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Loess-cement long-term strength – a facilitating factor for loess improvement applications

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Р. Ангелова — Долговременная прочность цементо-лессовых смесей — благоприятный фактор для их приложения при укреплении лесса. Исследования проводились с песчаным, типичным и глинистым лессом из Северной Болгарии. Полученные результаты показывают значительное (1.5–5 раз) увеличение прочности *цементо-лессовых* смесей после длительных сроков твердения по сравнению со стандартным периодом испытания (1 месяц). Увеличенная прочность является благоприятным фактором для разнообразного и широкого приложения этого материала. Методы, относящиеся ко группе поверхностного смешивания (цементо-лессовые подушки; противофильтрационные экраны и покрытия) широко используются в Болгарии. К сожалению группа методов глубинного укрепления (глубинное смешивание, гидроструйное укрепление и цементо-грунтовые сваи) используются только в качестве исключения. Глубинное укрепление обещает дать хорошие результаты при обработке сильнопросадочных лессовых грунтов, водонасыщенных лессов, в лессовых районах с повышенной сеисмической активностью и при приложениях с екологическим акцентом.

Abstract. The investigations are carried out with sandy, silty and clayey loess varieties from North Bulgaria. The obtained results manifest a significant increase of the compressive strength of loess-cement mixtures in time (1.5–5.0 times) in comparison with the standard test period (1 month). This is a favourable factor for wide and various application of this material. The methods included in the group of surface mixing (soil-cement cushions; impervious screens and protective facings) are developed and widely used in Bulgaria. Unfortunately, the group for deep stabilization (deep mixing method; jet-grouting and soil-cement piles) is only occasionally applied in Bulgaria. Deep mixing stabilization is of great promise in treatment of high collapsible loess bases, saturated loess, loess areas with high seismic intensity and different environmental applications.

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Key words: collapsible loess, loess-cement mixtures, strength gain, ground improvement methods, soil-cement mixing.

Introduction

The main unfavorable properties of loess with respect to construction are: its ability to collapse when moistened; its significant water permeability and its intensive softening in case of water interaction. These are the major prerequisites for application of different methods for loess improvement. In a number of regions, what threatens the structures besides collapsibility is also high seismic intensity. The anti-collapsible treatment of the base or reinforcement of the loess and of a building after its collapsing may come up to 10–20% of its cost, respectively, which by itself is an illustration of the importance of the research in this field (Evstatiev et al., 2002).

The greatest part of construction activities in Bulgaria is concentrated in Danubian loess area. All nuclear energy facilities and several thermal power stations in Bulgaria are situated and will be constructed over all this territory. The growth of the cities along the Danube River in the future will lead to utilization of high loess terraces, where the loess subsidence is the biggest. Stabilization of soils by mixing with binding substances has found wide application in creation of artificial material distinguished with properties designed in advance. This material is suitable for road construction; facing on earthen dams; impermeable screens and barriers; foundation cushions; walls and piles (Минков и Евстатиев, 1975; Litton and Lohnes, 1982; Ветштейн и Токин, 1982; Токин, 1984; Евстатиев и Ангелова, Ред., 1993; Zan Yuewen, 1996). These methods enable to utilize the local soils as a building material. The mixing of soils with binding substances (most often with cement) is carried out as well as on the ground surface as in depth. Using both technological schemes can broaden the application sphere of the soil improvement.

Characteristics of examined loess soils and investigation methods

The investigations are carried out with three loess varieties: sandy loess, silty loess and clayey loess (Table 1). They differ in their grain-size distribution and also in the chemical and mineral composition.

The examined loess soils are most often subjected to cement stabilization. The special features in their microstructure and mineral components have been discussed in details by Angelova and Evstatiev, 1990. The loess soils were stabilized with Portland cement PC 35. The cement content was 5, 7, 10 and 15%. Sandy loess-cement samples were compacted at optimum water content W_O = 16% to dry density c_d = 1.55; 1.58; 1.62; 1.65 g/cm^3. Silty loess-cement samples were compacted at W_O = 17.5% to c_d = 1.55; 1.60; 1.65; 1.70 g/cm^3 and clayey loess-cement samples – at W_O = 18% to c_d = 1.60; 1.64; 1.68; 1.73 g/cm^3. After different periods of curing (from 2 days to 2 years) in air-moisture environment the samples were water-soaked for 24 h and used for various kinds of analysis: unconfined compression test; scanning electron microscopy; determination of chemical and mineral composition; mercury porosimetry.

Loess-cement strength gain and main affecting factors

The strength of loess-cement mixtures increases in time at different rate (Fig. 1). Four stages have been found out: I – a quick increase of strength (up to one month); II – a slower increase (between the first and sixth month); III – a second increase at a higher rate (6–9 month); IV – an insignificant gain or retention of strength (9–24 month). During the first month products of intensive cement hydration have been observed – calcium silicate hydrates C-S-H and calcium aluminate hydrates C-A-H. Needle-like phases of calcium silicate hydrate C-S-H I type (Diamond, 1976) predominate in sandy loess-cement and silty loess-cement mixtures. The larger quantity of C-S-H I type is formed in the samples with lower dry density c_d and higher cement content. Till the 30th day the mixtures alkalinity is high (pH = 12–13). It has been established that the degree of bonding of water molecules increases 2–3 times during the 1st month, which affects the strength favorably in addition (Ангелова, 1987). About the end of the 1st month in all the three loess soils starts the formation of a network-like binding substance, probably a C-S-H II type (Евстатиев, 1984; Ангелова, 1987).

During the second stage (30–180 days) strength increases at a slower rate (Fig. 1). The initiation of phase transformation of the mass of calcium silicate hydrates has been observed in this period – the volume of needle-like C-S-H decreases and formation of network-like C-S-H and gel-like C-S-H increases. It has been established that pH continues to decrease and reaches values of 11–11.5.

The third stage (180–270 days) is characterized by a second period of relatively rapid increase of the strength. This is more typical for the silty loess mixed with more than 5% cement. Gel-like mass, similar to the III type C-S-H, connecting the soil particles can be observed in the silty loess-cement samples. The clayey loess – cement mixtures show different kind of structure and the main binding substance, depending on the degree of compaction (Angelova and Evstatiev, 1990). The processes determining the strength gain in this stage are: activation of the fine quartz particles surface; additional pozzolanic in-

Table 1
Index properties of the investigated loess soils

Index	Sandy loess	Silty loess	Clayey loess
Grain-size distribution, %			
Sand 2-0.05 mm	52	34	20
Silt 0.05-0.002 mm	48	64	71
Clay < 0.002 mm	0	2	9
Consistency limits, %			
Liquid limit W_L	26.9	25.2	34.2
Plastic limit W_P	25	21.1	18.6
Plasticity index I_P	1.9	4.1	15.6
Optimum water content W_O, %	16	17.5	18
Maximum dry density ρ_{dmax}, g/cm^3	1.62	1.69	1.72
Density of solid particles ρ_s, g/cm^3	2.76	2.74	2.74

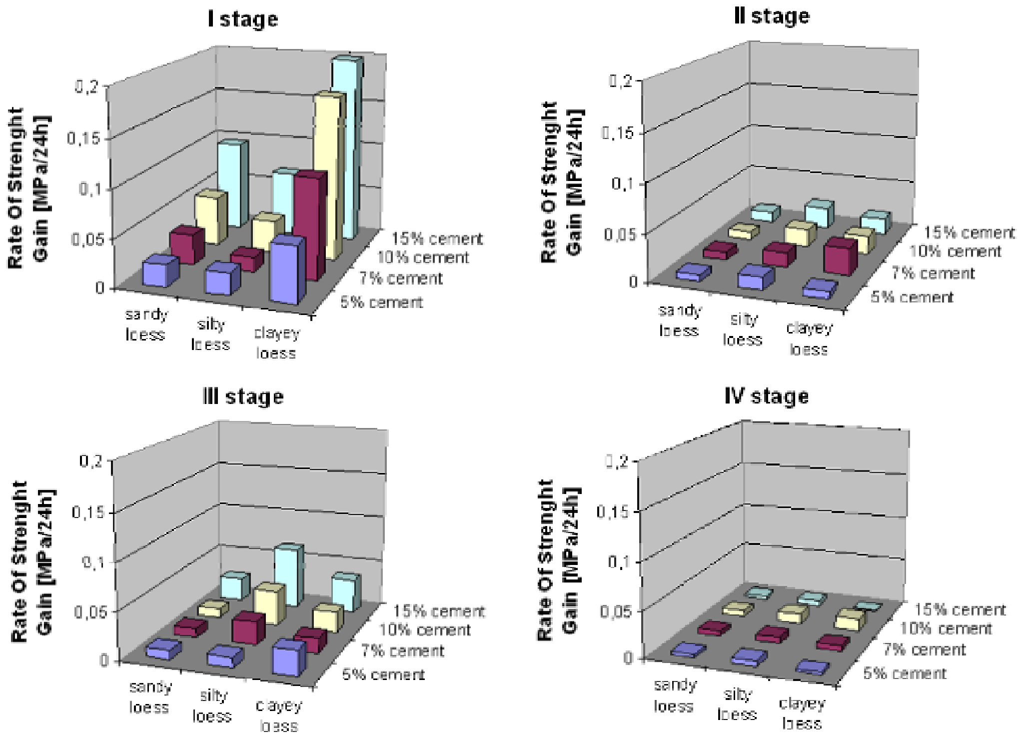

Fig. 1. Rate of loess-cement strength gain during a period of two years: I stage – 1–30 days; II stage – 30–180 days; III stage – 180–270 days; IV stage – 270–720 days

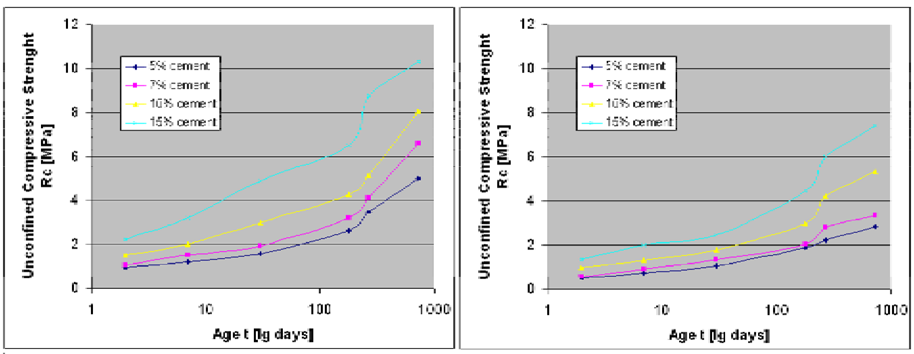

Fig. 2. Relationship between time and unconfined compressive strength R_C for sandy loess-cement mixtures: a) initial dry density $c_d = 1.65$ g/cm^3; b) initial dry density $c_d = 1.55$ g/cm^3

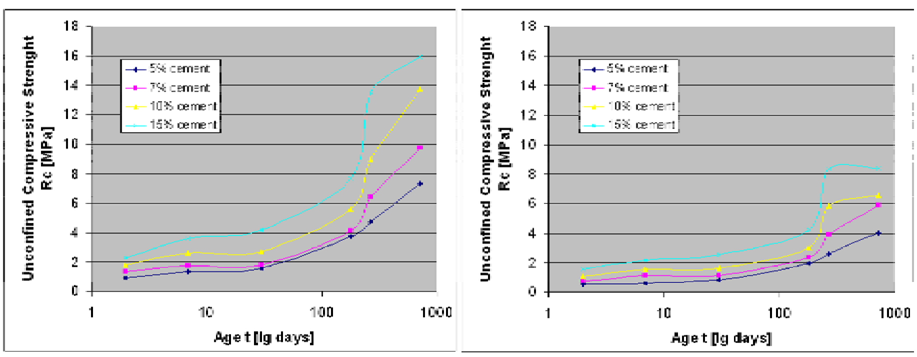

Fig. 3. Relationship between time and unconfined compressive strength R_C for silty loess-cement mixtures: a) initial dry density $c_d = 1.70$ g/cm^3; b) initial dry density $c_d = 1.55$ g/cm^3

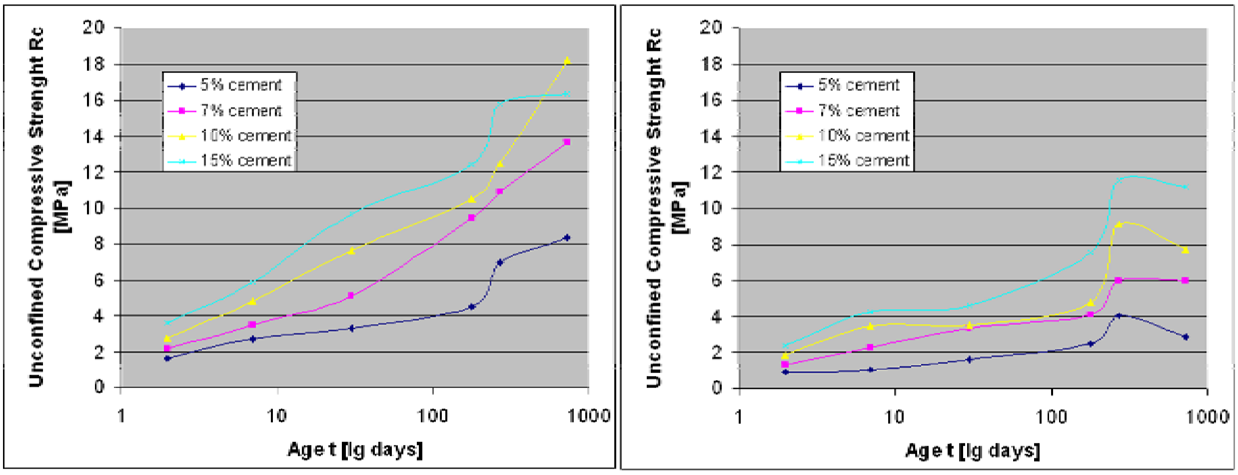

Fig. 4. Relationship between time and unconfined compressive strength R_C for clayey loess-cement mixtures: a) initial dry density c_d = 1.73 g/cm^3; b) initial dry density c_d = 1.60 g/cm^3

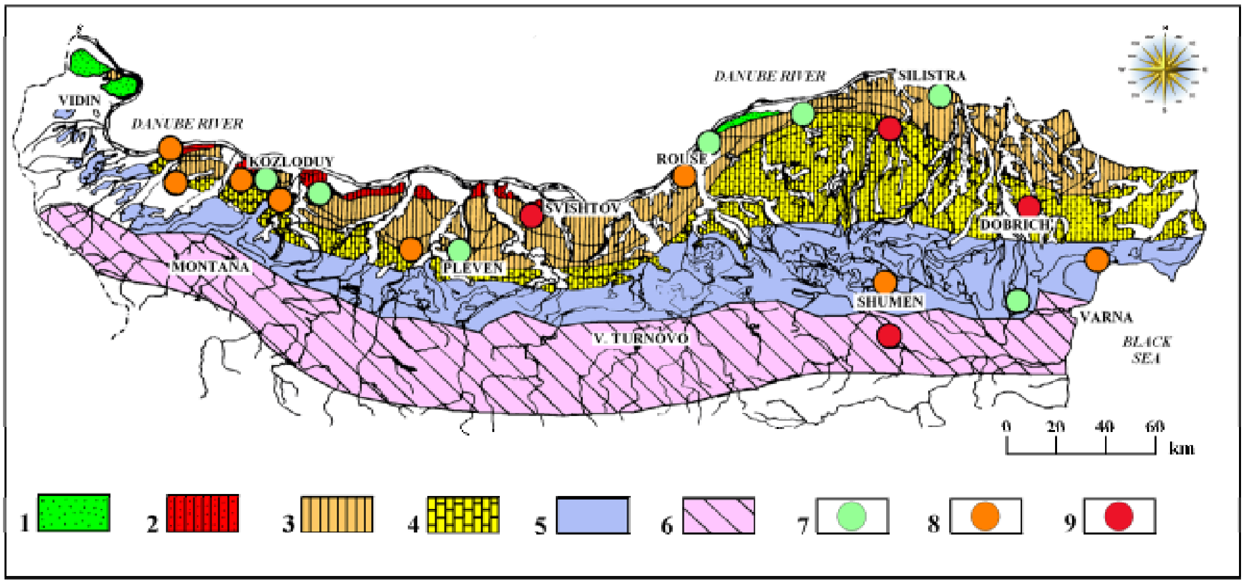

Fig. 5. Main applications of the loess-cement mixing in Bulgaria.
1 – loess-like sand; 2 – sandy loess; 3 – silty loess; 4 – clayey loess; 5 – loess-like clay; 6 – loess-like sediments, originated from weathered marls in Fore-Balkan; 7 – foundation cushions; 8 – impermeable screens and facings; 9 – road bases

teraction and growth of the new binding mass volume. The latter has been proved by the pore-size distribution data in silty loess-cement mixtures. The total porosity decreases insignificantly (1.87% for the mixture with 15% cement) till the 270th day, but the amount of pores > 0.1 μm decreases twice, while the amount if pores < 0.1 μm increases.

In the fourth stage (270–720 days) insignificant strength gain or strength retention are established. Only the mixtures of clayey loess and < 10% cement, compacted to a lower than the maximum dry density, exhibit a strength decrease from 0.5 to 1.5 MPa (Fig. 4). This could be explained with the formation of C-S-H, which are transformed and reduce the quantity of strong bonds in the case of active clay minerals and low cement content. The network-like and gel-like C-S-H are the main binding elements during the fourth stage, but the needle-like C-S-H are encountered too. The values of pH decrease to 9.4–9.7.

The influence of the initial dry density on the unconfined compressive strength is much stronger in later periods of hardening, especially after 2 years (Fig. 2, 3 and 4). The effect of cement quantity (5–15%) is manifested more considerably till 270th day. This is mainly due to the intensive cement hydration in the early stages. In a year alite is almost completely hydrated and belite — to the extent of about 70%.

For practical application it is important that investigated loess varieties, stabilized with 5–15% cement and compacted to maximum dry density, increase their strength after two years 1.5–5.0 times (Fig. 2, 3 and 4) in comparison with the standard test period (after 1 month).

Present and future fields of application of loess-cement mixtures in Bulgarian building activities

Soil-cement cushion has been widely used in foundation works on collapsible loess in Bulgaria (Минков и Евстатиев, 1975; Евстатиев и Ангелова, Ред., 1993; Ангелова, 2004). More than 100 buildings and installations have been constructed on loess-cement cushion including Kozloduy Nuclear Power Plant, high TV broadcast towers and water towers, residential and administrative structures (Fig. 5).

The total volume of these cushions exceeds 500 000 m^3. The prevailing application of this method is in Type I loess bases (mainly with loaded collapsibility; $\Sigma l_{cr} \leq 5$ cm), but in combination with other improvement methods (heavy tamping, for example) it has also been used in Type II (mainly with unloaded collapsibility; $\Sigma l_{cr} > 5$ cm). The soil-cement cushion is built using loess from the construction site itself, mixed with 3–7% Portland cement and compacted in layers of 0.15–0.20 m at W_O until the attainment of c_{dmax}. The thickness of the cushion is usually 1–1.5 m and only in rare cases exceeds 3 m.

In Bulgaria loess-cement impervious screens are used in construction of irrigation facilities as well as landfill isolation (Fig. 5). A total of 15 balancing reservoirs have been built with an area of about 150 000 m^2 whose bottoms are covered by 0.10–0.15 m thick ordinary (compacted at W_O) or plastic (at $W \approx W_L$) loess-cement mixture, overlaid by 0.15–0.20 m protective compacted soil layer. Soil stabilization by hydraulic binders (cement, lime fly ash) has found limited application in road base construction in Bulgaria. There are only a few cases of road base built by loess mixed with 6–12% Portland cement, which are located in the central and in the eastern part of Danubian plain (Fig. 5). Soil-cement piles, prepared by plastic loess-cement mixtures (silty loess with 10% Portland cement and additive of surface active agents) have been tested in the region of the town of Rouse. Deep cement mixing pile is another variant very suited for treating loess soils, especially the saturated ones. Deep mixing method is widely used for soft soil improvement and recently it is reported for good results obtained in stabilization of saturated loess (Zan Yuewen, 1996). The method has been applied successfully for improvement of the soil foundation of twelve and fifteen story buildings in China. Experiments of the jet-grouting improvement began in Bulgaria in 1985 and produced very good results (Евстатиев and Ангелова, Ред., 1993). Loess is quite suitable for stabilization according to this technology, because it is easily washed by the stream of cement-mortar and the resulting plastic loess-cement has great strength.

Conclusions

The loess-cement mixture is an artificial material with properties designed in advance (strength, density, water resistance, etc.). The results obtained in this study manifest a significant increase of the unconfined compressive strength of this material in time (1.5–5.0 times) in comparison with the standard test period (after 1 month). This is a positive factor for its more wide and multifarious application. The soil-cement is produced as a result of using of two main technological variants of soil mixing with binding substances — on the surface and in depth. The methods included in the group of surface mixing (cushions, impervious screens and protective facings) are developed and widely applied in Bulgaria. The next group for deep stabilization (deep mixing method, jet-grouting and soil-cement piles) is more universal, modern and possesses great potentials for soil base improvement. Unfortunately some of these methods are only occasionally used in Bulgaria because of the shortage of appropriate equipment. Deep stabilization is of great promise in treatment of high collapsible Type II loess bases, saturated loess, loess regions with high seismic intensity and environmental applications.

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Резюме. Р. Ангелова – Дълговременната якост на циментольосовите смеси — благоприятен фактор за прилагането им при подобряване на льоса. Неблагоприятните за строителството свойства, с които се отличават льосовите почви – склонност към пропадане, значителна водопропускливост и интензивно размекване при взаимодействие с вода – са важна предпоставка за прилагане на различни методи за тяхното подобряване. Една основна група методи е смесването на льос със свързващи вещества, в резултат на което се получава изкуствен материал с предварително проектирани свойства. Този материал е подходящ за изграждане на пътища, облицовки на земно-насипни язовирни стени, противофилтрационни екрани и бариери, подфундаментни възглавници, стени и пилоти.

Изследването е извършено с песъчлив, типичен и глинест льос от Северна България, които се отличават по своя състав и най-често са обект на заздравяване с цимент. Изучени са основните закономерности във формиране якостта на циментольосовите смеси. Доказан е стадийният характер при нарастване на якостта във времето. Установено е неколкократно увеличение на якостта на едноосен натиск на този материал във времето (1,5–5,0 пъти) в сравнение със стандартния срок на изпитване (1 месец), което е добра предпоставка за неговото широко и разнообразно приложение. В България често са използвани технологичните варианти за смесване на повърхността – изграждане на подфундаментни възглавници, противофилтрационни екрани и покрития. Методите за смесване в дълбочина (дълбочинно смесване, хидроструйно заздравяване, циментo-почвени пилоти) почти не са прилагани засега у нас поради липса на подходяща техника и оборудване. Те, обаче са твърде универсални и са особено перспективни при бъдещо строителство в силно пропадъчни или водонаситени льосови почви, в райони с повишена сеизмичност и при решаване на еколожки проблеми.