Influence of soil-cement composition on its deformability

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Abstract. The paper discusses the results of deformability tests of soil-cement composites made with cohesive and non-cohesive soils. The compositions of the materials analysed were diversified in terms of their cement paste volume fractions and water-cement ratios. The aim of the research was to determine the secant modulus of elasticity in uniaxial compression of soil-cement composites in accordance with the EN 12390-13 standard dedicated to concrete testing. Due to the lower level of strength of the materials in question in comparison with ordinary concrete, nominal stress was lowered and the loading and unloading rates were modified. The number of loading cycles required for the determination of stabilised deformations was verified. The test results obtained and their analysis indicate the significant impact of the type of soil on the deformability of soil-cement composites. It was also found that the deformability of the materials tested is sensitive to changes in their compositions.

1. Introduction

In the practice of designing engineering structures, e.g. ones made of soil-cement, the key mechanical parameter is the building material’s compressive strength. Owing to the ease of determining this feature, the high homogeneity and repeatability of the results obtained as well as the fact that it is possible to correlate these values with other characteristics, compressive strength is a basic and universal parameter of materials. According to the author of [1, 2], one of the fundamental parameters which can be correlated satisfactorily with the compressive strength of stabilised soil is its modulus of elasticity. However, the absence of an established methodology for testing the deformability of soil-cement composites and the strong dependence of this parameter on the type of reinforced soil translates into considerable variation with respect to the empirical relationships between the modulus of elasticity and compressive strength presented in literature. The insufficient homogeneity of the investigated soil-cements, which are produced e.g. using the DSM (Deep Soil Mixing) soil-cement pile construction technology, also has an equally fundamental effect on the discrepancies between the results obtained.

According to the author of [1, 3], when designing soil reinforcement based on the Deep Soil Mixing technology, the secant modulus of elasticity for soil-cement $E_{50}$, which is determined at 50% of the destructive stress value, is most often used. The expected value for soil-cement is the correlation coefficient between the secant modulus of elasticity and unconfined compressive strength $E_{50}/$UCS, which falls within different ranges depending on the UCS value. According to Topolnicki [1], for UCS < 2.0 MPa this range is from 50 to 300 UCS, and for UCS > 2.0 MPa it is from 300 to 1,000 UCS. A similar range for the $E_{50}$/UCS ratio, i.e. from 75 to 1,000, can be found in [4]. The authors claim that for design purposes, $E_{50}$ values are most often assumed at 300 UCS. Other relationships can be found in [4], where for UCS < 1.0 MPa $E_{50} = 120$ UCS, and for UCS > 1.0 MPa $E_{50} = 380$ UCS. In [3], Topolnicki presents the results of tests of several dozen soil-cement specimens which were made using cohesive
soil (loam) and differed in terms of their cement content. On the basis of those studies, it was found that the $E_{50}$/UCS correlation coefficient depends on the type of soil, cement content and the degree of homogeneity of soil-cement. However, the author of [1, 3] draws attention to the fact that during uniaxial compression in laboratory tests, soil-cement specimens are subjected to the different conditions than geotechnical structures. These tests do not take account for the presence of lateral stresses, which have a positive effect on the mechanical properties of soil-cement. In the presence of lateral stresses, soil-cement becomes more elastic-plastic and less brittle. In addition, under laboratory conditions a more favourable degree to which all soil-cement composite components are mixed is achieved. Therefore, secant moduli of elasticity of in-situ soil-cement are lower; according to [3], it can be assumed that in relation to the designed average compressive strength $f_{cm}$ such moduli are in the following range: $E_{50} = 300–500 f_{cm}$. The same author narrows the range to $E_{50} = 300–400 f_{cm}$ in [5].

A relationship concerning the correlation between the modulus of elasticity and UCS is also proposed in [6] on the basis of tests of moduli of elasticity of soil-cement specimens in the form of cores sampled from a structure. The stress levels applied ranged from 10% to 30% of the estimated UCS. The specimens tested differed in terms of the reinforced soil type (sand, clay and loam) as well as in terms of their curing time (30 to 200 days). As a result of those studies, empirical relationship in the form $E = 1482 \text{UCS}^{0.8}$ ($E$ and UCS in [MPa]) was determined, with the coefficient of determination close to 0.8. The range of correlation vs. UCS ranged from 1.5 to 35 MPa.

A broad review of literature concerning the search for correlation between the modulus of elasticity and compressive strength of soil-cements can be found in [7]. The authors state that the range between $E_{soil-cement} = 12900 \text{UCS}^{0.41}$ from [8] and $E_{soil-cement} = 30000 \text{UCS}^{0.5}$ from [9] is appropriate for calculating modulus of elasticity values.

2. Study objective

This paper presents the results of studies aimed at determining the impact of the composition of soil-cement on its secant modulus of elasticity in compression. Another purpose of the research conducted was to verify whether the methodology contained in the EN 12390-13:2014 standard, which concerns tests of secant module of concrete, can be used in the testing of soil-cement composites after minor modifications. The results obtained are intended to be used in order to determine the relationship between the secant modulus of elasticity of soil-cement and its compressive strength. This relationship could be used in designing the structures produced using the Deep Soil Mixing technology.

3. Materials

The research programme involved producing a series of soil-cement composites whose compositions varied in terms of soil type, the amount of cement paste $V_z$ used and water-cement (w/c) ratios. Three types of native soil, which are characterised in table 1, were selected for the production of the composites concerned. The soil-cements tested were produced by mixing those soils with water and with CEM II/B-S 32.5 R cement, which met the requirements of the EN 197-1:2012 standard.

| Table 1. Properties of the soils selected. |
|-------------------------------------------|
| Properties                                 | Medium sand | Clay | Loam |
| Particle size distribution [% by mass]     |             |     |      |
| - gravel fractions 2/40 mm                | 5           | -    | -    |
| - sand fractions 0.05/2 mm                | 95          | 40   | 30   |
| - dust fractions 0.002/0.05 mm            | -           | 42   | 42   |
| - loam fractions <0.002 mm                | -           | 18   | 28   |
| Bulk density $\rho$ [g/cm$^3$]            | 1.60        | 2.10 | 2.08 |

For each soil, three different compositions of soil-cement mixtures were designed so that they exhibited adequate workability during mixing and consistency after mixing. Mixtures were required
to be self-compacting with no segregation of ingredients. These requirements determined the amount of cement paste used and the adopted w/c ratios of the mixes produced. Fresh mix consistency tests were carried out in accordance with the standard [10]. Analysing the measurements conducted, it can be stated that in the case of the soils tested, mixtures with the appropriate consistency exhibited flow diameter values ranging from 150 to 270 mm. The liquidity of all mixtures guarantees the possibility of proper incorporation of these composites by the DSM method. All compositions are summarised in table 2.

Table 2. Compositions of soil-cement mixtures.

| Soil         | Paste content $V_z$ [dm$^3$/m$^3$] | w/c ratio | Cement content [kg/m$^3$] | Mixture designation |
|--------------|-------------------------------------|-----------|---------------------------|---------------------|
| Medium sand  | 400 450 450 600 600 650 700 750 800 | 1.6 1.2 0.8 2.0 1.4 1.2 2.6 2.0 1.6 | 208 296 401 258 348 427 240 323 416 | 400/1.6 450/1.2 450/0.8 600/2.0 600/1.4 650/1.2 700/2.6 750/2.0 800/1.6 |
| Clay         |                                    |           |                           |                     |
| Loam         |                                    |           |                           |                     |

4. Methods
Mixing of composite components was carried out in a laboratory mixer with a capacity of 50 cubic decimeters. The mixer was equipped with two agitators working counter-rotating. The mixing time was determined by the type of soil and lasted until a homogenous mixture was obtained. The formed samples were stored for 28 days at +20°C and 95% RH humidity until the mechanical properties were tested.

The modulus of elasticity was determined on the basis of the EN 12390-13 standard, which is dedicated to concrete testing. Owing to the lower compressive strength of the materials in question, test parameters were modified. The initial stress level was reduced by a factor of 10: from 0.5 MPa to 0.05 MPa. Depending on the type of soil used and the strength level achieved by the soil-cements produced from it, the rate at which the stress level changed was reduced from the standard value of 0.6 ±0.2 MPa/s to the values presented in table 3. The table also includes upper stress values $\sigma_a$ which are equal to 1/3 of the compressive strength $f_c$ of the soil-cements tested.

Table 3. Average compressive strength of soil-cements ($f_c$) and the technical parameters used in modulus of elasticity testing.

| Soil         | Medium sand | Clay | Loam |
|--------------|-------------|------|------|
| Mixture designation | 400/1.6 450/1.2 450/0.8 600/2.0 600/1.4 650/1.2 700/2.6 750/2.0 800/1.6 |
| Compressive strength $f_c$ after 28 days [MPa] | 2.9 7.2 17.1 3.6 4.8 8.1 2.1 2.7 3.3 |
| $\sigma_a = 1/3 f_c$ [MPa] | 1.0 2.4 5.7 1.2 1.6 2.7 0.7 0.9 1.1 |
| Loading rate [MPa/s] | 0.1 0.1 0.1 0.05 0.05 0.05 0.025 0.025 0.025 |

The EN 12390-13 standard recommends the use of cylindrical specimens with a diameter of 150 mm and a height of 300 mm. Since soil-cement composites do not contain large grain inclusions, the tests were conducted using representative cylindrical specimens with a diameter of 100 mm and a height of 200 mm whose opposite planes were ground before the test. Extensometers (figure 1) with a maximum measuring range of ±2.5 mm and an accuracy of 0.1 μm were used to measure longitudinal
strain. During the test, those sensors were installed on the side surfaces of the cylindrical specimens in a suitable frame with a measurement base length of 100 mm.

Each test consisted of three specimen loading and unloading cycles. At the beginning of the test, the specimen is loaded to the stress value $\sigma_{p}$, for which the preload strain $\varepsilon_{p}$ is measured along the compression axis. Subsequently, the load is increased to the stress level $\sigma_{a}$ and the strain value $\varepsilon_{a}$ is read.

Figure 1. Specimen during the test – measurement of strain ($\varepsilon$) using two extensometers.

The secant modulus of elasticity $E_{c,s}$ was calculated using formula (1), which uses mean strains at preload stress and at upper stress during the third cycle. Strain is measured each time after around 20 seconds of constant load value at each load level.

$$E_{c,s} = \frac{\sigma_{a,3} - \sigma_{p,3}}{\varepsilon_{a,3} - \varepsilon_{p,3}},$$

where:

- $E_{c,s}$ – secant modulus of elasticity in compression [MPa],
- $\sigma_{a,3}$ – measured stress corresponding to nominal upper stress [MPa],
- $\sigma_{p,3}$ – measured stress corresponding to nominal preload stress [MPa],
- $\varepsilon_{a,3}$ – average strain at upper stress on loading cycle 3,
- $\varepsilon_{p,3}$ – average strain at preload stress on loading cycle 3.

Figure 2. Diagram presenting stress level changes during the modulus of elasticity ($E_{c,s}$) test.
In the first place, before the basic deformability tests of all the specimens analysed were conducted, the number of cycles required for the assessment of the modulus of elasticity was verified. To this end, one series of specimens was selected, which was designated 750/2.0 (see table 2), and a total of 20 loading/unloading cycles were carried out, with strains at individual stress levels being measured at each time (see figure 2). Subsequently, the modulus of elasticity during individual cycles (from 3 to 20) was calculated; the results are presented in figure 3. Due to the instability of deformations in the first two cycles, they were omitted from figure 3 in accordance with the recommendations of the standard [11].

![Figure 3. Variability of the modulus of elasticity (E\textsubscript{c,s}) determined during 20 cycles for the soil-cement series designated 750/2.0.](image)

The results presented indicate that the variation in the modulus of elasticity value in individual cycles from 3 to 20 is small: the results ranged from 1892 to 1914 MPa. Therefore, it can be assumed that this small variation results from natural measurement errors, in particular deformations and heterogeneity of the material tested. Very importantly, no upward or downward trends in the modulus of elasticity were observed as the number of cycles increased. Therefore, it was considered that the number of cycles (three cycles) adopted in the standard [11] is sufficient in order to reliably evaluate the modulus of elasticity in the soil-cements analyzed. Therefore, in the results presented below, modulus of elasticity values were calculated on the basis of strain and stress measurements during the third cycle (figure 2).

5. Test results
The test results obtained are presented in table 4. The values of secant modulus of elasticity presented in each case represent the average for 3 specimens. Additionally, table 4 shows the ratios of the modulus of elasticity E\textsubscript{c,s} to compressive strength f\textsubscript{c}.
Table 4. Results of secant modulus of elasticity ($E_{c,s}$) tests after 28 days of curing [MPa].

| Soil          | Medium sand | Clay | Loam |
|---------------|-------------|------|------|
| Mixture design | 400/1.6     | 450/1.2 | 450/0.8 | 600/2.0 | 600/1.4 | 650/1.2 | 700/2.6 | 750/2.0 | 800/1.6 |
| Secant modulus of elasticity $E_{c,s}$ [MPa] | | | | | | | | | |
| Average       | 10500       | 15200 | 21200 | 3000    | 4500    | 6900    | 1200    | 1900    | 3300    |
| Min           | 10120       | 14820 | 20760 | 2930    | 4360    | 6580    | 1170    | 1880    | 3150    |
| Max           | 10880       | 15730 | 21620 | 3070    | 4620    | 7100    | 1220    | 2080    | 3450    |
| $E_{c,s}/f_c$ | 3621        | 2111  | 1240  | 833     | 938     | 852     | 571     | 704     | 1000    |

Figure 4 below shows the relationship between the modulus of elasticity and compressive strength for all partial results from 9 series of specimens made of 3 types of soil. Additionally, the graph shows the range of the $E_{c,s}/f_c$ ratio, which is from ca. 100 to 1000 according to [3, 5, 12].

![Figure 4](image-url)

Figure 4. Relationships between compressive strength ($f_c$) and secant modulus of elasticity ($E_{c,s}$) after 28 days of curing.

The analysis of the above results demonstrates that the $E_{c,s}/f_c$ ratios determined on the basis of the results obtained differ significantly depending on the type of soil used. For soil-cements made using cohesive soils, the average $E_{c,s}/f_c$ values were as follows: 874 for clay soil and 758 for loam soil. It should be emphasised here that all partial values of these ratios are within the 100–1000 range which is mentioned in the literature [3].

However, for non-cohesive medium sand soil all $E_{c,s}/f_c$ ratio values significantly exceed the upper limit of the range stated. The average $E_{c,s}/f_c$ ratio for this soil type was 2324.

In the analysis of the impact of the composition of soil-cements on their deformability, the most notable phenomenon is the variability of the results obtained depending on the soil used. Soil-cements made from non-cohesive soil (medium sand) are characterised by a secant modulus of elasticity which ranges from 10500 to 21200 MPa. Much lower $E_{c,s}$ values were obtained for composites made from cohesive soils. For clay soil, the results range from 3000 to 6900 MPa, while in the case of loam soil this range is as low as 1200 to 3300 MPa.
In general, soil-cements include cement pastes with relatively high w/c ratios compared to the pastes present in ordinary concrete. This is related to the differences between aggregate grain size distribution in concrete and soil grain size distribution in soil-cement. Soil-cement mixes exhibit significantly greater demand for highly liquid cement paste. Analysing the secant modulus of elasticity results obtained for soil-cements with the same amount of paste within the same soil type, it can be concluded that in the case of medium sand soil and a V_z equal to 450 dm³/m³, an increase in the w/c ratio from 0.8 to 1.2 results in a decrease in the modulus of elasticity value by 28%, while for clay soil and a V_z equal to 600 dm³/m³, an increase in w/c from 1.4 to 2.0 results in a decrease in the E_c,s value by 52%.

When analysing the impact of the composition of soil-cement composites on their deformability, tests concerning the effect of the amount of cement on the secant modulus of elasticity are of considerable value. The amount of cement results from the assumed w/c ratio and the amount of cement paste, thus it is a universal parameter of soil-cement composition [13]. For each soil type, an increase in the amount of cement increased the value of the secant modulus of elasticity. In the case of medium sand soil, an increase in cement content from 208 to 401 kg/m³ resulted in an increase in the E_c,s value by 102%. However, this impact is even more pronounced in the case of cohesive soils. For clay soil, an increase in cement content from 240 to 416 kg/m³ resulted in an increase in the E_c,s value by 130%, and for loam soil, an increase in cement content from 258 to 427 kg/m³ made it possible to achieve an E_c,s value higher by 175%. Obviously, this is due to the higher content of paste in soil-cement composition and, consequently, the greater impact of the amount of binder used on the properties of the entire composite.

6. Conclusions
The tests conducted have demonstrated that the application of the methodology contained in the EN 12390-13 standard for determining the secant modulus of elasticity of soil-cements is justified. It has been confirmed that during the third loading and unloading cycle, strains are already stabilised and no further cycles are required.

The fundamental factor in the composition of soil-cements which determines their deformability is the type of soil, which is the inclusion present in the composites. The use of loose (sand medium) soil in the composite, i.e. soil with coarser grains and lower demand for cement paste with the lowest possible w/c, enables a composite to be obtained with a relatively high compressive strength (f_c = 2.9–17.1 MPa) and a high modulus of elasticity (E_c,s > 10000 MPa). The E_c,s/f_c ratio determined for this group of soil-cements ranges from 1240 to 3621.

On the other hand, soil-cements made of cohesive (clay and loam) soils exhibit compressive strength values in the range from 2.1 to 8.1 MPa and moduli of elasticity in the range from 1200 to 6900 MPa. The E_c,s/f_c ratio values calculated in this case range from 571 to 1000.

The correlations between soil-cement compressive strength and the modulus of elasticity proposed most frequently in the literature (E_c,s/f_c = 100–1000) appear to hold for cohesive soils only. In the case of soil-cements made using loose soils, the E_c,s/f_c ratio may even exceed 3000.

Summing up, estimates of modulus of elasticity values based solely on soil-cement compressive strength can be highly inaccurate. The E_c,s/f_c ratio depends very much on the type of soil. Therefore, it is possible that soil-cements made from various soils may have significantly different moduli of elasticity despite exhibiting similar compressive strengths.

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