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Estimation of mechanical properties of soil stabilized by hydratized lime addition

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Abstract: *Estimation of mechanical properties of soil stabilized by hydratized lime addition.* Design of road pavement is connected with estimation of mechanical properties of each of the materials used for construction. This statement presents the need of estimating the mechanical moduli. For the purposes of this article, tests were carried out in order to establish physical and mechanical properties, especially penetrating resistance CBR. The main aim of this paper was to estimate the optimal lime and water content in soil – clayey sand. The paper presents the expected cyclic behavior of clayey sand, as well as method for calculating the resilient modulus (M_r).

Key words: lime stabilization, CBR, compressive strength, optimal lime content, resilient modulus

INTRODUCTION

The economic growth in Poland is one of the reasons behind the increase traffic load, which impacts the road structure. Pavements are influenced by this force, which changes their structure, causing ruts and cracks to appear on the surface of the pavement. Current techniques used for the designing of pavement layers are based on empirical methods (Uzan 2004). One of such methods, for establishing the strength of, is conducting a CBR test. This test allows us to establish California Bearing Ratio (CBR) of tested material and compare it with reference requirements.

In Poland large part of land surface consists of cohesive soils. In this category of subsoil clayey sand and sandy clay are most common soils. This material shows poor strength behaviour, especially when its plastic limit is crossed. CBR values for this kind of soils are below 10%, which eliminates this material from being used as a base for road construction.

Stabilization is needed to improve poor mechanical characteristics of this soil. Stabilization can be achieved, by mechanical and chemical means (Karol 2003). One from of such techniques is stabilization by the introduction of lime, which is for cohesive soils more effective and generates low costs.

To describe proper lime and water content in stabilized soil, empirical equations were made. However, the use of empirical formulas is subject to the possibility of underestimating the right proportions and thus not getting the desired mechanical properties. For this reason, an attempt to analyze the stability of stabilized ground containing different proportions of loamy sand, lime and water content was conducted.

By being stabilized through the introduction of lime, soil improves its mechanical properties. But the amount of added lime must be strict. Moreover, water addition also has to be specified in accordance with lime content. This depends on the quantity of lime added in order to provide top bearing capacity is various for cohesive soils.

LITERATURE REVIEW

Stabilization with lime is a chemical reaction, which occurs between the particles of soil, water and added lime. The stabilization process consists of two chemical reactions. The first part short-term reactions, which improve properties of soil through cation exchange and flocculation. Another type of reaction which occurs in soil with added lime is the pozzolanic reaction, a long-term reaction causing stabilization (NCHRP 2009; Al-Mukhtar 2010).

Complex and not well understood reaction between soil and lime particles depends on mineralogical changes. Pozzolanic reactions are time dependent. Factors such as quality of lime, temperature and moisture content also have an impact on stabilization process. These reactions cause stabilization, which results from the presence of new calcium hydrates (Al-Mukhtar et al. 2010).

Lime-treated soil shows improvement in various ways. First of all, compaction of soil impacts caring time and lime content and decrease in maximum dry density (Harichane et al. 2011). Secondly, changes in plasticity and workability of lime-stabilized soil also can be noted, as the material becomes more shrinkable. The increase in plasticity index, time of caring and lime content can also be noted (Harichane et al. 2011).

Moreover, lime stabilization results in the change of volume and strength. Addition of lime in order to obtain optimal condition improves strength properties of stabilized soil, on the basis of the relation between moisture content and lime addition and this dependency is further time-dependent.

MATERIAL AND METHODS

Soil used in tests was collected from a 30 cm deep earthwork construction site. Conducted tests, consisting of sieve and aerometric (Bouyoucos method using a modification made by Casagrande) analysis led to classification of porous material as clayey soil (clSa) in accordance with Eurocode 7 (EN ISO 14688-2:2004). Test results are shown in Figure 1. Studies performed under existing Polish standards (PN-B-02480, PN-B-02481, PN-B-03020, PN-B-06050, PN-S-02201, PN-S-02205, PN-S-96011). Figure 2 presents the samples during the tests.

Liquid limit was also estimated. Tests were conducted in Casagrande apparatus, with the use of soil paste. On the basis of six tests performed on with varying moisture content, plot of liquid limit was made (Fig. 3). Estimated liquid limit was 19.7%. Such range of liquid limit classifies this soil to as a clay of low plasticity.

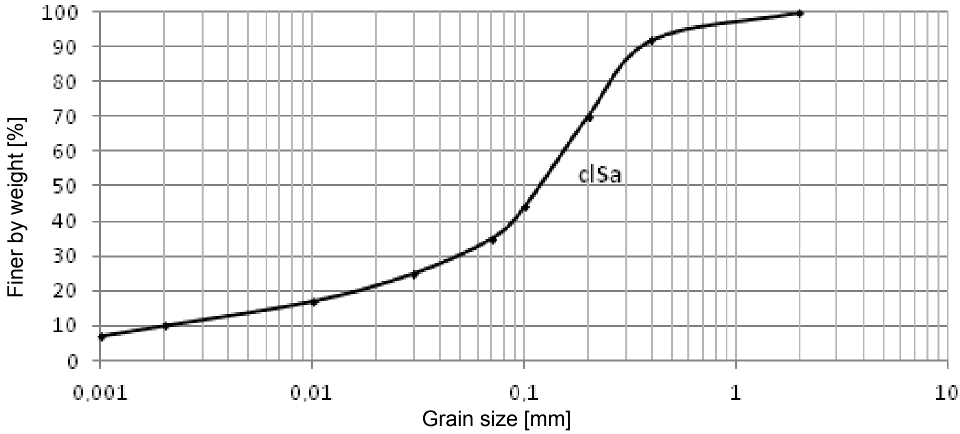

FIGURE 1. Particle size distribution of tested soil

FIGURE 2. Samples after the Proctor test and CBR molds

RESULTS AND DISCUSSION

For the purpose of estimating optimum moisture content, Proctor test was performed. The test was conducted by compaction in the Proctor mold, with the volume being 2 dm^3, using standard energy of compaction, which is 0.59 J/cm^2. Test results are presented in Figure 4. Optimum moisture content for clayey sand was 9.1% and maximum dry density at optimum moisture content reached 2.19 g/cm^3.

The Proctor test was also conducted for soil stabilized with lime ($CaOH_2$). Tests were performed for 5, 7.5 and 10% lime content. Results are presented in Figures 5 and 6.

Results of the Proctor test clearly present the impact of lime content on optimum moisture content and also on maximum dry density of mixture. For clayey sand with the addition of 5% lime content, optimum moisture content was 10.46%, while maximum dry density reached 2.15 g/cm^3. For 7.5% content

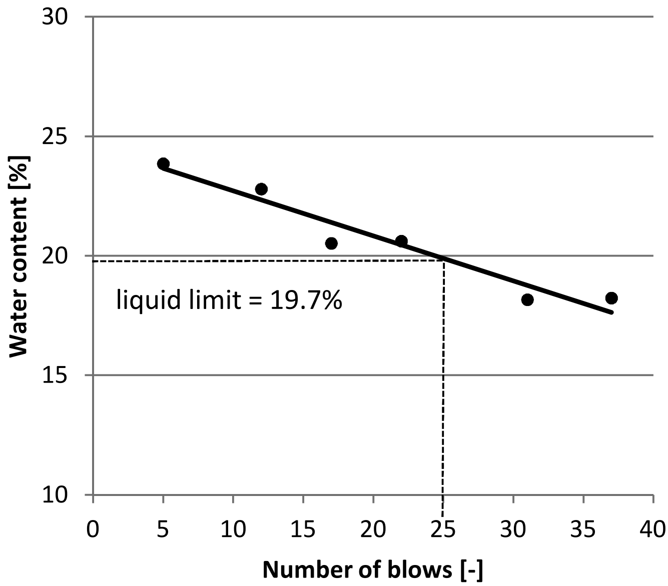

FIGURE 3. Liquid limit estimation test results

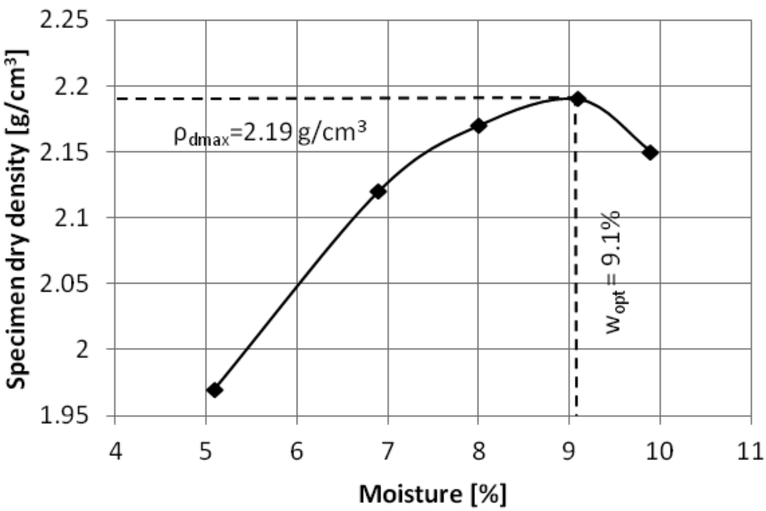

FIGURE 4. The Proctor test results for clayey sand

of lime specimens give optimal moisture content at 11.8% with maximum dry density being equal to 2.14 g/cm^3. Last test conducted on the soil with 10% lime content gave the following results: optimal moisture content was equal 13.5% and maximum dry density was equal 2.12 g/cm^3. Figure 5 present a 3D visualization of those three variables. By analyzing the graph surface, it is possible to estimate an equation containing variables denoting water and lime content.

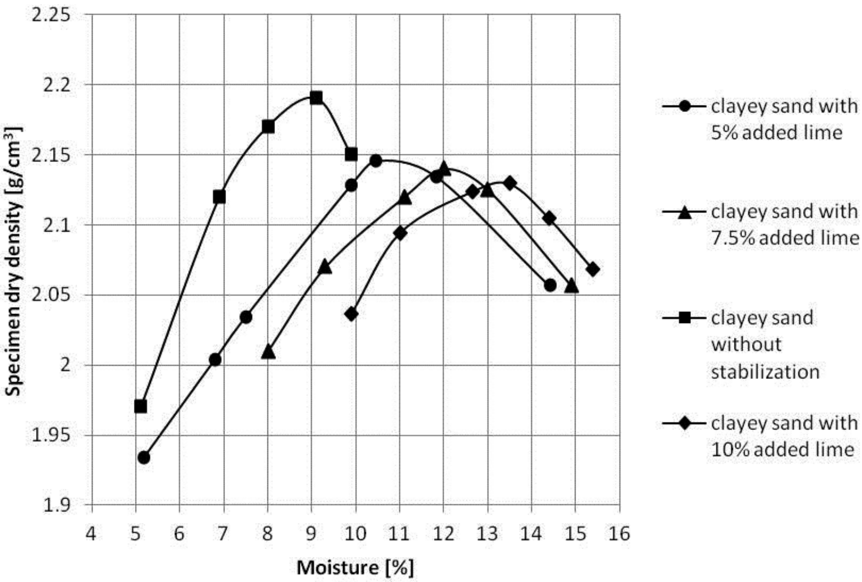

FIGURE 5. Results of the Proctor test for soil with varying lime content

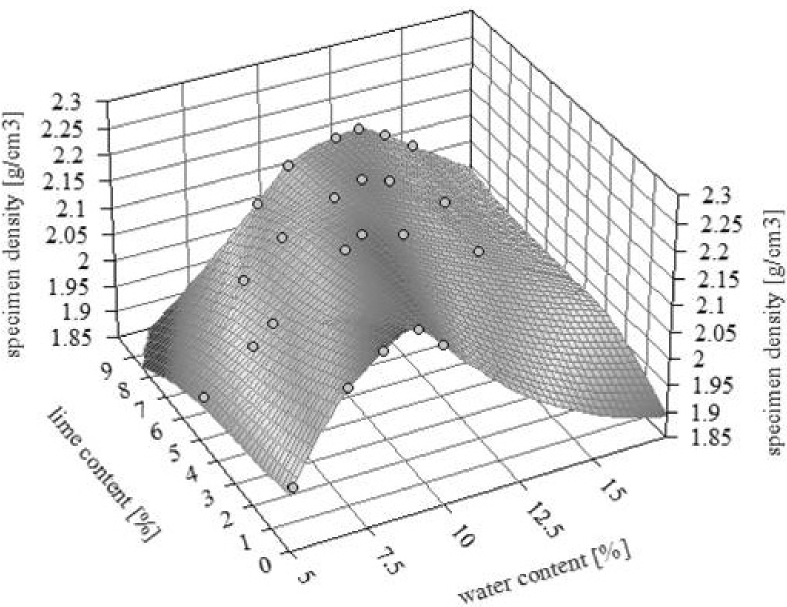

FIGURE 6. 3D plot of specimen dry density in soil with varying lime and water content

Equation (1) presents formula for calculating the density of soil (z) under with varying lime (y) and water (x) content expressed in %.

$$z = \frac{a + cx + ey + gx^2 + iy^2 + kxy}{1 + bx + dy + fx^2 + hy^2 + jxy} \qquad (1)$$

Where, letters from a to k are constants: a = 1.830147354; b = -0.21419130; c = -0.386028110; d = 0.135043775; e = 0.258866051; f = 0.014331182; g = 0.026577656; h = 0.000321902; i = 0.000145624; j = -0.013335690; k = -0.025355170. For this equation, the R^2 value amounts to 0.993. Equation (1) makes it possible to establish the optimal water and lime content for tested clayey sand, by establishing maximum dry density. Calculations based on the Polish standard PN-S-96011 were also made. Results of them are presented in Figure 7.

Calculations of optimum water content and lime addition based on the equation formulated on the basis of the Polish standard (PN-S-96011) were as follow:

$$w_{\text{opt}}^{w} = w_{\text{opt}}^{w} + 1.5 + 0.4D \qquad (2)$$

where:
w_{opt}^{w} – optimum moisture content for the mixture, expressed in %,
w_{opt}^{g} – optimum moisture content before the addition of lime,
D – lime content in %.

For tested clayey sand and with refererence to equation (2), the formula can be changed as follows:

$$w_{\text{opt}}^{w} = w_{\text{opt}}^{g} - 0.536 + 0.446D \qquad (3)$$

Results of calculations made on the basis of equation (3), when compared to scored data, indicate that R^2 value is approximately 0.9758. Correlation coefficient between values from equation (2) and equation (3) is 0.999. This is strong positive relation, which shows that equation (2) based on the Polish standard is suitable for clayey soils stabilized by lime. Equation (3) can be more suitable for clayey soils stabilized with lime with low liquid limit.

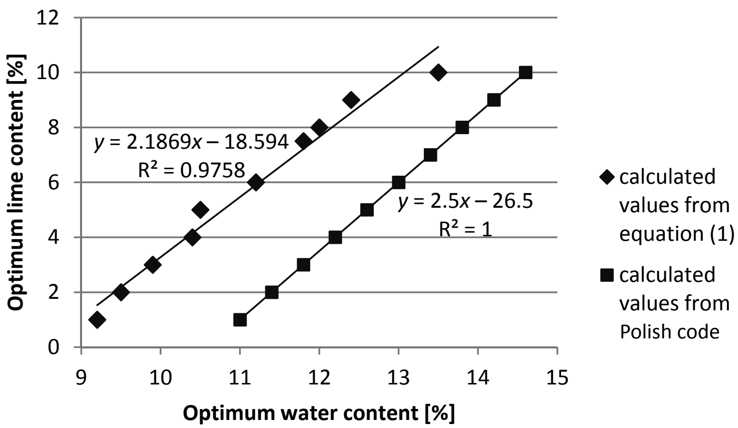

FIGURE 7. Results of optimal condition calculations for the mixture of clayey sand, water and lime, and calculations based on the Polish standard

After the conclusion of the Proctor tests, compressive strength of specimens was also tested, for various stages of stabilization, after 7 and 28 days. Scored data is presented in Figures 8 and 9.

Figure 8 presents changes in compressive strength coefficient after stabilization with varying lime content and in optimum moisture content. Plot of this data clearly shows that compressive strength coefficient depends on the stabilization time. A significant impact of lime content can also be noted. Compressive strength coefficient rises, until lime content is about 7.5%. Then, coefficient is constant until lime content reaches 10%.

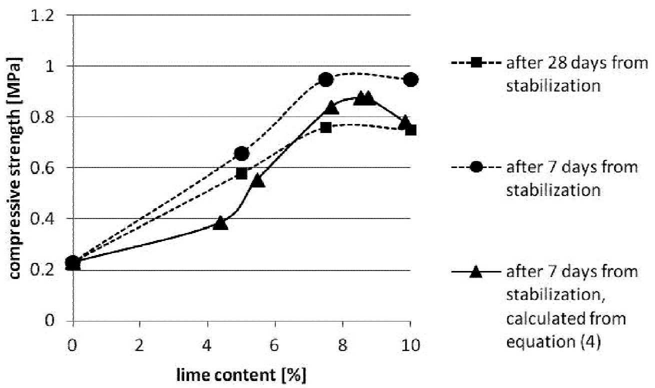

FIGURE 8. Plot of compressive strength coefficient in soil with varying lime content, after 7 and 28 days from stabilization

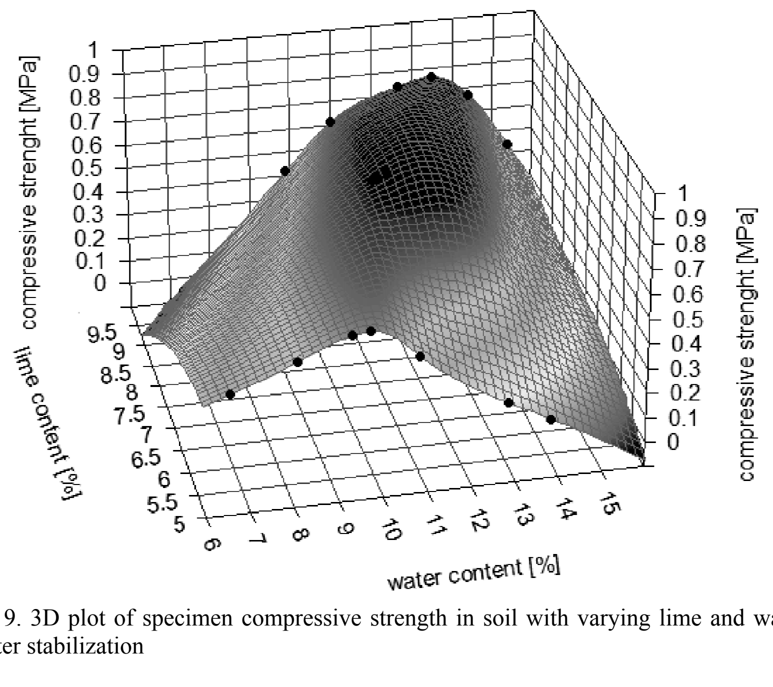

FIGURE 9. 3D plot of specimen compressive strength in soil with varying lime and water content, 7 days after stabilization

That indicates the importance of careful application of lime content during the stabilization of soils.

Equation (4) presents formula for calculating the compressive strength of clayey sand (z) with varying lime (y) and water (x) content, expressed in %.

$$z = a + bx + cy + dx^2 + ey^2 + fxy + + gx^3 + hy^3 + ixy^2 + jx^2y \quad (4)$$

Where, letters from a to j are constants: a = 7.8354234; b = -0.74022011; c = -2.3762628; d = -0.02308373; e = 0.068209671; f = 0.34308686; g = 0.0010651302; h = 0.00077037872; i = -0.0108536; j = -0.0060451359. For this equation the R^2 value is 0.983.

Compressive strength coefficients for optimum moisture and water content were calculated on the basis of equation (4) and (3). Plot of results from calculation is presented in Figure 8. Optimum moisture content is 12.4% for 8.5% added lime. Compressive strength coefficient for these conditions reaches 0.878 MPa, which is the highest predicted coefficient for lime stabilized clayey sand with low liquid limit.

The CBR test was the last element of studies on the stabilization of clayey sand with lime. Samples were tested on 7th and 28th day after stabilization. Lime content was 5, 7.5 and 10%. Results of performed tests are presented in Figures 10 and 11.

Equation (5) presents the formula for calculating the axial stress of clayey sand (z) with varying lime content (y) and axial displacement (x) content, expressed in % (Fig. 10).

$$z = a + bx + cy + dx^2 + ey^2 + fxy + + gx^3 + hy^3 + ixy^2 + jx^2y \quad (5)$$

Where, letters from a to j are constants: a = -0.6907802; b = 0.587777498; c = 0.0001453479; d = -0.12978132; e = -0.01006397; f = 0.182918606;

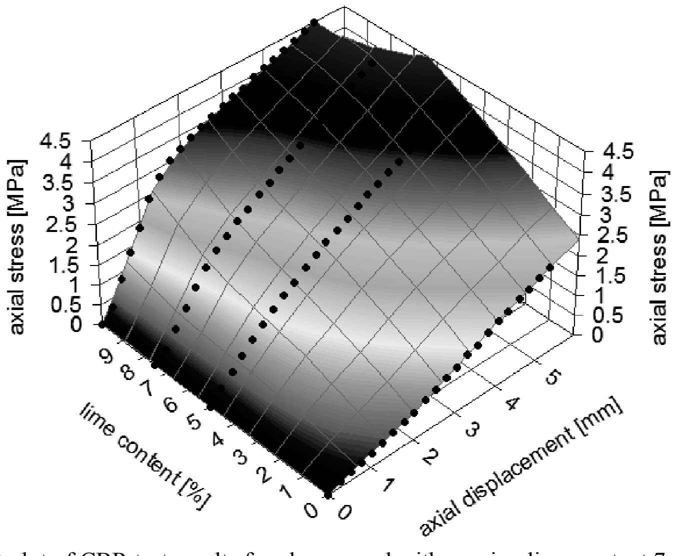

FIGURE 10. 3D plot of CBR test results for clayey sand with varying lime content 7 days after stabilization

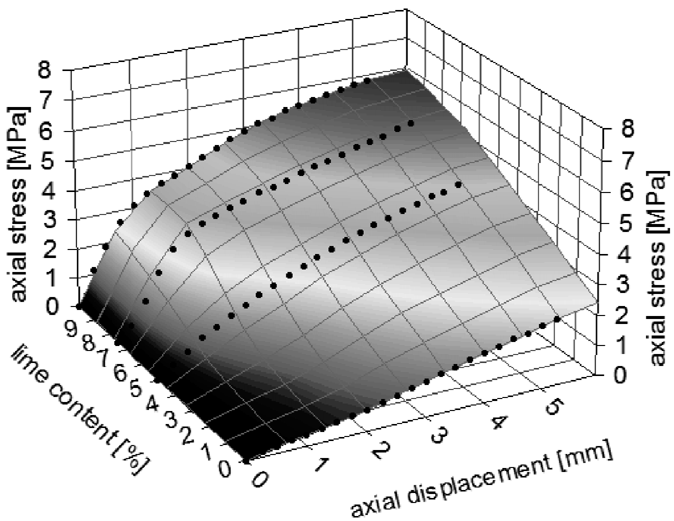

FIGURE 11. 3D plot of CBR test results for clayey sand with varying lime content 28 days after stabilization

g = 0.02009816; h = 0.0011389047; i = -0.00389047; j = -0.02032508. For this equation the R^2 value is 0.994.

Equation (6) presents formula for calculating the axial stress of clayey sand (z) with varying lime content (y) and axial displacement (x) content, expressed in % (Fig. 11).

$$z = \frac{a + cx + ey + gx^2 + iy^2 + kxy}{1 + bx + dy + fx^2 + hy^2 + jxy} \qquad (6)$$

Where, letters from a to k are constants: a = 0.044161825; b = 0.11208887; c = 0.210068777; d = -0.20485169; e = -0.00735506; f = 0.010245517; g = 0.105650016; h = 0.011339888; i = -0.00010459; j = 0.001658167; k = 0.039606958. For this equation the R^2 value is 0.997.

From equations (5) and (6), in optimal moisture content, CBR values for 2.54 and 5.08 mm axial stress in various lime content were calculated. Results of this analysis are presented in Figure 12.

The highest obtained CBR value was 66.1% for clayey sand stabilized with lime, 28 days after stabilization. Result obtained from the test was 64.2%. On the basis of calculation and test results, some conclusions can be made.

There is a difference between the compressive strength coefficient results and the CBR values. The highest compressive strength coefficient was noted in case of soil with 8.5% lime content. In the same conditions, the highest CBR value was reached during the CBR tests of soil with 10% lime content. That is because both of these tests have different purpose, compressive test is failure test and CBR test is penetrating resistance test. Because of these differences, the results of CBR test and compressive strength test should not be compared.

CBR test should reach stress-hardening of the soil to predict real properties

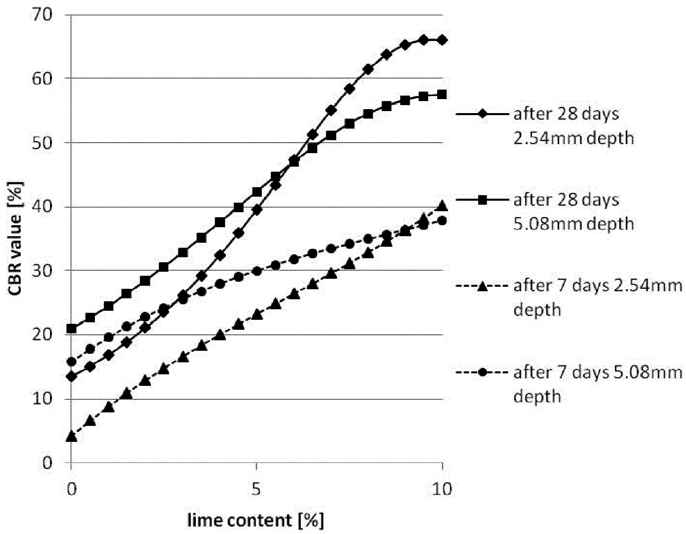

FIGURE 12. CBR values for various lime content calculated on the basis of equations (5) and (6)

of tested samples. Because of that, maximum CBR value for clayey sand should be 57.5%, on the basis of the equation (6) or 54.4% on the basis of test results for soil with 10% added lime, 28 days after stabilization.

Figure 13 presents chronological changes in resilient modulus (M_r) occurring after stabilization. Resilient modulus values were calculated on the basis of equation (7), proposed by AASHTO (2003). It is possible to calculate resilient modulus (M_r) on the basis of this equation, using CBR values.

$$M_r = 10\ 340 \cdot CBR \qquad (1)$$

Obtained results varied from 134.7 to 212.7 MPa for non-stabilized clayey sand and from 400.5 to 664.0 MPa for specimens tested 28 days after stabilization.

Based on the results presented by Sas et al. (2012), which describe the increase of resilient modulus after numerous series of cyclic loading, proposed function of change M_r values was used. For calculating the results of CBR value, for clayey sand and stabilized by the addition of 7.5% lime content, 28 days after stabilization process were conducted. Those conditions are the closest to conditions during the tests performed on cyclic CBR (Sas et al. 2012).

Initial M_r value obtained from tests was 595.4 MPa. Then, equation of M_r change in function of number of cycle is as follow:

$$M_r = 53.244 \cdot \ln(n) + 595.4 \qquad (2)$$

where n is a number of cycle.

Increase of M_r value in 50 cycle reached 803.7 MPa. Compared to initial value, resilient modulus increased 1.35 times. Results of calculations are presented in Figure 14. By analyzing Figures 13 and 14, a number of conclusions can be made.

Predicted M_r value after 50 cycles of loading (Fig. 14) give higher results than the same soil in static CBR test in different

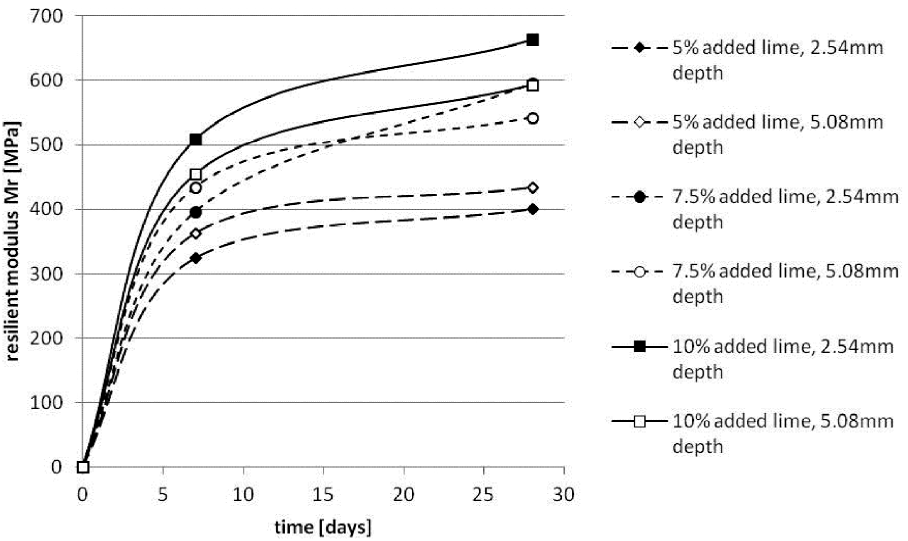

FIGURE 13. Change of calculated resilient modulus in time after stabilization

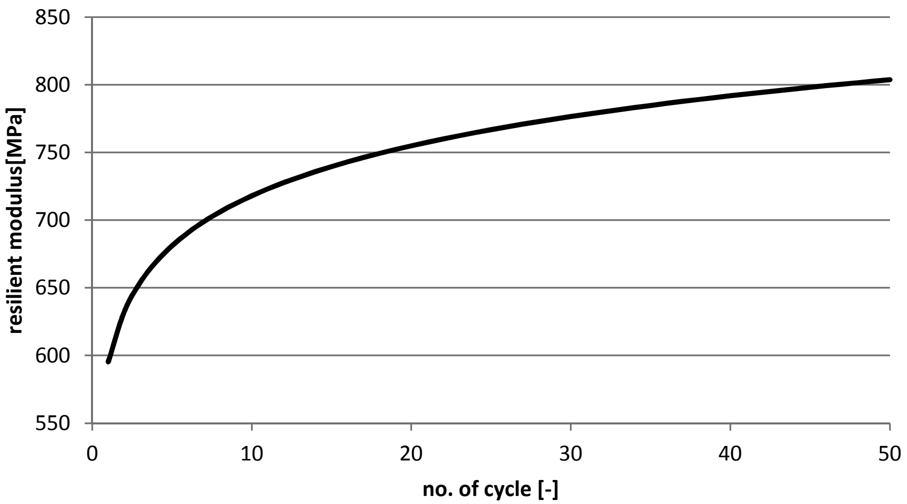

FIGURE 14. Change of resilient modulus in cyclic loading

conditions of penetration of plunger or lime content. This indicates that impact of cyclic loading can obtain better scores than stabilization with lime in optimal conditions without cyclic loading on stage of compacting.

CONCLUSIONS

Tests were conducted on clayey sand stabilized with lime. By analyzing test results, the following conclusions can be made:

1. Optimum moisture content obtained during the Proctor test for low liquid limit clayey sand is different than that obtained using the Polish standard.

2. For low cohesive soils new equation for optimum water addition was proposed.

3. By testing compressive strength properties of soil, optimal lime content was estimated as being 8.5% and moisture content as being 12.4%.

4. A number of equations can be used as an easy tool, to obtain optimum water content and lime addition in various time after stabilization to find mechanical properties of stabilized soil with low liquid limit.

5. Resilient modulus calculations suggest that cyclic loading of stabilized soil can be important for increasing of mechanical properties as the content of lime.

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Streszczenie: *Określenie właściwości mechanicznych gruntu stabilizowanego wapnem hydratyzowanym.* Projektowanie konstrukcji drogowych wiąże się z określeniem właściwości mechanicznych każdego materiału użytego do konstrukcji drogi. Oznacza to potrzebę wyznaczenia charakterystycznych wartości modułów wytrzymałościowych. W artykule podjęto badania mające na celu określenie właściwości fizycznych i mechanicznych gruntu. Wykonano badania wytrzymałościowe i badania nośności CBR gruntu. Celem badań było określenie na tej podstawie optymalnej zawartości wapna i wody w mieszance z gruntem naturalnym – piaskiem gliniastym. W artykule przedstawiono także przewidywane zachowanie się gruntu w wyniku obciążeń cyklicznych oraz obliczenia cyklicznego modułu sprężystości (M_R).

Słowa kluczowe: stabilizacja wapnem, CBR, nośność CBR warstwy konstrukcji drogowej, wytrzymałość na ściskanie, optymalna zawartość wapna, cykliczny moduł sprężystości

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