COMPACTIBILITY OF TRANSITION SOILS

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It is known from the practice that compaction methods are only efficient and economical in coarse-grained and well-graded soils (sand-gravel).

Purely cohesive soils (clays) can efficiently be compacted by sheepsfoot rollers or high-power tampers.

Compaction of soils of transition character, from the fine-grained, poor graded sand to silts, is rather difficult. In Fig. 1 the maximum value of compactness reached in each soil type and the actual compacting equipment is presented.

The compactness range has two maxima, viz. at the boundaries between coarse sand and gravel, and between silt and clay. The compactness minima belonged to transition soils, a phenomenon known since long in the literature. Explanation attempts were not based on comprehensive research.

The reasons referred to were:

- The possible compactness rather sensitively depends on water content. In most cases the natural conditions are not those for an optimum compactibility.

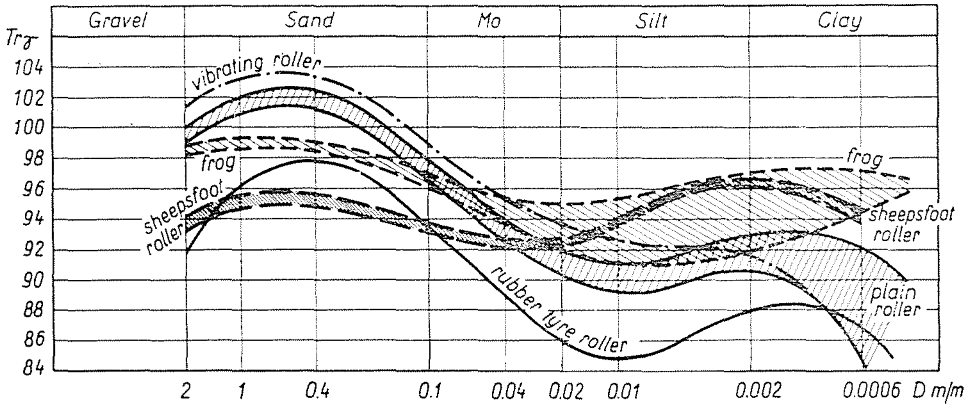

Fig. 1. Compactness maxima obtained with different compacting tools

- Different compacting means exhibit maximum efficiency in different conditions.
- In the course of compacting the saturation undergoes rapid variation; pore water pressure and neutral stresses arise, shear resistance decreases to a minimum and thus the soil eludes the compacting tool and escapes compaction.

Compacting characteristics of transition soils

The variation of compactness maxima of samples compacted by tamping and by static loading is presented in Fig. 2 as a function of phase composition.

The state optimum for compacting may be given but the most convenient state to occur in field conditions is not granted, neither are optimum features of a soil compacted most economically under optimum conditions.

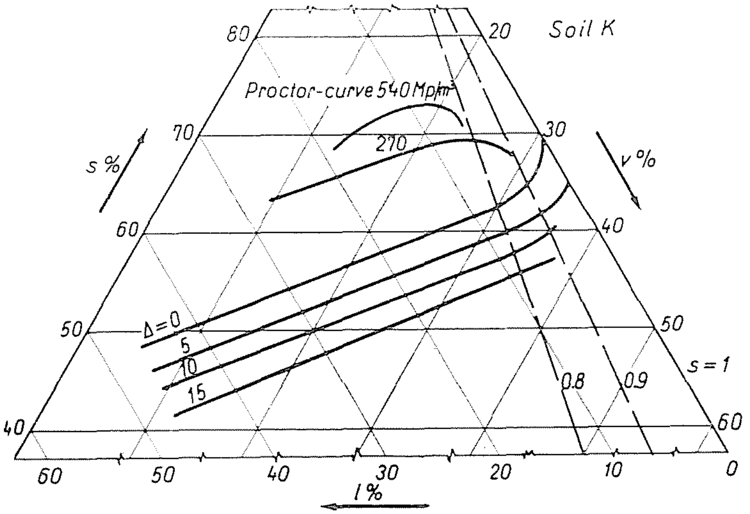

Fig. 2. Phase variation of samples compacted by tamping and static compression

To specify v_{opt} requires to be considerate since transition soils are difficult to identify. Soil classification results by grading or by the plasticity index may be different.

Cohesive soils compacted by different methods have different characteristics even for equal compactness values, and so have transition soils.

For instance SEED and CHAN demonstrated significant differences between compressive strengths of samples compacted by the four most known compacting procedures (Fig. 3). The maxima were not at, but somewhat above, the optimum water contents and for e.g. $\varepsilon = 5\%$ deformation, the strength of soils compacted statically was four times that of milled or tamped soils.

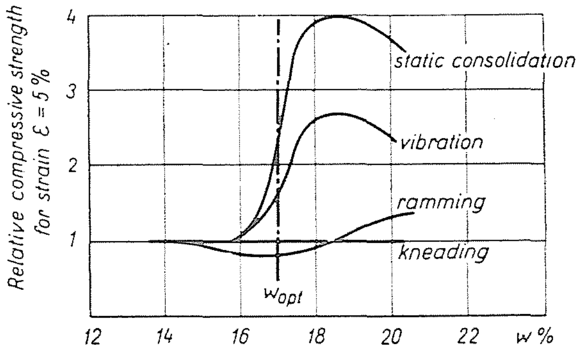

Fig. 3. Strength of soils compacted by different methods vs. initial water content

Thus, rather than the soil physical state yielding the highest dry density, that where the compacted soil has optimum strength characteristics has to be striven to.

Compacting is mainly done for mechanically strengthening the dams, hence the main task is to examine the soil physical characteristics for the stability of dams. Thus, in the following the object is to examine shear strength parameters, to confront them with compactness values obtained by the two most different compacting methods, that is, with dry bulk densities.

I am of the view each earthwork has to be affected by an index peculiar to its function; for instance, the earthwork of traffic lines by shear strength, and that of dams by the impermeability.

Relationship between dry bulk density and shear strength

Compaction, consolidation and shear tests have been made at the Department of Geotechnique on two typical transition soils with different phase compositions. Each point of the compaction curve indicates a defined state, a phase composition. The relevant shear strength parameteres were sought for (Tables I and II). The shear strength tests were made in a shear box of $6 \times 6 = 36$ cm^2 surface at a velocity $v = 2$ mm/min.

The φ and c values obtained on the basis of the phase composition for the γ_d values in each point of the compaction curve are presented in Figs 4 and 5.

These interesting curves have led to the following conclusions:

— The angle of friction does not increase directly with the compactness, but rapidly decreases with increasing initial water content. At full saturation

Table I

Shear strength parameters of soil K

Bulk density Mp/m^3 γ_d	Percentage by volume of solids s	Percentage by volume of water v	Angle of friction φ	Cohesion Mp/m^2 c
$M = 54$ mkp/lit				
1.56	57.7	9.4	30	0.4
1.61	59.5	12.9	29	0.4
1.64	60.8	16.4	28	0.4
1.67	61.8	20.0	27	0.4
1.69	62.6	23.8	26	0.4
1.69	62.6	27.0	25	0.38
1.66	61.6	30.0	23	0.31
$M = 108$ mkp/lit				
1.62	60.0	9.7	31	0.45
1.68	62.0	13.4	30	0.45
1.72	63.6	17.2	29	0.45
1.77	65.5	21.2	28	0.5
1.79	66.4	25.0	26.5	0.5
1.76	65.0	28.2	25	0.45
1.68	62.0	30.3	23	0.32
$M = 270$ mkp/lit				
1.71	63.4	10.2	32	0.55
1.78	65.9	14.2	31	0.58
1.82	67.5	18.2	30	0.60
1.86	69.0	22.3	28.5	0.68
1.85	68.5	25.9	26.5	0.58
1.76	65.0	28.2	25	0.45
1.68	62.0	30.3	23	0.32
$M = 540$ mkp/lit				
1.82	67.5	10.9	34	0.70
1.90	70.4	15.2	33	0.85
1.93	71.3	19.3	31	0.85
1.92	71.0	23.1	29	0.75
1.86	69.0	26.0	27	0.60
1.76	65.0	28.2	24.6	0.45
1.68	62.0	30.2	23	0.32

Table II

Shear strength parameters of soil T

Bulk density Mp/m² γ_d	Percentage by volume of solids s	Percentage by volume of water v	Angle of friction φ	Cohesion Mp/m² c
$M = 54$ mkp/lit				
1.55	57.0	12.4	29.5	0.4
1.64	60.3	16.4	29.6	0.45
1.69	62.1	20.3	28.8	0.4
1.74	63.9	24.3	28.3	0.38
1.75	64.2	28.0	27.0	0.24
1.71	62.8	30.8	25.5	0.16
$M = 108$ mkp/lit				
1.71	62.8	13.7	32.0	0.67
1.77	65.0	17.7	31.2	0.60
1.81	66.5	21.7	30.6	0.52
1.82	66.8	25.4	29.3	0.40
1.78	6.54	28.5	27.4	0.26
1.72	63.1	31.0	25.6	0.16
$M = 270$ mkp/lit				
1.78	65.3	14.2	32.8	0.77
1.81	66.5	18.1	31.8	0.65
1.84	67.5	22.1	31.0	0.52
1.84	67.5	25.8	29.4	0.40
1.80	66.2	28.8	27.8	0.27
1.73	63.6	31.2	25.7	0.16
$M = 540$ mkp/lit				
1.81	66.5	14.5	33.5	0.78
1.88	69.0	18.8	33.5	0.74
1.89	69.5	22.7	32.0	0.55
1.87	68.6	26.2	30.0	0.40
1.80	66.2	28.8	27.8	0.27
1.73	63.6	31.2	25.7	0.16

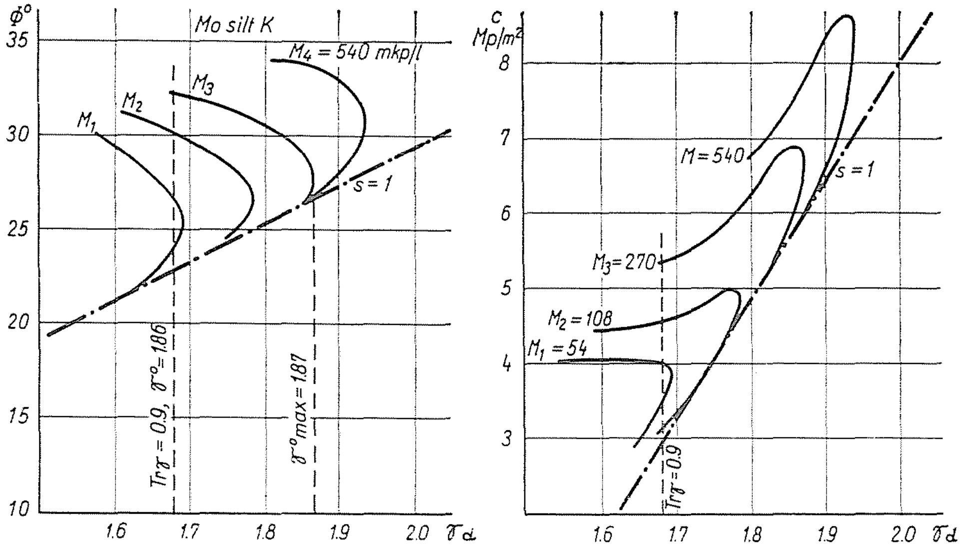

Fig. 4. Variation of shear strength parameters according to phase states in the Proctor diagram (soil T)

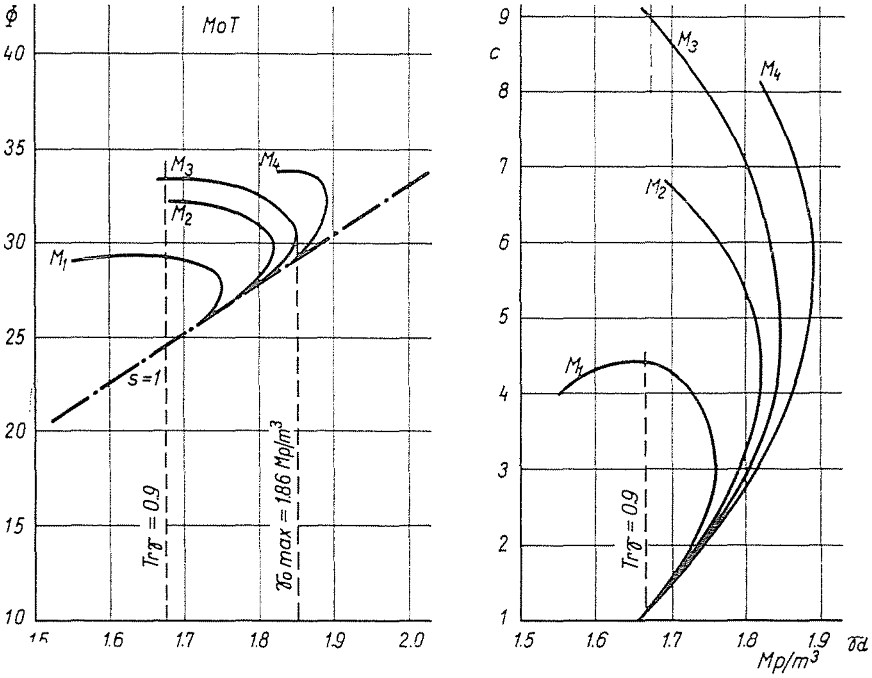

Fig. 5. Variation of shear strength parameters according to phase states in the Proctor diagram (soil K)

the φ values definitely tend to an asymptote. Namely the friction increases slower as a function of compactness than it decreases with the increase in saturation. In the course of compacting this latter effect prevails.

Increasing the water content to approach the optimum facilitates the earthwork, but just at the expense of decreasing the compressive strength of the soil. The $T_{r\gamma}$ value is only virtually characteristic of the compactness of the soil, but it cannot characterize stability.

— Cohesion values of the two soils differ. Cohesion of soil K increased along with γ_d but abruptly decreased towards saturation. Cohesion of soil T decreased from the very beginning, thus it virtually was maximum at the initial, low compactness. Anyhow, the cohesion loss has to be attributed to the increase of water content.

Effect of compacted soil structure on compressive strength

Soils compacted by different procedures are known to exhibit different structural characteristics. Even in the case of the same procedure the structural arrangement differs between dry and wet domains (Mc Rae, 1959), supported macroscopically by Mitchell (1956) and Pacey (1946).

Tests by Seed and Chan (1959) demonstrated differential linear shrinkage between the dry and the wet side of compacted samples. Also the strength tests referred to showed significant differences.

Let us have a closer look at this phenomenon.

As results in the former item refer to shear tests on statically placed, rather than on tamped samples, the following testing program has been established:

1. Standard Proctor test and determination of shear strength parameters in direct shear tests on the compacted samples.
2. Statically compacting samples to compactnesses found in the above test, determination of differences inherent to the compacting method.
3. The samples tamped on the dry side are added water to produce the state at the wet side and tested in shear. Arrangement of grains being different between the dry and the wet side, the results have to be different from those obtained in the 1st test series.

Shear tests on samples compacted by tamping

The test soil was silty mo from *Martonvásár* with a grading curve presented in Fig. 6.

The coefficient of uniformity $U = 5$

$$\gamma_{d\max} = 1.84 \text{ Mp/m}^3$$

$$w_{opt} = 12.2\%.$$

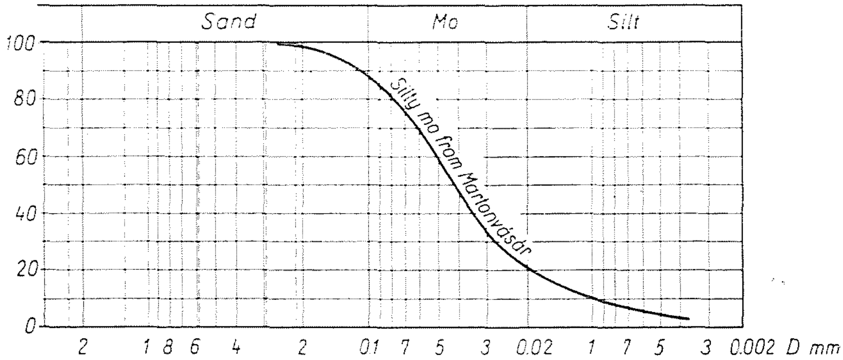

Fig. 6. Grading curve of the tested material

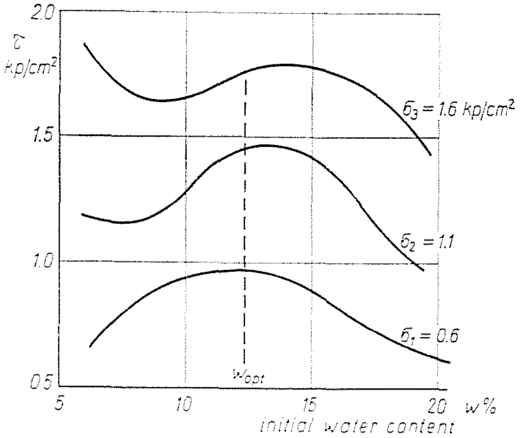

Fig. 7. Shear strength of tamped samples vs. water content

Table III

Tamped samples

Initial water content w %	Bulk density γ_d Mp/m³	Angle of friction φ°	Cohesion c Mp/m
6	1.79	45	0
8	1.79	40	2.0
10	1.81	38	4.0
12.2	1.838	36.5	5.0
13	1.83	36.5	4.8
14	1.81	36.5	4.0
15	1.77	36	3.0
17	1.70	35	2.5
19.5	1.65	34	2.0

To eliminate scatter, great many tests have been made with slightly different water contents, and shear strength variations belonging to each normal load have been plotted as a function of water content. The plots and the three curves are presented in Fig. 7.

The parameters φ and c for any water content can be read off these three curves.

The γ_d value corresponding to the initial water content can be determined by Proctor test and thus parameters φ and c can be plotted vs. γ_d (Table III).

Conclusions

Shear strength parameters of samples compacted on the wet and on the dry side significantly differ as a function of dry bulk density. On the dry side the angle of friction rapidly decreases to a $\gamma_{d\max}$ value. There is slow increase on the wet side. The paradoxal case arises that the sample looser on the dry side has a greater angle of friction. The angle of friction on the wet side varies in accordance with our former knowledge. Also the variation of cohesion is interesting. On the dry side the cohesion rapidly increases while the compactness little varies. The maximum is at $\gamma_{d\max}$ to proportionally decrease again on the wet side with decreasing compactness.

The problem is still more interesting from the aspect of water content variation. The angle of friction monotonously decreases with increasing water content. The decrease slows down near w_{opt}. Thus, the water content affects the decrease of the angle of friction more than does the change or even growth of compactness. But in spite of the increasing water content the cohesion vigorously increases on the dry side to be maximum at the w_{opt} value corresponding to the maximum compactness. From this point on the cohesion decreases on the wet side according to the exponential function known from the literature.

The compactness can be stated to be decisive for the variation of cohesion.

The most important conclusion is that the difference between the dry and the wet side can be attributed to the soil structure differences. Variations on the dry and the wet side are governed by different laws.

Structural differences may arise from the compacting method as proven by the second test series.

Shear test on statically compacted samples

a) *Experimental*

The soil examined was the same as in the former tests.

For the sake of comparison, the phase composition of samples varied in the same steps as in the course of tamping. That is, only phases fitting the

Proctor curve were examined. The dry material was homogeneously mixed with water and the required quantity was compressed to the prescribed volume by a hand press. (The recorded compression power permitted to conclude on the compacting work.)

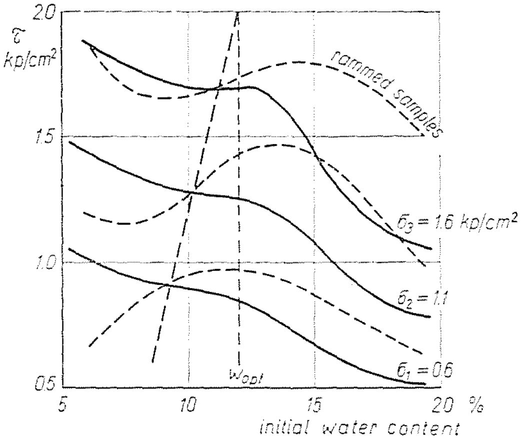

Fig. 8. Variation of shear strength of statically compacted samples

Thereafter the prepared samples were tested in shear as were the tamped samples.

The test results have been processed by the same method. The results are presented in Figs 8 and 9.

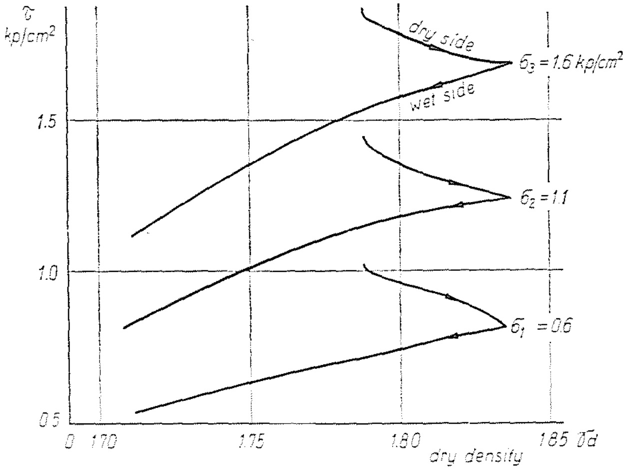

Fig. 9. Shear strength parameteres vs. initial water content

b) *Evaluation of results*

According to Fig. 8 shear strengths of the statically compacted samples monotonously decrease vs. initial water content (even in the vicinity of w_{opt} where the compactness increases significantly.)

Structural differences are seen in Fig. 9 to exist between the wet and dry sides of statically compacted samples. On the dry side the shear strength decreases as a function of compactness, obviously due to the water content. On the wet side, it varies linearly with compactness, just as in the case of tamped samples.

Comparison of tamped and statically compacted samples

The shear strength of tamped samples has been plotted in dashed line in Fig. 8. In the $w < 10\%$ range, the shear strength of the tamped samples is lower on the dry side. Above this point, tamping provides significantly higher shear strengths all along the wet side in the water content range $w = 10$ to 20%.

Unambiguous explanation is rather difficult but a close approximation is possible by examining separately the shear strength components.

In Fig. 10, variations of the parameters φ and c for both the tamped and the statically compacted samples are presented superposed. In the $w < 10\%$ range the φ values are somewhat higher for tamped than for pressed samples, but the cohesion is significantly less.

Namely, tamping creates a disordered structure on the dry side, raising the angle of friction, but not contributing to cohesion.

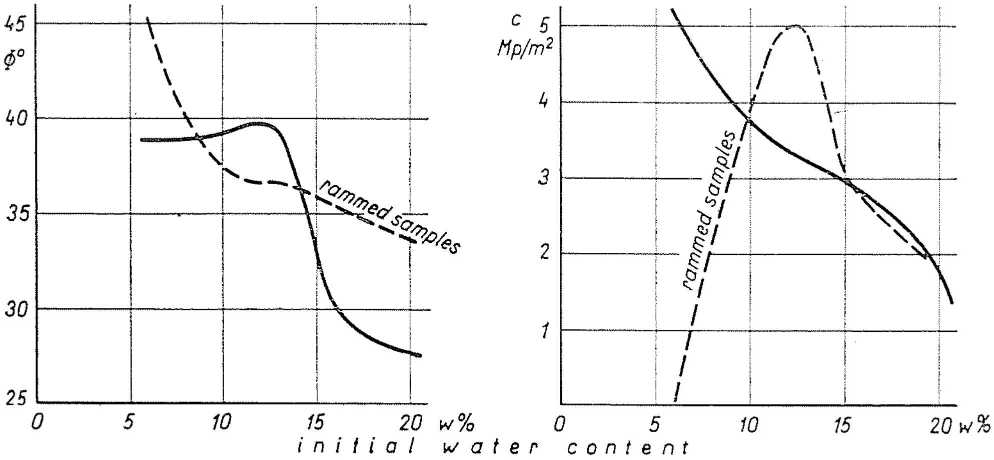

Fig. 10. Shear strength variation due to wetting of samples tamped on the dry side

In the vicinity of the optimum water content the grains get gradually arranged, reducing the angle of friction. It is interesting to see that the decrease rate is rather low on the wet side and less significant than in the case of static compression. The friction on the wet side of tamped samples is throughout greater. The maximum of cohesion is at w_{opt} and from this point on it gradually decreases, to soon fit, and coincide with, the curve characteristic of static samples. Thus, on the wet side, the cohesion of tamped and statically compacted samples does not differ.

Thus, the structural arrangement is such that the grains will be oriented on the wet side in either case. This is enough to keep up cohesion.

But in static compaction the orientation is stronger (the grains are less free to move). Thus here the friction is significantly less while in tamping the orientation is reduced, at a greater friction.

Since differences mainly originate from structural changes of the tamped samples, this effect was examined next. Essentially, the samples tamped on the dry side were artificially moistened to test shear strength.

Variation of shear strength of tamped samples upon water absorption

a) For the sake of comparison, tamping was made by the same technology as in the first test series. The initial water content was chosen so that its dry side value be on the rising limb of the *Proctor* curve.

The sample put into the shear box was flooded by water from below and from above, while normal load was kept on to prevent loosening.

Water dosage was controlled so as not to saturate the sample. The test was successful when the water content was at least 14% or over, possible to check only after the shear test. Variation of shear strengths for different water contents permitted to determine the shear strength belonging to the water content $w = 14\%$.

b) Shear test results in Fig. 11 unambiguously show that with increasing water content, shear strength on the wet side of the samples tamped on the dry side is much below that of the samples tamped on the wet side under the same conditions.

The structural differences are obvious, the results obtained are perhaps unexpected. Accordingly, the material with presumably dispersed, disordered structure on the dry side has a lower shear strength than that ordered and oriented on the wet side. This is only possible if ordering is perpendicular to the shear plane, hence actually vertical. This fact may be responsible for the higher wet-side strengths of tamped than of statically compacted samples.

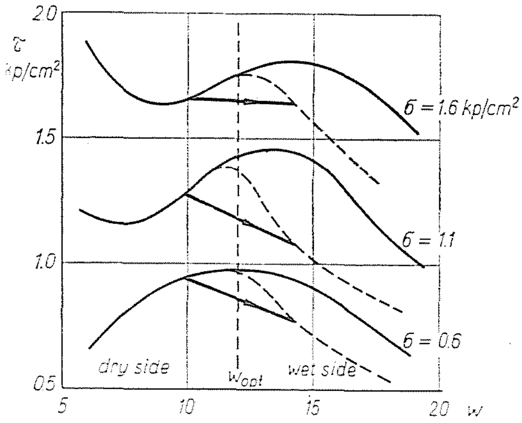

Fig. 11.

Conclusions

Depending on the manner of compaction, the soil shear strength critical for the dam stability is not at the compactness possible at the optimum water content, but

a) in the case of tamping, at a water content higher by 1 to 2%;

b) in the case of static compaction on the dry side at rather small water contents.

Another important conclusion is that the compactness due to tamping on the dry side is not satisfactory in itself since ulterior wetting reduces the shear strength much below that for wet compaction.

Table IV

Shear strength values in the three examined states

	$\sigma = 0.6$ kp/cm²	$\sigma = 1.1$ kp/cm²	$\sigma = 1.6$ kp/cm²
w = 10%	0.95	1,28	1.65
w = 14%	0.95	1.47	1.80
tamping at w = 10% and ulterior wetting to w =14%	0.80	1.10	1.64
Strength loss related to w = 10%	15.7%	14.1%	0.6%
Strength loss for w = 14%	15.7%	25%	8.9%

This can be proved by numerical data. In our tests the compactness of samples tamped at a water content $w = 10\%$ is

$$T_{r\gamma} = 1.81/1.84 = 0.98 \, .$$

The same compactness was obtained on the wet side for a water content $w = 14\%$.

Shear strength values presented in Table IV show a shear strength decrease by even 1/4 possible for the same compactness.

Still greater deviations are possible if a specified $T_{r\gamma}$ value, e.g. $T_{r\gamma} = 0.9$ is insisted on. In this case the bulk density

$$\gamma_d = 1.84 \times 0.9 = 1.66 \text{ Mp/m}^3$$

may be achieved for almost the complete range of water contents from 0 to 19%. Instead of designing on the basis of compactness specifications, the following procedure is suggested:

a) The shear strength parameters required for the dam stability are determined.

b) Shear tests are made on samples tamped or else compacted at a few different values of water content.

c) Determination of the range of phases likely to permit the required strength from the variation of shear strength, to be indicated in specifying the physical characteristics of the soil to be compacted.

d) The compacting work is specified, taking the power of the compacting tool into consideration.

Summary

Characteristics of the so-called transition soils, the most difficult to compact, are examined. The soil structure developing in compaction significantly affects the soil shear strength. Strength differences between transition soils compacted by different means are demonstrated by test data. Static and dynamic compaction brings about different soil structures, leading to different optimum compactnesses and different shear strength maxima. Test results suggest to determine strength characteristics on samples taken of the compacted soil rather than by Proctor tests.

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