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# The use of cohesive soils improved with lime as an example of circular economy in earthworks

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## Abstract

A common practice in civil engineering during earthworks is the usual replacement of cohesive soils (fine soils), excavated during earthworks, with non-cohesive soils (coarse soils). Until recently, such a procedure was dictated primarily by economic and technical reasons. From an economic point of view, the ease of access and therefore low cost of using such soils instead of cohesive soils was crucial. The technical reason is, above all, the ease of compacting fine soils (as opposed to cohesive soils) and well-developed and well-known engineering methods for controlling their compaction.

The situation changed radically when the new environmental regulations came into force and enforcement by the inspection authorities began. Currently, soil removed from a construction site according to regulations should be classified as waste. This fact has completely changed the approach of participants in the construction process to the use of local soils, especially cohesive soils (e.g. clays). Their use "on site" has stopped being an expensive option and has become a necessity.

This paper presents aspects of the use of lime-improved cohesive soils that can be successfully used on site as excavation backfill. Problems related to the proper preparation of soil-lime composites are described, as well as the results of compaction tests. The paper presents the author's own methodology for selecting the content of quicklime in the soil-lime composite.

**Keywords:** soil improvement, cohesive soil, excavation, backfill, compaction.

## Introduction

Subsoils built of made grounds used in earthworks should have sufficient bearing capacity and stiffness to meet design criteria for ultimate and serviceability limit states. These criteria are designed to ensure the durability of the earth-structure and the safety of its use. Since the problem of made grounds concerns a very wide spectrum of human construction activities, many papers have been dedicated to this topic (e.g. Sulewska, 2009; Sulewska 2012). In Poland, one of the most respected authors dealing with the subject of soil compaction and compactability is Stanisław Pisarczyk (Pisarczyk, 2015; Pisarczyk, 2014). From an engineering point of view, an important element in the process of soil structure designing and performing earthworks are standards, regulations and various types of guidelines issued by opinion-giving research and development centers. The standards in the analyzed field are primarily concerned with the area of road construction. The reason for this is that all earthworks are a natural and integral part of this type of construction. From a formal point of view, an important source of guidelines for the requirements for

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earthworks and soil structures is the Regulation of the Minister of Infrastructure dated June 24, 2022 on technical and construction regulations for public roads (effective from September 21, 2022).

The PN-S-02205: 1998 standard is still used in the design practice of road construction in Poland. It should be noted that the standard for earthworks EN 16907-1: 2018 is now formally in force. Also important are materials issued by the General Director of National Roads and Highways, among which it is necessary to list, for example, the "Catalogue of typical constructions of flexible and semi-rigid pavements", which is an Appendix to Order No. 31 of 16.06.2014, and the "Conditions for the execution and acceptance of construction works" (D-02.00.0 1 v03. Earthworks. General requirements. General Directorate of National Highways of September 30, 2019).

The requirements for soils as materials for use in earthworks given in the documents mentioned above have a major impact on design decisions as well as decisions made during the execution of earthworks. In engineering practice, there are often situations where local cohesive soils were classified as unsuitable or even unsuitable for further use after excavation. Such soils were transported to an offsite, often many kilometers away, and replaced with delivered soils, usually non-cohesive. Quite rarely was the decision made to reuse local soil after it had been properly improved. This was due to the factors, which are discussed below.

1) Non-cohesive soils are considered more useful than cohesive soils due to their easier compaction. In addition, non-cohesive soils are less sensitive to moisture and do not create frost heave.

2) Sourcing and transporting non-cohesive soils (gravels, sands) was relatively cheap.

3) The standard techniques used to improve cohesive soils have quite a few limitations (primarily due to equipment availability) and can be time-consuming and expensive.

4) The technology of using improved cohesive soils is well developed for earth-structures with large volumes and work areas. It is very seldom used for linear trench.

5) Quality control of the compaction of embankments and backfills made of non-cohesive soils is easier to carry out than in cohesive soils. Inspection and acceptance procedures for non-cohesive soils are better known and there are correlative relationships that allow the use of dynamic probing tests and light falling weights deflectometers.

6) Often in the project documentation, the authors impose the need to use only backfill of non-cohesive soils without analyzing the possibility of using cohesive soils.

7) The habits and beliefs of participants in the decision-making process very often influence the disqualification of cohesive soils as a possible building material already at the initial design stages.

In addition, an important element of the problem discussed seems to be the lack of precision in the area of existing and applied norms and guidelines. An example is the removal of Appendix No. 4 in the Announcement of the Minister of Infrastructure and Construction dated December 23, 2015. (on the announcement of the consolidated text of the Ordinance of the Minister of Transport and Maritime Economy on the technical conditions to be met by public roads and their location), which a discussion of the bearing capacity classes of road subsoil were included. However, the classification into bearing capacity classes is still present, for example in the "Catalogue of typical constructions of flexible and semi-rigid pavements." Not surprisingly, designers and construction managers are consternated by the problem presented.

The implementation of new environmental regulations (THE ACT of December 14, 2012 on waste. Journal of Laws of 2020, item 797, 875, as amended) harmonized with European Union law (Directive 2008) has significantly changed the situation. According to the new regulations, soil removed from a construction site must be classified as waste, which cause significant additional costs. The use of cohesive soils as trench backfill or embankment material has basically become a necessity instead of an expensive alternative.

# 1 Improvement and stabilization of cohesive soils with lime

According to classical terminology, soil improvement should be understood as such modification that improves the geotechnical properties of soils to increase their suitability for construction. Soil improvement operations can dry the soil, improve its compaction, increase its bearing capacity and increase its resistance to water and frost. Soil stabilization, on the other hand, is the process of engineering soil reinforcement for construction purposes, when the properties of the stabilized soil are included in the design, and the stabilized soil layer is a construction component of the structure (e.g., road subgrade). As a rule, such layers are expected to have high strength and frost resistance. In fact, appropriate additives (e.g., cement, lime, fly ash, etc.) are used for both soil improvement and stabilization. The main difference, however, is the amount of additive used. In the case of the use of lime, it should be considered that stabilization can be mentioned with a binder mass addition of 3 to 8% (PN-S-96011:1998) or 3 to 12% (Pisarczyk, 2015). Therefore, it should be concluded that the application of a smaller amount of binder should be considered an improvement. This is supported by information found in papers by Celauroa at. al. (2012a, 2012b), in which the authors state that the typical amount of CaO quicklime used to improve cohesive soils is up to 3% for construction of road embankments and up to 6% for capping layers.

The PN-EN 14227-15:2015-12 standard introduced a new approach to the classification and naming of soil mixtures with hydraulic binders. The first classification was made into: aggregate mixtures bound with hydraulic binder and soil stabilized with hydraulic binder or lime. The definition of stabilization has been significantly expanded and, in a sense, "absorbed" improvement. Currently, soil stabilized with hydraulic binder is classified into soil bound with hydraulic binder or lime and soil improved with hydraulic binder or lime.

Improving and stabilizing soils with lime can be done with both quicklime (CaO) and hydrated lime $Ca(OH)_2$. Various literature sources (e.g., Pisarczyk, 2015; Rolla, 2001; PN-S-96011:1998) report that cohesive soils with a plasticity index $IP \geq 7\%$, which contain clay minerals that react with lime, are suitable for lime stabilization. Soils with an organic content of more than 10% and with a high sand equivalent value (greater than 30%) are not suitable for improvement. Quicklime can be used for cohesive soils with a clay fraction content $fi > 10\%$. When the moisture content of the soil is quite low and does not exceed the optimum moisture content ($w < w_{opt}$), the so-called „lime milk" should be applied. Analogous information can also be found in the studies of Bicalhoa at. al, 2018 and Baldavina at. al, 2018.

The improvement of geotechnical properties of soils with lime addition is the result of crystallization of $Ca(OH)_2$ and carbonation of calcium hydroxide with simultaneous exchange reactions resulting in the formation of  (Di Sante et al., 2014). These processes cause soil strengthening. It is also important to reduce the moisture content of the soil after the addition of lime (there is drying of the soil - the addition of 1% lime reduces the moisture content of the soil by 0.8-1.4%, 1% can be taken as a guideline) as well as increasing its optimum moisture content. This is an effect that improves the compactability of soils containing too much water. So here we can say about the simultaneous double effect of lime. According to Pisarczyk (2015), the optimum moisture content of soil with the addition of lime can be calculated from the formula:

$$w_{opt}^{m} = w_{opt} + 1{,}5 + 0{,}4 \cdot D, \quad \%, \ (1)$$

where:

$w_{opt}^{m}$ – the optimum moisture content of soil with the addition of lime, %,

D – quicklime content, %.

The addition of lime also makes the preparation and processing of the soil significantly easier. This is due to the fact that aggregation occurs - the soil is much easier to crumble, easier to mix and homogenize. The plasticity index and liquidity index of cohesive soils decreases and the soil becomes more crumbly and granular and thus easier to build and compact (Di Sante at. al., 2014).

## 2 Methodology of improving cohesive soils with lime and their embedding

Cohesive soils after being excavated from the trench should be properly prepared at the construction site before being embedded again. At the first stage, the soils should be crushed so that they become material in the form of clumps. Crushing can be carried out with a recycler, commonly known as a sieving bucket, (Fig. 1).

Figure 1. Crushing cohesive soil with a recycler

After initial fragmentation, a defined (based on geotechnical tests) amount of quicklime is added to the soil using a doser (Fig. 2). Next, the cohesive soil is mixed with the lime, initially using a blade rake (Fig. 3), then again, with further grinding, using a recycler (Fig. 4). This phase continues until a well-mixed homogeneous lime-soil mass (lime-soil composite) is obtained in the shape of small clods.

Figure 2. Adding quicklime to the soil using a doser

Figure 3. Mixing soil with quicklime using a blade rake

Figure 4. Mixing the soil with lime and further crushing with a recycler

The prepared soil-lime mixture is then poured into the excavation using a recycler (Fig. 5) with further crushing of the soil.

Figure 5. Filling a layer of soil mixed with lime into a excavation

Embankments should be raised in layers of about 30 - 40 cm thick with simultaneous compaction. It is particularly effective to use plate compactors mounted to the excavator (Fig. 6). Each of the performed layers (e.g., Fig. 7) should be inspected geotechnically (make an acceptance of the quality of earthworks).

Figure 6. Compaction of the soil layer in the excavation by means of a hydraulic plate compactor

Figure 7. The layer of compacted lime-improved cohesive soil

The peculiarity of all the presented stages of the technological process of soil preparation and embedding is the use of individual pieces of equipment, which are very efficiently mounted to the excavator by means of a fully automatic hydraulic quick connector. In addition, this technique, unlike the standard method used in road construction, makes it possible to carry out operations in cuttings.

## 3 Determination of the appropriate content of quicklime in the soil-lime composite

The methodology for calculating the proper content of quicklime in a soil-lime composite will be presented as an example. This is the author's simple procedure, which works well for soil improvement but not for stabilization. In the case of stabilization, standard procedures should be used (e.g. PN-S-96011:1998). In addition, the proposed procedure is much less time-consuming than the one presented in Rolla (2001).

The cohesive soil under study and the soil improvement binder (Lhoist Proviacal ST) were obtained from The Drabent company. The soil, according to Drabent's construction manager, came from the construction of DK678 road.

To begin with, identification and description of the soil was carried out in accordance with EN ISO 14688-1 and additionally based on PN-88/B-04481. The type of soil, its moisture content and color were evaluated. The tests were performed several times during the laboratory studies. It is estimated that a total of a dozen tests were carried out. It was found that the tested soil should be classified as:

- according to PN-88/B-04481 - brown silty clay (Gπz) layered with gray sandy silt (πp) with stiff consistency,

- according to EN ISO 14688 - brown silty clay (siCl) layered with gray sandy silt (saSi) with stiff consistency.

The moisture content of the soil was determined by the drying method in accordance with PKN-CEN ISO/TS 17892-1 and PN-88/B-04481. A total of 8 moisture content tests were performed. The average moisture content of the tested soil was 19.6%.

The determination of optimum moisture content ($w_{opt}$) and maximum dry density ($r_{ds}$), was carried out in accordance with PN-EN 13286-2:2010-11E and its accompanying appendices. This test is based on the Proctor method. Due to the grain size of the tested soils, the A+A method was used. The laboratory compaction test is based on compacting the soil in a standardized cylinder and determining the dry density of the soil ($r_d$) at different soil moisture contents (w). Based on the relationship $r_d$(w), the optimum moisture content ($w_{opt}$) and maximum dry density of the soil ($r_{ds}$) were determined (the coordinates of the maximum on the graph), (Fig. 8).

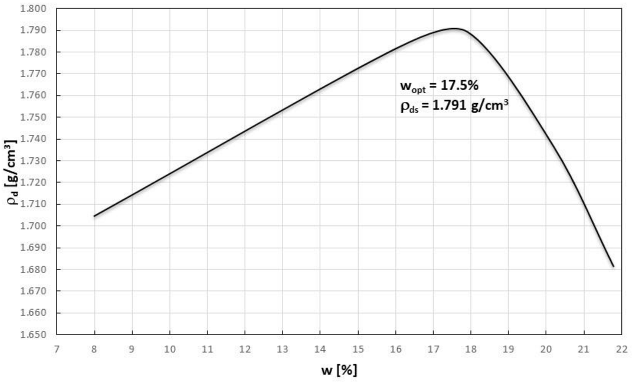
The Proctor compaction test was aimed at determining the correct amount of improvement additive. This test was conducted a total of 4 times using the method of successive trials using incremental increases in the amount of quicklime. A total of 4 complete test series were made:

- once for the soil without any improvement additives,

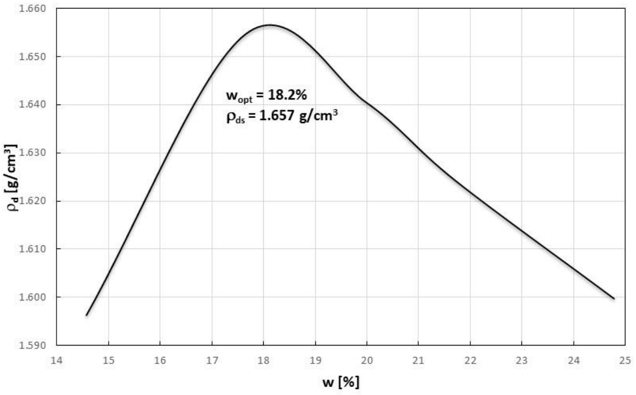
three times for soil improved with the addition of Proviacal ST quicklime (0.5%, 1.0% and 1.5% by weight of soil in the natural state).

The results of the compactability test are shown in Figure 8.

a)



b)



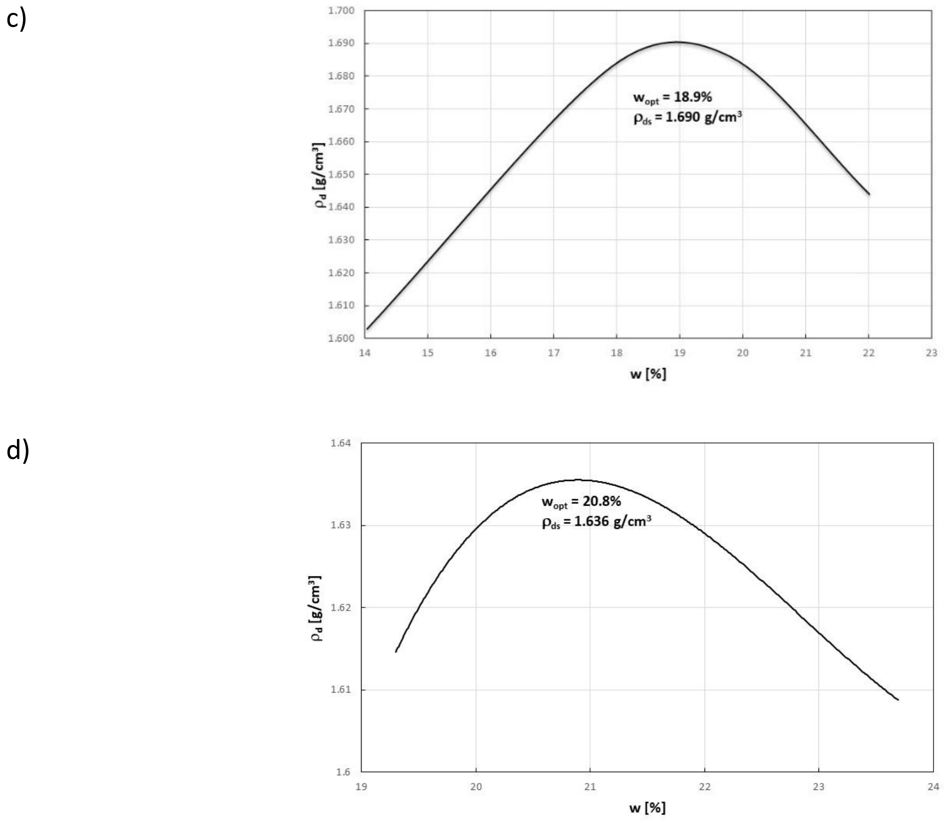


Figure 8. Results of the test of optimum moisture content ($w_{opt}$) and maximum dry density *($\rho_{ds}$):*
a) cohesive soil without the addition of quicklime; cohesive soil with the addition of quicklime: b) 0.5%, c) 1.0%, d) 1.5%

It is assumed that a one-percent addition of lime reduces the moisture content of the soil by about 1%. Analyzing the results given in Figure 8 and taking into account the natural moisture content of the tested soil of 19.6%, it was determined (from proportionality) that the needed additive of quicklime is 0.83%. Therefore, for practical reasons, an addition of 1.0% was assumed in the case under study.

The earthwork company used the proposed formula to improve the tested cohesive soil. In each case, they obtained, after embedding the properly prepared soil-lime composite, the required value of the degree of compaction $I_s \geq 0.97$ and the value of the secondary deformation modulus of the subsoil $E_{v2} \geq 40$ MPa, which were the values required by the design for the reconstruction of underground pipelines under the modernized road.

In the Report (Gosk at. al., 2018), it was shown that soil-lime composites with a properly selected amount of quicklime additive can be properly compacted and subsoils made from them can obtain even higher values of degree of compaction and stiffness parameters. During the realization of the project, values of degree of compaction $I_s = 1$ and the plate load test modulus of the subsoil $E_{v2}$ exceeding 70 MPa were obtained. These values successfully meet the standard requirements for backfilling of excavations of municipal infrastructure (e.g., pipelines) as well as for the construction of traffic embankments.

## 4 Economic aspect of improving cohesive soils with lime

Cost data shows that improving cohesive soils with lime is clearly a more cost-effective solution than replacing soils with non-cohesive ones. Table 1 presents the costs related to soil replacement and the costs to be paid for the application of improved cohesive soil. The data shown are for August 2021 and August 2022 prices.

Table 1. Summary of cost of embedding 1 m3 of soil with replacement and improvement

| | 2021 | 2022 |
|---|---|---|
| Option 1 – replacement | | |
| 1) Costs of removal, storage, planting of cohesive soil | 15 zl/m$^3$ | 65 zl/m$^3$ |
| 2) Gravel or sand, embedding | 30 zl/m$^3$ | 48 zl/m$^3$ |
| Total | 45 zl/m$^3$ | 113 zl/m$^3$ |
| Option 2 – improvement | | |
| 1) Binder requirement of 20 kg/m$^3$ | 9 zl/m$^3$ | 32 zl/m$^3$ |
| 2) Excavator approx. 20 tons + excavator equipment (doser, blade cutter, recykler, plate compactor - all items with hydraulic quick connector) | 6 zl/m$^3$ | 9 zl/m$^3$ |
| Total | 15 zl/m$^3$ | 41 zl/m$^3$ |

It can be observed a very large, about 2.5-times increase in price in the perspective of one year. The benefits associated with the use of lime-improved soil are unquestionable. While in 2021 it was possible to save PLN 30 per 1 m3 of earthworks (67%), in 2022 the amount of savings is PLN 72 (64%). In the case of the work of one brigade during one work shift, during which an average productivity of about 300 m3 is achieved, the cost savings amount is PLN 21600!

## 5 Conclusions

The author's previous research has shown that the cohesive soils analyzed can be successfully used as backfill for excavations performed during the construction of underground infrastructure of municipal engineering, as well as foundation excavation of buildings and road embankments. Noteworthy is the fact that even a small one percent addition of lime has a very positive effect on the characteristics of cohesive soils and improving their compactability and suitability in terms of use for earth structures. The expected values of degree of compaction of cohesive soils with lime can be gained with great care during their construction. Such soils should be compacted in layers so that after compaction the individual layers are 30-40 cm thick. A key element in the correct construction process of the embankments in question is to bring the embedded cohesive soil-lime mixtures to a moisture content close to the optimum. At this moisture content, the soil is most easily compacted and can then achieve the maximum dry density and a high value of the density index.

Previous experience of the author of the paper shows that in the case of cohesive soils, this is a challenging task. In contrast to the use of non-cohesive soils as embankment or trench backfill material, the requirements for supervision, inspection and acceptance of works during construction increase in the case under consideration. It can be stated that cohesive soils are more difficult to use due to the fact that they are not forgiving of construction errors. Despite these difficulties, the on-site use of cohesive soils obtained during excavation is becoming an indispensable part of the construction process, is economical and in line with the philosophy of sustainability. In particular, it should be noted that there is no need to obtain and transport non-cohesive soil from mines. In a sense, a closed cycle of material is realized, which is cohesive soil re-installed and not taken out of the construction site and replaced with non-cohesive soil.

In addition, the use of the technique of using parts mounted to the excavator arm largely eliminates the need for personnel to be in the excavation, which is not insignificant in terms of workplace safety.

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## References

1. Sulewska, M. J.: Sztuczne sieci neuronowe w ocenie parametrów zagęszczenia gruntów niespoistych. Studia z zakresu inżynierii. Nr 64. PAN. Warszawa-Białystok 2009.
2. Sulewska, M.J.; The Control of Soil Compaction Degree by Means of LFWD. The Baltic Journal of Road and Bridge Engineering 2012, 7(1), 36-41.
3. Pisarczyk St.: Gruntoznawstwo inżynierskie. PWN. Warszawa, 2014.
4. Pisarczyk St.: Grunty nasypowe. Właściwości geotechniczne i metody ich badania. Oficyna Wydawnicza Politechniki Warszawskiej. Warszawa, 2015.
5. ROZPORZĄDZENIE MINISTRA INFRASTRUKTURY z dnia 24 czerwca 2022 r.w sprawie przepisów techniczno-budowlanych dotyczących dróg publicznych. Warszawa, dnia 20 lipca 2022 r. Poz. 1518 (wejście w życie 21.09.2022).
6. PN-S-02205:1998. Drogi samochodowe. Roboty ziemne. Wymagania i badania.
7. EN 16907-1: 2018. Earthworks - Part 1 – 6. Principles and general rules. CEN, Brussels, 2018.
8. WARUNKI WYKONANIA I ODBIORU ROBÓT BUDOWLANYCH. D-02.00.01v03 ROBOTY ZIEMNE. WYMAGANIA OGÓLNE. GENERALNA DYREKCJA DRÓG KRAJOWYCH I AUTOSTRAD. Warszawa 30 wrzesień 2019.
9. Katalog typowych konstrukcji nawierzchni podatnych i półsztywnych. Załącznik do zarządzenia Nr 31 Generalnego Dyrektora Dróg Krajowych i Autostrad z dnia 16.06.2014 r.
10. Obwieszczenie Ministra Infrastruktury I Budownictwa z dnia 23 grudnia 2015 r. w sprawie ogłoszenia jednolitego tekstu rozporządzenia Ministra Transportu i Gospodarki Morskiej w sprawie warunków technicznych, jakim powinny odpowiadać drogi publiczne i ich usytuowanie (obowiązujące wraz ze zmianami do 21.09.2022 r.).
11. USTAWA z dnia 14 grudnia 2012 r. o odpadach. Dz. U. z 2022 r. poz. 699, 1250, 1726.
12. DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance). Official Journal of the European Union. L 312/3. 22.11.2008.
13. PN-S-96011:1998. Drogi samochodowe. Stabilizacja gruntów wapnem do celów drogowych.
14. Celauroa, B.; Bevilacquaa, A.; Lo Bosco, D.; Celauroa, C. Design Procedures for Soil-Lime Stabilization for Road and Railway Embankments. Part 1 - Review of Design Methods. Procedia - Social and Behavioral Sciences 53 ( 2012a) 755 - 764. SIIV - 5th International Congress - Sustainability of Road Infrastructures. .
15. Celauroa, B.; Bevilacquaa, A.; Lo Bosco, D.; Celauroa, C. Design Procedures for Soil-Lime Stabilization for Road and Railway Embankments. Part 2 - Experimental Validation. Procedia - Social and Behavioral Sciences 53 ( 2012b) 568 - 579. SIIV - 5th International Congress - Sustainability of Road Infrastructures.
16. PN-EN 14227-15:2015-12. Mieszanki związane spoiwem hydraulicznym. Specyfikacje. Część 15: Grunty stabilizowane hydraulicznie (wersja angielska).
17. Rolla S.: Ulepszanie gruntów wbudowywanych w nasyp. Drogownictwo, nr 8/2001, 248 - 251.
18. Kátia V. Bicalhoa, Yasmina Boussafirb, Yu-Jun Cuic Performance of an instrumented embankment constructed with lime-treated silty clay during four-years in the Northeast of France. Transportation Geotechnics 2018 17 100-116

19. Jair A. Baldovino, Eclesielter B. Moreira, Wagner Teixeira, Ronaldo L.S. Izzo*, Juliana L. Rose Effects of lime addition on geotechnical properties of sedimentary soil in Curitiba, Brazil. Journal of Rock Mechanics and Geotechnical Engineering 2018 10 188-194
20. Marta Di Sante, Evelina Fratalocchi, Francesco Mazzieri, Erio Pasqualini Time of reactions in a lime treated clayey soil and influence of curing conditions on its microstructure and behaviour. Applied Clay Science 99 (2014) 100-109
21. EN ISO 14688-1: 2018. Geotechnical Investigation and Testing. Identification and Classification of Soil. Identification and Description. ISO: Geneva, Switzerland, 2018.
22. PN-88/B-04481. Grunty budowlane. Badania próbek gruntu.
23. PKN-CEN ISO/TS 17892-2. Badania geotechniczne. Badania laboratoryjne gruntów. Część 2: Oznaczanie gęstości gruntów drobnoziarnistych.
24. PN-EN 13286-2:2010-11E Mieszanki niezwiązane i związane hydraulicznie. Część 2: Metody badań laboratoryjnych gęstości na sucho i zawartości wody. Zagęszczanie metodą Proctora + poprawka PN-EN 13286-2:2010/AC:2014-07E.
25. Gosk W., Sulewska M. J., Tymosiak D, Kalicki A. Wstępna ocena możliwości zastosowania gruntów spoistych jako zasypek wykopów wąskoprzestrzennych budownictwa komunalnego. Raport z realizacji prac badawczo-rozwojowych. Politechnika Białostocka. Wydział Budownictwa i Inżynierii Środowiska. Zleceniodawca Drabent Sp.j. Białystok, 2018.