QUALITY CONTROL OF CEMENT-IMPROVED SOIL

Le contrôle de la qualité du sol amelioré par le ciment

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ABSTRACT: Middle plasticity clay was situated below the concrete floor of a storage hall. It was necessary to increase the bearing capacity and decrease the settlement of this soil layer. The 400 mm - thick layer of soil was improved by the addition of 5% cement. The static load tests showed that the required deformation modulus was not fulfilled. In the next step, the laboratory tests of E_{oed} using different initial cement content were executed. X-ray and DTA analyses of the cement content in the soil were also applied. The laboratory tests were aimed at identifying the properties of the improved clay after adding 3, 5, and 7% of cement to the varied moisture levels of the soil. The results of the compressibility of the unimproved and improved clay samples are presented in the paper.

RÉSUMÉ: L'argile de plasticité moyenne se trouvait au-dessous du plancher en béton du foyer. Il était nécessaire d'améliorer la capacité portante et de réduire l'abaissement de cette couche de sol. L' épaisseur d'une couche de sol de 400 mm a été ameliorée par ajoutement du 5% ciment. Les essais de chargement statique ont montré que l'exigence du module de déformation n'a pas été respectée. Ensuite, les essais laboratoires E_{oed} avec ajoutement de la quantité variée du ciment dans le sol ont été executés. De même, l'analyse avec des rayons X et DTA a été apliquée afin de déterminer le contenu du ciment dans le sol. Les essais laboratoires ont été concentrés sur l'identification des propriétés de l'argile amelioré après addition du 3 – 5 – 7 % ciment en faisant varier l'humidité du sol. Le document présente les résultats des tests de compressibilité de l'argile amélioré et non amélioré.

KEYWORDS: soil improvement, laboratory tests, compressibility of soil.

1 INTRODUCTION

The requirement to accelerate construction in unsuitable conditions (bad weather, degenerate soil conditions, etc.) leads many times to a need to improve the underlying layers of the structures. To solve these problems, technology similar to what is used to improve road construction is employed. Among the popular technologies is the addition of a certain percentage of cement into fine-grained soils. Mixing cement with soil and compacting it reduces the compressibility of the soil. The subsequent quality control of the improved soil is mostly achieved by static load tests.

Construction began on a large storage hall in Slovakia with an area of 100,000 m^2 during the winter months. After the landscaping arrived, the climatic conditions unexpectedly worsened. In February, rainfall exceeded 300% of the long-term normal precipitation. The underlying layers of the future floors were improved during the rainy weather but were not protected. The adverse weather situation resulted in the suspension of work. The quality of the underlying layers was checked by static load tests after the layers had been improved. The results of the improved soil stabilization showed insufficient strength. After sampling, the properties of the original and improved soil were checked by laboratory tests.

2 LABORATORY ANALYSIS OF SOILS

Intact soil samples improved by cement were removed from the on-site construction of the factory buildings, as well as the original soil, which had not been improved by the cement. An analysis of the basic descriptive soil characteristics was conducted on the original soil samples. Based on Slovak standard STN 72 1001, the soil was classified as firm clay with a low degree of plasticity (F6 - CL). The original moisture of the soil was more than 20%. The moisture of the improved soil with cement did not differ from the moisture of the original soil.

To determine the optimum moisture of the soil for compaction, the Proctor test (see Fig. 1) was used. The optimum moisture of the tested soil was determined to be w_{opt} = 15.2%, which corresponded to the maximum dry density of soil ρ_{max} = 1.768 g/cm^3. The collected samples had a significantly higher moisture content than its optimal moisture should be.

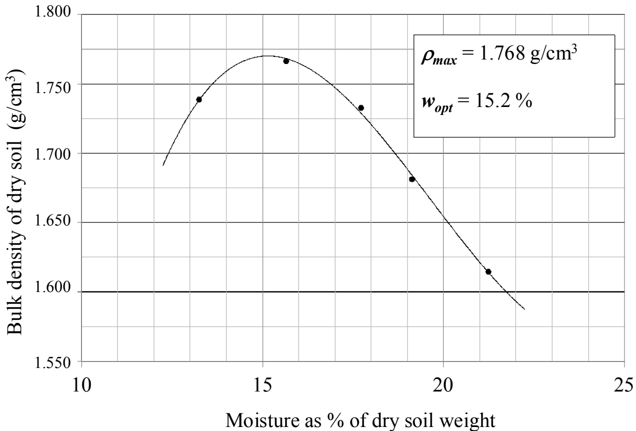

Figure 1. Determination of the maximum bulk density and optimum moisture

3 OEDOMETRIC TESTS ON UNDISTURBED SOIL SAMPLES

A compressibility test using an oedometer was conducted on the original and improved soil too. As an improvement, 5% of cement was added to the soil. The results of the average deformation characteristics of the original and improved soil are collected in Table 1.

Based on the laboratory results, the following increase in the deformation characteristics was determined for the improved soil:

- stresses in soil $\sigma \leq 50$ kPa

$$\frac{E_{oed\ stab}}{E_{oed\ not}} = \frac{32.25}{5.10} = 6.32$$

- stresses in soil $50 \leq \sigma \leq 100$ kPa

$$\frac{E_{oed\ stab}}{E_{oed\ not}} = \frac{14.13}{5.70} = 2.47$$

- stresses in soil $100 \leq \sigma \leq 200$ kPa

$$\frac{E_{oed\ stab}}{E_{oed\ not}} = \frac{15.19}{9.62} = 1.58$$

Note: $E_{oed,\ stab}$ – oedometer modulus of the improved soil,
$E_{oed,\ not}$ – oedometer modulus of the original soil.

Based on the stress range of its own weight and the expected load from the buildings, the improvement of the soil after adding the cement was 1.5 to 2 times better. The recommended values of the deformation modulus of improved soil should not exceed E_{oed} = 14 MPa.

Table 1. Deformation modulus of soils determined from compression tests

Normal stress $\sigma_1 - \sigma_2$ (kPa)	Average modulus			
	Improved soil		Primary soil	
	E_{oed} (MPa)	E_{def} (MPa)	E_{oed} (MPa)	E_{def} (MPa)
10 – 25	35.73	16.79	3.84	1.81
25 – 50	32.25	15.16	5.10	2.40
50 – 100	14.13	6.64	5.70	2.68
100 – 200	15.19	7.14	9.62	4.52

4 COMPRESSION TESTS OF THE SOIL WITHOUT ANY IMPROVEMENT UPON COMPACTION, ACCORDING TO THE PROCTOR STANDARD

Artificially prepared samples of the soil, which was compacted according to the Proctor standard, were tested with the oedometer. The resulting average oedometer modulus corresponding to different moistures of the tested soils are evaluated in Table 2.

Table 2. Average oedometer modulus of the tested soils at various moistures levels

Normal stress $\sigma_1 - \sigma_2$ (kPa)	Oedometer modulus E_{oed} (MPa)				
	w = 13.25%	w = 15.65%	w = 17.73%	w = 19.13%	w = 21.24%
10 – 25	23.05	18.31	6.66	5.35	3.18
25 – 50	21.72	16.61	4.72	2.42	2.22
50 – 100	13.36	9.40	5.49	3.20	3.04
100 – 200	13.36	9.66	7.44	5.12	4.98

The effects of the changes in the soil moisture according to the oedometer modulus are shown in Fig. 2. The plasticity index of the soil was I_P = 10 % (liquid limit w_L = 30.5 % and plasticity limit w_P = 20.5 %). When the soil was in its natural condition with a firm consistency, very small values of the deformation characteristics of the tested soil in all the extensities of the normal stresses were found. When the soil stiffness was increased, it was possible to observe a decrease in the soil moisture below 17%. The consistency of soil at such a level of moisture was I_C = 1.4. Decreasing the moisture below 17% significantly increases oedometer modulus of the soil.

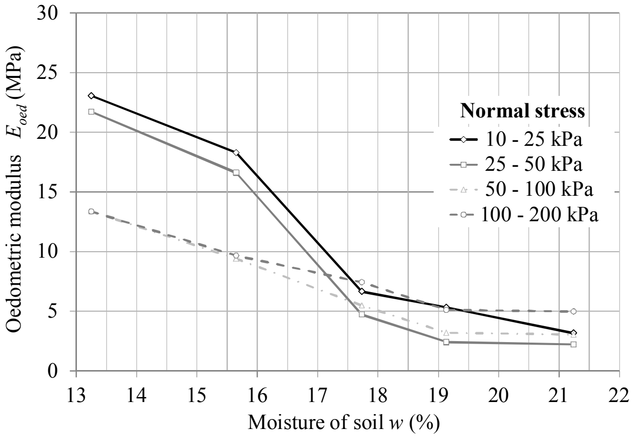

Figure 2. Relationship between the moisture of the tested soil and the oedometer modulus

After the analysis shown in Fig. 2 and also taking into account Fig. 1, it can be stated that:

- Exceeding the optimum moisture w_{opt} occurred in samples loaded by a normal stress of 50 kPa caused a rapid decreasing of E_{oed}.
- When the moisture increased, a significant decrease of E_{oed} of more than 5 times at a lower normal stress (< 50 kPa) was observed. When the value of the normal stress of 50 kPa was exceeded and the moisture was increased, a decrease of E_{oed} of approximately 3.5 times was determined.

Within the test range of the normal stress, E_{oed} was significantly affected by the moisture. Fig. 3 shows the relationship between the deformation characteristics and the normal stresses of the soil at various initial degrees of the soil moisture. Also, this evaluation proved the moisture around 17% as the limit value. At lower degrees of moisture, significantly different deformation parameters were detected, especially at a normal stress of up to 50 kPa.

5 IMPROVING THE SOIL CHARACTERISTICS BY ADDING CEMENT

The collected samples with a natural moisture of 20% indicated that the values of the deformation modulus of the original soil were very low. The addition of cement in the soil caused a decrease in the soil moisture, but the increase in the deformation parameters was not sufficient.

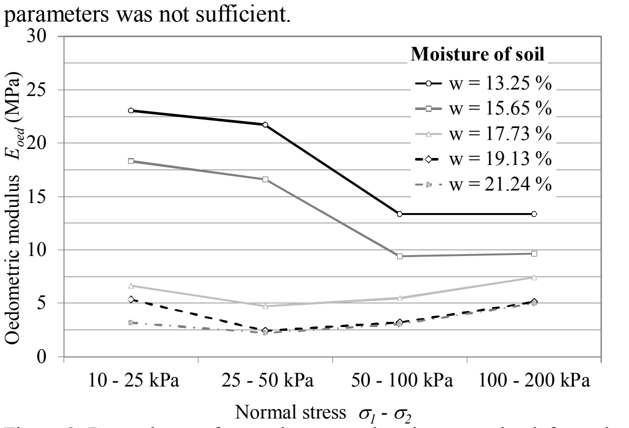

Figure 3. Dependence of normal stress and moisture on the deformation characteristics of the soil

Very interesting results were obtained from an evaluation of the effect of the addition of 5% of cement (see Fig. 3). At a moisture level lower than 20.5% (a stiff consistency), a significant effect of the cement was observed. At the same time, the effect of the improvement increased with lower levels of the normal stress. It can be assumed that with an initial moisture content in excess of w_{opt} + 5%, a significant decrease in the effect of the stabilization is to be expected. The resulting oedometer modules corresponding to the different moisture and cement contents in the tested soil are listed in Table 3.

Table 3. Oedometer modulus of the soil improved by cement at various levels of moisture of the soil and cement contents

Normal stress $\sigma_1 - \sigma_2$ (kPa)	Cement content				
	5%			3%	7%
	Moisture of soil w (%)				
	15.60	17.95	24.56	14.10	14.27
	Oedometer modulus of the improved soil E_{oed} (MPa)				
10 – 25	101.26	36.04	6.04	31.06	93.61
25 – 50	43.85	13.22	2.70	17.84	43.11
50 – 100	20.98	10.83	3.31	18.51	24.37
100 – 200	18.71	10.37	3.90	18.66	24.06

The effects of the addition of 5% of cement in the soil on the oedometer modulus at different levels of moisture are shown in Fig. 4. The results indicate that the impact on the cement by increasing the strength of the improved soil is limited by the degree of moisture. If the natural soil moisture content is less than 20.5%, this means that the soil has a stiff consistency, so the addition of the cement will result in increased strength. The effect of adding 5% of the cement content was reflected in the full range of the test load, but in varying degrees. The greatest rate of improvement was observed for loads up to 25 kPa.

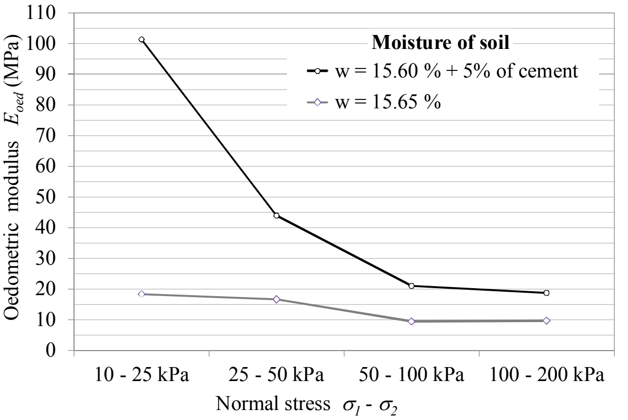

Figure 4. Effect of addition 5% cement into the soil on E_{oed} at optimum degree of moisture

Based on the laboratory results, the following increase in the deformation characteristics can be determined for the improved soil:

- stresses in soil $10 \leq \sigma \leq 25$ kPa

$$\frac{E_{oed\ stab\ 5\%}}{E_{oed\ not}} = \frac{101.26}{18.31} = 5.53$$

- stresses in soil $25 \leq \sigma \leq 50$ kPa

$$\frac{E_{oed\ stab\ 5\%}}{E_{oed\ not}} = \frac{48.85}{16.61} = 2.94$$

- stresses in soil $50 \leq \sigma \leq 100$ kPa

$$\frac{E_{oed\ stab\ 5\%}}{E_{oed\ not}} = \frac{20.98}{9.4} = 2.23$$

- stresses in soil $100 \leq \sigma \leq 200$ kPa

$$\frac{E_{oed\ stab\ 5\%}}{E_{oed\ not}} = \frac{18.71}{9.6} = 1.95$$

Note: $E_{oed,\ stab\ 5\%}$ – oedometer modulus of the improved soil with 5 % of cement,
$E_{oed,\ not}$ – oedometer modulus of the original soil.

Assuming that a load is caused by objects, it is possible to expect an improvement in the properties of the soil by approximately 2 to 3 times over the soil without cement with the addition of 5% of cement at an optimum moisture. Increased moisture above the mentioned value w = 20.5% passes through the soil and forms a solid consistency. The impact of cementation on such a level of moisture is much lower or negligible. Fig. 5 indicates these results. The figure shows the dependence between the oedometer modulus of the soil with and without the added cement and the moisture at various loads. At higher values of normal stresses after exceeding the initial moisture, w_{opt} + 5% reduces the effect of the added cement.

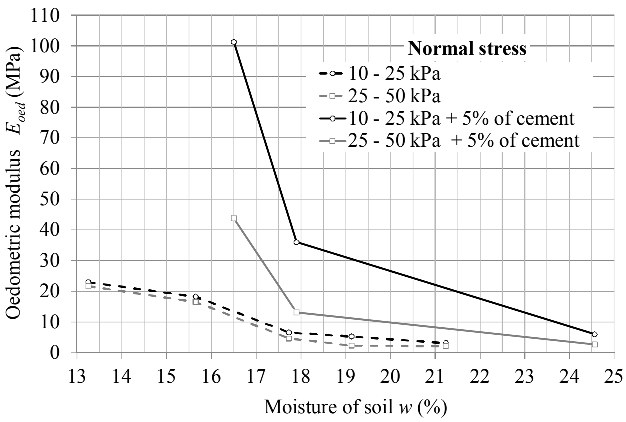

Figure 5. Effect of moisture on the oedometer modulus for the soil without cement and the soil improved with cement

The cement added to the soil with a natural moisture content (which was between 19 to 21%) absorbed a portion of the water available for hydration. This effect will inevitably reduce the moisture of the soil itself. It is believed that an initial moisture content above the w_{opt} + 5% should be expected to decrease in the stabilization effect. The laboratory tests showed one more interesting effect. The compressibility of the soil without the addition of the cement was less sensitive to the increase in the initial moisture. The same tendency was observed when increasing the normal stress on the soil.

The next step studied the reinforcing effect of the cement content of the soil. Tab. 3 shows the resulting values of the oedometer modules that were covered using three different amounts of cement. The treatment of this data is in Fig. 6, which graphically displays the effect of the cement content on the oedometer modules at different stages of loading. An important factor in this assessment is the virtually identical initial moisture of the samples.

Increasing the cement content in soil to 7% slightly increased the oedometer modulus at higher loads. However, this effect is not considered significant enough to make it worthwhile in many cases to increase the dose of cement. Reducing the cement content to 3% was reflected in a reduction of E_{oed} at lower loads (up to 50 kPa). For stresses ranging from 50 to 100 kPa, differences in the percentage of added cement are nearly negligible. The cement content in soil initially decreases the moisture content of the soil, but the cement absorbs the water and subsequently increases the strength of the soil. The results indicate that the cement content of 5% appears to be the most appropriate. Increasing the cement content is relevant only in the case of a higher load or in cases when the natural soil has a higher moisture content.

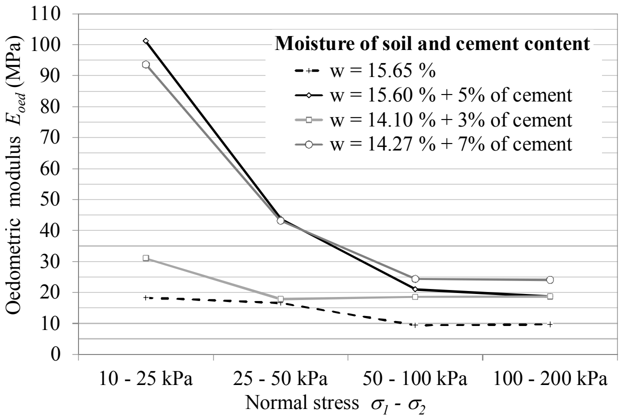

Figure 6. Effect of cement content in soil on the oedometer modulus at various loads

6 THE QUALITY ASSESSMENT AND THE CEMENT CONTENT IN THE SOIL

The discussed cement and its contents were independently tested in stabilized soil. Laboratory tests of the physico-mechanical properties of the cement were carried out and supplemented by X-ray and DTA analyses. The stabilized soil was also investigated by DTA and X-ray analyses.

The tested cement was used to stabilize the soil at the construction site. The properties studied and the results reached are as follows:
After 28 days, the compressive strength reached 48.3 MPa. This value is in accordance with the requirements of the class of cement 42.5 MPa according to EN 197-1.

- After 28 days, the compressive strength reached 48.3 MPa. This value is in accordance with the requirements of the 42.5 MPa class of cement according to EN 197-1.
- The bulk density with a time deposit of the test samples slightly increased. After 28 days, the bulk density reached a value of around 2190 kg/m^3, which corresponds to the standard values.
- After testing the cement slurry, it was found that the cement needs to reach a slurry of a normal density of 32% of the water.
- The initial setting of the cement slurry, which was observed after 195 minutes, fulfilled the limit set by the standard. The final setting occurred after 250 minutes.
- The soundness of the tested cement was 6.0 mm, which met the standard set limit of 10 mm.
- The bulk density of the fresh cement mortar was 2160 kg/m^3. All the testing samples had a low scatter compared to the average.
- The X-ray analysis showed the incidence of cement clinker minerals as Alite - C3S (Tricalcium silicate), Belite - C2S (Dicalcium silicate), Brownmillerite - C4AF (Tetracalciumaluminoferrite), C3A (Tricalcium aluminate), and gypsum setting regulator (CaSO4.2H2O). Furthermore, Silica (SiO2), Calcite (CaCO3) and Portlandite Ca(OH)2 were observed. According to this composition, it can be assumed that this was Portland-composite cement CEM II.

The tests of the stabilized soil by the X-ray and DTA methods showed that the samples taken from the storage hall after the defective area of the static load tests contained less than 2% of the cement. By applying the same method to the artificially prepared samples, good agreement with the percentage of added cement was found.

7 CONCLUSION

Based on the compressibility tests of the stabilized soil, it is clear that the high moisture content of the soil after the rainy season decreased the soil parameters. The tests showed two reasons for the failure to achieve the criteria required for the static load testing. The first reason was the lower cement content as determined by the project. Instead of 5% of the cement, the samples taken from the subgrade at the construction site showed only a cement content in the range of 1 to 2%. Significant precipitation caused the natural soil moisture to exceed 20%. The laboratory experiments showed that at such a level of moisture of the unimproved original soil, the deformation properties of the soil were very low. The mixed cement decreased the soil´s moisture, but it reflected only a small increase in the E_{oed}. By adding cement, the deformation parameters of soil may increase 2-3 times. This effect is linked to the initial soil moisture before stabilization; the value w_{opt} should not be exceeded by 5%. Exceeding this level of moisture is not expected to have a major stabilization effect.

8 ACKNOWLEDGEMENTS

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