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Static and dynamic strength parameters of stabilized loess soils from the Kozloduy Town Area

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Резюме. Статията представя определяне на якостни показатели на заздравен с портландцимент льос от района на АЕЦ „Козлодуй" и на площадка „Радиана" във връзка с изграждането на Националното хранилище за радиоактивни отпадъци. Досегашните изследвания доказват, че този льос може да се заздравява с малки количества портландцимент под формата на циментопочвени смеси, като се подобряват значително неговите якостно-деформационни свойства; увеличава се водоплътността, като коефициентът на филтрация намалява неколкократно. Пример за успешното приложение на този род смеси е циментопочвената възглавница, върху която са фундирани всички съоръжения на АЕЦ „Козлодуй".

Въз основа на натрупания опит се предвижда използването на тези смеси като част от инженерните бариери за ограничаване на разпространението на радионуклиди от Националното хранилище за радиоактивни отпадъци, което ще се изгражда на площадка „Радиана" в непосредствена близост до атомната централа. С цел повишаване на сорбционната способност на бариерите спрямо миграция на радионуклиди, към смесите се прибавят и вещества с вече доказани задържащи свойства - зеолит и бентонит. Една от задачите на това изследване е да се установи как тези добавки влияят върху формирането на якостта и дали няма да имат негативен ефект при малките количества цимент (3-12%), които се използват при заздравяването на льоса. Методологията на изследването включва изготвяне на смеси от два типа льос (песъчлив и типичен) със 7 и 12% цимент при стандартна плътност ρ_{ds} и оптимално водно съдържание w_{opt}. Количеството на добавките - зеолит (клиноптилолитов тип) и бентонит е 10 и 20%. Изготвените образци със съотношение h/d 1:1 са съхранявани в ексикатор при влажна среда и стайна температура. Изпитванията се провеждат след 1 и 12 месеца отлежаване на пробните тела с цел да се получи представа за развитието на якостта във времето. При статичните якостни показатели се определя якостта на едноосен натиск (R_c); при динамичните се изчисляват коефициентът на Поасон (ν), еластичният модул (модул на Юнг, E_d) и модулът на срязване (G_d), на базата на лабораторно определени чрез ултразвуков сеизмоскоп надлъжните и напречни вълни. За изясняване на структурните особености на смесите е използван сканиращ електронен микроскоп.

От изследванията са получени следните резултати: наблюдава се очаквано подобряване на якостните свойства на льоса при добавяне на цимент – R_c е между 1,51 MPa и 2,64 MPa при песъчливия льос и между 3,10 MPa и 4,51 MPa при типичния (прахов) льос. В допълнение, има развитие на дълговременната якост при пробите с песъчлив льос, като за една година увеличението е 74 и 45%, съответно при 7 и 12% цимент. Използването на вещества с висока сорбционна способност е изразено положително на R_c само с едно изключение (типичен льос с добавка на 10% бентонит). При пробите със зеолит се наблюдава нарастване на R_c спрямо тези без добавка със 119 и 86% при 10% зеолит и със 133 и 128% при 20% зеолит при образците с песъчлив льос. За пробните тела с типичен льос стойностите са 44 и 31% при 10% зеолит. Има увеличаване на якостта при песъчливия льос с 49 и 26% с 10% бентонит и с 27 и 23% при 20% бентонит. При пробите от типичен льос използването на 10% бентонит води до влошаване на якостните показатели съответно с 38 и 31% при двете количества цимент. При пробите с песъчлив льос и при двете добавки се отбелязва нарастване на якостта с течение на времето. Резултатите от лабораторните определяния на V_p и V_s са общо погледнато в съответствие с якостта на едноосен натиск. И при двата типа льос има нарастване на динамичните показатели в сравнение с резултати на естествен льос (от литературни източници), като при смесите от песъчлив льос и цимент то е значително. Използването на зеолит води до увеличение (понякога значително) на E_d при всички вариации от смеси с изключение на пробите от типичен льос с 12% цимент и 10% от добавъчно вещество. Употребата на бентонит има разнопосочно действие: 10% бентонит води до увеличение на еластичния модул при пробите с песъчлив льос и съответно до намаляване при тези с типичен льос. При случаите с 20% бентонит се отбелязва запазване или леко намаляване на модула на Юнг при пробите с песъчлив льос. При модула на срязване резултатите са еднакви. Снимките от сканиращия електронен микроскоп на пробите с добавки показват развитие на носителите на якостта: при калциевите хидросиликати (C-S-H) и калциевите хидроалуминати (C-A-H) то е идентично с това на смесите само с цимент, а при пробите със зеолит, е налице ускорено трансформиране на иглоподобните C-S-H с мрежо- и гелоподобни. В заключение може да се каже,че льосът от района на АЕЦ „Козлодуй” и площадка „Радиана” се поддава на заздравяване с портландцимент, като използването на вещества с висока сорбционна способност подобрява в повечето случаи якостните свойства на циментопочвените смеси и съответно ги прави перспективни за по-нататъшни изследвания.

Ключови думи: радиоактивни отпадъци, инженерни бариери, смеси от льос, цимент и зеолит и льос, цимент и бентонит, якост на едноосен натиск, динамичен еластичен модул

Abstract. The location of the National radioactive waste repository is in the vicinity of Kozloduy NPP (Radiana site). The area offers advantages from the viewpoint of the local population reaction, the hazards related to radioactive waste transport and the natural conditions. It is important that the loess soils can be easily stabilized with hydraulic binders and it can be transformed in impermeable and strong material. On such material, used as soil cement cushion, were build up all the Kozloduy NPP facilities. This cushion will be also constructed under the modules of the National radioactive waste repository Radiana. The strength parameters and strength-strain behaviour of soil cement cushion have been object of many publications in the Bulgarian geotechnical literature. In this report are presented the author's results from investigation of the static and dynamic strength characteristics of loess-cement mixtures and loess-cement mixtures with the addition of some natural sorption materials as zeolite and bentonite, the latter with the task to improve the nuclide retardation properties of soil-cement in the time and having in mind their use in the foundation work of the Radiana repository. So, the paper deals with the laboratory static strength and seismic waves investigations on mixtures made on the base of loess with a zeolite and bentonite additives, stabilized by ordinary Portland cement. The values of the unconfined compressive strength (UCS) of loess-cement-zeolite and loess-cement-bentonite samples are compared with the values of the UCS of loess-cement mixtures without any additives. The values of the primary (V_p) and secondary (V_s) waves of the samples are compared with the V_p and V_s values of a natural loess and the loess cement mixtures without any additives. SEM photographs have been made for evaluation of the samples texture. The results have shown that both compositions – with zeolite and bentonite additives are prospective for further investigations.

Key words: radioactive waste, engineered barriers, loess-cement-additive mixtures, unconfined compressive strength, dynamic Young modulus

Introduction

The location of the future National radioactive waste repository (NRWR) is in the vicinity of Kozloduy NPP (Radiana site). The geological cross-section is represented by loess complex overlaying Neogene clay. The area offers advantages from the viewpoint of the local population reaction, the hazards related to radioactive waste transport and the natural conditions. It is important that the loess soils can be easily stabilized with hydraulic binders and therefore its strength and impermeability would be significantly improved. On such material, used as soil cement cushion, were build up all the Kozloduy NPP facilities. Such a cushion will also be constructed under the modules of the National radioactive waste repository Radiana.

The strength parameters and strength-strain behaviour of the loess cement cushion, respectively of the loess-cement mixtures have been object of many publications in the Bulgarian geotechnical literature. Minkov and Evstatiev (1973), Evstatiev (1976) and Minkov et al. (1981) summarized field and laboratory investigations of the strength and deformation properties of the loess-cement cushion as a part of the foundation of the Kozloduy NPP. Their studies confirmed the prognosed settlements of the facilities and the redistribution role of the cushion to the normal stresses at the loess-cement and natural loess boundary. Followed detailed research work on the mechanism of the physical-chemical processes taking place in the loess stabilization by using ordinary Portland cement. Evstatiev (1984) showed that the calcium silicate hydrates C-S-H formed under the primary cement hydration and under the secondary (pozzolanic type) reactions are of the greatest importance for the mixture strength, realizing the cohesion between the mineral particles. The kinetics of the strength formation processes of the mixtures including the strength increase with long-time aging were studied and analyzed (Angelova, Evstatiev, 1985; Angelova, Evstatiev, 1989). A summary of the loess-cement cushion performance as a foundation of the nuclear power plant could be found in Jefferson et al. (2008). Investigations of several chemical compounds (NaOH, CaO, $CaCl_2$) and surface-active substances influence on the mechanical properties of the mixtures were performed as well (Angelova 1987; 1992). In connection with the eventual Romanian nuclear repository for low and intermediate level radioactive waste in loess terrains near Černavoda NPP, there are investigations for the loess layer mechanical and impermeability improvement by adding some percentage of polymer substances (Giurgea, 1999).

In this paper are presented the author's results from investigation of the static and dynamic strength characteristics of two types of loess, spread in the area of Kozloduy Town, stabilized with 7 and 12% cement, having in mind their use in the foundation work of the Radiana repository. On the other hand, there are research studies for utilization of a zeolite (clinoptilolite type) as a high sorbing substance in the Bulgarian nuclear power plant (Gradev et al., 1978).

From the viewpoint of this problem it would be of significant importance to investigate not only the strength properties of the loess-cement mixtures but also of loess-cement mixtures with the addition of natural sorption materials as zeolite and bentonite, with the scope to improve the nuclide retardation properties of soil-cement towards the NRWR operation.

Due to the relatively small amount of the hydraulic binder and the high natural sorbing capacity of the applied additives, the formation of the C-S-H and C-A-H could be compromised or negatively influenced, so an elucidation of the mechanical properties of mixes made of loess, cement and additives is needed. Hence, the paper deals with the laboratory static strength and seismic waves investigations on mixtures made on the base of loess with a zeolite and bentonite additives, stabilized by ordinary Portland cement.

Methodology

Materials origin and samples preparation

Two types of loess have been investigated, both from the Kozloduy NPP region. The first one according to Bulgarian geological loess classification (Minkov, 1968) is sandy loess and the second one – typical loess. Data about the classification parameters and the chemical composition of the both loess varieties are presented in Tables 1 and 2.

Table 1. Index properties of the used loess soils

Таблица 1. Класификационни показатели на използваните льосови разновидности

Soil	Grain-size distribution [%]				Specific density	Plasticity		
	> 2 mm	2 – 0.1 mm	0.1 - 0.005 mm	< 0.005 mm	ρ_s, g/cm^3	W_L, %	W_P, %	I_P, %
Sandy loess	0	10	84	6	2.74	28.0	25.3	2.7
Typical loess	4	11	68	17	2.72	25.5	20.0	5.5

Table 2. Chemical composition of the used loess soils

Таблица 2. Химичен състав на използваните льосови разновидности

Soil	Water extract 1:10 - 24 h meq/100g							Carbonate content	Humic content	Cation Exchange Capacity
	HCO_3^-	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	dry extract [%]	pH	[%]	[%]	[meq/100g]
Sandy loess	0.976	1.0	0.4	0.27	0.17	0.12	8.1	22.4	0.22	5.88
Typical loess	1.31	1.0	1.0	0.11	0.15	0.12	8.0	16.32	0.67	6.20

As a hydraulic binder a standard Ordinary Portland Cement (OPC) was used, with standard unconfined compressive strength of 35 MPa. Two kinds of high-sorption additives were used: Na^+ activated bentonite from the BENTONITE Ltd., Bulgaria and zeolite (with a clinoptilolite content of about 70%) from the Beli Plast Quarry. The samples were prepared as a mixture of disturbed loess with respective percentage of OPC and of additives, all compacted at the optimum moisture content w_{opt} till attainment of standard dry density ρ_{ds}. The cylindrical samples, with dimensions of *h/d* - 5/5 cm are aged 1 and 12 months in hermetic glass tanks with approximately 100% humidity. The weight percents of the composites are listed in Table 3.

Table 3. Compaction indices and composition percentages of the investigated mixtures

Таблица 3. Уплътнителни характеристики и процентов състав на изследваните смеси

Soil	Moisture content, w_{opt}	Maximum dry density, ρ_{ds}	Ordinary Portland Cement, q	Zeolite	Bentonite
	[%]	[g/cm^3]	[%]	[%]	[%]
Sandy loess	18.24	1.63	7	-	-
"	19.34	1.58	7	10	-
"	21.11	1.63	12	-	10
"	20.80	1.56	7	20	-
"	22.30	1.54	12	-	20
Typical loess	14.85	1.87	7	-	-
"	16.15	1.77	7	10	-
"	18.36	1.72	12	-	10

Apparatus

For the strength tests a electromechanical press is used with 5 mm/min loading rate and 0.5% precision. For the laboratory seismic wave investigations an ultrasonic apparatus "OYO-Model 5217 – new Sonic" is used.
The following equations are used in order to estimate the Poison`s ratio $v$, Young`s E_d and shear G_d moduli (by Lomtadze, 1977):

$$v = (V_p^2 - 2V_s^2)/2(V_p^2 - V_s^2), \text{ [-]} \quad (1)$$
$$E_d = V_s^2 \rho_n 2(1 + v), \text{ [MPa]} \quad (2)$$
$$G_d = V_s^2 \rho_n, \text{ [MPa]}, \quad (3)$$

where ρ_n is the bulk density of the sample in 10^3 kg/m^3.
A scanning electronic microscope "JEOL JSM – T300" is used for the investigation of the microstructure of the samples.

Results and discussion

The samples prepared according to the mentioned methodology are tested after one and 12 months, and approximately 10 months for sandy loess with bentonite additive (Tabl. 4). The results of the press loading tests are in accordance with the previous investigations. The greater the amount of cement is, the stronger the samples are. The effect of the additives is strongly positive, except in the case s of 10% bentonite for the typical loess (Tabl. 4). In the latter case the decrease of the strength is 38% and 31% for the 7% and 12% cement respectively. The addition of zeolite leads to a strength increase for the both type of loess soils, up to 133%. Please note that the observed and well-explained increasing of the soil-cement mixtures strength gain with long-time aging (Evstatiev, 1987; Angelova, Evstatiev, 1989) is observed in our cases as well, and again up to 136% (in the case of the sandy loess mixtures).

Table 4. Unconfined compressive strength (UCS) of the samples aged 1 and 12 months (by Antonov, 2002).

Таблица 4. Якост на едноосен натиск на образци отлежали 1 и 12 месеца (по Antonov, 2002)

Soil	Additive		UCS after 1 month aging, R_c, [MPa]		UCS after 12 months days aging, R_c, [MPa]	
	zeolite	bentonite	Cement percentage, q		Cement percentage, q	
	[%]		7 [%]	12 [%]	7 [%]	12 [%]
Sandy loess	-	-	1.51	2.64	2.65	3.82
“	10	-	3.31	4.91	5.81	7.34
“	20	-	3.52	6.03	6.27	8.56
“	-	10	2.25	3.22	3.21*	5.91*
“	-	20	1.92	3.25	2.80*	5.15*
Typical loess	-	-	3.10	4.51	N/A	N/A
“	10	-	4.47	5.94	N/A	N/A
“	-	10	1.91	3.08	N/A	N/A

* Note: After 300 days of aging

In the technical design stage of a surface repository seismic behaviour of the soil base has to be estimated using the dynamic characteristics of the soil base. For that purpose a lot of data for the seismic wave laboratory V_p and V_s measurements of natural loess in the region of Kozloduy NPP have been analysed. Samples only of loess-cement have been laboratory measured as base values for the estimation of the effect of additives. The measurements were done according to the above-described procedure. The results from the analyses and investigations are listed in Table 5, 6 and 7. The use of cement leads to increase of the V_p and V_s and resp. Young`s modulus for both type of loess. The effect of the zeolite and bentonite additives is diverse. The addition of 10% bentonite increases values of the waves, resp. moduli for the sandy loess mixtures (compare Tabls. 6 and 7). Mixtures with 20% bentonite possess decreased or almost the same moduli. On the other hand, the addition of zeolite always leads to increase of the velocities, resp. of the moduli,except in the case of the typical loess with 12% cement and 10% zeolite (Tabl. 7).

Table 5. Average values of the dynamic strength parameters of natural loess samples (by Gogov, 1978)

Таблица 5. Осреднени стойности на динамични якостни показатели на естествен льос (по Gogov, 1978)

Soil	Primary wave (avr. value/ number of tests)	Secondary wave (avr. value/ number of tests)	Poison`s ration	Young`s modulus
	V_p [m/s]	V_s [m/s]	v [-]	E_d, [MPa]
Sandy loess	290 – 1160 (680/37)	140 – 580 (315/37)	0.36	487
Typical loess	1200 – 1970 (1690/7)	550-990 (810/7)	0.35	3368

Table 6. Dynamic strength parameters of loess-cement samples

Таблица 6. Динамични якостни показатели на проби от льос и цимент

Soil	Cement percentage	Primary seismic wave	Secondary seismic wave	Poison`s ratio	Young`s modulus	Shear modulus
	q [%]	V_p [m/s]	V_s [m/s]	v [-]	E_d [MPa]	G_d [MPa]
Sandy loess	7	1570	928	0.23	4 100	1665
“	10	1729	971	0.26	4622	1820
“	12	1913	1051	0.28	5479	2134
Typical loess	7	2004	1043	0.31	6147	2338
“	10	2125	1128	0.30	7133	2735
“	12	2241	1161	0.32	7630	2898

Table 7. Dynamic strength parameters of loess-cement-additive samples

Таблица 7. Динамични якостни показатели на проби от льос-цимент и добавки

Soil	Cement percentage, q	Additives		Primary seismic wave, V_p	Secondary seismic wave, V_s	Poison`s ratio, v	Young`s modulus, E_d	Shear modulus, G_d
		zeolite	bentonite					
	[%]	[%]		[m/s]	[m/s]	[-]	[MPa]	[MPa]
Sandy loess	7	10	-	2206	1122	0.32	6349	2395
“	12	10	-	2475	1159	0.35	6941	2552
“	7	20	-	2245	1113	0.33	6228	2329
“	12	20	-	2475	1089	0.37	6161	2232
“	7	-	10	2073	897	0.38	4397	1588
“	12	-	10	2318	1108	0.35	6513	2409
“	7	-	20	1881	900	0.35	4165	1541
“	12	-	20	2148	925	0.38	4484	1617
Typical loess	7	10	-	2300	1252	0.29	8327	3229
“	12	10	-	2466	1133	0.37	7225	2644
“	7	-	10	1977	944	0.35	4916	1817
“	12	-	10	2100	1024	0.34	5750	2139

In order to understand the reasons of the increased strength and for the comparison of the structure of the samples, SEM analysis have been performed (Fig. 1, 2 and 3). The first photo presents natural undisturbed sandy loess structure. The structure is “light” i.e. with a lot of pores of different size, even macro-pores.

Fig. 1. Natural loess. Magnified x 100

Фиг. 1. Естествен льос. Увеличение 100 пъти

The SEM photographs taken on the sandy loess-cement-bentonite (Fig. 2) and sandy loess-cement-zeolite (Fig. 3) samples show one much more dense structure with well-spread compact mass covering the grains and almost completely fulfil the pore space. On the other hand, it could be seen that the needle-like type of C-S-H have been transformed into the network-like and gel-like types (especially with the loess-cement-zeolite mixtures), fact leading together with the more dense structure to the increased strength.

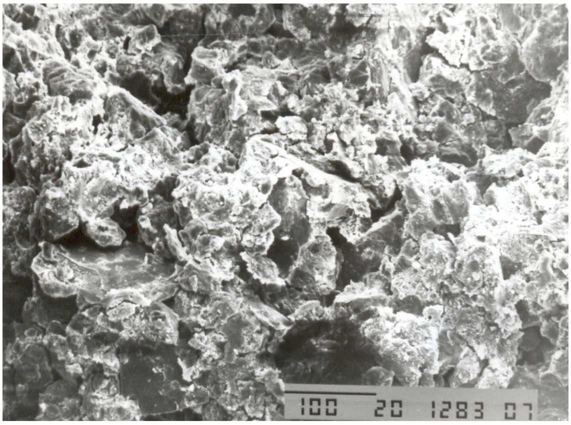

Fig. 2. Loess with 12% cement and 20% bentonite. Magnified x 200

Фиг. 2. Льос с 12% цимент и 20% бентонит. Увеличение 200 пъти

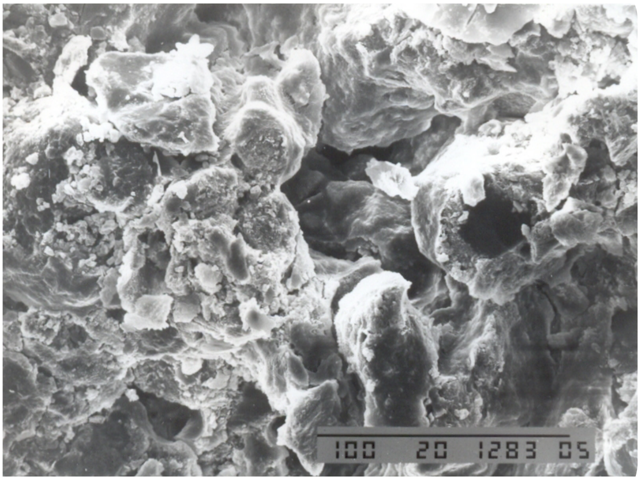

Fig. 3. Loess with 12% cement and 20% zeolite. Magnified x 500

Фиг. 3. Льос с 12% цимент и 20% зеолите. Увеличение 500 пъти

Conclusion

The results of the tests show that the stabilized loess has high unconfined strength which increases up to two times after adding of zeolite and bentonite additives. So, from mechanical point of view the mixtures could be used as engineered barrier in radioactive waste repository. Furthermore, the investigations show that the well-known data of time strength increasing of loess-cement samples is valid also for the sandy loess-cement-additives ones. In general, there is an increase of the seismic wave velocities of the loess-cement-additive mixtures up to 1000 % in comparison with those of the natural loess and up to 55% to those of only loess-cement mixtures. The laboratory seismic wave measurements except for the dynamic characterization give additional information for the strength behavior of the samples and are a secondary sign of showing the increase of the strength properties. The diverse effect of the both additives could be explained with the different impact of the bentonite and zeolite compounds. The observed increased UCS in the bentonite case could be a result of the more dense structure, i.e. approaching to a structure with the optimal grain-size content. On the other hand, the origin of the strength in the zeolite case could be in the increased intergranular C-S-H and C-A-H bonds and their faster transformation from needle-like type to network-like and gel-like types.

Therefore, depending on the eventual tasks both loess-cement-additives mixtures are perspective for further investigation from the safety point of view of the radioactive waste disposal system, while additional studies on the adsorption properties of the compounds are needed.

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