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Selection of optimum loess-cement mixture for construction of a compacted soil-cement cushion

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Резюме. Циментопочвената възглавница представлява уплътнен и заздравен слой от земната основа, изграден непосредствено под фундаментите, който е предназначен да замени част от пропадъчния пласт, да увеличи носещата способност на земната основа и/или играе роля на инженерна бариера срещу миграция на вредни вещества в геоложката среда. Циментопочвената възглавница не е продължение на фундамента, а част от земната основа. Обикновено тя се изгражда с льоса от изкопите на съоръжението, заздравен с портландцимент.

Многобариерно инженерно повърхностно хранилище за радиоактивно отпадъци се планира да се построи в България. Една от инженерните бариери се предвижда да бъде циментольосова възглавница под хранилищните клетки. Циментопочвената възглавница се планира да бъде изградена от уплътнена на място смес от местен льос и портландцимент, приготвена в стационарен смесител. Начална фаза в целия итеративен процес на проектиране е изборът на оптимална циментольосова смес за изграждане на уплътнена циментольосова възглавница. На практика това включва определяне на трите основни параметъра на циментольоса: минималното количество цимент за заздравяване на льоса, така че циментольосовата възглавница да притежава необходимите геотехнически параметри; оптималното водно съдържание на циментольосовата смес; плътността, до която циментольосът трябва да бъде уплътнен.

В настоящата статия се описват последователните стъпки за определяне на горните параметри: i) класификационни тестове на льоса, който ще се използва за изграждането на циментольосова възглавница; ii) плътностно-влажностни изпитвания за определяне на целевите стойности на оптималното водно съдържание и стандартната плътност на циментольосовата смес; iii) определяне на якостта на едноосен натиск и дълготрайността за диапазон от съдържания на цимент; iv) избор на оптимална циментольосова смес за изграждане на уплътнената циментольосова възглавница.

Ключови думи: заздравяване на почви, циментольос, избор на оптимална смес.

Abstract. The soil-cement cushion represents a compacted and stabilized layer of the soil base, built under the foundation, which is intended 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. The soil-cement cushion is not a continuation of the foundation, but it is a part of the soil base. Normally it is built with local soil from the excavation, mixed with Portland cement.

A multi-barrier engineering near-surface radioactive waste repository is planned to be constructed in Bulgaria and a loess-cement cushion beneath repository cells is envisaged to be one of the engineering barriers. The cushion is going to be constructed by in-situ compacted mixture of local loess and Portland cement, prepared in a central mixing plant. Initial stage in the overall iterative design process is selection of optimum loess-cement mixture for construction of compacted loess-cement cushion. Actually this includes the determination of the three basic parameters of loess-cement: the minimum cement content needed to harden the loess adequately; the optimum water content of the mixture; the density to which the loess-cement must be compacted.

The present paper describes the consecutive steps for determination of the above parameters as following: 1) classification tests of loess to be used for the construction of the loess-cement cushion; 2) moisture-density tests to determine the target values of the optimum water content and standard density of the loess-cement mixture; 3) determination of the unconfined compressive strength and durability for a range of cement contents; 4) selection of optimum loess-cement mixture for construction of compacted loess-cement cushion.

Key words: soil stabilization, loess-cement, selection of optimum mixture.

ABBREVIATIONS AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Association for Testing and Materials
BDS EN	Bulgarian State Standard European Norm
BS	British Standard
c	cement content, % by the dry weight of soil
E	Young's modulus of elasticity, MPa
E_o	modulus of deformation, MPa
E_{50}	Young's modulus of elasticity corresponding to 50% of q_u, MPa
G_S	specific gravity, [-]
LL	liquid limit, %
PL	plastic limit, %
PI	plasticity index, %
q_a	allowable (design) bearing capacity, kPa
q_u	unconfined compressive strength, kPa/MPa
s_u	undrained shear strength, MPa
W_{opt}	optimum water content, %
ρ_{ds}	maximum dry density, g/cm^3

Introduction

Soil stabilization with Portland cement became a widespread practice in the second half of the XX century mainly in road construction. In contrast to other countries, in Bulgaria this stabilization has found application mainly in foundation works by loess-cement cushion and in irrigation construction by impervious screen in collapsible loess.

The soil-cement cushion represents a compacted and stabilized layer of the soil base, built under the foundation, which is intended 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. The soil-cement cushion is not a continuation of the foundation, but it is a part of the soil base. Normally it is built with local soil from the excavation, mixed with Portland cement.

A multi-barrier engineering near-surface radioactive waste repository is planned to be constructed in Bulgaria and a loess-cement cushion beneath repository cells is envisaged to be one of the engineering barriers. The cushion is going to be constructed by in-situ compacted mixture of local loess and Portland cement, prepared in a central mixing plant. Initial stage in the overall iterative design process is selection of optimum loess-cement mixture for construction of compacted loess-cement cushion. Actually this includes the determination of the three basic parameters of loess-cement:

– the minimum cement content needed to harden the loess adequately to ensure the loess-cement cushion meets the required geotechnical parameters;
– the optimum water content of the loess-cement mixture;

– the density to which the loess-cement must be compacted.

The present paper aims to describe the consecutive steps for determination of the above parameters as following:

1. Classification tests of loess to be used for the construction of the loess-cement cushion;
2. Moisture-density tests to determine the target values of the optimum water content and standard density of the loess-cement mixture;
3. Determination of the unconfined compressive strength and durability for a range of cement contents;
4. Selection of optimum loess-cement mixture for construction of compacted loess-cement cushion.

The tests and analyses described in the paper are 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 maintained a very detailed and comprehensive set of normative documents for the design and analysis of soil-cement mixtures. In all cases, where it is possible and relevant, reference is made to respective BDS EN or other European standards.

Materials used – loess, Portland cement, water

Loess

All laboratory analyses and tests were performed with disturbed loess bulk sample, collected during drilling works of a site investigation campaign. The whole amount of about 500 kg of loess material was air dried and then repeatedly mixed until reaching the necessary degree of homogenization, so that an average composite soil sample was obtained, meeting the following requirements:

- the target values of the optimum water content and standard density of the soil-cement mixture could be measured directly from the composite soil sample;
- the mixing (composing) should not be a source of additional errors due to insufficient homogenization of the combined soil samples.

The attainment of the necessary degree of homogenization is confirmed by the performed classification analyses described below.

Portland cement

The tests were carried out with 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 28^{th} day ≥42.5MPa and ≤62.5MPa), normal strength growth;sulphate resistant.

The main reasons for the choice of this type of cement are as follows:

- The use of cement of the second or third type (that are most widespread and with available necessary strength classes) is considered inappropriate, since these are mixed (fly ash or other composite) Portland cements (II type) or slag cements (III type), containing up to 20-35% (II type) and over 35% (III type) various additives – fly ash from TPP, fired schists, blast furnace slag, etc. Moreover, some of these additives comprise, although in trace amounts, different radionuclides.
- The maximum sulphate content in the loess used for the tests (total SO_4^{2-}) is up to 0.073%, as will be shown below, while the allowable content is 0.2% according to BDS EN 12620:2002. However, the decision is made that it is appropriate to use sulphate resistant Portland cement because of the extremely long operation period of the radioactive waste repository.

Water

Drinking water is 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.

Classification tests of loess to be used for the construction of the loess-cement cushion

The mineral, chemical and grain-size composition and plasticity limits were determined using six separate test specimens, randomly collected from the average composite soil sample. Except at characterizing the loess for the laboratory tests, this approach is aimed at verifying the achievement of the necessary degree of homogenization of the entire amount of soil material, sampled during the drilling works.

Mineral composition

The mineral composition was determined using X-ray phase analysis. The diffraction spectra were obtained by means of powder X-ray diffractometer Bruker D8 Advance with LynxEye detector, 2006.

The results obtained prove that the mineral composition of the individual test specimens is very close, practically identical – minerals as quartz, albite, muscovite, orthoclase and clinoenstatite are predominant in all specimens, and this confirms the homogeneity of the average composite loess sample. The mineral composition of loess, used for laboratory testing, is shown in a summarized form in Table 1.

Table 1. Summary mineral composition of the average bulk loess sample

Таблица 1. Обобщен минерален състав на осреднената комбинирана льосова проба

Mineral	*Chemical formula*	*Content, %*
Quartz	SiO_2	33
Albite	$NaAlSi_3O_8$	13
Muscovite	$KAl_2(AlSi_3O_{10})(F,OH)_2$	11
Orthoclase	$KAlSi_3O_8$	11
Clinoenstatite	$MgSiO_3$	11
Kaolinite	$Al_2Si_2O_5(OH)_4$	3
Chamosite	$Fe^{2+}{}_3Mg_{1.5}AlFe^{3+}{}_{0.5}Si_3AlO_{12}(OH)_6$	6
Dolomite	$CaMg(CO_3)_2$	7
Calcite	$CaCO_3$	4
other		1

Chemical composition

The chemical composition was obtained by complete decomposition of the soil samples to determine the full element content. The analyses were conducted using an ICP-AES "Ultima-2" atomic emission spectrometer with inductively-coupled plasma excitation of the Jobin Yvon –Horiba. The total SO_4^{2-} content is found according to a standardized method for sulphate determination in aggregate materials that is applicable to concrete (BDS EN 1744-1:2009), and the organic matter content – according to the Walkley-Black method, laid down in BS 1377-3.

The average chemical composition of the analysed loess is given in Table 2. As seen, the average sulphate content of loess is 0.057%, while according to BDS EN 12620:2002 the allowable content for implementing non-sulphate resistant cement is 0.2%. As already pointed out above, regardless of this the decision is made that it is appropriate to conduct the laboratory tests with sulphate-resistant Portland cement because of the very long operation period of the repository. The organic matter content is also very low (< 0.2%), which is favourable for stabilizing the soil with cement.

Table 2. Average chemical composition in % of the bulk loess sample*
Таблица 2. Осреднен химичен състав в % на комбинираната льосова проба*

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	MnO	Na_2O	K_2O	P_2O_5	SO_4	organic matter	loi	mois-ture
57.55	0.67	10.52	3.67	3.76	9.44	0.08	1.04	1.65	0.109	0.057	0.16	11.43	1.21

* *Note - The total sum is 101.346%, moisture being 1.21%, which must not be summed, and the remaining difference to 100 % of 0.136 % results from averaging and/or inaccuracies in the analyses.*

* Забележка - *Общата сума е 101,346%, като 1,21% е влагата, която не следва да се сумира, а останалата разлика до 100 % от 0,136% е резултат на осредняване на резултатите и/или неточности при анализите.*

Grain-size composition, plastic limits and soil classification

The grain-size composition is determined according to ASTM D 422-63, the plastic limits - in accordance with ASTM D 4318 and the soil classification is made according to the procedures of ASTM D 2487 – Unified Soil Classification System. The results obtained for the analysed six soil samples are given in Table 3. The difference in the classification characteristics of the samples is insignificant from practical viewpoint (Table 3), which is the main evidence for the homogeneity of the composite loess sample.

Table 3. Classification parameters of the analysed loess samples

Таблица 3. Класификационни параметри на анализираните льосови проби

Sample No	*Grain-size composition*			*Spec. gravity*	*Liquid limit*	*Plastic limit*	*Plasticity index*	*Classification symbol and designation*
	>4.75	4.75-0.075	<0.075					
	mm	*mm*	*mm*	G_s	*LL*	*PL*	*PI*	
	%	%	%	-	%	%	%	-
7099	0	3	97	2.75	30.5	18.8	11.7	CL – lean clay
7100	0	3	97	2.74	30.4	18.9	11.5	CL – lean clay
7101	0	3	97	2.74	30.1	19.4	10.7	CL – lean clay
7102	0	3	97	2.74	30.4	18.6	11.8	CL – lean clay
7103	0	3	97	2.74	30.6	18.3	12.3	CL – lean clay
7104	0	4	96	2.73	30.7	18.4	12.3	CL – lean clay

The classification characteristics of loess, intended for the construction of the loess-cement cushion, are defined as follows:

- *Classification symbol and designation (according to USCS)* **CL – lean clay**
- *Specific gravity, Gs* **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 analysed loess falls on the boundary between sandy and typical loess but could be rather defined as sandy loess. According to AASHTO 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.

Moisture-density tests to determine the target values of the optimum water content and standard density of the loess-cement mixture

The moisture-density tests were performed according to the procedures of ASTM D 558 using an automatic Proctor apparatus to determine the values of the optimum water content W_{opt} of the loess-cement mixture and the density ρ_{ds} to be achieved by loess compaction. The tests were carried out for five cement contents – 4, 6, 8, 10 and 12% with respect to dry weight of soil. The specific gravity of each loess-cement mixture with 4, 6, 8, 10 and 12% of cement was also determined according to ASTM D 854. All tests were performed with the composite loess sample and cement CEM I 42.5 N – SR 5, described above.

The moisture-density tests in the common practice of soil strengthening are conducted only with the average cement content (Soil-Cement Laboratory Handbook, 1991), since the maximum dry density is slightly affected by small changes in the binder content. In this case, however, because of the significance of the studied object, the moisture-density tests of loess-cement mixtures were carried out for each of the cement contents. Moreover, the changes in the water content and density with the addition of cement are not always predictable. Flocculation of the silty and especially the clayey particles by the cement may provoke increasing of W_{opt} and decreasing of ρ_{ds} of the soil-cement mixture and meanwhile the higher density of cement causes higher density of the mixture.

The results from the conducted tests for determination of the moisture-density relations are shown in a summarized form in Table 4 and Figure 1.

Table 4. Results from the tests for determination of the moisture-density relation

Таблица 4. Резултати от изпитванията за определяне на зависимостта плътност-влажност

Mixture	*Symbol*	*Specific gravity*	*Standard (maximum) dry density*	*Optimum water content*
		G_s, [-]	ρ_{ds}, g/cm^3	W_{opt}, %
loess + 4 % cement	LC 4	2.78	1.73	17.0
loess + 6 % cement	LC 6	2.78	1.71	17.5
loess + 8 % cement	LC 8	2.79	1.71	17.5
loess + 10 % cement	LC 10	2.80	1.72	18.0
loess + 12 % cement	LC 12	2.83	1.71	18.0

Determination of the unconfined compressive strength and durability for a range of cement contents

Preparation of test specimens

All procedures related to test specimen preparation – mixing and homogenization of loess, Portland cement and water, moulding, compacting and curing, were performed in accordance with ASTM D 1632.

After mixing and homogenizing the mixtures at the optimum water content, the moulding of the test specimens was carried out in a mold (Figure 2a), whereby specimens were obtained with a diameter/height ratio of 1:2 (d=71.0 mm and h=142.0 mm). The compaction was conducted using a hydraulic press at a compaction load of 50 kN (Figure 2b), whereby the target bulk density was achieved. After remolding of the test specimens from the mold (Figure 2c) measurements of their weight, height and diameter were made and they were placed in a climatic chamber for curing at a relative humidity exceeding 95% and a temperature of 21^{o}C (Figure 2d). The test specimens were cured for 7 and 28 days respectively, and then tested to determine the unconfined compressive strength and freeze-thaw and water-saturation/drying resistance.

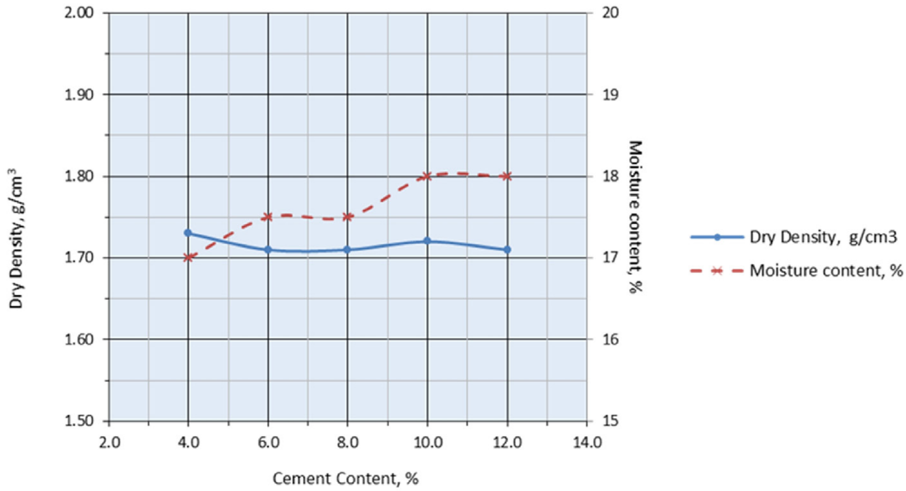


Figure 1. Dependence of W_{opt} and ρ_{ds} on cement content

Фигура 1. Зависимост на W_{opt} и ρ_{ds} от съдържанието на цимент

a.

b.

c.

d.

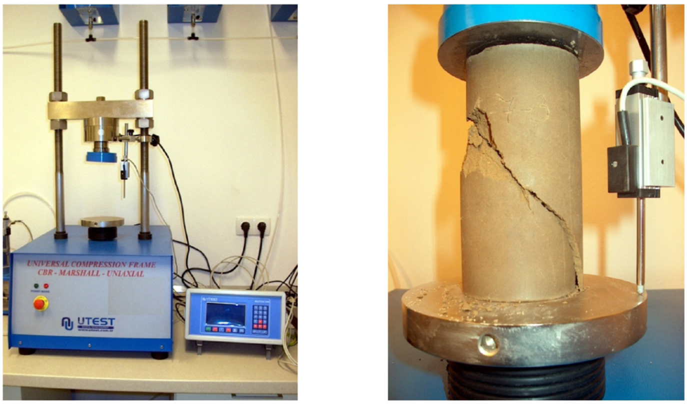
Figure 2. Preparation and curing of loess-cement test specimens: a. mold for preparation of the test specimens; b. molding of the specimens by compaction with a hydraulic compression machine; c. remolding of the test specimen; d. test specimens in the curing chamber.

Фигура 2. Подготовка и отлежаване на пробните образци от циментольос: a. матрица за формуване на телата; b. формуване на телата чрез уплътняване на хидравлична преса; c. изваждане на пробния образец; d. пробните образци в камерата за отлежаване.

Three test specimens were produced for each of the analysed range of cement contents – 4, 6, 8, 10 and 12%, for the three tests – unconfined compressive strength, freeze-thaw and water-saturation/drying, respectively for the two ages of curing – 7 and 28 days. The test specimens were prepared at the optimum water content and standard (maximum) dry density, corresponding to the cement content according to Table 4. The total number of prepared test specimens for all test types and for each of the two ages of curing is 90 (Figure 2d).

Unconfined compressive strength

The unconfined compressive strength q_u of the cured test specimens was determined in accordance with ASTM D 1633. After the respective curing period the test specimens were immersed in water for 4 hours before the testing of their unconfined compressive strength. An electromechanical compression machine (Figure 3a) with precise electronic control of the loading rate was used to conduct the test (in the particular case 1 mm/min according to the requirements of ASTM D 1633) and constant digital recording of load and deformation (Figure 3b).



a. b.

Figure 3. Apparatus (a) and testing for determination of the unconfined compressive strength (b)

Фигура 3. Апаратура (a.) и изпитване за определяне на якостта на едноосен натиск (b.)

The results are presented in Table 5. The test results provide the grounds to calculate not only the unconfined compressive strength q_u (Figure 4), but also the undrained shear strength s_u and modulus of elasticity E_{50} (Figure 5) for 50% of q_u which mean arithmetic values are also given in the Table 5.

Table 5. Strength and deformation parameters of the tested loess-cement mixtures

Таблица 5. Якостни и деформационни параметри на изпитваните циментольосови смеси

LC mixture	c, % of dry weight	q_u, MPa		s_u, MPa		E_{50}, MPa	
		7th day	28th day	7th day	28th day	7th day	28th day
LC 4	4	1.34	2.06	0.67	1.03	346.89	458.79
LC 6	6	1.79	2.71	0.90	1.36	380.99	551.19
LC 8	8	1.92	3.11	0.96	1.55	519.81	669.60
LC 10	10	2.69	3.75	1.35	1.88	559.45	696.53
LC 12	12	2.85	4.20	1.42	2.10	594.74	776.14

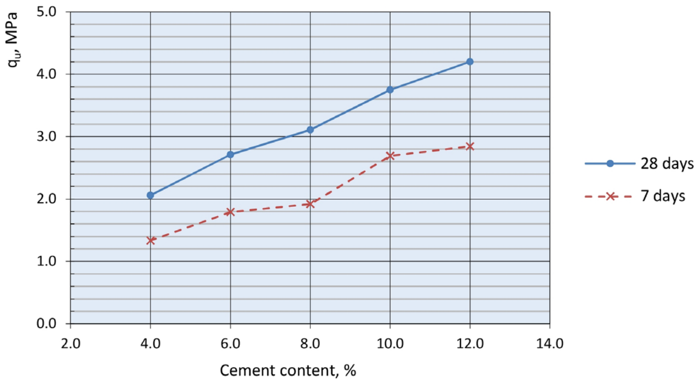


Figure 4. Relationship of q_u and cement content

Фигура 4. Зависимост на q_u от съдържанието на цимент

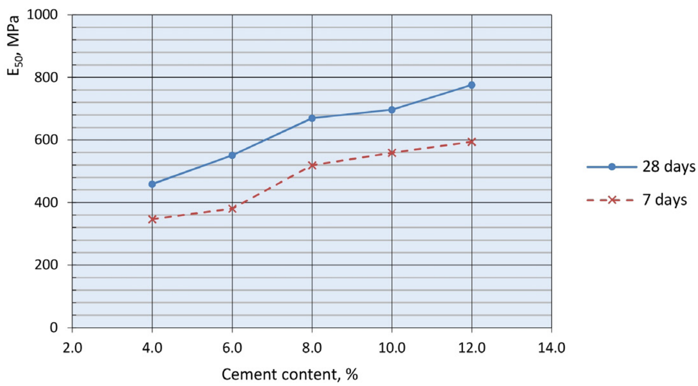


Figure 5. Relationship of E_{50} and cement content

Фигура 5. Зависимост на E_{50} от съдържанието на цимент

The analysis of the results shows that the analysed loess is strengthened very successfully by the Portland cement used. After 7-day curing, even at 4% of cement the value of q_u exceeds 1.3 MPa and increases up to 2.85 MPa for the specimens with 12% of cement. After one month of curing q_u is in the interval 2.1 ÷ 4.2 MPa for the range from 4 to 12% cement. The growth of q_u from the 7th to the 28th day of curing is 1.4-1.6 times. Based on the results of numerous experiments Evstatiev (1987) proposed the empirical relationship $q_{u28}= 1.5q_{u7}$, which is confirmed by the tests conducted in this case.

The modulus of elasticity (Young's modulus) is calculated for the studied loess-cement mixtures after one month of curing using the correlation relationship proposed by Arellano & Thompson (1998) for silty and clayey soils stabilized with cement (Table 6) as follows:

$$E=440.q_u+0.28.q_u^2, \quad (1)$$

where:

E - modulus of elasticity, *psi*,
q_u - unconfined compressive strength, *psi.*

Table 6. Modulus of elasticity E of the studied loess-cement mixtures after 28-day curing according to the parametric equation (1)
Таблица 6. Еластичен модул E на изследваните циментольосови смеси след 28-дневно отлежаване по параметричната зависимост (1)

Loess-cement mixture		LC 4	LC 6	LC 8	LC 10	LC 12
q_u	MPa	2.06	2.71	3.11	3.75	4.20
	psi	299	393	451	544	609
E	psi	156457	216200	255439	322141	371930
	MPa	**1 079**	**1 491**	**1 761**	**2 221**	**2 564**

Durability

The durability of the investigated loess-cement mixtures with 4, 6, 8, 10 and 12% of cement is evaluated by means of two types of tests: freezing-thawing and wetting-drying, respectively after 28-days curing of the test specimens.

The freezing-thawing testing was conducted in accordance with the procedures of ASTM D 560 (method A). It included 12 freezing-thawing cycles, the duration of one cycle being 48 h, of which 24 h freezing at a temperature of −23°C in a refrigerating chamber and 23 h thawing in a climatic chamber at a temperature of 21°C and relative humidity above 95%. After each cycle the specimens were cleaned with a metal brush and their sizes and weight were measured. After the last cycle the specimens were dried at a temperature of 110°C and their dry mass was determined. On the base of the results the mass loss of the soil-cement specimens was calculated, thus evaluating their durability under the impact of cyclic freezing-thawing.

The wetting-drying tests were carried out in accordance with the procedures of ASTM D 559 (method A), similar to these of the previous investigation. The testing included 12 cycles of wetting-drying, the duration of one cycle being 48 h, of which 5 h water saturation by immersion in water bath at room temperature and 42 h drying at a temperature of +71°C in a laboratory oven. After each cycle the specimens were cleaned with a metal brush and their sizes and weight were measured. After the last cycle the specimens were dried at a temperature of 110°C and their dry mass was determined. On the base of the results the mass loss of the soil-cement specimens was calculated, thus evaluating their durability under the impact of cyclic wetting-drying.

According to Soil-Cement Laboratory Handbook (1991) the criterion in the assessment of durability for both tests (freezing-thawing and wetting-drying) is that the maximum allowable mass loss of the soil-cement specimens for soils of group A-6 (according to the AASHTO classification) should not exceed 7% and for soils of group A-6 – 10%. As stated above, the investigated loess falls on the boundary between group A-5 (silty soils) and A-6 (clayey soils), with slight predominance of the soils with a group index A-6. However, it has to be taken into account that these criteria, as well as the AASHTO classification, are directed to road and transport construction and are rather orientational for the foundation of buildings and facilities.

The summarized results from the conducted freezing-thawing and wetting-drying tests are given in Table 7. They show that after 28 days of curing (Figure 6) the losses of loess-cement mass after 12 freezing-thawing cycles are negligible for cement content of 8, 10 and 12% (less than 1.3%). The mass losses of the loess-cement mixtures with 4 and 6% of cement after 12 freezing-thawing cycles are larger than the admissible ones. These data prove that in the case of construction of loess-cement with cement content less than 6%, the cushion shall be protected against freezing by a sufficiently thick cover. After 28 days of curing the studied loess-cement mixtures exhibit minor losses of loess-cement mass after 12 wetting-drying cycles, irrespective of cement content (Figure 7).

Table 7. Mass losses of soil-cement after 28 days curing in % after 12 freezing-thawing cycles / 12 wetting-drying cycles

Таблица 7. Загуба на циментопочва след 28-дневно отлежаване в %-ти след 12 цикъла на замразяване–размразяване / 12 цикъла на водонапиване–изсъхване

LC mixture	c, % of dry weight	freezing-thawing	wetting-drying
LC 4	4	22.22	3.55
LC 6	6	10.06	0.83
LC 8	8	1.29	1.07
LC 10	10	1.27	0.98
LC 12	12	1.19	1.63

a. b.

Figure 6. Condition of the test specimens after 28-days curing and 12 freezing-thawing cycles: a. for 6% of cement; b. for 12% of cement

Фигура 6. Състояние на пробните образци след 28-дневно отлежаване и 12 цикъла на замразяване–размразяване: a. при 6% цимент; b. при 12% цимент

a. b.

Figure 7. Condition of the test specimens after 28-days curing and 12 wetting-drying cycles: a. for 6% of cement; b. for 12% of cement

Фигура 7. Състояние на пробните образци след 28-дневно отлежаване и 12 цикъла на водонапиване–изсъхване: a. при 6% цимент; b. при 12% цимент

Conclusion - selection of optimum loess-cement mixture for construction of compacted loess-cement cushion

Based on the analysis of the results obtained from the classification and physico-mechanical tests of the loess-cement mixtures, prepared with W_{opt} and ρ_{ds} of loess and Portland cement type CEM I 42.5 N – SR5 in proportions of 4, 6, 8, 10 and 12% of soil dry weight, it is proposed that the design cement content for the construction of the compacted loess-cement cushion of the radioactive waste repository to be 5% (by the dry weight of soil) of Portland cement CEM I 42.5 N – SR 5. The grounds for this choice are as follows:

- the unconfined compressive strength after 28-days curing at 4% of cement is q_u = 2.06 MPa and at 6% of cement q_u = 2.71 MPa; on the basis of these results it may be assumed with a high degree of reliability that at 5% of cement q_u will be in the range 2.35÷2.40 MPa after 28 days of curing; to assess the allowable loading (q_a – allowable bearing capacity) the almost universal in soil mechanics and sufficiently conservative dependence can be used: $q_a \approx q_u$, (Bowles, 1996), i.e. in the case of 5% of cement q_a will amount to about 2350-2400 kPa; it has been determined in the repository design that the loess-cement cushion should possess a minimum value of q_a=447 kPa; in other words, with the proposed optimum cement content this requirement will be met with a high degree of safety;
- the parametrically calculated modulus of elasticity (Young's modulus) after 28-days curing for 4% of cement is E = 1079 MPa, and for 6% E = 1491 MPa; for 5% of cement it may be expected that E will be about 1250-1300 MPa; it has been established from previous experience that the deformation modulus defined by plate loading test E_o is about 3 to 5 times smaller than the modulus of elasticity E, i.e. for 5% of cement E_o of the loess-cement cushion it will be in the range of 250-400 MPa; even higher values of the deformation modulus (470-480 MPa) are obtained if E_o is determined by the parametric dependence E_o=200.q_u (Palmström & Singh, 2001), which refers to brittle materials with predominantly elastic nature of deformation as loess-cement compared to construction soils; the main requirement in the technical design for the cushion is to have E_o=110 MPa after 28 days of curing; the evaluations show that this requirement is also met with a sufficient degree of safety for the proposed optimum cement content;
- after 28 days of curing the studied loess-cement mixtures, including with 4 and 6% of cement, meet entirely the criterion for loess-cement mass loss after 12 cycles of wetting-drying;
- after 28 days of curing the mass losses of the loess-cement mixtures with 4 and 6% of cement after 12 freezing-thawing cycles are larger than the admissible ones; however, it has to be taken under consideration that the loess-cement cushion according to the repository design will be covered everywhere by a sufficiently thick layer, including aside of the repository modules there will be 1 m thick road cover; this will fully protect the loess-cement from the freezing-thawing processes; the data obtained from the frost resistance test prove that during and immediately after the construction of the cushion its freezing should be inadmissible;
- based on data from the experience so far, including from the loess-cement cushion of other constructions, as well as on the results obtained for the physico-mechanical parameters of the studied loess-cement mixtures, it is assumed that the geotechnical parameters of the loess-cement cushion constructed with 5% of cement type CEM I 42.5 N will meet the requirements pursuant to the technical design of the repository with a reasonable safety reserve;
- these requirements can be also met with 4% of cement, but *first* – no sufficient reserve will be available to cover technological differences between laboratory preparation of test specimens and in-situ implementation of the loess-cement cushion and *second* – in terms of the function of the cushion as an engineering barrier restricting radionuclide migration, the presence of a medium with higher cement content is favourable;
- the optimum water content W_{opt} and the standard density ρ_{ds} of the chosen loess-cement mixture with 5% (of the dry weight of soil) Portland cement type CEM I 42.5 N – SR 5 were determined as follows:
  - optimum water content W_{opt} = 17.0%
  - standard (maximum) dry density ρ_{ds}= 1.73 g/cm^3

The above conclusions have to be confirmed by proper testing of small size experimental loess-cement cushion constructed with the selected of optimum loess-cement mixture.

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