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QUALITATIVE RELATIONSHIPS OF WATER MIGRATION IN HIGHWAY EMBANKMENT CLAY SOILS BY THE RESULTS OF LABORATORY AND FIELD RESEARCH

As a result of quantitative data analysis by laboratory and field experiments quantitative patterns of water migration in compacted silty loam embankment, including the stabilized (or final) clay soil moisture values, depending on their type (number plasticity), soil skeleton density, embankment height and time «rest» of the subgrade before it's operation are established. The soil moisture changes graphs at what the loam was compacted from soil skeleton density and stabilized soil moisture of already compacted loam after the subgrade «rest» from soil skeleton density are plotting in the article. The empirical dependence of compacted silty loams stabilized moisture for their multilayer consolidation is obtained. Empirical dependence parameter corresponds to maximum molecular moisture capacity at what it is advisable to do the subgrade clay soils multilayer consolidation for the ensuring their long-term strength.

Keywords: *water migration, compacted loam, soil skeleton density, plasticity number, stabilized moisture, two-factor analysis, empirical dependence.*

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КІЛЬКІСНІ ЗАКОНОМІРНОСТІ МІГРАЦІЇ ВОДИ В ТОВЩІ УЩІЛЬНЕНИХ ГЛИНИСТИХ ҐРУНТІВ ДОРОЖНІХ НАСИПІВ ЗА РЕЗУЛЬТАТАМИ ЛАБОРАТОРНИХ І ПОЛЬОВИХ ДОСЛІДЖЕНЬ

За результатами кількісного аналізу даних лабораторного та польового дослідів установлено кількісні закономірності міграції води в товщі ущільнених пилуватих суглинків дорожнього насипу, зокрема величин стабілізованої (чи кінцевої) вологості глинистого ґрунту залежно від їх виду (числа пластичності), щільності скелета ґрунту, висоти насипу та часу «відпочинку» земляного полотна до початку експлуатації. Побудовано графіки залежності вологості ґрунту, при якій суглинок ущільнювали, від щільності скелета ґрунту та стабілізованої вологості ґрунту вже ущільнених суглинків після «відпочинку» земляного полотна від щільності скелета ґрунту. Отримано емпіричну залежність стабілізованої вологості пилуватих суглинків для їх пошарового ущільнення, параметр котрої відповідає вологості максимального вмісту зв'язаної води, за якої доцільно виконувати пошарове ущільнення глинистих ґрунтів для забезпечення їх тривалої міцності.

Ключові слова: *міграція води, ущільнений суглинок, щільність скелета ґрунту, число пластичності, стабілізована вологість, двофакторний аналіз, емпірична залежність.*

Introduction. For the reliable subgrade operation it's necessary not only to achieve maximum multilayer consolidation values of its soil skeleton density ρ_d and soil strength, but also to save them during normative time. On the embankment soils condition over time significantly affects moisture, at what the compaction was done. That's why for subgrade erection it's important long-term strength ensuring, i. e., when during normative operational time the values of soil mechanical characteristics, obtained after compaction, have been saved and excess soil's deformation isn't appear [1 – 3].

Review of recent sources of research and publications. It was established earlier by authors [4, 5] that on moisture condition and, in accordance, on long-term strength parameters of highway embankment clay soils significantly affects few factors, what it's neccesary to consider at its erection:

– clay soil type, i.e. its indicative data: liquid limit W_L; plastic limit W_p; soil plasticity number I_p;

– soil skeleton densityρ_d within compacted subgrade;

– soil moisture w, at what the compaction is conducting;

– compacted embankment height;

– the number of days, what compacted clay embankment «rests» after its erection, and before the operation.

Now both in Ukraine and in the world at the highway embankments erection it is normalized soil skeleton density, determined for each type of soil in the laboratory by Proctor test or its modification. However, the problem is that domestic regulations prescribe optimal parameters of compacted clay soil (maximum soil skeleton densityρ_d and optimum moisture content W_{opt}), based on the obtained values of laboratory conditions for a particular soil type and dynamic load characteristics without actual mechanisms characteristics [6 – 9].

When soil compacts due to high moisture, with a degree of saturation close to S_r = 1,0, then, of course, that the soil dries and held its sedimentation and therefore additional deformations, when soil compacts due to low moisture, it will be difficult to do the compaction, by the way, it's a little probability of desired soil skeleton density achieving, even with the modern mechanisms possibilities. Also national standards recommend for optimum clay soils moisture content, at the compaction by roller, to take plastic limit W_p, but this parameter is not related on how much unfree water the soil is actually containing.

The assertion that the current mechanisms by rolling can achieve maximum soil skeleton density at moisture, lower than plastic limit, confirms Romanian and British experts research [9 – 11].

Parts of the common problems that earlier unsolved. That's why optimal compaction criteria of highway embankment soils require improvement, wherefore authors [4] developed and realized physical laboratory experiment for water migration in compacted heavy and light silty loam relationships establishment, including the stabilized (or final) clay soil moisture values w_k, depending on their type (number plasticity), soil skeleton density, embankment height and time «rest» of the subgrade before it's operation.

Purpose of the research is to do the statistical analysis of compacted highway embankment clay soil stabilized moisture w_k from subgrade soil skeleton density ρ_d and plasticity number I_p.

Main material and results. The methodology of physical water migration modeling by the highway embankment height through time changes research of clay loams moisture, placed in plastic tubes and compacted at water saturation factor S_r = 0,85 to soil skeleton density ρ_d = 1,50 – 1,65 g/cm^3, changeable factors in what were: soil type – heavy and light silty loam, tube height – from 0,45 to 2,85 m; time «rest» of the subgrade before it's operation, – from 60 – 180 days is in details described in [4, 5].

The average results of determining the compacted clay soil stabilized moisture w_k by whole tube height, except it's upper and lower links for each preset soil skeleton value:

ρ_d = 1,50 g/cm^3;

ρ_d = 1,55 g/cm^3;

ρ_d = 1,60 g/cm^3;

ρ_d = 1,65 g/cm^3, – placed in Tab. 1 and Tab. 2.

In the last column of both tables the variation coefficient values of w_k parameter is presented, by what the soil can be accepted as homogeneous.

Table 1 – Average of final moisture w_k of compacted heavy loam (research soil № 1) by whole tube height

Preset soil skeleton density ρ_d, g/cm^3	Corresponding void volume ratio e	Preset soil moisture w (at S_r = 0,85)	Final soil moisture w_k	Variation coefficient w_k, υ
1,50	0,786	0,250	0,203	0,071
1,55	0,729	0,231	0,190	0,068
1,60	0,675	0,214	0,176	0,063
1,65	0,624	0,198	0,167	0,065

Table 2 – Average of final moisture w_k of compacted light loam (research soil № 2) by whole tube height

Preset soil skeleton density ρ_d, g/cm^3	Corresponding void volume ratio e	Preset soil moisture w (at S_r = 0,85)	Final soil moisture w_k	Variation coefficient w_k, υ
1,50	0,786	0,250	0,162	0,072
1,55	0,729	0,231	0,143	0,070
1,60	0,675	0,214	0,130	0,072
1,65	0,624	0,198	0,114	0,068

By datum Tab. 1 and Tab. 2 the dependings graphs (Fig. 1 and Fig. 2) are drew:

– graph with domed markers curve – soil moisture w, at what both research soils were compacted from soil skeleton density ρ_d in highway embankment (plastic tube);

– graph with squarely markers curve – stabilized soil moisture w_k of already compacted loams after subgrade «rest» time from ρ_d within tube height.

Comparing by datum Tab. 1 and Tab. 2 the final average soil moisture values w_k of compacted loams after two months «rest» with initial moisture values w of this soil we can state, that:

– final average soil moisture value w_k of compacted loams compared with initial moisture w, at what the clay soil was compacted, decreased for all soil skeleton density value ρ_d almost for all tube height except it's upper link, for what soil moisture approached to the value w_{sat},what corresponds to degree of saturation $S_r \approx 1,0$ by raising capillary moisture; soil moisture in lower tube link decreased to w = 0,10 – 0,12 and light silty loam moisture to w = 0,08 due to evaporation of free water;

– final moisture value w_k of compacted subgrade loams within experimental range ρ_d = 1,50 – 1,65 g/cm^3 decreases by dependence, close to logarithmic with soil skeleton value increasing, what explains by the fact that with ρ_d increasing due to the fact of ρ_d increasing film thickness of unfree water something decreases and besides, the coefficient of permeability also decreases, what reduces to moisture speed redistribution;

– stabilized soil moisture w_k in all cases come to be less than soil plasticity number W_p and approach to its, so-called, maximum molecular moisture capacity w_{mm});

– moisture decreasing of initial w, at what the soil was compacted, within highway embankment in practice causes to it's additional settlement.

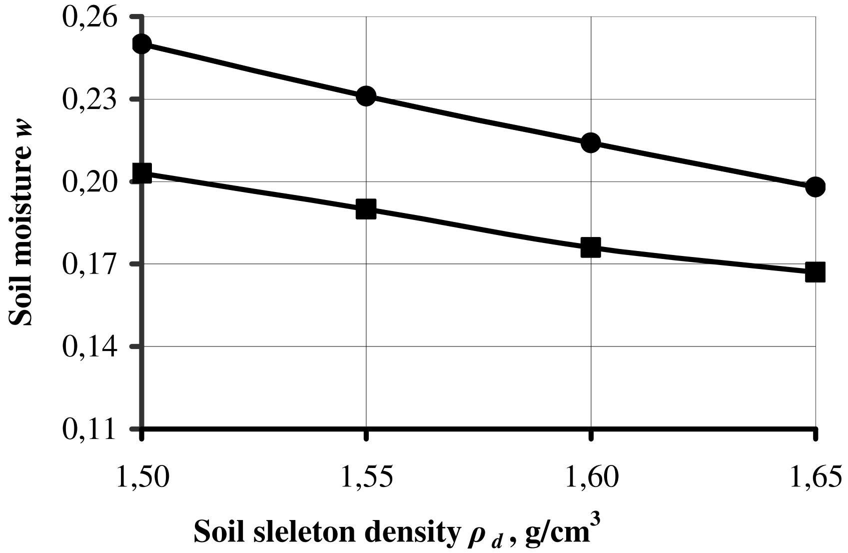

Figure 1 – Plots relation of soil moisture *w* at what the heavy loam was compacted from soil skeleton density ρ_d (curve with domed markers), and final average soil moisture w_k of already compacted heavy loam from ρ_d within tube height (curve with squarely markers)

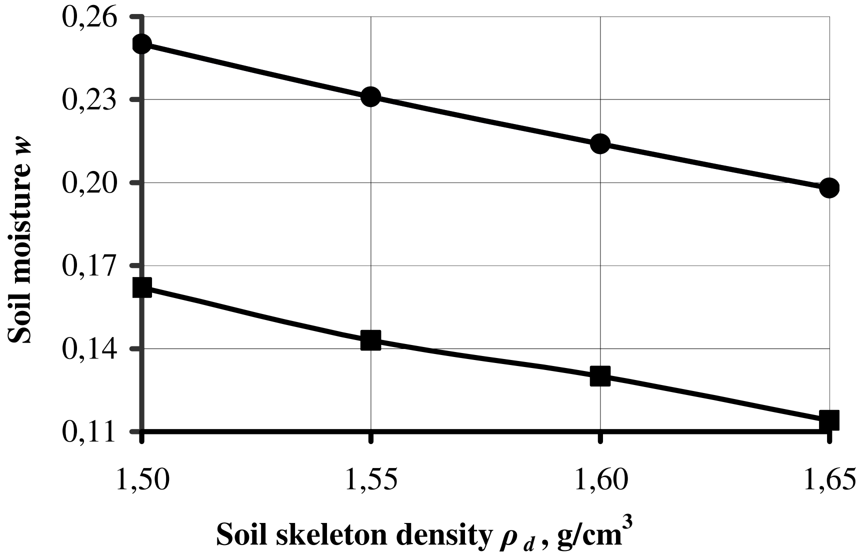

Figure 2 – Plots relation of soil moisture *w* at what the light loam was compacted from soil skeleton density ρ_d (curve with domed markers), and final average soil moisture w_k of already compacted light loam from ρ_d within tube height (curve with squarely markers)

As a result of statistical processing by least squares method of research data Tab. 1 (and Fig. 1) it is found that the decreasing of stabilized moisture value w_k of compacted heavy silty loam (research soil № 1) depending on the soil skeleton density growth within the experimental range $\rho_d = 1{,}50 - 1{,}65$ g/cm^3 it is most correctly to describe by logarithmic function of the form

$$w_k = a + b\ln\left(\frac{\rho_d}{\rho_{d0}}\right) , \qquad (1)$$

where is $\rho_{d0} = 1$ g/cm^3;

empirical coefficient is: a = 0,358; b = - 0,384.

At this multiple correlation coefficient r and variation coefficient v values in accordance is: r = 0,997; v = 0,008, what indicates about close relationship between the experimental data and about the correctness of their approximation by the logarithmic function.

A similar logarithmic dependence is obtained also for stabilized moisture value w_k of compacted light silty loam (research soil № 2).

Empirical coefficient of equation (1) is: a = 0,362; b = - 0,494.

At this multiple correlation coefficient r and variation coefficient v values in accordance is: r = 0,998; v = 0,0115, what indicates about close relationship between the experimental data and about the correctness of their approximation by the logarithmic function.

The results of physical laboratory experiment related to quantitative patterns of water migration in compacted silty loams embankment (clay soils type – its plastic index I_p, soil skeleton density ρ_d, g/cm^3, stabilized moisture of compacted clay soil w_k) are presented in Tab. 3.

From it, in particular, clearly shows that an increase of its plasticity number I_p at the same soil skeleton density values ρ_d, stabilized moisture of compacted clay soil w_k increases.

Earlier [5] it was established, that: highway embankment height with layer by layer compacted clay soil did not significantly affect on its moisture conditions; the «rest» time of subgrade after 2 months did not significantly affect on the stabilized clay soil moisture value. Therefore, it is advisable to perform two-factor statistical analysis of compacted clay soil stabilized moisture depending on its soil skeleton density and plasticity index.

Table 3 – Stabilized moisture values of compacted heavy and light silty loams within tube height for each preset soil skeleton density of subgrade

Preset soil skeleton density, ρ_d, g/cm^3	Soil plasticity number, I_p	
	0,162	0,080
1,50	0,203 -0,95%	0,162 2,36%
1,55	0,190 -0,51%	0,143 -0,86%
1,60	0,176 -0,58%	0,130 -0,21%
1,65	0,167 2,35%	0,114 -2,04%

Note: numerator – the experimental values of stabilized clay soil moisture w_k; the denominator – the relative error of this parameter, calculated by the expression (2)

As a result of this statistical processing by least squares method of research data Tab. 3 the empirical dependence of compacted clay soil stabilized moisture w_k from soil skeleton density and its plasticity number is obtained

$$w_k = a_0 + a_1\left(\frac{\rho_d}{\rho_{d0}}\right) + a_2 \cdot I_p \quad (2)$$

empirical coefficient is: a_0 = 0,531; a_1 = -0,279; a_2 = 0,570.

At this multiple correlation coefficient is $r = 0,995$, and Fisher's ratio test $F = 106,326$, what more than its table-valued $F_{табл} = 4,89$ at test significance $p = 5\%$ and the degree of freedom $v_1 = 7$ and $v_2 = 5$.

Statistical values indicates about close relationship between the research data and therefore, about the logarithmic function (2) correctness. Stabilized moisture relative error value, calculated by the expression (2), compared with its experimental values is also presented in Tab. 3. They do not exceed 2,36%.

So, by the statistical processing analysis of laboratory experiment results, the empirical dependence of compacted loams stabilized moisture for their multilayer consolidation depending on soil skeleton density specified rate and plasticity number is obtained. This parameter corresponds to maximum molecular moisture capacity at what it is advisable to do the subgrade clay soils multilayer consolidation for their long-term strength ensuring.

Also two-factor statistical analysis of compacted clay soil embankment stabilized moisture dependence from subgrade soil skeleton density and its plasticity number by the results of five areas field research is done. As a result of this two-factor statistical analysis the empirical dependence, similar to the expression (2), (received by the results of laboratory tests), of compacted clay soil stabilized moisture from soil skeleton density and plasticity number, empirical coefficients of what in this case is : a_0 = 0,490; a_1 = -0,238; a_2 = 0,440 is obtained.

At this multiple correlation coefficient is $r = 0,993$, and Fisher's ratio test $F = 76,73$, what more than its table-valued $F_{табл} = 19,25$ at test significance $p = 5\%$ and the degree of freedom $v_1 = 4$ and $v_2 = 2$ (at the experiments number $n = 5$). Statistical values indicates about close relationship between the research data and therefore, about the logarithmic function (2) correctness.

Conclusions. Consequently, multilayer consolidation of clay soil embankment it is desirable to do by the moisture, that corresponds to maximum molecular moisture capacity, accepted by the expression (2) depending on soil skeleton density specified rate and plasticity number of this soil. The value of this moisture is lower than plastic limit, but present-day compacted machines makes it possible to sufficiently increase the specific compaction energy for the soil compaction at moisture less than plastic limit with a maximum soil skeleton density.

By the full-scale experiment it is approved the general form of obtained by laboratory experiments silty loams stabilized moisture for their multilayer consolidation from subgrade soil skeleton density and its plasticity number dependence.

For new optimal compaction criteria substantiation, which provide their long-term strength new methodology of physical water migration modeling by the highway embankment height through time changes research of clay loam moisture, placed in plastic tubes and compacted at water saturation factor S_r = 0,85 to soil skeleton density ρ_d = 1,50 – 1,65 g/cm^3 is developed and realized. Soil's research results by author's development were compared with values, obtained by officially accepted method.

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