soil with the stabiliser is also limited and should not exceed 2-5 minutes [12]. It is especially important in the case of soil with a high content of organic matter. Longer mixing could damage the natural structure of the soil.

The resistance of the soil to shear forces is a measure of its strength. The undrained shear strength of soil composites ($c_u$) is determined using a specific method in a triaxial test apparatus for unconfined compression strength (UCS) testing. The property can also be identified using standard strength testing machines, i.e. hydraulic presses. The undrained strength of the soil can be determined as a half of the shear strength obtained in a uniaxial stress condition [15, 17], provided that the angle of repose is close to zero ($\phi = 0^\circ$). This is not always the case in actual field conditions, therefore it is prudent to use the value of unconfined compression strength of the soil than its shear strength [17, 18].

It should be noted that the values of UCS obtained for composites in laboratory tests are higher than the same obtained in situ, because of better mixing and curing conditions provided in the lab. The strength of laboratory-tested specimens is usually 10 to 50 times the values obtained for non-stabilised soil, however in actual deep mixing the obtained parameters account for 20% to 50% of the strength determined in laboratory setting. In the case of mass stabilisation, the differences are smaller [12].

3. Methodology and testing programme

The tests were performed on 20 different composite mixtures, identified as K1-K20, in which the independent variables were the organic matter content ($I_{om}$) and the ratio of cement added to the dry mass of the soil ($m_c/m_s$). The analysis concerned the content of organic matter, $I_{om}=20-84.40\%$, and the variable content of cement, identified in relation to the dry mass of the soil, $m_c/m_s=0.75-2.75$. A total of 150 cylindrical specimens with a diameter of 71 mm and a height of 140 mm were put to unconfined compressive strength tests after 7 and 28 days of curing.

The main ingredient of the mixtures was low moor peat of the sedge and reed type and a mean natural content of organic matter, $I_{om} = 83.64-84.40\%$. The organic matter content was controlled by adding a specific quantity of chemically inert silica sand, so the share of organic substances decreased as the share of mineral content increased. Portland fly ash cement with a high early strength (CEM II/B-V 32.5R) was used as the binder.

In order to compare the results of the performed tests with other results, Table 1 below shows the content of cement and silica sand in kg/m$^3$ of the peat in the different mixtures, determined for a mean natural moisture content of the peat, and the water-cement ratio (w/c). The values are only illustrative, considering that the moisture content of the peat, which served as a basis for the identification of the share of the ingredients, was determined a number of times during the research which lasted a dozen or so months.
4. Results of compressive strength tests

The strength determined for the specimens which were cured for 7 days ranged from 34.1 kPa to 1,227.5 kPa, whereas after 28 days' specimens improved their strength from 45.5 kPa to 1,528.7 kPa. Tables 2 and 3 and Figures 1-3 provide a summary of the test results. As expected, the unconfined compressive strength (UCS) of the components decreased as the organic matter content increased, but it improved as the mC/mS ratio increased.

Table 1. The content of cement (C) and silica sand (P), expressed in kg/m³ of peat in respective mixtures, and the w/c ratio

| Table 1 | Mixture design | Cement to soil dry mass ratio mC/mS |
|---|---|---|
| | 0.75 | 1.25 | 1.75 | 2.25 | 2.75 |
| 20 | C: 691.93 | C: 1153.21 | C: 1614.51 | C: 2075.79 | C: 2537.07 |
| | P: 701.97 | P: 701.97 | P: 701.97 | P: 701.97 | P: 701.97 |
| | w/c: 1.18 | w/c: 0.71 | w/c: 0.51 | w/c: 0.39 | w/c: 0.32 |
| 40 | C: 345.96 | C: 576.61 | C: 807.25 | C: 1037.89 | C: 1268.54 |
| | P: 240.68 | P: 240.68 | P: 240.68 | P: 240.68 | P: 240.68 |
| | w/c: 2.37 | w/c: 1.42 | w/c: 1.02 | w/c: 0.79 | w/c: 0.65 |
| 60 | C: 230.64 | C: 384.40 | C: 538.17 | C: 691.93 | C: 845.69 |
| | P: 86.92 | P: 86.92 | P: 86.92 | P: 86.92 | P: 86.92 |
| | w/c: 3.55 | w/c: 2.13 | w/c: 1.52 | w/c: 1.18 | w/c: 0.97 |
| 84.40 | C: 172.98 | C: 288.30 | C: 403.63 | C: 518.95 | C: 634.27 |
| | P: - | P: - | P: - | P: - | P: - |
| | w/c: 4.74 | w/c: 2.84 | w/c: 2.03 | w/c: 1.58 | w/c: 1.29 |

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Table 2. Unconfined compressive strength σ7 (kPa) of mixture specimens K1-K20 after 7 days of curing

| Table 2 | Mixture design | Cement to soil dry mass ratio mC/mS |
|---|---|---|
| | 0.75 | 1.25 | 1.75 | 2.25 | 2.75 |
| 20 | K1 σ7: 98.0 | K2 σ7: 444.0 | K3 σ7: 939.6 | K4 σ7: 1169.4 | K5 σ7: 1227.5 |
| 40 | K6 σ7: 34.1 | K7 σ7: 87.4 | K8 σ7: 120.7 | K9 σ7: 124.0 | K10 σ7: 170.2 |
| 60 | K11 σ7: 35.2 | K12 σ7: 46.0 | K13 σ7: 59.4 | K14 σ7: 109.1 | K15 σ7: 106.5 |
| 84.40 | K16 σ7: 40.4 | K17 σ7: 54.6 | K18 σ7: 60.1 | K19 σ7: 66.2 | K20 σ7: 91.7 |

- composites with UCS σ7 ≥ 1000 kPa
- composites with UCS σ7 ≥ 100 kPa
Figure 1. Unconfined compressive strength $\sigma_7$ (kPa) of mixture specimens K1-K20 after 7 days of curing

The composites identified as K1-K5, whose organic matter content was $I_{om}=20\%$ after 7 days of curing, regardless of the cement content, reached the UCS values $\sigma_7>100$ kPa, which is the smallest mean compressive strength of the composites tested after 28 days of curing, made from saturated deposits and organic soil [19]. The composites K3-K5, with the highest content of cement, $m_c/m_s=1.75-2.75$, reached the UCS $\sigma_7>1,000$ kPa, whereas the only mixture with a low natural organic content which demonstrated a strength of about 100 kPa was the K20, which was due to its higher content of organic matter.

Table 3. Unconfined compressive strength $\sigma_{28}$ (kPa) of mixture specimens K1-K20 after 28 days of curing

| Mixture design | Cement to soil dry mass ratio $m_c/m_s$ |
|----------------|----------------------------------------|
|                | 0.75 | 1.25 | 1.75 | 2.25 | 2.75 |
| Cement to soil dry mass ratio $m_c/m_s$ |
| 20              | K1   | K2   | K3   | K4   | K5   |
|                 | $\sigma_{28}: 170.5$ | $\sigma_{28}: 493.8$ | $\sigma_{28}: 1111.3$ | $\sigma_{28}: 1334.9$ | $\sigma_{28}: 1521.8$ |
| 40              | K6   | K7   | K8   | K9   | K10  |
|                 | $\sigma_{28}: 61.9$ | $\sigma_{28}: 138.9$ | $\sigma_{28}: 219.7$ | $\sigma_{28}: 239.9$ | $\sigma_{28}: 373.8$ |
| 60              | K11  | K12  | K13  | K14  | K15  |
|                 | $\sigma_{28}: 49.3$ | $\sigma_{28}: 83.4$ | $\sigma_{28}: 111.1$ | $\sigma_{28}: 171.8$ | $\sigma_{28}: 266.5$ |
| 83.64 (84.40)   | K16  | K17  | K18  | K19  | K20  |
|                 | $\sigma_{28}: 45.5$ | $\sigma_{28}: 56.8$ | $\sigma_{28}: 66.9$ | $\sigma_{28}: 74.5$ | $\sigma_{28}: 107.4$ |

- composites with UCS $\sigma_{28}>1,000$ kPa
- composites with UCS $\sigma_{28}>100$ kPa
Figure 2. Unconfined compressive strength $\sigma_{28}$ (kPa) of mixture specimens K1-K20 after 28 days of curing

After 28 days of curing, the composites K1-K5, with the lowest organic matter content, $I_{om}=20\%$, reached the UCS $\sigma_{28}>100$ kPa, and those composites with the highest cement content, $m_c/m_s=1.75-2.75$, reached UCS values exceeding $\sigma_{28}>1,000$ kPa. In the case of the composites with the highest organic content, only K20 reached the UCS of more than 100 kPa ($\sigma_{28}=107.4$). After 7 days 45% of all the composites, and after 28 days 65% of them exceeded the compressive strength of 100 kPa.

Figure 3. The increase in compressive strength $\Delta \sigma$ (%) of mixture specimens K1-K20 after 28 days of curing compared to 7-day curing
The obtained results of unconfined compressive strength tests support a conclusion that in the case of soil composites the relationships established for concrete are not applicable. The increase in compressive strength of peat soil-cement binder mixtures after 28 days is variable and diverse. It can reach as much as 150% of the initial strength (K15). It was observed that the greatest increase was demonstrated by the composites K6 – K15, whose respective organic matter content (Iom) was 40% and 60%.

5. Summary and conclusions

In practical applications assuming the criterion of a minimum unconfined compressive strength (UCS) equals to σ=100 kPa, assumed economic criterion and considering the technical limitations of the deep-mixing method, the composites identified as K8, K9, K10, K14 and K15, and – after 28-day curing – also K7 and K13 are particularly advantageous for engineering purposes. In the case of K3-K5, the UCS can exceed 1,000 kPa if an appropriately high cement content is provided. The values of σ>1,000 kPa are similar to those yielded by rigid piles. However, cement-soil columns are recommended not to exceed the UCS of about 150-250 kPA, to allow for certain flexibility with regard to the surrounding weak-bearing soil. Unlike concrete piles, the columns hardly ever transfer loads directly to lower bearing strata. They are mainly designed to stabilise and reinforce the surrounding soil. If a higher strength was required, the extra quantities of cement would not be economically justified. In a situation like this, the cement content should be reduced and replaced by a suitable admixture of chemically active industrial waste, such as blast furnace slag or fly ash.

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