THE EFFECT OF GRADING ON THE COMPACTIBILITY OF COARSE-GRAINED SOILS*

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(Received December 1, 1973)

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1. Introduction

Stability, bearing capacity, deformation and durability of earthworks are known to depend on the phase composition of the soil. This phase composition can be improved by compaction.

Because of the importance of compaction, several studies analysed the problem but most of them referred to fine-grained soil — clays and so-called transition soils.

This great number of papers could not help vagueness in several questions such as the relation between grading and compactibility. Statements are mostly qualitative; reliable values refer to individual cases.

In the following, some new numerical data will be presented on the compactibility of sand and gravel. Compactibility of regular and continuous mixes will be examined, together with the analysis of the compactibility of natural and gap-graded bulks, and of published laboratory and field test data.

2. Tested granular materials

Materials used for laboratory tests were processed by mixing different fractions of Danube sand and gravel. First, the sandy gravel was separated into fractions, then only the 20.0 mm to 0.06 mm size grains were used, divided into 11 sub-fractions.

Each fraction included grains with nearly uniform size and surface features, the fractions differed step-wise. Microphotos of the 2.0 mm to 0.125 mm range of the tested material are shown enlarged 40-fold in Fig. 1. Apparently, the larger the grain, the smoother, the more worn its surface; spherical or rounded in form. The tested 20.0 to 2.0 mm range consisted of highly worn, smooth surfaced, spherical grains, and but a minor part was elongated. The range $d > 0.125$ mm consisted of sharp-edged, mostly cubic grains with intact fractured surfaces, but a small part being platy. The photos show fine

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* Abridged text of the Dr. Techn. Thesis of the Author.

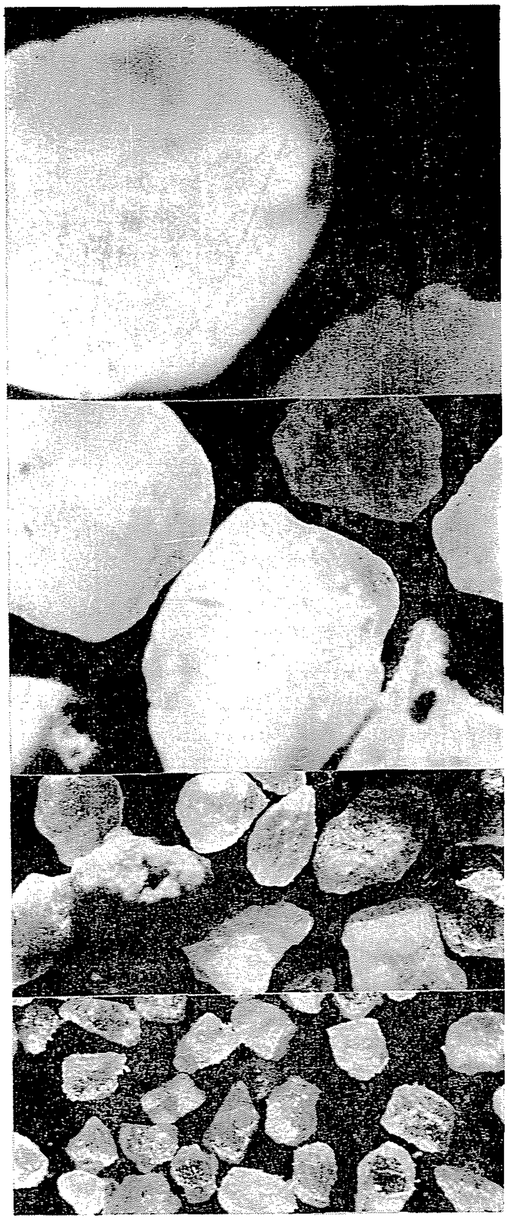

Fig. 1. Microphoto of the 2.0 mm $\geq d \geq$ 0.125 mm fraction of the tested material (enlarged 40 times)

grains — rockflour, silt — adhered to the grains $d > 0.25$ mm in an air-dry state which cannot be removed by dry screening.

The mixes were composed of grains with the described characteristics. It was necessary for the purpose of the tests to obtain grading curves with parameters d_{max}, d_{10}, U varying according to a given rule. According to this arbitrary rule, one parameter of the curve was selected to be constant, and the other two were changed so as to give a smooth continuous curve.

In compliance with the described arbitrary rule, three mix groups had to be produced:

$$\begin{array}{ll} (\mathrm{A}_i): U & = \text{constant} \\ \left.\begin{array}{l} d_{10} \\ d_{\text{max}} \end{array}\right\} & \neq \text{constant} \\ (\mathrm{B}_i): d_{10} & = \text{constant} \\ \left.\begin{array}{l} U \\ d_{\text{max}} \end{array}\right\} & \neq \text{constant} \\ (\mathrm{C}_i): d_{\text{max}} & = \text{constant} \\ \left.\begin{array}{l} U \\ d_{10} \end{array}\right\} & \neq \text{constant} \end{array}$$

Fig. 2 shows the characteristic mix groups A_i, B_i, C_i prepared for the tests. Of course, tests were extended to mixes of assemblies A_i, B_i, C_i produced by shifting the curves parallel to themselves to the right or to the left within the investigated range 20.0 to 0.06 mm.

The mixes can be considered as individual grain assemblies. It was expedient to introduce a new plotting method for specifying the grain assemblies using the parameters d_{max} d_{10}, U of the grading curve.

The grading curve is known to be a random distribution curve and can therefore be deduced — with some exceptions — from the Gaussian curve. Several studies have dealt with this problem. In the Hungarian literature JÁKY (1933) gave the following relationship for the grading curve:

$$S_i = 100\, e^{-\frac{1}{p^2} \ln^2 \frac{d_i}{d_{\text{max}}}}, \qquad (1)$$

with the distribution index:

$$p = 2{,}3 \lg \frac{d_{\text{max}}}{d_{37}}. \qquad (2)$$

The quantities in formulae (1) are shown in Fig. 3. The grading curve formula (1) contains the initial point d_{max} and the slope of a section p. To determine the p value, however, the grading curve has to be plotted in a $\lg d$, $\sqrt{\lg S}$ co-ordinate system and the grain sizes d_{max} and d_{37} are obtained by drawing the best fitting line to the points of the grading curve.

It follows that the distribution index p is only exact if the assembly closely follows the regular probability distribution. In connection with the

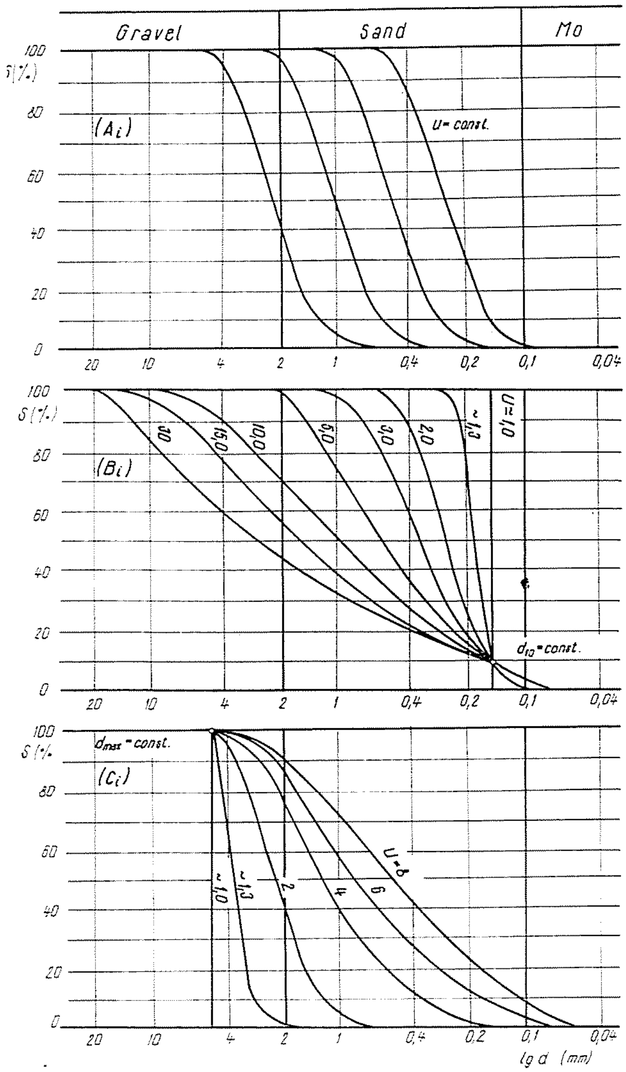

Fig. 2. Three typical groups of tested mixes

described procedure, JÁRAY (1955) showed that real soils seldom followed the rule described by (1) and so p had to be considered as an approximate value.

For comparing grain mixes, in view of the above theoretical and practical points, a simple method has been developed. The grading curve in Fig. 3 can be represented by a single point in the rectangular co-ordinate system $d_{\max}$, U according to the grain diameters assigned to its three points a, b, c. To facilitate the representation of coarse and fine grains alike, it is expedient to use a logarithmic scale. In the new representation method, the "affin" mix groups

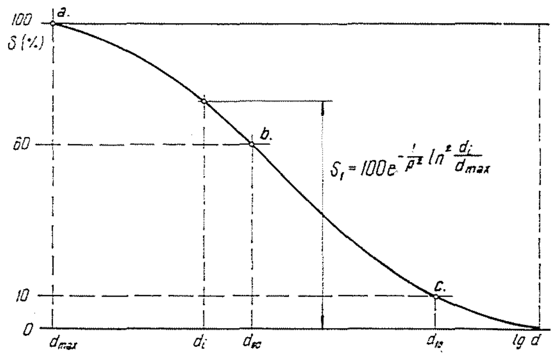

Fig. 3. **Grading curve parameters**

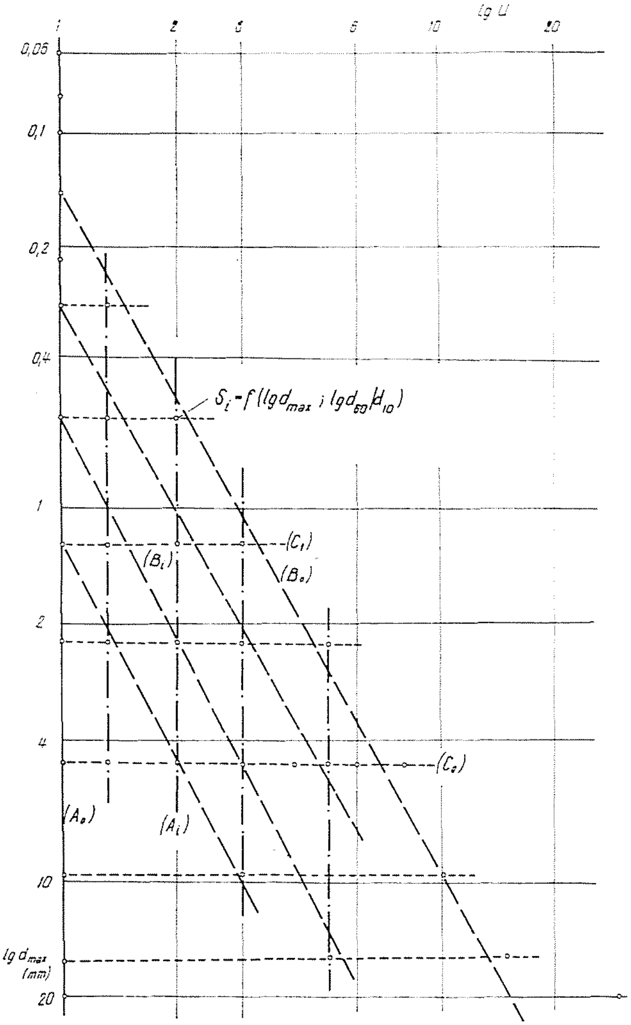

Fig. 4. New representation of grading

$$[A_0, A_1, \ldots A_I \ldots],$$
$$[B_0, B_1 \ldots B_I \ldots],$$
$$[C_0, C_1, \ldots C_I \ldots];$$

are aligned along parallel straight lines. Fig. 4 shows all the tested components and mixes.

The new plotting method is of course arbitrary and approximate, nevertheless its practical value has been proven by compaction test results discussed below.

3. Compaction procedure

The compaction tests were carried out on mixes shown in Fig. 4. It is known that several parameters may be used to characterize density. In this paper the dry bulk density will be used for this purpose:

$$\varrho_d = \varrho_s \cdot s = \varrho_s(1 - \mathrm{n}) \tag{3}$$

where ϱ_s means solid density, s the ratio of solids, and n the volume of voids.

Density is known to range between wide limits, therefore the knowledge of extreme values for ϱ_d and analysis of their causes is decisive in the evaluation of compactibility. The extreme values of the loosest and densest condition have also been investigated. To get the loosest state, the material was poured through a funnel into the Proctor mould, with a possible minimum of mechanic or dynamic disturbance.

The densest state was determined by means of the Proctor test, as a function of the varying water dosage w and compacting work E. Rather than to analyse the different compacting effects, only the effect of ramming was investigated. Neither proportions of spent energy (useful power, lost power) were analysed.

The total power spent to compact the different mixes is:

$$E = m \cdot x \cdot n \frac{h}{\Delta h} \cdot \frac{1}{V} \tag{4}$$

where m the mass of the ram (4560 g);
x average dropping height (0.45 m);
n number of blows per layer;
Δh average layer thickness;
h $5 \cdot \Delta h$ total thickness of compacted layers;
V volume of the mould (diameter 102 mm, height 116 mm).

The number of compacting blows and the compacting work are given in Table 1.

Table 1

Blows per layer n	Specific compacting work E (kNm/m^3)
0	0*
2	216.0
4	432.0
8	865.0
16	1730.0
25	2700.0
32	3460.0

*$E = 0$ indicates loosely poured bulks.

To prevent loosening during the compaction tests and for uniform distribution of blows, a 8 mm thick steel disk was placed on the surface. Using the disk improved uniformity of density and effectiveness of compaction, (see LEUSSINK—KUTZNER, 1962).

4. Regular, continuous mixes

Main results of the tests are discussed and evaluated below.

Fig. 5 shows the new method of representing the minimum dry bulk densities ($\varrho_{do}^{\min}$) pertaining to the loosest condition of mixes in Fig. 4. Fig. 5 shows projection in the log-log co-ordinate system lg $d_{\max}$, lg$U$, ϱ_d of constant parameter lines of the surface $\varrho_{do}^{\min}$. Results proved the previously introduced parameters to be suitable for evaluating the mixes. The results showed them to vary greatly in the range of fine sand and silt. With decreasing grain diameter, the minimum bulk density decreases rapidly beyond a certain limit ($d < 0.2 \div 0.1$ mm). This change is shown in Fig. 6, containing data of the components A_0 — grain size, bulk density and specific surface. In the $d > 0.1$ to 0.2 mm range, the change is due to the shape and surface characteristics of the grains. This is confirmed also by tests of REZNÁK (1957) and LELKES—REZNÁK (1972). In the $d < 0.1 \div 0.2$ mm range, not only the mentioned effect but also absorption is of importance for the change; this is evident from a consideration of the specific surface. The specific surface of assemblies was calculated as:

$$A_r = \frac{6}{\varrho_s} \frac{S_i}{d_i} \tag{5}$$

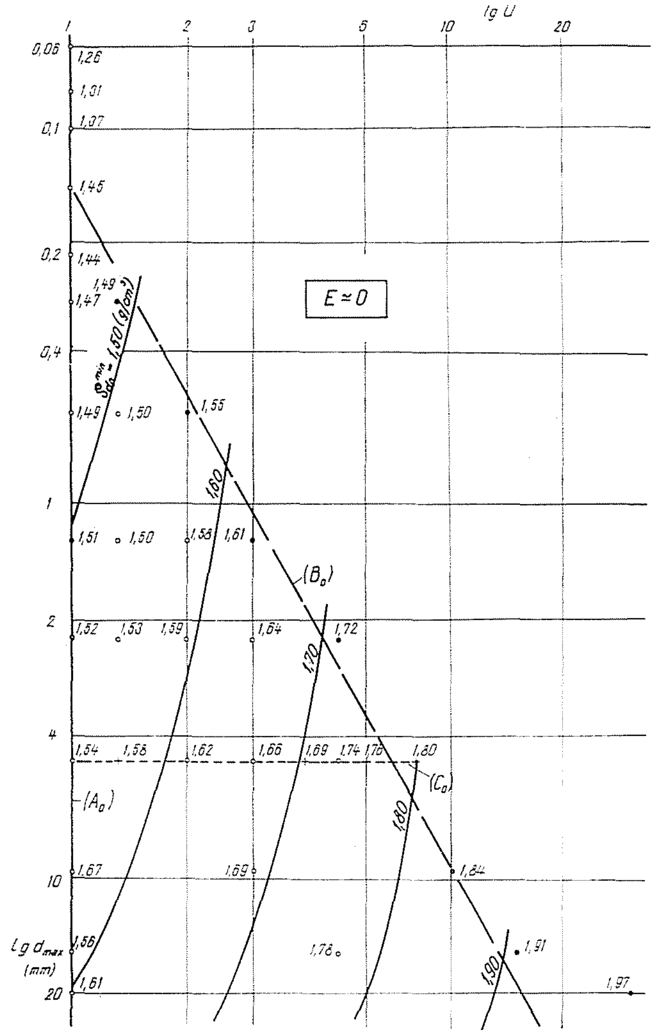

Fig. 5. Poured bulk densities of granular mixes

where d_i stands for the average diameter of each component, and S^i for the proportion by weight of the component. The dash-and-dot line in Fig. 6 shows the result of the computation. Earlier assumptions were justified by the results. This is why grains $d < 0.06$ mm were excluded from the test, and the proportion of grains $d < 0.1$ mm was kept at a minimum.

Fig. 7 shows the shape of Proctor curves resulting from constant compacting work. The test confirmed the published results (see LEUSSINK—KUTZNER, 1962; BARKAN, 1964). The line $\varrho_{di} = f(w)$ had two maxima (at points *a* and *c*) of practically identical values. The decrease ($\Delta\varrho_{diw}$) at point *b* is due to the known phenomenon of surface tension of water. Accord-

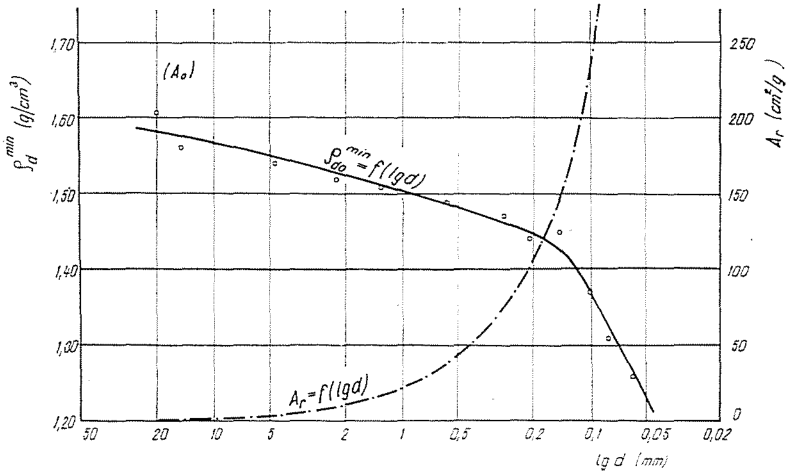

Fig. 6. Specific surface and density of components vs. grain size

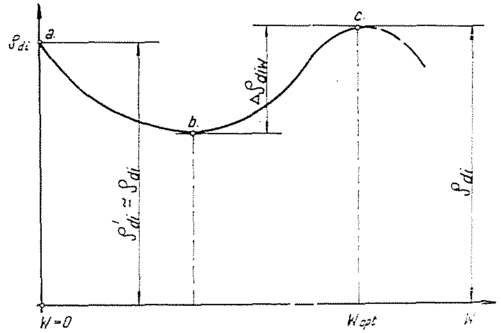

Fig. 7. Shape of the Proctor curve

ing to practice, an important amount of energy is spent to overcome meniscus bonds. Without a detailed analysis of the results it can be mentioned that in the modified Proctor tests with water contents corresponding to point *b* an excess of 8 to 26% of energy was necessary to obtain ϱ_{di} pertaining to point *c*. Therefore it is economical to compact at $w \cong 0$ or w_{opt}. Bulks compacted in condition $w = 0$ tend to loosen upon very slight effects — wind, sunshine, rain etc. Adding a few per cent of silt can stop this phenomenon, provided the mixture is uniform (see Voss, 1961, Mrs. Csicsely, 1972).

Fig. 8 shows the maximum dry densities $E = 2700$ kN m/m³) belonging to the modified Proctor compacting work ($\varrho_{\text{di}}^{\text{max}}$) whereas the optimum water content w_{opt} is shown in Fig. 9. Figs 5 and 8 prove that there is a unique relationship between the grading and the density distribution. The surfaces $\varrho_{\text{do}}^{\text{min}}$, $\varrho_{\text{di}}^{\text{max}}$ and w_{opt} are described approximately by:

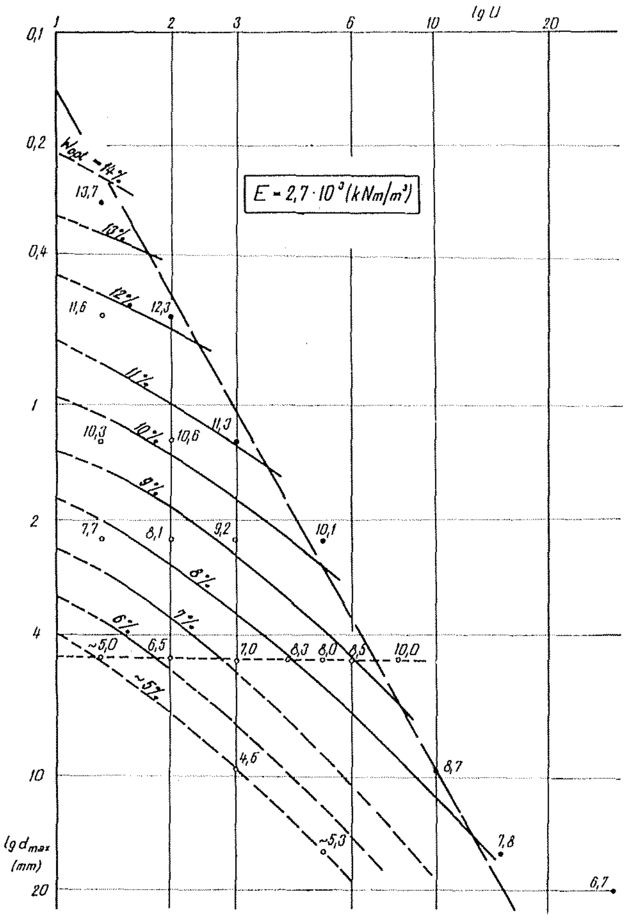

Fig. 9. Optimum water content vs. grading

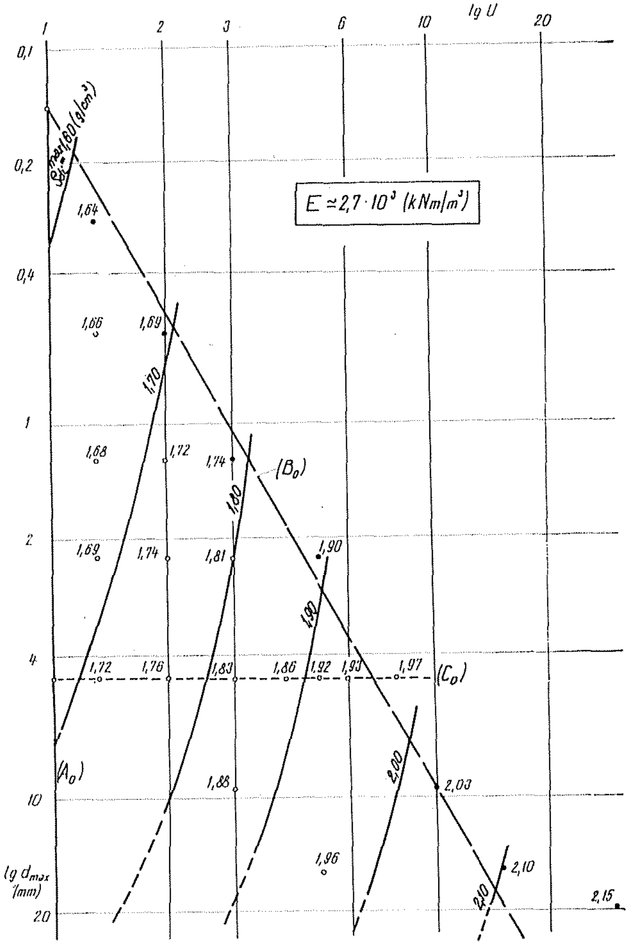

Fig. 8. Bulk densities for $E = 2.7 \cdot 10^3$ kNm/m^3 compacting work vs. grading

$$z_i = a_i x + b_i y + c_i \tag{6}$$

the coefficients in the equation being:

$$x = \lg U;$$

$$y = \lg d_{\max};$$

$$a_i,\ b_i,\ c_i.$$

Coefficients of the tested mixes are given in Table 2. a_i, b_i, and c_i are not dimensionless quantities, therefore in case of dimensions in Table 2, $d_{\max}$ in Eq.(6) is understood in mm. With regard to the results it must be pointed out that $d_{\max}$ could be replaced by parameter d_{10} (see KABAI, 1968).

Table 2

Magnitude	Factors		
	a_i (g/cm^3)	b_i (g/cm^3 mm)	c_i (g/cm^3)
$\varrho_{d\min}$ (g/cm^3)	+0.269	+0.080	+1.51
$\varrho_{d\max}$ (g/cm^3)	+0.286	+0.097	+1.66
Magnitude	a_i (%)	b_i (%/mm)	c_i (%)
W_{opt},(%)	+5.18	−7.32	+9.68

A similar result would be obtained as in Figs 8 and 9 for any arbitrarily selected compacting work. To prove the above statement, a single detail of the tests (bulk B_0) is shown in Fig. 10. It appears that the compaction tendencies of the different bulks are similar. The initial value $\varrho_{do}^{\min}$ is decisively affected by grading, this effect is, however, fading away with increasing E. This is shown in Fig. 11, giving the values

$$\Delta\varrho_{di} = \varrho_{di} - \varrho_{do}^{\min} \tag{7}$$

as a function of E. The quantities in formula (7) are those in Fig. 10. The shaded domain $\Delta\varrho_{di(E)}$ in Fig. 11 shows the effect of grading, the domain beneath the effect of the compacting work. With increasing E the total increment of dry density $\Delta\varrho_{di}$ increases at a diminishing rate. Still less is the influence of grading, namely:

$$\Delta\varrho_{di(U)} \ll \Delta\varrho_{di(E)}\,.$$

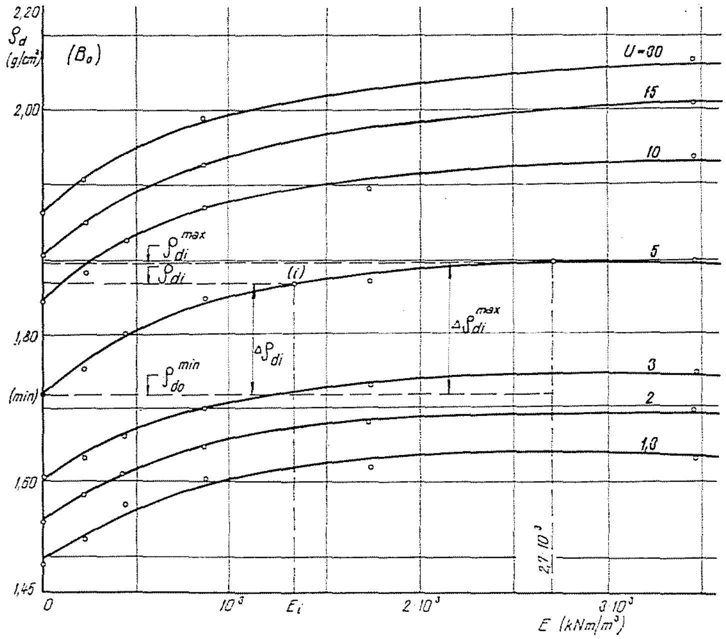

Fig. 10. Density of mix B_0 vs. uniformity coefficient and compacting work

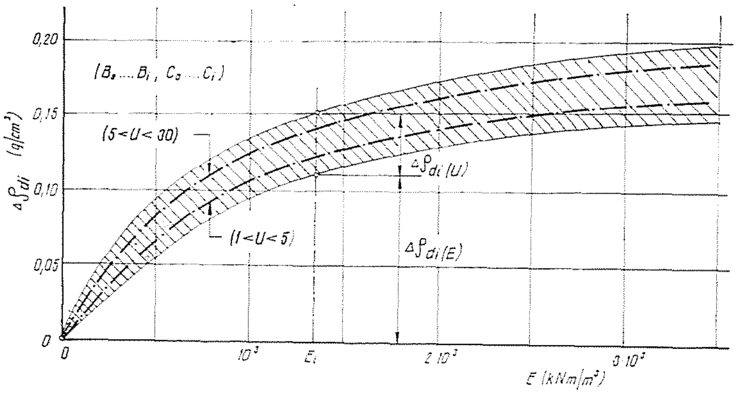

Fig. 11. Density increment vs. grading and compacting work

An interesting result was obtained after introducing the compaction ratio:

$$\eta = \frac{\varrho_{\mathrm{do}}^{\mathrm{min}}}{\varrho_{\mathrm{di}}^{\mathrm{max}}} \tag{9}$$

Symbols in Eq. (9) are shown in Fig. 10, the results in Fig. 12. The compaction ratio $\eta \simeq 0{,}92$ can be stated to be *independent of grading;* it depends on the shape and surface properties of the grains, but its value changes within a narrow range. This will be proven by results discussed later.

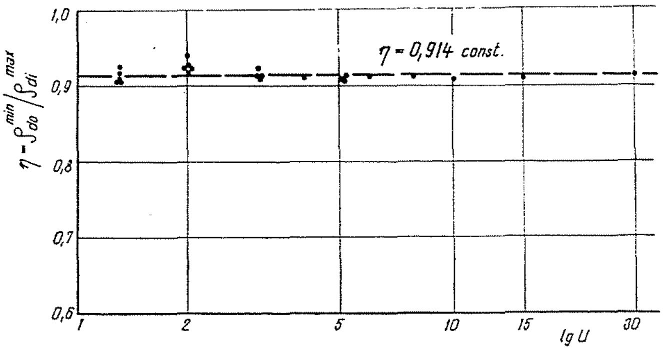

Fig. 12. Relationship between grading and compaction ratio

5. Effect of the shape of the grading curve on compactibility

Granular mixes in section 4 are generally described by formula (1). Compaction results justify the assumption that the relationships obtained may be extended to any mix of arbitrary composition. This is proven on data taken from the literature, thereby the results have a more general validity.

Let us examine first the test results on mixes which can be approximated by the Talbot relationship:

$$S_i = 100 \left(\frac{d_i}{d_{\max}} \right) . \tag{10}$$

Data of the mix groups C_I, C_{II} given in Table 3 are taken from tests by CHAMBERLIN-YODER (1958).

Mixes C_I, C_{II} are similar to mix C_0 plotted in Fig. 4, since $d_{\max} =$ constant. For a comparative evaluation of the mixes, the uniformity coefficient U may be used. Results are shown in Fig. 13. The relationship in Fig. 13 is very similar to the preceding ones. The compaction ratio $\eta \simeq 0,92$ is the same as that from the author's own tests, except for mixes containing also 2 to 8% of silt. Results are shown in Fig. 14. The dashed line section in Fig. 14 illustrates the effect of increasing the silt percentage.

The laboratory tests were intended to describe gap-graded mixes as well. These tests have still to be continued. However, some important statements can be made with respect to the results obtained so far. In general, it can be stated that continuous and gap-graded mixes with indentical $d_{\max}$, $d_{\min}$, U give practically the same bulk densities.

As concerns the evaluation of test results for natural soils, of the multitude of data published in connection with the compaction of natural soils, unfortunately but a minor part could be used because of their incompleteness.

Table 3

Soil symbol	d_{max} (mm)	$_{10}$ (mm)	Exponent n	U
C_I	4.74	1.50	2.0	2.4
		1.05	1.5	3.2
		0.75	1.2	4.2
		0.47	1.0	6.1
		0.22	0.8	11.4
		0.11	0.6	18.6
		0.06	0.5	30.8
C_{II}	19.5	6.5	2.0	2.4
		4.3	1.5	3.3
		2.6	1.2	5.0
		1.95	1.0	6.5
		1.0	0.8	10.8
		0.29	0.6	30.0
		0.14	0.5	50.5
		0.05	0.4	106.0

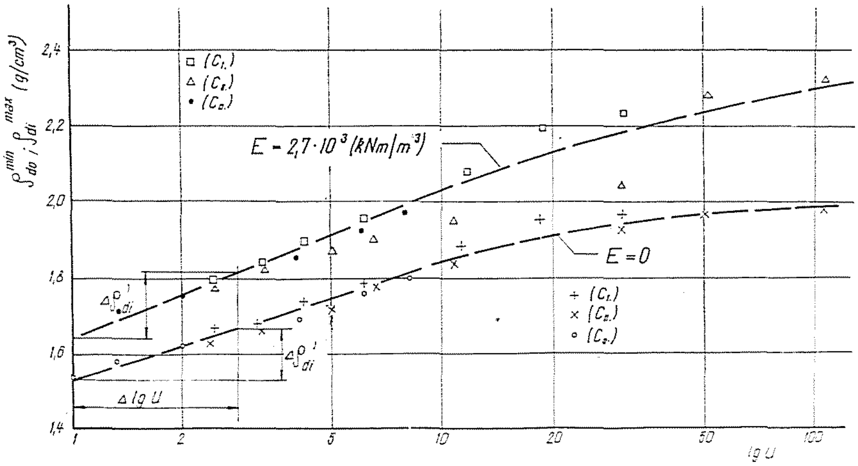

Fig. 13. Density vs. uniformity coefficient for constant compacting works

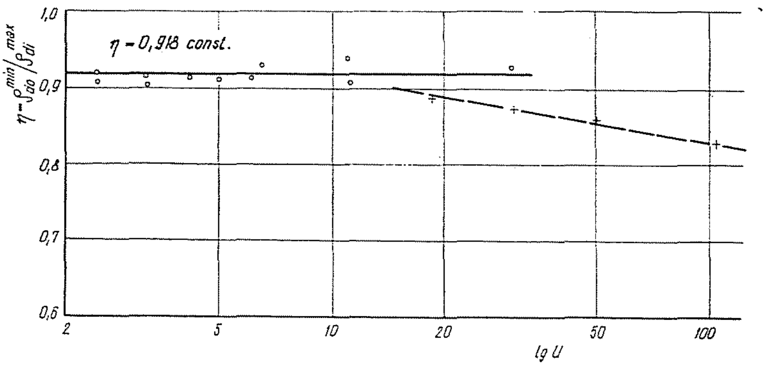

Fig. 14. Relationship between grading and compaction ratio

Grading domains of the tested materials and the frequency distribution of the fractions are shown in Fig. 15. The tested materials have been divided into three groups:

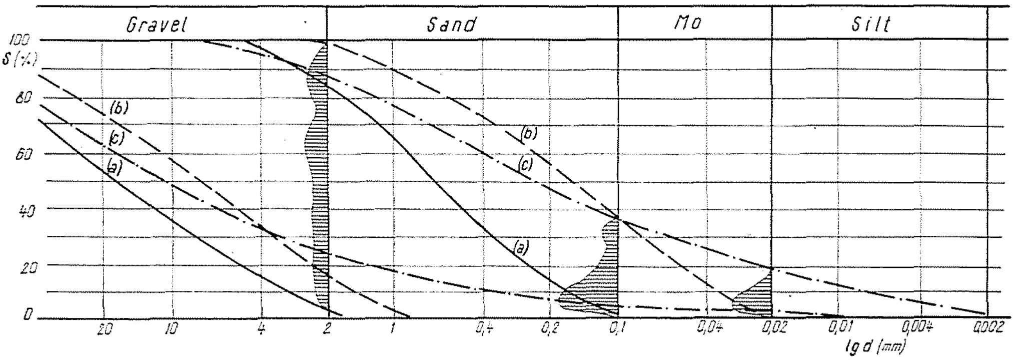

Fig. 15. Grading domains of natural soils and frequency distribution of fractions

group (a—a): $d \geq 0{,}1$ mm

group (b—b): $d \geq 0{,}02$ mm

group (c—c): $d \geq 0{,}002$ mm, and

$2{,}0 \geq d \geq 0{,}02$ mm, resp.

Because of their incompleteness, literature data could not be evaluated in the manner of Figs 5 to 8 and 9. On the other hand, it is surprising that data considered reliable but otherwise quite heterogeneous — from tests carried out by different laboratories under different circumstances — yielded a very good relationship between $\varrho_{\text{di}}^{\text{max}}$ and U values, as shown in Fig. 16. Comparing results in Figs 16 and 13, no further explanation seems to be necessary.

Identical compacting tendencies of coarse-grained soils and the comparative evaluation of the results obtained so far are shown in Fig. 17, plotted with functions in Figs 13 and 16:

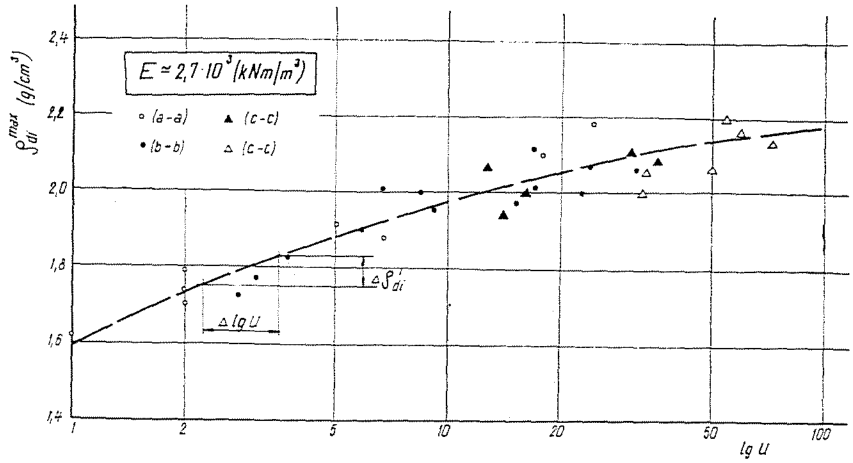

Fig. 16. Density vs. uniformity coefficient for a constant compacting work

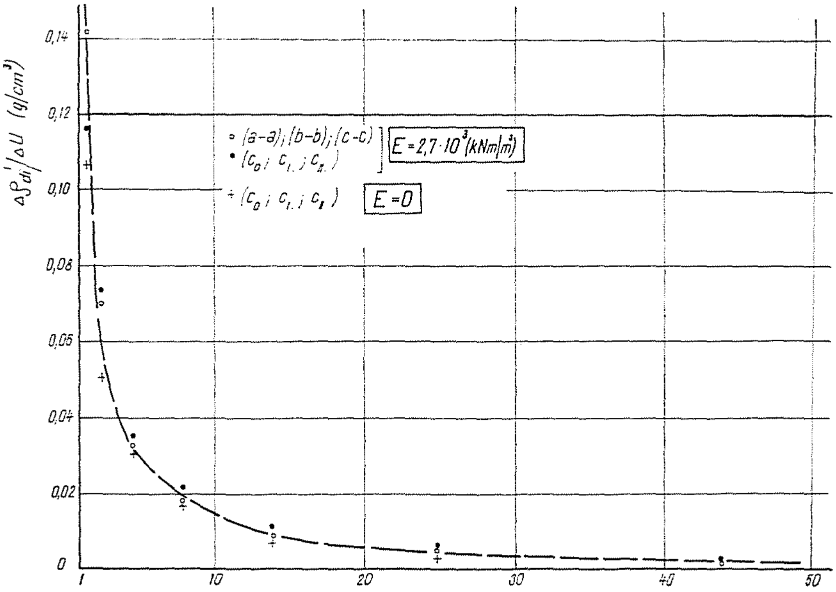

Fig. 17. Derivatives of functions $\varrho_{do}^{\max} = f(U)$ and $\varrho_{do}^{\min} = f(U)$ vs. uniformity coefficient

$$\text{and}\quad \left.\begin{aligned} \varrho_{\mathrm{do}}^{\mathrm{min}} &= f(U) \\ \varrho_{\mathrm{di}}^{\mathrm{max}} &= f(U) \end{aligned}\right\}. \tag{11}$$

Fig. 17 shows the variation of the derivatives of functions (11) versus the uniformity coefficient:

$$\frac{\Delta \varrho_{\mathrm{di}}}{\Delta U_i} = f(U). \tag{12}$$

In Eq. (12), ΔU_i is the difference of two arbitrary uniformity coefficients, and $\Delta \varrho_{\mathrm{di}}$ denotes the difference of their densities produced by compacting powers $E = 0$ and $E = 2{,}7 \cdot 10^3$ kNm/m^3, respectively. Fig. 17 demonstrates again the general compaction tendency, furthermore, it shows that over a value $U > 10$ to 15, compactibility can hardly be improved by increasing graduation and if so, only to a gradually decreasing degree.

For natural soils too, interesting conclusions could be drawn from grading and bulk density plotted in a triangle diagram. The tested materials were divided into three components S_1, S_2, S_3 with diameters ranging as:

Component S_1: $d \geq 2{,}0$ mm

Component S_2: $2{,}0 \geq d \geq 0{,}1$ mm

Component S_3: $d \leq 0{,}1$ mm.

Assuming three components, the grading curve can be represented by a point in the triangle diagram, with the bulk density as assigned parameter. Results are shown in Fig. 18 where four data (S_{1i}, S_{2i}, S_{3i}, $\varrho_{\mathrm{di}}^{\mathrm{max}}$) are assigned to each point P_i.

The results followed a relationship similar to test results by DOMJÁN (1965). Fig. 18 provides a further contribution to the so-called "macromeritic liquid" analogy (see FINDLAY—CAMBELL—SMITH, 1951; WINTERKORN, 1953, GROFCSIK, 1956, KÉZDI, 1964).

Results in Fig. 18 can well be explained theoretically by the liquid analogy and the Gibbs rule. According to the Gibbs rule, the melting point of molecular fusions depends on the proportion — or concentration $K = S_1/S_2$ — of the components. In "macromeritic liquids" the temperature corresponds to porosity n and it also reaches a minimum.

Results in Fig. 18 exhibit a minimum of porosity n_{min}, along axis S_1 or S_2 at a given proportion of the two components. In accordance with the results, the density depends on the concentration and the ratio of the grain diameters d_2/d_1:

$$\varrho_{\mathrm{di}}^{\mathrm{max}} = \varrho_s (1 - n_{\mathrm{min}}) = f(K, d_2/d_1). \tag{13}$$

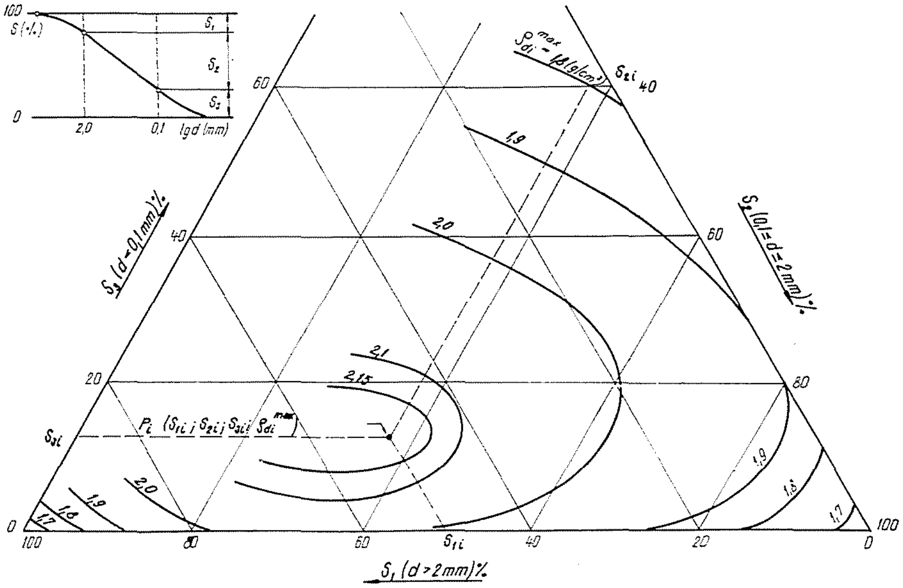

Fig. 18. Density distribution in natural soils due to compacting work, represented in a triangle diagram

From the results it is obvious that on the axes representing the two components

$$\left.\begin{array}{r} d_3/d_2 < d_2/d_1 \\ \text{and}\qquad K' = \dfrac{S_2}{S_3} > K'' = \dfrac{S_1}{S_2} \end{array}\right\} . \tag{14}$$

The inherent densities $\varrho_{d1}^{\max}$; $\varrho_{d2}^{\max}$; $\varrho_{d3}^{\max}$ of the components are lower than the densities ($\varrho_{d1-2}^{\max}$; $\varrho_{d2-3}^{\max}$) developed for mix concentrations K' and K'', hence:

$$\left.\begin{array}{r} \varrho_{d1-2}^{\max} > \varrho_{d1}^{\max} > \varrho_{d2}^{\max} \\ \text{and}\qquad \varrho_{d2-3}^{\max} > \varrho_{d2}^{\max} > \varrho_{d3}^{\max} \end{array}\right\} . \tag{15}$$

This is valid also for point P_i representing the mix of three components. The exact location of the minimum is not known but it is certainly within the triangle because also forces acting on the surfaces of grains $d = 0{,}1$ mm influence the process.

In evaluating the results it has to be reminded that the division into two or three components ($N = 2$ or $N = 3$) is arbitrary hence the concentration is also the function of this arbitrary value:

$$K = f(d_1/d_2, N). \tag{16}$$

a statement perfectly supported by the results of FURNAS (1931) and KÉZDI (1964). Fig. 19 was obtained by using the test results of Furnas — modifying the so-called phase diagram — where functions

$$K = f(d_2/d_1) \tag{17}$$

and

$$\varrho_{\text{do}}^{\text{max}} = f(d_2/d_1; K) \tag{18}$$

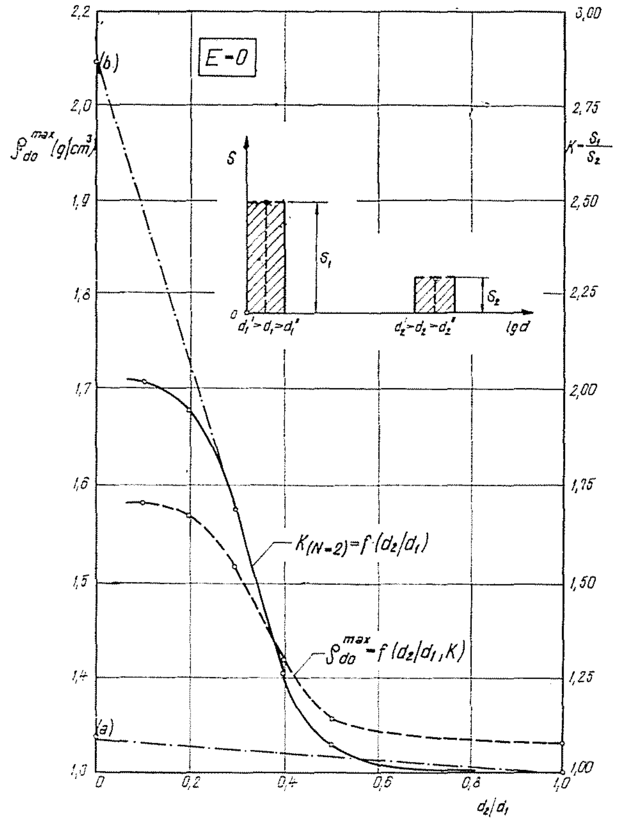

Fig. 19. Relationship between concentration, density and grain size

are plotted by continuous and dashed line, respectively. Relationships from Figs 18 and 19 are in good agreement. $\varrho_{\text{do}}^{\text{max}}$ is the maximum bulk density for a given concentration.

Fig. 19 illustrates two theoretical cases of interest. At point *a* the loosest packing of equal spheres is shown, with voids filled by a "liquid" of identical density, the concentration being:

$$K_a = \frac{\varrho_s(1-n_{\max})}{\varrho_s \cdot n_{\max}} \simeq 1{,}10.$$

Point *b* refers to the densest packing of spheres with voids filled with a "liquid" of identical density, to yield the concentration

$$K_b = \frac{\varrho_s(1-n_{\min})}{\varrho_s \cdot n_{\min}} = 2{,}87\,.$$

According to Furnas, the concentration is the average of the two extreme values for

$$d_2/d_1 \to 0$$

since

$$K \to 2.0\,.$$

The results can also be used to determine the shape of that continuous grading curve which gives the maximum bulk density with a constant compacting work — not to be discussed here. Results in Figs 18 and 19 prove the grading curve to be a power function conform to formula (10). The shape of the function is influenced by the shape and quality of the component grains, hence trial mixes are needed for it to be exactly given.

Finally, in connection with the laboratory tests it must be mentioned that the relationships — tendency of compaction — seem to be valid also in field tests, as suggested by Hungarian tests (Vajda—Lánczos—Párdányi, 1966) though data are still insufficient for a comprehensive evaluation.

Summary

Experiments proved similar relationships to govern porosity changes for both loose and compacted coarse-grained soils. The ratio of densities in the loosest and the compacted state is independent of grading.

Also tests on natural soils proved the "macromeritic liquid" analogy, supporting the power function form of regular and continuous grading curves.

Experiments could probably be extended to transition and cohesive soils, provided the intergranular force effect can be taken into consideration in evaluating the results.

Tests will be extended on gap-graded bulks, likely of help in knowing the relationships of "fusions". Field tests supported the generally valid laws.

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* In Hungarian

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