Problems Sealing the Composite in an Artificial Soil Foundations and Embankments and Their Solutions

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Abstract. The article suggests, in the absence of federal standards, a method to determine the compaction parameters, which is based on years of research on compaction of composite soils in embankments. We found the interrelation of compaction parameters and physical characteristics of the composite soil components. The principle of calculating the maximum density of composite soils by their physical characteristics is given in the article. Two patterns of compaction of composite soil in accordance with its macrostructure are presented in the article, and compaction parameters corresponding to these patterns are determined. For the first time, we have obtained interdependences between the maximum density of composite soils and the granulometric composition and physical mechanical characteristics of their components. Composite soil compaction coefficients for artificial bases of buildings and structures are defined in the article. Charts of maximum density of composite soils in artificial bases are given in the article.

1. Introduction

Questions of compaction and compressibility of soils in embankments were developed and solved with reference to the tasks of hydraulic engineering and road construction at the institutes of NIIOSP (Gersevanov Research Institute of Bases and Underground Structures), SoyuzDorNII (All-Union Road Research and Engineering Institute), KhADI (Kharkov Road Institute), VNII (All-Russian Vedeneev Hydraulic Engineering Research Institute), and VNIIVODGEO (All-Union Research And Engineering Institute For Water Supply, Sewage Systems, Hydraulic Engineering Structures And Engineering Hydrogeology) in the 1970s-1980s [1-5]. In their studies, these institutes selected optimal non-suffosion mixtures that provided high-performance strength and deformation characteristics of compacted soils.

In particular, the foundations of the theory of compaction of dispersed soils, methods for studying their compactability, consistency of response of their physical and mechanical properties to compaction, and methods for monitoring the compaction parameters [6] have been developed. The use of composite soils in artificial bases for industrial and civil construction had been studied, mainly, in the Urals region [7, 8, 14, 15].

In the Russian Far East, it is important to build artificial bases mainly from composite soils that are well presented in the region [9, 11] and possess such positive structural properties as increased stress-strain and strength properties. Subnormal soil expansion parameters allow building artificial bases from composite soils in winter as well.
The parameter of compaction of soils in artificial bases set in the design and controlled during works is the Coefficient of compaction ($K_{\text{упл}}$), i.e. the ratio of the dry unit weight reached during works ($\rho_{d\times\text{фак}}$) to the maximum density of the same soil ($\rho_{d\times\text{макс}}$).

$$K_{\text{упл}} = \frac{\rho_{d\times\text{фак}}}{\rho_{d\times\text{макс}}} \quad (1)$$

The maximum density for fine (clay or sandy) soil is established at the standard compaction-measuring device in accordance with GOST (State Standard) 22733-2002 (Soils. Method of Laboratory Determination of Maximum Density). Such a standard for composite and very coarse soils is not available. The maximum density of such soils is determined experimentally on the construction site by leveling the marks established in the subgrade.

The problem of using composite soils in the embankment is the lack of regulatory documents specifying the parameters of their compaction. The quality of compaction is verified by various indirect methods of control, like measuring the subsidence of soil by leveling or determining the dynamic modulus of soil by dynamic densitometers. The most promising methods for determining the density of soil in its undisturbed condition are gamma-ray methods. Gamma densitometers based on the method of scattered gamma radiation should be calibrated before use. The calibration process takes considerable time, so the use of gamma densitometers at construction sites is limited.

However, as a rule, the maximum coefficient of compaction of 0.98 is specified in the design project, while the “compacted” mark is put in place of the coefficient of compaction in the Operational Statement Report. While the actual density of the soil in the embankment can be identified by GOST 28514-90 (Construction Geotechnics. Determination of Density of Soils by Method of Replacement of Volume), the degree of its compaction ($K_{\text{упл}}$) without determining the value of the maximum soil density in the embankment cannot be specified.

Thus, the main task of studying the compaction of composite soils in embankments is to develop a methodology for determining the maximum density and associated compacting parameters.

2. Determination of maximum density of composite soils of different macrostructure

A number of researchers have been recently studying the problem of calculating the stress-strain state, bearing capacity, and deformability of weak water-saturated bases [12, 13, 16-26].

One way to harden weak bases is to construct compacted embankments. As already noted, in the Russian Far East, mainly very coarse soils with different volumes of a fine (silt and clay) aggregates (composite soils) are used in the construction of embankments. This paper considers parameters characterizing the quality of embankment compaction.

Parameters of soil compaction can be divided into two categories.

Technological parameters include the maximum density of banked soil ($\rho_{d\times\text{макс}}$) and the degree of its compaction ($K_{\text{упл}}$). These parameters are the basis of the workflow charts: the thickness of the filled-in layer and the maximum subsidence value of the compacted soil layer are determined, and then the number of passes of the compactor along one track is calculated.

The design parameters include the stress-strain and strength properties of the banked soil, according to which the type and size of the foundations of structures are assigned.

Both groups of parameters should be available in the project and be identified according to the results of engineering and geological surveys. According to the SoyuzDorNII classification [10], composite soils in embankments are divided into three types according to their macrostructure: frameless soils, incomplete framed soils and framed soils.

DalNIIS uses the SoyuzDorNII classification of composite soils by macrostructure as a basis for the research of composite soils building properties. Our studies confirmed the validity of such a classification and proved that the following interrelations of rocky fragments and fine aggregates in the composite soil are boundary on the soils property change.

Frameless structure is formed with a small amount of rocks in clay soil (up to 50 percent). Being separated by considerable distance, the fragments seem to “float” in the clay soil. The maximum density of the composite soil is achieved by compacting the fine soil to the maximum density.
**Incomplete framed structure** is formed with higher concentration of large inclusions in clay soils (from 50 percent to 70 percent). The fragments draw together when compacted making a denser structure of fine soil in gathering spots. Such a macrostructure creates a continuous framework and operates as a single system, in which the clay aggregate reaches its maximum density.

Consequently, the maximum density of frameless composite soil and incomplete framed composite soil is reached, when the clay aggregate is of the maximum density that corresponds to its optimum moisture content.

The maximum density of frameless and incomplete framed composite soils is calculated using the formula (1) with determination of the maximum density of the clay aggregate \( \rho_{d \text{max}} \) in accordance with GOST 22733-2002 (Soils. Method of Laboratory Determination of Maximum Density), the average density of fragments \( \rho_{2d} \) - according to GOST 5180-2015 (Soils. Methods of Laboratory Determination of Physical Characteristics) and the weight content of soil components of fine soil \( P_1 \) and large fragments \( P_2 \) [5]:

\[
\rho_{d \text{max}} = \frac{1}{[(P_1/\rho_{d \text{max}} + P_2/\rho_{2d})]
\]

The formula is simple, but determining the maximum density \( \rho_{d \text{max}} \) and the optimum moisture content of the aggregate \( W_o \) according to GOST 22733-2002 is a very laborious and busy process. Therefore, the search for correlations between \( \rho_{d \text{max}} \) and \( W_o \) with physical properties of fine soil is quite reasonable and justified. Predecessors (N.Ya. Kharhuta, Yu.M. Vasil’ev [6]) established relationships between the optimum moisture content \( W_o \), the upper yield point \( W_L \) and the plasticity index \( I_p \) of clayey soil, as well as between its maximum density \( \rho_{d \text{max}} \), the optimum moisture content \( W_o \), solid particles density \( \rho_s \) and the volume of entrapped air \( V_o \) (A.K. Birul’s formulas):

\[
W_o = 1,5 (0,5 W_L - 0,25 I_p - 1)
\]

\[
\rho_{d \text{max}} = \frac{[\rho_s (1-V_o)]}{[1 + W_o \rho_s]}
\]

Long-continued studies of the interpretation of the maximum density of composite soils based on their physical properties were carried out at DalNIIS.

The studies of 1984-1989 have been systematized and supplemented with the results received from monitoring the roadbed construction of the M60 highway, which was built in 2008-2011 in advance of the Asia-Pacific Economic Summit (APEC), and new experimental data of 2012 through 2017. Based on these comprehensive materials, we have obtained new correlation relationships of composite soil compaction parameters with the physical mechanical properties of their components.

We received correlation dependences between the maximum density \( \rho_{d \text{max}} \) and the optimum moisture content \( W_o \), which is determined by moisture content at the liquid limit \( W_L \), for composite frameless soils and soils with imperfect frame for clay aggregate:

\[
\rho_{d \text{max}} = 0,031 * W_o + 2,309
\]

\[
W_o = 0,537 * W_L + 0,904
\]

The root-mean-square deviation of the moisture content was 0.83 percent (with the GOST 5180-2015 requirement of 2.0 percent), and the root-mean-square deviation of the density was 0.023 g/cm³ (with the GOST 22733-2002 requirements of 0.03 g/cm³).

Formula (5) allows to determine the optimum moisture content of the clay aggregate by its own property, the liquid limit, in contrast to formula (2), where you should use two indicators, the liquid limit \( W_L \) and the plasticity index \( I_p \), which are determined in accordance with GOST 5180-2015.

The maximum density of composite soil \( \rho_{d \text{max}} \) of the frameless macrostructure and with the imperfect frame is determined by formula (1).

The optimum moisture content of the composite soil is determined by the formula:

\[
W_{oc} = W_{o1} * P_1 + W_{2o} * P_2
\]

where \( W_{2o} \) is the humidity of water absorption of large rock segments.

Moisture content of water absorption of large fragments \( W_{2o} \) is determined according to GOST 8269.0-97 (Crushed Gtone and gravel from Dense Rocks and Wastes of Industrial Production for Construction Work. Methods of Physical and Mechanical Testing) and depends on the porosity of the fragments (petrographic composition) and the degree of weathering (strength and abrasion of the debris). These characteristics correlate with the density of the stone \( \rho_{2d} \).
You can use table 1 for preliminary estimation of the maximum density of composite frameless soil and of incomplete framed composite soil. The maximum density of composite soil for intermediate values of $P_2$ and $\rho_{2d}$, should be determined by linear interpolation.

| Density of rocks $\rho_{2d}$ g/sm$^3$ | Content of fragments in the ground $P_2$, % | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 |
|--------------------------------------|--------------------------------------------|----|----|----|----|----|----|----|----|
| Sand loam ($1<P_2\leq7$, $W_{al}=12.68\%$, $\rho_{d1\ max}=1.92$ g/sm$^3$) | 3.00 | 2.07 | 2.08 | 2.11 | 2.15 | 2.24 | 2.34 | 2.45 | 2.57 |
| 2.80 | 2.05 | 2.05 | 2.07 | 2.12 | 2.20 | 2.28 | 2.37 | 2.46 |
| 2.60 | 2.03 | 2.04 | 2.06 | 2.08 | 2.14 | 2.21 | 2.28 | 2.35 |
| 2.40 | 2.00 | 2.01 | 2.02 | 2.04 | 2.09 | 2.13 | 2.18 | 2.23 |
| Mild clay ($7<P_2\leq17$, $W_{al}=18.31\%$, $\rho_{d1\ max}=1.74$ g/sm$^3$) | 3.00 | 1.90 | 1.91 | 1.95 | 1.99 | 2.09 | 2.20 | 2.33 | 2.46 |
| 2.80 | 1.88 | 1.89 | 1.92 | 1.96 | 2.05 | 2.15 | 2.25 | 2.37 |
| 2.60 | 1.86 | 1.87 | 1.90 | 1.93 | 2.01 | 2.08 | 2.17 | 2.26 |
| 2.40 | 1.84 | 1.85 | 1.87 | 1.90 | 1.96 | 2.02 | 2.08 | 2.15 |
| Clay ($P_2>17$, $W_{al}=24.00\%$, $\rho_{d1\ max}=1.57$ g/sm$^3$) | 3.00 | 1.74 | 1.75 | 1.78 | 1.83 | 1.94 | 2.06 | 2.20 | 2.36 |
| 2.80 | 1.72 | 1.73 | 1.76 | 1.81 | 1.90 | 2.01 | 2.13 | 2.27 |
| 2.60 | 1.71 | 1.72 | 1.75 | 1.78 | 1.87 | 1.96 | 2.06 | 2.17 |
| 2.40 | 1.69 | 1.70 | 1.72 | 1.75 | 1.82 | 1.90 | 1.98 | 2.07 |

Table 2 gives the data on the water absorption of fragments of different densities.

| $P_{2d}$ g/sm$^3$ | 2.42 | 2.44 | 2.42 | 2.72 | 2.42 | 2.06 | 1.98 | 2.42 | 2.44 | 2.42 |
|------------------|------|------|------|------|------|------|------|------|------|------|
| $W_{2con}$ %     | 3.54 | 2.50 | 2.80 | 2.24 | 3.19 | 4.33 | 8.62 | 3.54 | 2.5 | 2.8 |

The dependence of the moisture content of the water absorption of fragments on their density, which was obtained experimentally, is approximated closely by the formula:

$$W_{2\ con} = -7.105 * \rho_{2d} + 20.388$$  \hspace{1cm} (7)

The framed structure is characterized by the maximum content of rock fragments in the soil (over 70 percent), when the fragments approach each other during compaction, they become stuck and form tight irreversible couplings at their junctions. At the same time, fine soil being in a closed volume occurs in an undercompacted state.

Its granulometric composition, the bulk density and the mechanical strength of the fragments determine the maximum density of composite soil with framed structure (fragments in the soil account for more than 70 percent). A standard for determining the maximum density of composite soil with framed macrostructure does not exist. Some researchers determine the maximum density under
standard compaction by impact using large-size makeshift device, which is also labor-intensive and busy, like determining the maximum density of fine soil.

Different researchers express the parameters of the granulometric composition by different criteria. For example, N.P. Lushnov [1] applies the criterion of relative linear dimensions of fractions $d_{wp}/d_{ma}$, OA Pakhomov [2], M.P. Pavcic [3], and S.V. Bortkiewicz [4] use the inhomogeneity index of the granulometric composition $C_u = d_{90}/d_{10}$.

If we assume that, when under compaction, the maximum density of the composite soil with the framed macrostructure is achieved under the minimum interstices of the soil, it will be logical to determine the maximum density in terms of the grain composition parameter, which best reflects the voidness of the soil. In this case, we assumed the following suppositions: a definite granulometric composition corresponds to a certain mechanical strength of the fragments in the compacted soil, and a certain voidness of the soil corresponds to a certain granulometric composition in the state of maximum compaction. Thus, the voidness at maximum compaction is the feature that identifies both the grain composition of the soil and the mechanical strength of the fragments. The way to solve the problem of compaction of composite framed soils is to find such a criterion of granulometric composition that best reflects the bulk density of the composite soil.

In order to determine the optimal granulometric composition parameter for compaction, we made experiments to compact the soil containing fragments from 60 percent to 90 percent by weight, with different density and strength of fragments of different petrographic composition. We used a hydraulic press in a cylinder 150 mm in diameter, 145 mm high with a force of 200 kN for the soil compaction. The pressure on the sample was 11.3 MPa. The pressure of the compactor on the soil is at least 10.0 MPa. Consequently, the compaction experiments were carried out at a pressure corresponding to the pressure of the compactor on the soil during the construction compaction. The compaction under compression in the cylinder on the press corresponds to the compression compaction in the standard compaction device. In addition to the above parameters of the granulometric composition of the soil, we chose as criteria an average-weighted diameter $d_{wp,ew}$ the ratio between the mass fractions of the fragments and the aggregate (hereinafter, the granulometry index $G_r = P_2/P_1$), the ratio between the content of the structure-forming fractions in the soil (fractions $d>10$ mm and fractions $5>d>2$ mm, hereinafter the index of the soil structure $G_{ar} = d_{10}/P_2$) and the content of large fragments $P_2$ in the soil. These parameters are determined in accordance with GOST 12536-2014 (Soils. Methods of Laboratory Determination of Granulometric (Grain) and Microaggregate Composition.)

The best statistical parameters (standard deviation 0.013 and maximum error 0.020) were received for the granulometry index $G_r = P_2/P_1$ — a simpler parameter (in terms of the complexity of the determination) in comparison with the indices of the heterogeneity of the granulometric composition $C_u$ and the average-weighted diameter $d_{wp,ew}$.

Thus, we found the criterion of granulometric composition - the granulometry index $G_r = P_2/P_1$, which is the identifier of the volume of voids (voidness) of the composite soil $n$:

$$n = 0.018 * G_r + 0.229$$

The maximum density of composite soil of the framed macrostructure is determined by the formula:

$$\rho_{d_{max}} = \rho_{ds_{x}} \times (1-n)$$

If the composite soil of the framed macrostructure contains the fine soil $P_1$ (compacted, naturally, not to the maximum density value), then the maximum density of the composite soil is determined through the value of the average-weighted density of the whole soil $\rho_{ds_x}$:

$$\rho_{ds_{x}} = P_1 \times \rho_{1s} + P_2 \times \rho_{2d}$$

where $\rho_{1s}$ is the particle density of the fine soil, which is determined by GOST 5180-2015.
Table 3 can be used for a preliminary estimate of the maximum density of the composite soil of the framed macrostructure. For intermediate values of $P_2$ and $\rho_{2d}$, the maximum density should be determined by linear interpolation.

| $\rho_{2d}$, g/sm$^3$ | Content of fragments in the ground $P_2$, % |
|------------------------|-----------------------------------------|
| 71($n=0.273$) | 80($n=0.301$) | 90($n=0.391$) | 95($n=0.571$) |
| **Sand loam** ($1<J_\rho$ $\leq7$, $W_{at} = 12.68\%$, $\rho_{d1 \ max} = 1.92$ g/sm$^3$, $\rho_{1s} = 2.70$ g/sm$^3$) | | | |
| 3.00 | 2.121 | 2.055 | 1.809 | 1.280 |
| 2.80 | 2.019 | 1.943 | 1.699 | 1.199 |
| 2.60 | 1.917 | 1.831 | 1.589 | 1.117 |
| 2.40 | 1.815 | 1.719 | 1.479 | 1.036 |
| **Mild clay** ($7<J_\rho$ $\leq17$, $W_{at} = 18.31\%$, $\rho_{d1 \ max} = 1.74$ g/sm$^3$, $\rho_{1s} = 2.71$ g/sm$^3$) | | | |
| 3.00 | 2.124 | 2.056 | 1.809 | 1.280 |
| 2.80 | 2.022 | 1.945 | 1.699 | 1.199 |
| 2.60 | 1.919 | 1.833 | 1.590 | 1.118 |
| 2.40 | 1.817 | 1.721 | 1.480 | 1.036 |
| **Clay** ($J_\rho >17$, $W_{at} = 24.00\%$, $\rho_{d1 \ max} = 1.57$ g/sm$^3$, $\rho_{1s} = 2.72$ g/sm$^3$) | | | |
| 3.00 | 2.126 | 2.058 | 1.810 | 1.281 |
| 2.80 | 2.024 | 1.946 | 1.700 | 1.199 |
| 2.60 | 1.922 | 1.834 | 1.591 | 1.118 |
| 2.40 | 1.819 | 1.722 | 1.481 | 1.036 |

**Conclusion**

1. Composite soils are divided according to their macrostructures into three varieties: *frameless*, with an incomplete frame and *framed*. Compaction of composite soils in accordance with their macrostructure should be done according to two patterns.

The *first pattern* is for the compaction of composite *frameless* soils and soils with incomplete frame containing no more than 70 percent of large fragments by mass. The clay aggregate is compacted to the maximum value. The determining compacting parameter is the maximum density of the clay aggregate $\rho_{1d \ max}$.

The *second pattern* is for the compaction of composite soils of the framed macrostructure containing more than 70 percent of large fragments by mass, when the fragments approach each other during compaction, become stuck and form tight irreversible couplings at their junctions. At the same time, clay aggregate, as a rule, remains undercompacted. The voids not filled with fine soil persist. The defining parameter of the compaction is the volume of voids or the voidness $n$.

2. The value of the maximum density of composite soil compacting on the first pattern is calculated by the formula (2) with determination of the following physical quantities: maximum density of clay aggregate $\rho_{1d \ max}$ (GOST 22733-2002), average density of large fragments $\rho_{2d}$ (GOST 8269.0-97), and the content of clay aggregate by weight $P_1$ and fragments $P_2$ (GOST 12536-2014).

3. The maximum density of composite soil compacted on the second pattern, is calculated by formulas (9-11) with determination of the following physical characteristics: density of clay aggregate particles $\rho_{1s}$ (GOST 5180-2015), average density of fragments $\rho_{2d}$ (GOST 8269.0-97), and granulometry index $G_r = P_2/P_1$ (GOST 12536-2014).

4. The maximum density of clay aggregate can be determined by its physical characteristics: the optimum moisture content $W_{at}$ and liquid limit $W_l$ by formulas (5 and 6).
6. The optimum moisture content of the composite soil is determined by the moisture content of the water absorption of fragments $W_{2a}$, the optimum moisture content of the clay aggregate $W_{cl}$, and the granulometric composition of the soil according to the formula (7).

7. The maximum density of composite soil depending on its macrostructure (Charts 1 and 3), can be practically used by design companies, when designing artificial bases, and controlling agencies for quality control of soil compaction.

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