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LONG-TERM PERFORMANCE OF LOESS-CEMENT

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Abstract

In Bulgaria, comprehensive research and practical experiments of loess-cement have been started in the sixties of the last century in the Geological Institute of Bulgarian Academy of Sciences and later an extensive application has taken place mainly in foundation works and irrigation facilities. The construction of soil-cement impervious screen at the bottom of the irrigation levelling reservoir of the Lom Agricultural Testing Station in the late sixties of the last century was one of the earliest applications of the loess-cement. Recently a comprehensive analysis of the microstructure, physical and mechanical parameters of the loess-cement from this impervious screen was executed aiming to assess the long-term performance of the soil-cement after more than 50 years of curing at field conditions. The current paper discusses the main outcomes and findings of that investigation. It was found that the phase transformations of the C–S–H of the cementitious mass in the inter-aggregate pore space resulted in denser microstructure and higher strength of the loess-cement after long-term curing.

Key words: loess-cement, long-term performance, 51 years of curing at field conditions, microstructure, physical and mechanical parameters

Introduction. The stabilization of local loess soil with Portland cement is a soil improvement method widely applied in constructing works in loess terrains. Depending on the consistency of the mixture of soil and cement, two types of loess-cement have been applied: the so-called *rigid* and *plastic*. The *rigid* one is

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compacted at optimum water content W_{opt} up to standard (maximum) dry density ρ_{ds}. The *plastic* loess-cement is prepared at water content W much higher than the W_{opt}, usually at or slightly above the liquid limit W_L of the soil and it is placed without or with minor compaction. In Bulgaria, comprehensive research and practical experiments of loess-cement have been started in the sixties of the last century in the Geological Institute of Bulgarian Academy of Sciences (GI–BAS) [1–3] and later an extensive application has taken place mainly in foundation works and irrigation facilities [4–7]. Impervious screens built out of local loess soil stabilized with cement have been used effectively as a substitute for concrete linings on irrigation water reservoir bottoms in collapsible loess terrains. To date, approximately 160 000 m^2 of impervious screens have been constructed in this way in Bulgaria [8].

The construction of soil-cement impervious screen at the bottom of the irrigation levelling reservoir of the Lom Agricultural Testing Station (ATS) in the late sixties of the last century was one of the earliest applications of the loess-cement. Recently a comprehensive analysis of the microstructure, physical and mechanical parameters of the loess-cement from this impervious screen has been executed aiming to assess the long-term performance of the soil-cement after more than 50 years of curing at field conditions. The current paper discusses the main outcomes and findings of that investigation.

Characteristics of the analysed loess-cement impervious screen. The irrigation levelling reservoir of the Lom ATS is located in the close vicinity of the town of Lom, North Bulgaria (Fig. 1a). The levelling reservoir with a working volume of 2500 m^3 and a bottom area of 1200 m^2 was built in 1965 and additionally upgraded in 1971. The ground base consists of Quaternary collapsible loess deposits with a thickness of 18–20 m overlaid Pliocene clay (Fig. 1b) [3,4].

The loess-cement impervious screen was built by *plastic* soil-cement. The local loess was mixed with 10% (by the dry weight of the soil) of Portland cement type 400 (according to the current cement classification designated as CEM I 42.5 N) in a stationary mixer at $W \approx W_L$ of the soil. The used local loess (from the L_1) was classified as low plasticity clay (ClL) with $W_L = 31\%$ and plasticity index $I_p = 14\%$ [3].

The ready mixture was spread at the bottom of the reservoir in stripes with a 4.5 m width and 10–12 cm thickness after minor compaction by a hand vibrating compactor up to dry density ρ_d = 1.48–1.52 g/cm^3. Several hours after the placement and compaction the ready strip was covered by a 15 cm protective soil layer to preserve moisture and ensure sufficient frost resistance. Test samples taken from the loess-cement screen after 28-day curing showed unconfined compressive strength (UCS) after 10 freezing-thawing cycles $q_u = 0.7$–0.8 MPa [4].

During the operation of the irrigation levelling reservoir UCS control tests of the loess-cement samples were carried out several times. The main results from these tests were as follows:

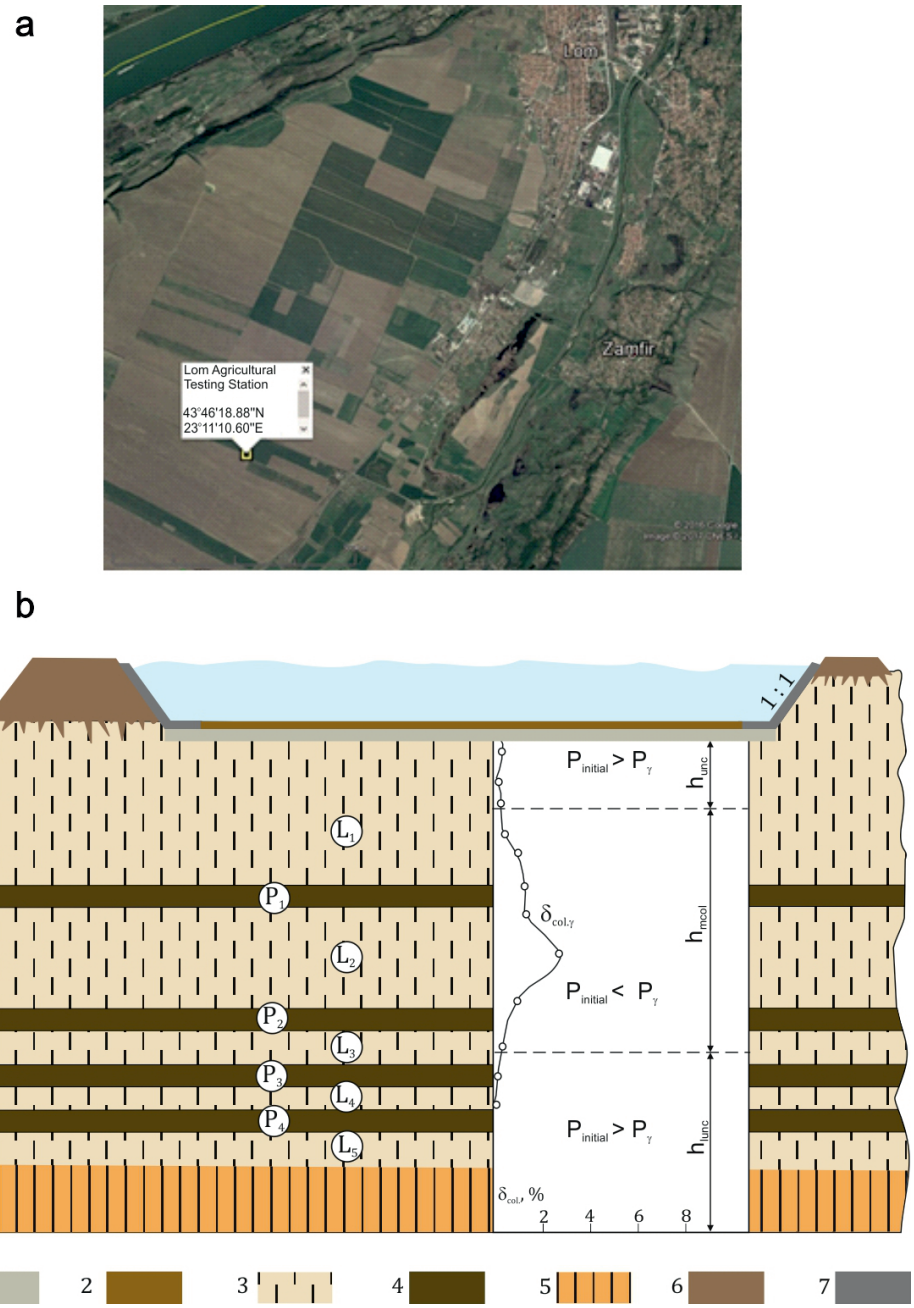


Fig. 1. a. Location of the irrigation levelling reservoir (the white rectangle) of the Lom ATS; b. Cross-section of the ground base at the Lom ATS irrigation levelling reservoir: 1 – impervious screen from plastic loess-cement; 2 – protective soil cover; 3 – loess horizons; 4 – paleosols; 5 – Pliocene clay; 6 – embankment; 7 – concrete lining along the embankment slopes; $\delta_{col.\gamma}$ – collapse potential under overburden stress; h_{unc} – upper zone without unloaded collapsibility but with potential loaded collapsibility; h_{lunc} – lower uncollapsible zone; h_{mcol} – middle zone with unloaded collapsibility (after [4] with modifications)

- After one year of operation the loess-cement possessed $q_{u1:1} = 1.0$–1.5 MPa (for specimens with ratio 1:1 of diameter to length) or $q_{u1:2} = 0.9$–1.3 MPa [3].

- After four years of operation the UCS of the loess-cement was about two times higher $q_{u1:1} = 2.5$ MPa or $q_{u1:2} = 2.2$ MPa [9].

- After 21 years of operation the UCS of the loess-cement was about ten times higher, i.e. $q_{u1:1} = 12.0$ MPa or $q_{u1:2} = 10.4$ MPa [10].

Testing and analysis of the loess-cement after 51-year curing at field conditions. The protective soil layer above the screen was removed at three randomly located sectors with an area of 1.20×0.80 m each. No cracks and/or deformations were observed due to moistening-drying or freezing-thawing of the loess-cement surface at the all sectors.

Totally 39 undisturbed samples were taken from the three testing sectors (13 samples from each) by an electrical core drilling machine using a 55 mm drill bit for concrete. After the samples extraction all the holes were filled up by a plastic loess-cement mixture prepared with local loess and 10% of cement.

Microstructural analysis. The microstructure of the loess-cement after 51-year curing at field conditions was studied by SEM analysis conducted using a JEOL 733 Superprobe SEM. The loess-cement samples were secured on aluminium mounting stubs by carbon glue and sputters coated with one layer of carbon in order to enhance the conductivity of the tested specimen, and then were coated with a 20-nm layer of gold. The samples were analyzed with a focused electron beam with accelerating voltage of 14 kV and secondary electron images were produced. SEM images were taken at different levels of magnification to provide a detailed view of the treated soil matrix.

Two main elements in the loess-cement microstructure have been observed – silty and sandy (quartz, feldspar, mica and carbonate) particles forming the skeleton of the stabilized soil and fine grained cementitious mass filling up the space between the particles (Fig. 2a). At higher magnification, it is seen that the main connecting substance in the cementitious mass are the hydration products of the pozzolanic reactions such as calcium-silicate hydrates (C–S–H), calcium-aluminate hydrates (C–A–H) and calcium-aluminium-silicate-hydrates (C–A–S–H). As time goes by, phase transformations of the C–S–H took place – the initially formed fibrous phases have modified in gel-like phases (Fig. 2b). This modification of cementitious mass in the inter-aggregate pore space resulted in denser microstructure and higher strength of the loess-cement after long-term curing.

Moisture-density parameters. The density ρ, the moisture content W and the dry density ρ_d were determined of 30 soil-cement samples totally (by 10 samples from each of the testing sectors) in compliance with the requirements of ASTM D 7263 and ASTM D 2216. The mean values of the moisture-density parameters by sectors are given in Table 1. The testing results show that the

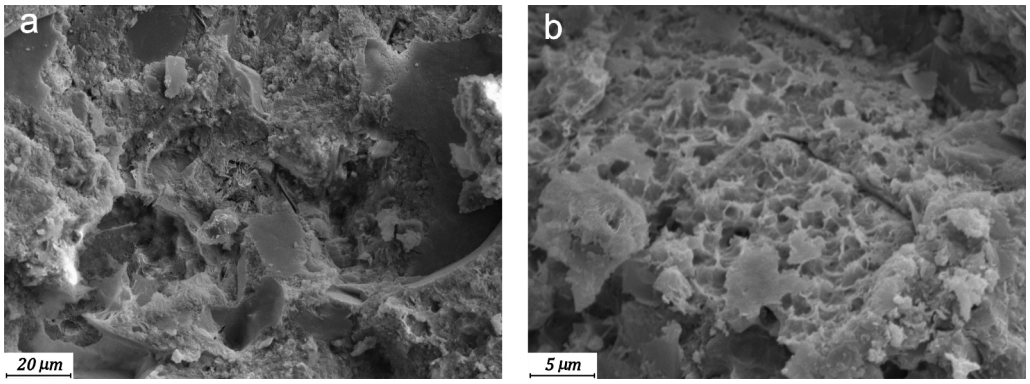


Fig. 2. SEM images of the loess-cement after 51-year curing: a. ×1000 magnification; b. ×4000 magnification

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Parameters of the loess-cement after 51-year curing

Testing sector No.		I	II	III
ρ	[g/cm^3]	1.81	1.81	1.80
W	[%]	21.20	21.36	21.60
ρ_d	[g/cm^3]	1.49	1.51	1.48
$q_{u1:2}$	[MPa]	10.30	10.99	10.98
s_u	[MPa]	5.15	5.49	5.49
E_{50}	[MPa]	2482	2863	2853
σ_{tsp}	[MPa]	1.08	1.33	1.72
σ_{tsp}/q_u	[-]	0.105	0.121	0.157
$\sigma_t = 0.9 * \sigma_{tsp}$	[MPa]	0.97	1.20	1.40
E	[GPa]	6.60	7.13	7.57
μ	[-]	0.15	0.13	0.11
k	[m/s]	1.21E−09	9.13E−10	9.60E−10

initial density of the loess-cement has not changed after 51-year curing at field conditions.

Unconfined Compressive Strength. The UCS was determined in compliance with ASTM D 1633 of nine loess-cement samples (by three samples from each of the testing sectors). The samples were immersed in water for 4 h prior to UCS measurement. The test results are presented in Fig. 3a. The determined mean values of the UCS q_u, undrained shear strength s_u and the Young's modulus of elasticity E_{50} corresponding to 50% of q_u are shown in Table 1.

The test results clearly indicate that the UCS of loess-cement has remained unchanged from 21-year curing up to 51-year curing, i.e. the q_u after 51-years curing is still about ten times higher in comparison with the q_u after 1-month curing. Considering the results reported previously [9,10], it can be presumed that the substantial part of the strength gain has taken place during the first

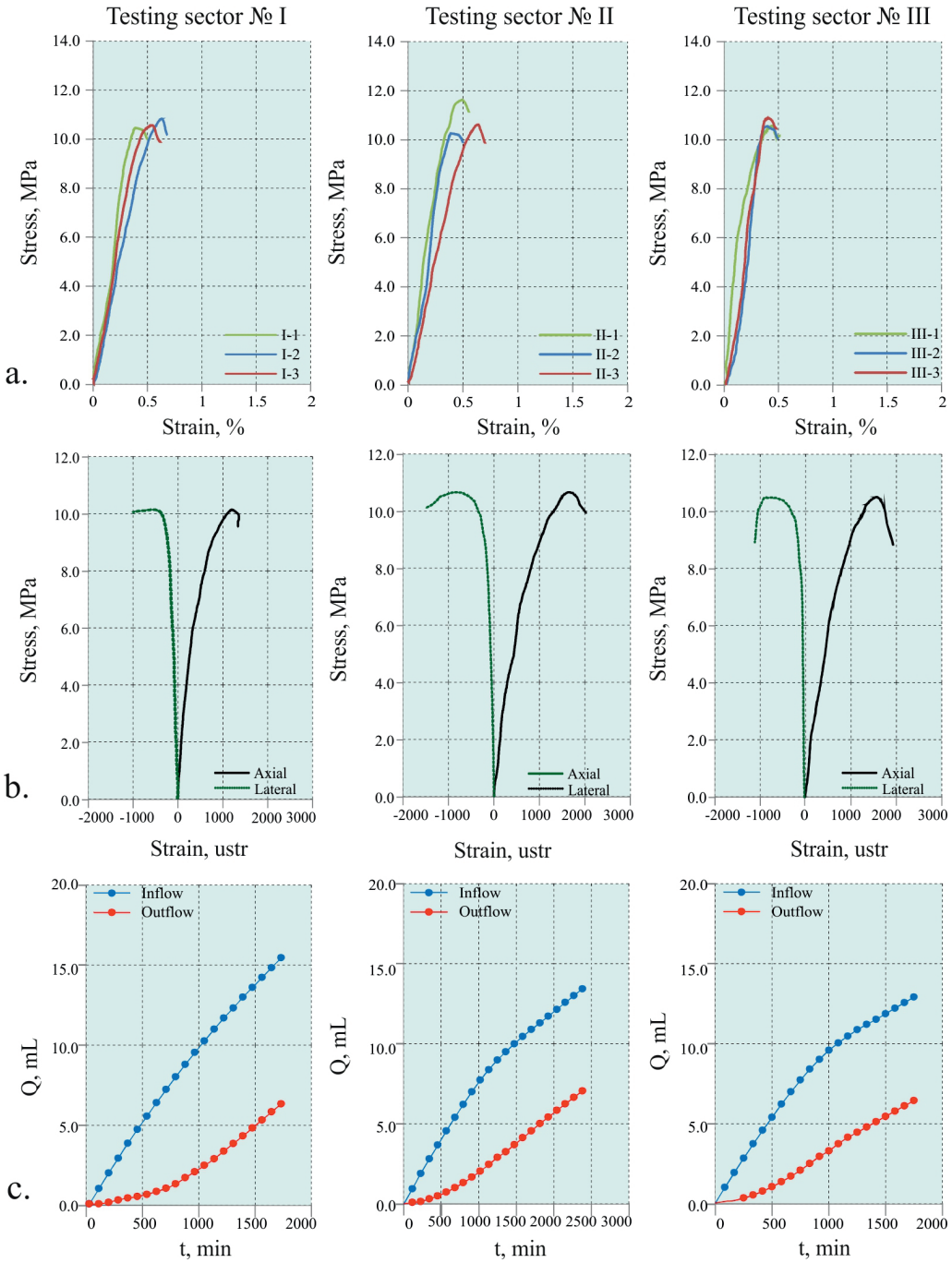


Fig. 3. Test diagrams of the loess-cement after 51-year curing: a. UCS test; b. elastic parameters test by compressometer-extensometer (1 ustr = 1.10^{-6}); c. hydraulic conductivity by Constant Rate of Flow Test

twenty years. Subsequently the strength of loess-cement has been retained at field conditions. Obviously the protective soil cover of 15 cm has been sufficient to provide a long-term protection of the loess-cement under the climatic conditions of Northwest Bulgaria.

Splitting Tensile Strength. Totally 30 samples (ten samples from each of the testing sectors) were tested in compliance with ASTM D 3967 to evaluate the tensile strength of loess-cement after 51-year curing. The samples were immersed in water for 4 h before tensile strength testing. The mean values of the slitting tensile strength σ_{tsp} and the ratio of σ_{tsp}/q_u for each sector are given in Table 1. In the case of the tested loess-cement σ_{tsp}/q_u is 0.13 on average which corresponds to the values of this ratio for concrete which is in the range of 0.07–0.17 as reported by [11]. Using a correction coefficient of 0.9 which is defined for the concrete [12], the direct tensile strength σ_t of loess-cement is calculated from the splitting tensile strength test values (Table 1).

Elastic parameters. The static elastic constants (Young's modulus of elasticity, E, and Poisson's ratio, μ) were obtained of three samples (one from each of the testing sectors) in compliance with ASTM C 469 and ASTM D 7012 (Method D). The samples were immersed in water for 4 h 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 $d/h = 1/2$. The test graphs are shown in Fig. 3b and the values of E and μ in Table 1. There are no data for the elastic parameters of the loess-cement after the construction of the impervious screen. Considering available data for the modulus of elasticity of plastic loess-cement (also with 10% cement) [13], it can be summarized that after 51-year curing the E is increased about 11 and 5 times in comparison with E after 28-day curing and after 180-day curing, respectively.

Hydraulic conductivity. The hydraulic conductivity k of loess-cement after 51-year curing was determined of three samples (one from each of the testing sectors) in compliance with ASTM D 5084 applying Method D – Constant Rate of Flow Test. The test graphs and the k values are given in Fig. 3c and Table 1. The test results show that the hydraulic conductivity varies in a narrow range mainly due to the close densities of the loess-cement samples. The average hydraulic conductivity is $k = 1.03\text{E} - 9$ m/s. There are no data for this parameter after the construction of the loess-cement screen. Taking into account the available studies [14] it can be assumed that the permeability of the loess-cement has decreased over time by one order of magnitude.

Conclusion. The microstructure, physical and mechanical parameters of the loess-cement from an impervious screen were comprehensively analysed to assess the long-term performance of the soil-cement after 51 years of curing at field conditions. It was found that the phase transformations of the C–S–H of the cementitious mass in the inter-aggregate pore space resulted in denser microstruc-

ture and higher strength of the loess-cement after long-term curing. The strength of loess-cement has been retained at field conditions. The UCS of loess-cement after 21-year curing has been increased about ten times in comparison with the q_u after 1-month curing and up to 51-year curing this magnitude of UCS has remained unchanged. The modulus of elasticity E is increased about 11 and 5 times in comparison with E after 28-day and 180-day curing, respectively. The permeability of the loess-cement has decreased over time by one order of magnitude. No cracks and/or deformations were observed due to moistening-drying or freezing-thawing of the loess-cement. Obviously under the climatic impact of Northwest Bulgaria the protective soil cover of 15 cm has been sufficient to provide a long-term protection of the loess-cement.

REFERENCES

[1] Evstatiev D. (1965) Investigations into the stabilizations for the loess in Northern Bulgaria with Portland cement, Works on the Geology of Bulgaria, Ser. Engineering Geology and Hydrogeology, **4**, 131–153 (in Bulgarian).

[2] Evstatiev D. (1969) On the effect of initial moisture on the strength of the cement–soil, Bulletin of the Geological Institute, Ser. Engineering Geology and Hydrogeology, XVII–XVIII, 127–136 (in Bulgarian).

[3] Minkov M., D. Evstatiev, A. Alexsiev (1968) Revetment of the leveller with plastic loess–concrete, Hydrotechnics and Amelioration, **1**, 22 – 2 (in Bulgarian).

[4] Minkov M., D. Evstatiev (1975) Loess Stabilization in Foundation Work and Irrigation Constructions, Sofia, Tehnica, 189 pp (in Bulgarian).

[5] Minkov M., D. Evstatiev (1979) On the seismic behavior of loess soil foundations. In: 2nd US Nat. Conf. on Earthquake Engin., Stanford University, 988–996.

[6] Minkov M., D. Evstatiev, P. Karachorov, P. Slavov, G. Stefanoff et al. (1981) Stresses and deformations in stabilized loess. In: Proc. 10th ICSMFE, Stockholm, 2, 193–197.

[7] Evstatiev D., Y. Evlogiev, M. Nedelcheva (2008) Foundation work of high TV tower in collapsible loess. In: 6th Int. Conf. on Case Histories in Geotech. Engin., Arlington, 1–6.

[8] Jefferson I., Ch. Rogers, D. Evstatiev, D. Karastanev (2005) Treatment of metastable loess soils: Lessons from Eastern Europe. Chapter 25. Ground Improvement – Case Histories, Elsevier Geo-engineering Book Ser., Vol. 3, Elsevier, 723–762.

[9] Minkov M., D. Evstatiev (1970) Revétment de sol-cement des resérvoirs des compensation. In: 1er Congrés Internat. de Géologie de l'Ingéneiur, Paris, France, 8–11 sept., 1970, 636–642.

[10] Karastanev D. (1988) Improvement of Collapsible Loess Soils in Construction of Irrigation Structures, PhD Thesis, Geotechnics Lab, BAS, 161 pp (in Bulgarian).

[11] Akinpelu M. A, S. O. Odeyemi, O. S. Olafusi, F. Z. Muhammed (2017) Evaluation of splitting tensile and compressive strength relationship of self-compacting concrete. In: J. King Saud Univ., Engin. Sci., 1–7.

[12] CEB–FIP Model Code for Concrete Structures (1990) Evaluation of the Time Dependent Behaviour of Concrete. In: Bulletin d'Information No. 199, Comité Européen du Béton/Fédération Internationale de la Précontrainte, Lausanne, 1991, 201 pp.
[13] Tchakalova B. (2018) Engineering Barriers of Plastic Loess-cement Mixtures for Waste Isolation, PhD Thesis, Geological Institute, BAS, 135 pp (in Bulgarian).
[14] Tchakalova B., D. Karastanev (2017) Geotechnical parameters of loess-cement mixture for construction of compacted soil-cement cushion, Geologica Balcanica, **46**(2), 117–124, https://doi.org/10.52321/GeolBalc.46.2.117.

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