GEOLOGICA BALCANICA, 46 (2), Sofia, Nov. 2017, pp. 117–124.

Geotechnical parameters of loess-cement mixture for construction of compacted soil-cement cushion

Boriana Tchakalova, Doncho Karastanev

Geological Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 24, 1113 Sofia, Bulgaria; e-mails: boriana@geology.bas.bg; doncho@geology.bas.bg

(Accepted in revised form: November 2017)

Abstract. Soil-cement cushions are compacted and stabilized layers of the soil base, built under the foundation. Usually, they are constructed with local soil from the excavation, mixed with Portland cement. In Bulgaria, this soil improvement technique has been applied in foundation works in collapsible loess ground, aiming to replace a part of the collapsible layer, to increase the bearing capacity of the soil base, and/or to play a role of engineering barrier against migration of harmful substances in the geoenvironment. A multi-barrier near-surface short-lived low- and intermediate-level radioactive waste repository is under construction in Bulgaria. A loess-cement cushion beneath repository cells is going to be built by *in-situ* compacted mixture of local loess and Portland cement. Based on the results from classification and physico-mechanical tests of a set of loess-cement mixtures, it was proposed optimum cement content of the loess-cement cushion beneath the radioactive waste repository to be 5% of Portland cement. The present paper aims to assess the following geotechnical parameters of the selected loess-cement mixture after proper curing: unconfined compressive and flexural strength; shear strength parameters; static and dynamic elastic constants; and hydraulic conductivity. The results obtained prove that the mixture prepared at W_{opt} and ρ_{ds} of local loess and 5% (by the dry weight of soil) of Portland cement type CEM I 42.5 N – SR 5 possesses strength and deformation characteristics that completely meet the design stress-strain requirements to the soil-cement cushion beneath the repository foundation.

Tchakalova, B., Karastanev D. 2017. Geotechnical parameters of loess-cement mixture for construction of compacted soil-cement cushion. *Geologica Balcanica* 46 (2), 117–124.

Keywords: soil stabilization, loess-cement cushion, geotechnical parameters.

INTRODUCTION

Soil-cement cushions are compacted and stabilized layers of the soil base, built under the foundation. Usually, they are constructed with local soil from the excavation, mixed with Portland cement. In Bulgaria, this soil improvement technique has been applied in foundation works in collapsible loess ground, aiming to replace a part of the collapsible layer, to increase the bearing capacity of the soil base, and/or to play a role of engineering barrier against migration of harmful substances in the geoenvironment.

A multi-barrier near-surface short-lived low- and intermediate-level radioactive waste repository is under construction in Bulgaria. A loess-cement cushion beneath repository cells is going to be built by *in-situ* compacted mixture of local loess and Portland cement, prepared in a central mixing plant. Based on the analysis of the results obtained from classification and physico-mechanical tests of a set of loess-cement mixtures, prepared with optimum water content W_{opt} and maximum (standard) dry density ρ_{ds} of loess and Portland cement, it has been proposed optimum cement content for the construction of the compacted loess-cement cushion beneath the radioactive waste repository to be 5% (by the dry weight of soil) of Portland cement CEM I 42.5 N – SR 5 (Karastanev *et al.*, 2016).

The present paper aims to assess the geotechnical parameters of the selected loess-cement mixture after proper curing as follows: unconfined compressive strength (UCS); flexural strength; shear strength parameters; static and dynamic elastic parameters; and hydraulic conductivity.

The tests and analyses described herein were conducted mainly according to the procedures laid down in the relevant ASTM standards, since only the American Society for Testing and Materials (ASTM) has developed and maintains a very detailed and comprehensive set of normative documents for the design and analysis of soil-cement mixtures. In all cases, where possible and relevant, reference is made to respective BDS EN or other European standards.

MATERIALS USED AND PREPARATION OF TEST SPECIMENS

For the preparation of the test specimens, the following materials were used.

Loess – disturbed loess bulk sample with classification characteristics as follows:

- Classification symbol and designation (according to USCS) CL – lean clay
- Specific gravity G_S 2.74
- Liquid limit LL, % 30.4
- Plastic limit PL, % 18.7
- Plasticity index PI, % 11.7

According to the classification of Minkov (1968) for loess soils, the considered loess falls on the boundary between sandy and typical loess but could rather be defined as *sandy loess*. According to AASHTO classification, the loess falls on the boundary between group A-5 (silty soils) and A-6 (clayey soils), although there is small predominance of the soils classified by group index A-6**.**

More detailed information about the mineral, chemical, and grain-size composition of the used loess soil can be found in Karastanev *et al.* (2016).

Cement – Portland cement CEM I 42.5 N – SR 5 according to the classification of cement in BDS EN 197-1. The classification index means Portland cement of type I (*i.e.*, with 96–100% clinker content); strength class 42.5 (standard compressive strength at the 28th day ≥42.5 MPa and ≤62.5 MPa), normal strength growth; sulphate resistant. The reasons for the choice of this type of cement can be found in Karastanev *et al.* (2016).

Water – drinking water was used for preparation of the loess-cement test specimens, which is considered suitable for making concrete and soil-cement, according to BDS EN 1008:2003 and ASTM D 1632-07, and does not need examination.

Before preparation of the test specimens, the values of the optimum water content W_{opt} and standard (maximum) dry density ρ_{ds} of the selected loess-cement mixture were determined in accordance with the procedures of ASTM D 558-11 (Method A) for standard compaction effort, using the Proctor apparatus. The results are presented in Fig. 1.

The determined compaction characteristics of the optimum loess-cement mixture are as follows:

- optimum water content W_{opt} = 17.0%
- standard (maximum) dry density ρ_{ds}= 1.73 g/cm^3

All procedures on the preparation of the test specimens (*i.e.*, mixing and homogenization of loess, Portland cement and water, molding, compaction, and curing) were conducted pursuant to ASTM D 1632-07.

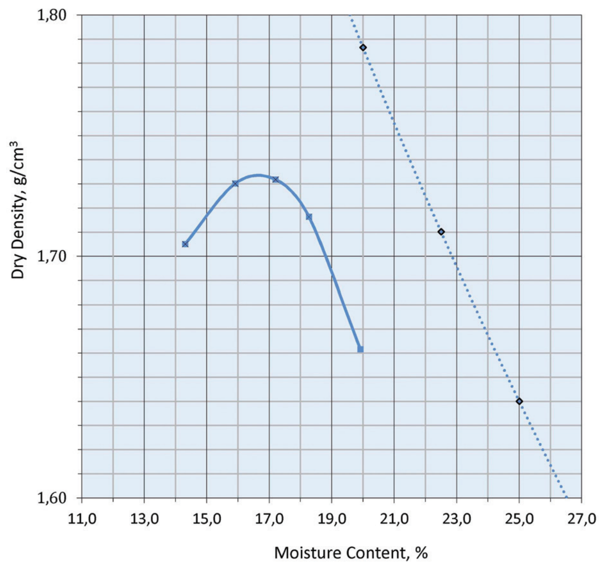


Fig. 1. Optimum water content W_{opt} and standard dry density ρ_{ds} of the optimum loess-cement mixture with 5% of Portland cement (of the dry weight of soil).

After mixing and homogenization of loess-cement at the respective optimum water content, the molding of test specimens needed for the corresponding test type was carried out in various molds as follows:

- mold for cylindrical test specimens with d = 71 mm and h = 142 mm to conduct the unconfined compressive strength test, as well as for cylindrical test specimens with d = 71 mm and h = 100 mm to determine the hydraulic conductivity;
- mold for parallelepiped test specimens with sizes 160×40×40 mm to conduct the flexural strength test;
- mold for cylindrical test specimens with d = 38 mm and h = 76 mm to conduct the triaxial compression test (UU test);
- mold for cylindrical test specimens with d = 100 mm and h = 200 mm to conduct the uniaxial compression test for determination of the static elastic parameters;
- mold for cylindrical test specimens with d = 50 mm and h = 50 mm to carry out measurements of the pulse velocities of compression (V_p) and shear waves (V_s) and the determination of the dynamic (ultrasonic) elastic parameters.

Compaction was carried out by using a hydraulic press with the relevant compaction load, necessary to achieve the target bulk density. The weight, height, and diameter of the test specimens were recorded after remolding from the mold, and they were placed in a climatic chamber for curing at relative humidity exceeding 95% and a temperature of 21 °C (Fig. 2). The

Fig. 2. Test specimens placed in the curing chamber.

Table 1
UCS q_u and undrained shear strength s_u of the tested loess-cement mixture

Parameter	q_u, MPa		s_u, MPa	
Curing time, days	*28*	*90*	*28*	*90*
No of specimens	6	6	6	6
Average value, X_{mean}	2.27	3.12	1.14	1.56
Standard deviation, s_x	0.16	0.13	0.08	0.07
Coef. of variation, V_x	0.07	0.04	0.07	0.04
Maximum	2.50	3.35	1.25	1.68
Minimum	2.10	3.03	1.05	1.52
X_{mean}+St. dev.	2.43	3.25	1.21	1.63
X_{mean}-St. dev.	2.11	2.99	1.06	1.50
t factor, t_α	2.015	2.015	2.015	2.015
Statistical coef., k_n	2.18	2.18	2.18	2.18
Characteristic value, X_k	1.93	2.84	0.96	1.42

test specimens were cured for 28 and 90 days before carrying out the respective tests.

STRENGTH PARAMETERS

Unconfined compressive strength (UCS)

The UCS q_u of the cured test specimens was determined in accordance with ASTM D 1633-00. After expiring of the respective curing period (28 and 90 days), the specimens were immersed in water for 4 hours prior to unconfined compressive strength measurement. An electromechanical compression machine with precise electronic control of the loading rate (in the particular case, it was 1 mm/min) and constant digital recording of loading and deformation was used to conduct the test (Fig. 3).

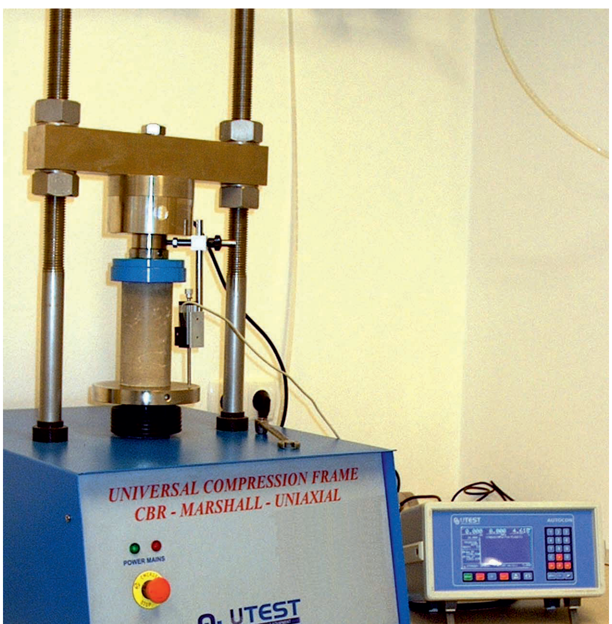


Fig. 3. Testing for determination of the unconfined compressive strength.

The test results after 28-day and 90-day curing of the samples, in a summarized form and statistically processed according to the requirements of Eurocode 7 (EN 1997-1:2004), are shown in Table 1. On the basis of the q_u, the undrained shear strength s_u (Bowles, 1996) was also calculated and is shown in the same table.

The characteristic value of the UCS of the tested loess-cement mixture after 28-day curing was q_u = 1.93 MPa, and after 90-day curing q_u = 2.84 MPa. The results prove that, between the 28th and the 90th day, the strength had increased with about 37%. For comparison, the strength of loess-cement with 4% and 6% cement (Karastanev *et al.*, 2016) was increased with about 34% between the 7th and the 28th day. This confirms the conclusion for delayed strength growth after the 28th day, due to phase transformations of the calcium hydrosilicates (main binding substance in soil-cement) from needle-like to network- and gel-like phases (Evstatiev, 1984; Angelova, 2007).

Flexural strength

The flexural strength R of the cured test specimens was determined in accordance with ASTM D 1635-12. After expiring of the respective curing period (28 and 90 days), the specimens were immersed in water for 4 hours before flexural strength testing. An electromechanical compression machine with precise electronic control of the loading rate (in the particular case, it was 0.6 mm/min) and constant digital recording of loading and deformation was used to conduct the test (Fig. 4).

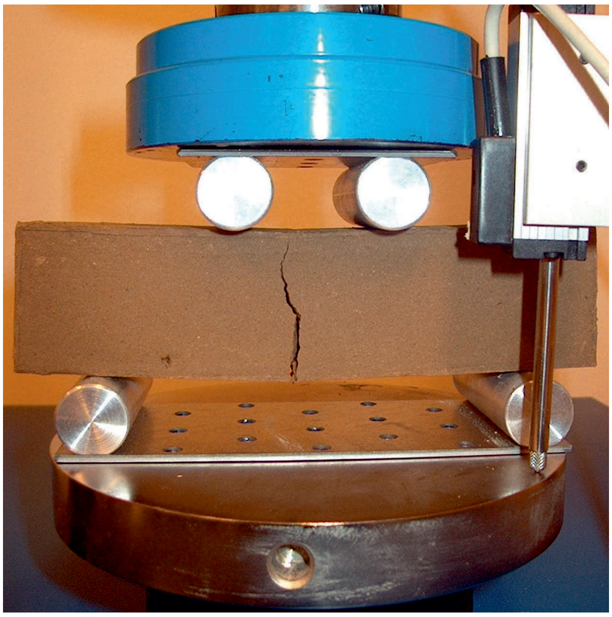


Fig. 4. Testing for determination of flexural strength.

The test results after 28-day and 90-day curing of the samples, in a summarized form and statistically processed pursuant to the requirements of Eurocode 7 (EN 1997-1:2004), are shown in Table 2. The characteristic value of the flexural strength of the tested loess-cement mixture after 28-day curing was $R = 0.57$ MPa, and after 90-day curing $R = 0.72$ MPa.

The results obtained for the unconfined compressive strength q_u and the flexural strength R for the both curing periods are in agreement with the correlation relationship proposed in the report of the ACI Committee 230 (1997) as follows:

$$R = 0.51(q_u)^{0.88},$$

where R and q_u are in *psi.*

Shear strength parameters

The shear strength parameters (*i.e.*, angle of internal friction φ and cohesion c of the tested loess-cement mixture) were determined by unconsolidated-undrained testing (UU test) under conditions of triaxial compression in conformity with ASTM D 2850-03a. This type of testing was chosen, because it corresponds best to the geotechnical conditions of the loess-cement cushion operation (in accordance with the design model analyses of the radioactive waste repository, for the values of vertical loading within the area of the cushion of 200–400 kPa, it is not expected that consolidation processes or inundation of the cushion may occur).

After expiring of the respective curing period (28 and 90 days), the test specimens were immersed in water for 4 hours prior to testing. The test was conducted, using a testing device for triaxial loading, with computer control and constant digital recording of stress and strain (Fig. 5).

The results obtained for the undrained shear strength parameters φ_u and c_u, in a summarized form and statistically processed pursuant to the requirements of Eurocode 7 (EN 1997-1:2004) are shown in Table 3. The characteristic values of the UU shear strength parameters of the tested loess-cement mixture after 28-day curing were $\varphi_u = 36.1$ ° and $c_u = 446$ kPa, and after 90-day curing: $\varphi_u = 33.0$ ° and $c_u = 529$ kPa.

Additionally, the normative values of φ_u and c_u were obtained by the least square method processing of the direct (particular) values of the normal and shear stresses in conformity with Norms for Design of Flat Foundations (1996) as follows (Fig. 6):

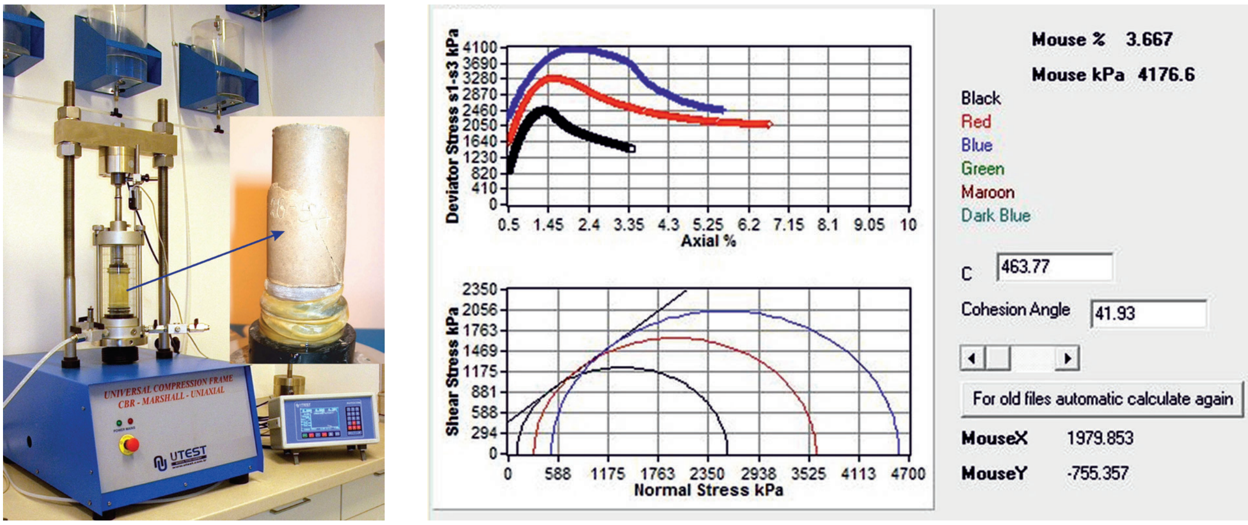
- normative values after 28-day curing: φ_u = 39.8 °, c_u = 508 kPa;

Table 2
Flexural strength R of the tested loess-cement mixture

Parameter	*R*, MPa	
Curing time, days	*28*	*90*
No of specimens	6	6
Average value, X_{mean}	0.64	0.75
Standard deviation, s_x	0.03	0.02
Coef. of variation, V_x	0.05	0.02
Maximum	0.68	0.78
Minimum	0.60	0.73
X_{mean}+St. dev.	0.67	0.77
X_{mean}-St. dev.	0.61	0.74
t factor, t_α	2.015	2.015
Statistical coef., k_n	2.18	2.18
Characteristic value, X_k	0.57	0.72

Table 3
UU shear strength parameters of the tested loess-cement mixture

Parameter	φ_u, deg		c_u, kPa	
Curing time, days	*28*	*90*	*28*	*90*
No of specimens	6	6	6	6
Average value, X_{mean}	40.25	35.67	505.67	637.40
Standard deviation, s_x	1.89	1.20	27.30	49.96
Coef. of variation, V_x	0.05	0.03	0.05	0.08
Maximum	41.90	37.61	534.80	686.80
Minimum	37.05	34.61	463.80	572.61
X_{mean}+St. dev.	42.14	36.87	532.97	687.37
X_{mean}-St. dev.	38.36	34.47	475.37	587.44
t factor, t_α	2.015	2.015	2.015	2.015
Statistical coef., k_n	2.18	2.18	2.18	2.18
Characteristic value, X_k	36.14	33.05	446.26	528.66



a ***b***

Fig. 5. Unconsolidated-undrained testing under conditions of triaxial compression (*a*) and determination of the UU shear strength parameters (*b*).

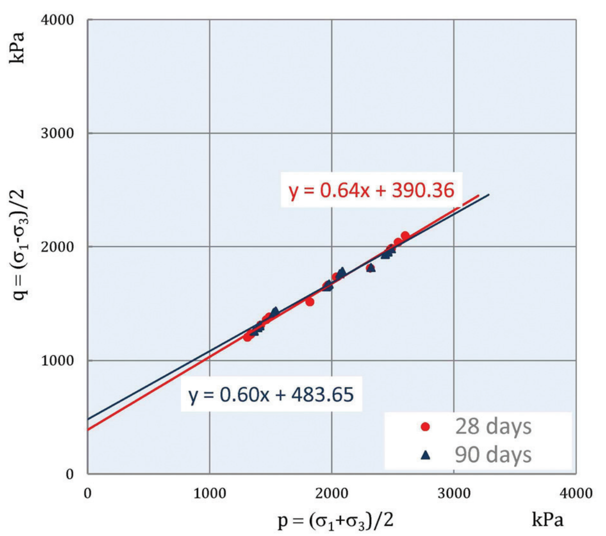


Fig. 6. Normative values of φ_u and c_u of the tested loess-cement with 5% Portland cement after 28-day and 90-day curing, determined according to Norms for Design of Flat Foundations (1996).

- normative values after 90-day curing: φ_u = 36.9 °, c_u = 605 kPa.

STATIC AND DYNAMIC ELASTIC PARAMETERS

Static elastic constants

The static elastic constants (Young's modulus of elasticity, E, and Poisson's ratio, μ) were obtained according to ASTM C 469-14 and ASTM D 7012-14 (Method D). After expiring of the respective curing period, the specimens were immersed in water for 4 hours before testing. The testing itself was conducted, using a deformation device, the so-called compressometer-extensometer, allowing the measurement of axial and radial deformations under conditions of uniaxial compression of cylindrical test specimens with d/h = 1/2 (d = 100 mm and h = 200 mm) (Fig. 7).

The summarized results are shown in Table 4. The characteristic values of Young's modulus and Poisson's ratio of the tested loess-cement mixture after 28-day curing were E = 800 MPa and μ = 0.19, and after 90-day curing E = 1480 MPa and μ = 0.28.

The results obtained for the modulus of elasticity are in agreement with the correlation relationship between E and q_u for silty and clayey soils stabilized with cement (Arellano and Thompson, 1998) as follows:

$$E = 440q_u + 0.28q_u^2,$$

where E and q_u are in *psi.*

For compacted soil-cement, tested according to the same procedure and with similar equipment, Felt and Abrams (1957) and Arellano and Thompson (1998) reported, values close to those of Poisson's ratio.

It is well known that the values of the elastic parameters of construction soils are not constant and depend on many factors, mostly on stress range and the corresponding strain. Therefore, leading researchers consider that it is not correct to use the term elastic modulus (Young's modulus), and it should be replaced by the so-called *stress-strain modulus* E_s (Bowles, 1984, 1996). Although the term elastic modulus is in general use for construction soils, the stress-

Fig. 7. Testing for determination of the static elastic constants.

Table 4
Static elastic constants of the tested loess-cement mixture

Parameter	E, MPa		μ	
Curing time, days	*28*	*90*	*28*	*90*
No of specimens	6	3	6	3
Average value, X_{mean}	1211.50	1770.33	0.13	0.13
Standard deviation, s_x	188.88	85.98	0.03	0.05
Coef. of variation, V_x	0.16	0.05	0.25	0.38
Maximum	1546.00	1842.00	0.17	0.15
Minimum	1005.00	1675.00	0.08	0.08
X_{mean}+St. dev.	1400.38	1856.31	0.16	0.18
X_{mean}-St. dev.	1022.62	1684.35	0.09	0.08
t Factor, t_α	2.015	2.920	2.015	2.920
Statistical coef., k_n	2.18	3.37	2.18	3.37
Characteristic value, X_k	800.41	1480.44	0.19	0.28

strain range to which it is referred should always be taken into account. Since the smaller the strains, the greater the elastic modulus values are, in the ultrasonic test, where the strain is of the order of 10^{-6} to 10^{-5}, the determined elastic parameters are highest (as will be seen below). These parameters are defined as dynamic elastic parameters, which are used in the analyses of seismic impact resistance. The usual range of deformations under static conditions, for which the analyses of bearing capacity and allowable deformations of the facilities are carried out, is in the range of 10^{-2} to 10^{-1}. In these analyses, especially in Bulgaria, the most commonly used is the so-called modulus of total deformation E_o, determined by plate loading test, also known as plate modulus E_{PLT}. This test reproduces somewhat most accurately the actual stress-strain conditions in the ground base of the facility.

The static elastic modulus E, determined in this case by a compressometer-extensometer under conditions of uniaxial compression, refers to strains of the order of 10^{-3} to 10^{-2}. It is also designated as *initial tangent modulus* and is most often determined in laboratory practice, since it does not depend much on the type of testing and confined pressure. The deformation modulus from plate loading test E_o or E_{PLT} is about 3 to 5 smaller than the static elastic modulus E.

Dynamic elastic parameters

The dynamic elastic parameters were determined according to ASTM D 2845-08. After expiring of the respective curing period, the specimens were immersed in water for 4 hours prior to testing. The actual test was conducted, using a *V-Meter Mark III* ultrasonic device with excitation of ultrasonic pulses, which measures their velocities through the test specimens that, in turn, depend on the elastic characteristics and density of the material. The velocities of the longitudinal (compression) waves V_p and transverse (shear) waves V_s were measured, using special end tips (Fig. 8), from which, using the corresponding relationships, the dynamic elastic parameters were calculated according to ASTM D 2845-08: elastic modulus E_d, Poisson's ratio μ_d, shear modulus G_d, and bulk deformation modulus K_d.

Fig. 8. Ultrasonic testing for determination of the dynamic elastic parameters.

Table 5
Dynamic elastic parameters of the tested loess-cement mixture

Parameter	V_p, m/s		V_s, m/s		E_d, GPa		μ_d		G_d, MPa		K_d, MPa	
Curing time, days	*28*	*90*	*28*	*90*	*28*	*90*	*28*	*90*	*28*	*90*	*28*	*90*
No of specimens	6	6	6	6	6	6	6	6	6	6	6	6
Average value, X_{mean}	1591	1902	779	926	3.36	4.74	0.34	0.34	1.25	1.77	3.55	5.09
Standard deviation, s_x	49.82	52.27	19.84	38.19	0.14	0.34	0.02	0.02	0.06	0.15	0.35	0.42
Coeff. of variation, V_x	0.03	0.03	0.03	0.04	0.04	0.07	0.05	0.06	0.05	0.08	0.10	0.08
Maximum	1662	1965	813	965	3.58	5.14	0.36	0.37	1.36	1.92	4.03	5.54
Minimum	1526	1839	762	859	3.19	4.16	0.32	0.31	1.19	1.52	3.20	4.52
X_{mean}+St. dev.	1641	1954	799	964	3.50	5.09	0.36	0.36	1.32	1.91	3.91	5.51
X_{mean}-St. dev.	1541	1850	759	888	3.21	4.40	0.32	0.32	1.19	1.62	3.20	4.67
t factor, t_α	2.015	2.015	2.015	2.015	2.02	2.015	2.02	2.015	2.02	2.015	2.02	2.015
Statistical coef., k_n	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18
Characteristic value, X_k	1483	1788	736	843	3.04	4.00	0.30	0.30	1.11	1.45	2.78	4.17

The results obtained from the conducted ultrasonic tests for determination of the dynamic elastic parameters, in a summarized form after statistical processing in conformity with the requirements of Eurocode 7 (EN 1997-1:2004), are shown in Table 5. The characteristic values of the dynamic elastic parameters of the tested loess-cement mixture after 28-day curing were: E_d = 3.04 GPa, μ_d = 0.30, G_d = 1.11 GPa, K_d = 2.78 GPa, and after 90-day curing E_d = 4.00 GPa, μ_d = 0.30, G_d = 1.45 GPa, K_d = 4.17 GPa.

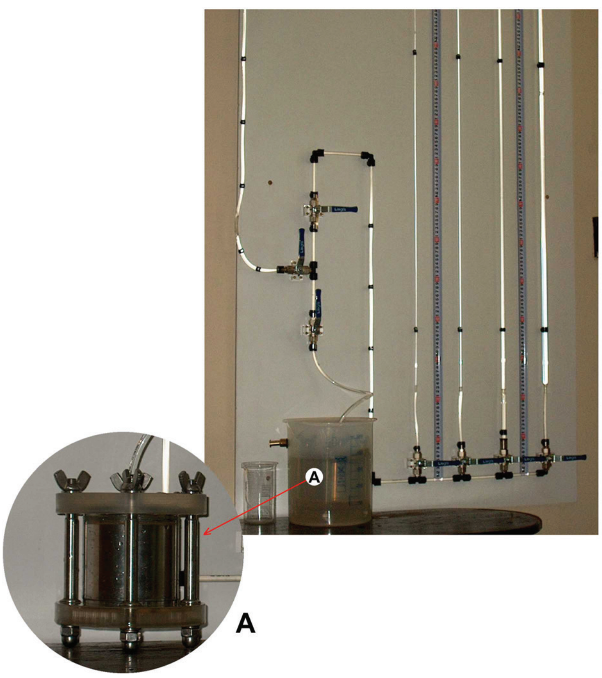


Fig. 9. Determination of the hydraulic conductivity with falling head method – “A” filtration cell.

HYDRAULIC CONDUCTIVITY

The hydraulic conductivity *k* was determined by filtration tests according to the falling head method (Head, 1982) (Fig. 9). The tests were carried out with cylindrical specimens with d = 71 mm and h = 100 mm, prepared with the design ρ_{ds} and W_{opt} after 28-day and 90-day curing. Before the assembly of the filtration cell, the space between the specimen and the cell walls was covered once with water impermeable cement-based mixture CX 5. After hardening of this mixture, the filtration cell was subjected to vacuum until reaching full saturation and overcoming the so-called initial threshold filtration gradient.

The test results after 28-day and 90-day curing of the samples, in a summarized form and statistically processed in conformity with the requirements of Eurocode 7 (EN 1997-1:2004), are shown in Table 6. The characteristic value of the hydraulic conductivity

Table 6
Hydraulic conductivity k of the tested loess-cement mixture

Parameter	*k*, m/s	
Curing time, days	*28*	*90*
No of specimens	6	6
Average value, X_{mean}	5.47E-08	2.11E-09
Standard deviation, s_x	1.82E-08	2.19E-09
Coef. of variation, V_x	0.33	1.04
Maximum	8.12E-08	5.14E-09
Minimum	3.00E-08	2.70E-10
X_{mean}+St. dev.	7.29E-08	4.29E-09
X_{mean}-St. dev.	3.66E-08	-7.83E-11
t factor, t_α	2.015	2.015
Statistical coef., k_n	2.18	2.18
Characteristic value, X_k	9.42E-08	6.86E-09

of the tested loess-cement mixture after 28-day curing was k = 9.42×10^{-8} m/s, and after 90-day curing k = 6.86×10^{-9} m/s.

CONCLUSION

Geotechnical parameters, namely UCS, flexural strength, shear strength parameters, static and dynamic elastic constants, hydraulic conductivity of loess-cement mixture selected for construction of compacted soil-cement cushion beneath the repository cells of a radioactive waste facility, have been determined. The results of the conducted laboratory tests prove that the mixture prepared at W_{opt} and ρ_{ds} of local loess and 5% (by the dry weight of soil) Portland cement type CEM I 42.5 N – SR 5 after proper curing acquires strength and deformation characteristics that completely meet the design stress-strain requirements to the soil-cement cushion beneath the repository foundation.

ABBREVIATIONS AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASTM	American Association of for Testing and Materials
BDS EN	Bulgarian State Standard European Norm
USCS	Unified Soil Classification System

c_u	cohesion (undrained), kPa/MPa
E	Young's modulus of elasticity, MPa
E_d	dynamic Young's modulus of elasticity, MPa/GPa
E_o	modulus of deformation, MPa
E_{PLT}	plate modulus, MPa
G_d	dynamic shear modulus, MPa/GPa
G_S	specific gravity, [-]
k	hydraulic conductivity, m/s
K_d	dynamic bulk modulus, MPa/GPa
LL	liquid limit, %
PL	plastic limit, %
PI	plasticity index, %
q_u	unconfined compressive strength (UCS), kPa/MPa
R	flexural strength, MPa
s_u	undrained shear strength, MPa
V_p	velocity of compression waves, m/s
V_s	velocity of shear waves, m/s
W_{opt}	optimum water content, %
φ_u	angle of internal friction (undrained), degree (º)
μ	Poisson's ratio
μ_d	dynamic Poisson's ratio
ρ_{ds}	standard (maximum) dry density, g/cm^3

REFERENCES

ACI Committee 230. 1997. *State-of-the-Art Report on Soil Cement*. ACI 230.1R-90, 23 pp.

Angelova, R. 2007. Loess-cement long-term strength – a facilitating factor for loess improvement applications. *Geologica Balcanica* 36 (3–4), 21–24.

Arellano, D., Thompson M. 1998. *Stabilized base properties (strength, modulus, fatigue) for mechanistic-based airport pavement design*. Technical Report on Research, Department of Civil Engineering, University of Illinois, Illinois, 119 pp.

Bowles, J.E. 1984. *Physical and geotechnical properties of soils*. The McGraw-Hill Companies Inc. New York, St. Louis, San Francisco, Auckland, Bogota. Caracas, Lisbon, London, Madrid, Mexico City, Milan, Montreal, New Delhi, San Juan, Singapore, Sydney, Tokyo, Toronto, 578 pp.

Bowles, J.E. 1996. *Foundation analysis and design*. The McGraw-Hill Companies, Inc., 1175 pp.

Evstatiev, D. 1984. *Strength formation of soil-cement*. Bulgarian Academy of Sciences Publishing House, Sofia, 94 pp.

Felt, E.J., Abrams M.S. 1957. *Strength and elastic properties of compacted soil-cement mixtures*. Special Technical Publication 206, ASTM, 152–178.

Karastanev, D., Antonov, D., Tchakalova, B., Trayanova, M. 2016. Selection of optimum loess-cement mixture for construction of a compacted soil-cement cushion. *Engineering Geology and Hydrogeology* 30, 3–15.

Minkov, M. 1968. *The loess in North Bulgaria. A Complex Study*. Bulgarian Academy of Sciences Publishing House, Sofia, 202 pp. (in Bulgarian).