New Interpretation of Proctor Test

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(Experiences of BC Part 2)

1 Introduction, antecedents

One of the most important parameter of earthworks, granular materials and building materials of railway, roadways and hydraulic structures is the compactibility which is handled as an important qualification test by all regulations. The main character of the compactibility test is the *reference density*, as one of the possible and wide-spread reference basis of the calculation of compactness.

So far this reference density could be determined by Proctor tests in the laboratories (in a simplified or modified way). At the same time, European tests included in the EN Standards allow new testing methods for compactibility tests near the Proctor for the determination of the relevant density i.e. vibrating cylinder, vibrating table and vibrating hammer tests.

For the compactibility tests new requirements and recommendations were published, too, seemingly independent of compactness specifications. For example, FGSV 516 (and ÚT 2-1.222 Hungarian specification also) specifies to provide in some cases smaller than, or equal 12% air content besides reaching the required compactness, which is yet so new that most Hungarian tenders pass it by. There is no specification (or concept) for the allowed saturation, neither in the standards, nor in the tender. Although the above-mentioned air content can be interpreted such as a specification of saturation (saturation is calculated according to the water content and the porosity coefficient**),** it cannot be considered as a routine.

In the construction works today it is considered unusual to measure the moisture content of the material to be compacted on the site, just as to indicate in-building water content limits correctly in the qualification test. This latter does not only refers to the density value which is the product of the maximal dry density and the specified compactness, but to the distinguishing of the dry and the wet branch, and furthermore, to the indication of plasticity and in-building limits of the wet compaction owing to saturation, which limits are *asymmetric* of the optimal water content.

2 Laboratory compactibility tests

The application of the modified Proctor test as the relative density is typical in Hungary also, just as in other European countries. The prevailing old test specification was MSZ 14043-7, valid is the standard EN 13286-2 (7.4 has been recommended, as the modified Proctor test) since the EU accession, *without any considerable deviation*. According to standards (i.e. Hungarian ÚT 2-1.222), the specification of the design of earthworks the EN 13286-2 standard reflecting the European specifications became effective upon its publication. It was published in 2005.

<u>*Compactibility standards*</u>

Accordingly, nowadays, not only Proctor tests made with a rammer, but also other very different testing methods applying compaction are allowed. These are:

EN 13286-3 Test methods for laboratory reference density and water content. Vibrocompression with controlled parameters

EN 13286-4	Test methods for laboratory reference density and water content. Vibrating hammer
EN 13286-5	Test methods for laboratory reference density and water content. Vibrating table

The conformity of the tests to each other is not known for the time being, they are not converted. It is expected that *they will not correspond with each other* because of the different model effect. Nevertheless, the basic condition in their comparison is that the *compaction work must accord*.

It is evident that later a primary question will include which laboratory compactibility test comes nearest to the real compactibility facilities (machines). One cannot avoid to compare the relative densities from the different compacting methods besides a compacting work that is the same or is supposed to be the same.

Therefore, *it is important* in EN 13286-2 to highlight the calculation method of the *amount of the executed work*, which is in our opinion faulty, as well as the inaccuracies of the indicated data (which is supposed to be suitable for reference and comparison).

Main points of the error

The area of the rammer differs from the area of the mould; but at the same time, the calculation supposes the ramming of the whole surface for all drops (instead of one quarter!). The height of the attachment placed on the mould is regulated only approximately (>50 mm), but during the calculation of the executed work neither its height, nor its volume is taken into consideration. In our opinion, at the execution of work projected on the volume not the remaining roller volume, but the volume of the heightened roller at the time of the compaction (i.e. the parameters of the roller without removing the attachment) should be taken into consideration.

The impact of the above-mentioned factors is even then significant if we analyse the differences between certain types of the Proctor test, but it could lead to very serious mistakes if we used it in the comparison with other – above mentioned - compacting methods.

Calculation of the executed work

In our opinion, the EN 13286-2 calculates the value of the finished compaction work *incorrectly*, because it does not take into consideration, that the compacted area is only one quarter of the mould area. We disagree also with the considered value of the compacted height, because it does not consider the height of the attachment (top-ring).

According to our calculations, the executed work of the modified Proctor test is the following:

Ramming area: $\pi*5.1^2/4 = 20.4$ cm^2, area of the rammer 81.67 cm^2. Their ratio = 4.0. So the rammer compacts one quarter of the area of the sample with one drop, and then the sample turns away and the rammer compacts the whole sample area round. On the basis of 25 drops/layer/4 = 6.25 beats/surface 31.25 drops in average arise for the total of 5 layers instead of the present rate of 125 (!) drops. The work is $W= mgh = 4.5 \text{ kg} \times 0.46 \text{ m} \times 31.25 = 64.7$ mkp/sample and 64.7×9.81 = 634.7 Joule (and not its four-fold).

In our case, the another error is that an attachment of +50mm top-ring also belongs to the mould height of 116mm, therefore 0.7925 mkp/cm^2 surface-proportional, or rather 64.7/1356 cm^3 = 0.048 mkp/cm^3 specific work projected on the volume of the compact material height of 166mm was calculated.

3 Calculated work of the CWA 15846 dynamic test

The ramming area determined by a plate diameter and a shaping that is in accordance with CWA 15846 (ÚT 2-2.124) 208.57 cm^2, the drop height of the deflectometer is 75cm, and its weight is 11kg. The executed work is W = 8.25 mkp, the ratio of the work/surface = 8.25/208.57 = 0.0395 mkp/cm^2 for one drop, besides a supposed effective layer thickness of 20 cm.

According to that mentioned above, we can reach a compaction of *the same amount of work on site* than with the laboratory modified Proctor test (EN 13286-2 par.7.4) by (0.792/0.0395)×(20/16.6) = 24 drops, where, besides the ratio of the executed work, the ratio of a layer thickness supposed to be 20cm and the laboratory layer thickness of 16.6cm is also taken into account. Accordingly, 24 drops are necessary to have a compaction that ranges from a theoretical minimal relative compactness degree of 70.8% to a degree of 100%. Typically, measuring cases are expected to have an initial compactness of at least 80 to 85%. To reach the compactness degree of 100% (100–80)/(100–70.8)×24 = 16,4 drops are needed, by proportioning the compaction generated by the drops.

It follows from this that the 18 drops specified i.e. in the Hungarian and the planned EN specification which are suitable for the determination of the relative compactness degree in the range between 78.1% and 100%.

4 Features of the Proctor test and the Proctor-curve

It is typical that qualification tests of filling materials and granular materials are incomplete or superficial, even though they include very important information as regards the practice of the construction work. We feel it highly necessary that the number of Proctor test points (w_i % – ρ_{di}) determined by different water contents be at least 4-5, and in case of large-scale works, it is better to indicate even more, 6 to 8 points based on more site samplings and present them in one processing.

The present specifications neither put up for accuracy nor do they determine any confidence (tolerance) interval in the calculation of the compactness degree as regards the $\rho_{d\max}$ relative density which is derived from the Proctor test. Because of this, the error of the compactness degree can reach 4 to 5% which can further increase by cumulating with other gauge accuracy parameters of the compactness measuring. We made a complex analysis from a large-scale round test (Institute For Transport Sciences, Proctor round test of the year 2005), which showed very large deviations in all material samples (Figure 1, Figure 2, Figure 3)

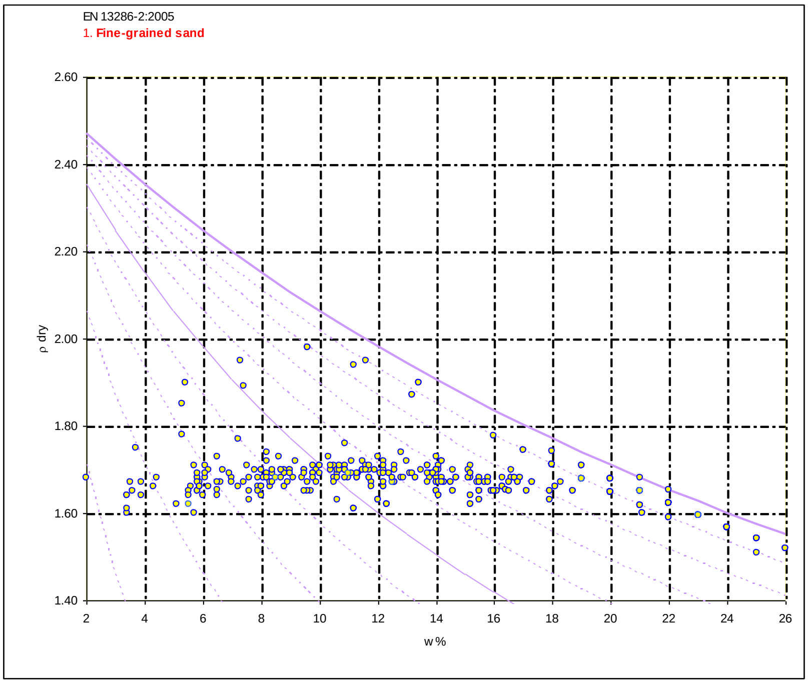


Figure 1 Proctor round test: Fine-grained sand (siSa)

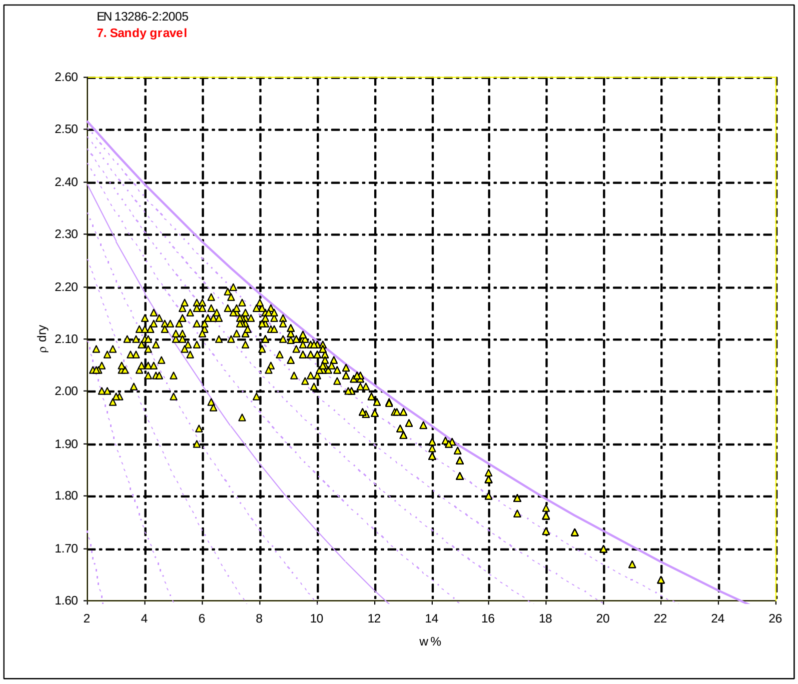


Figure 2 Proctor round test: sandy Gravel (saGr)

We must to mention that this figures content the “calculated virtual” Proctor-point also, on the wet branch S≥0,95 used the void-free density. In the qualification test, it is important to know the saturation lines, among which the saturation line belonging to the optimal water content (w_{opt}) has a distinguished role (on the figure for example S=0.88). Typically, we have plotted the saturation lines *S*=1.0; *S*=0.9 and *S*=0.8 at the most so far. Saturation lines can be calculated from the Proctor test and the void-free material density to any distance, even at *S* = 0.1. We found that the calculation and plotting of the saturation lines helps in the new interpretation of the regression curve of Proctor points.

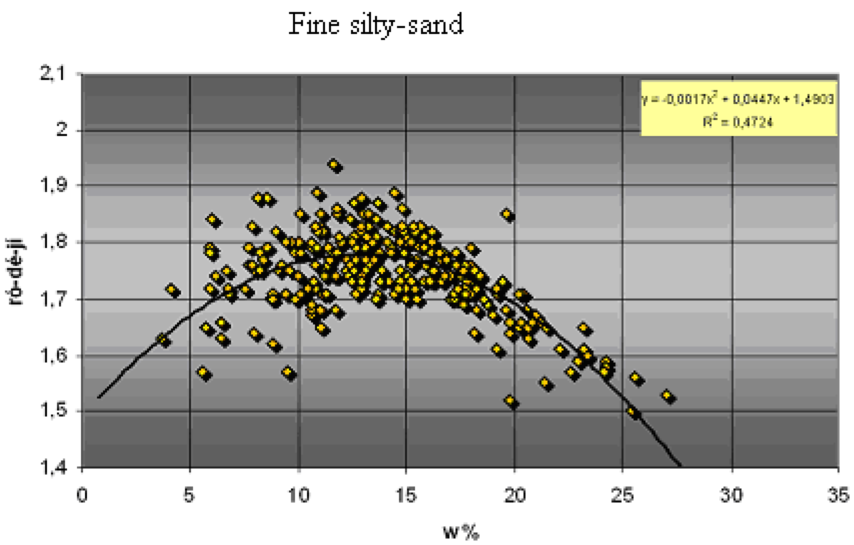
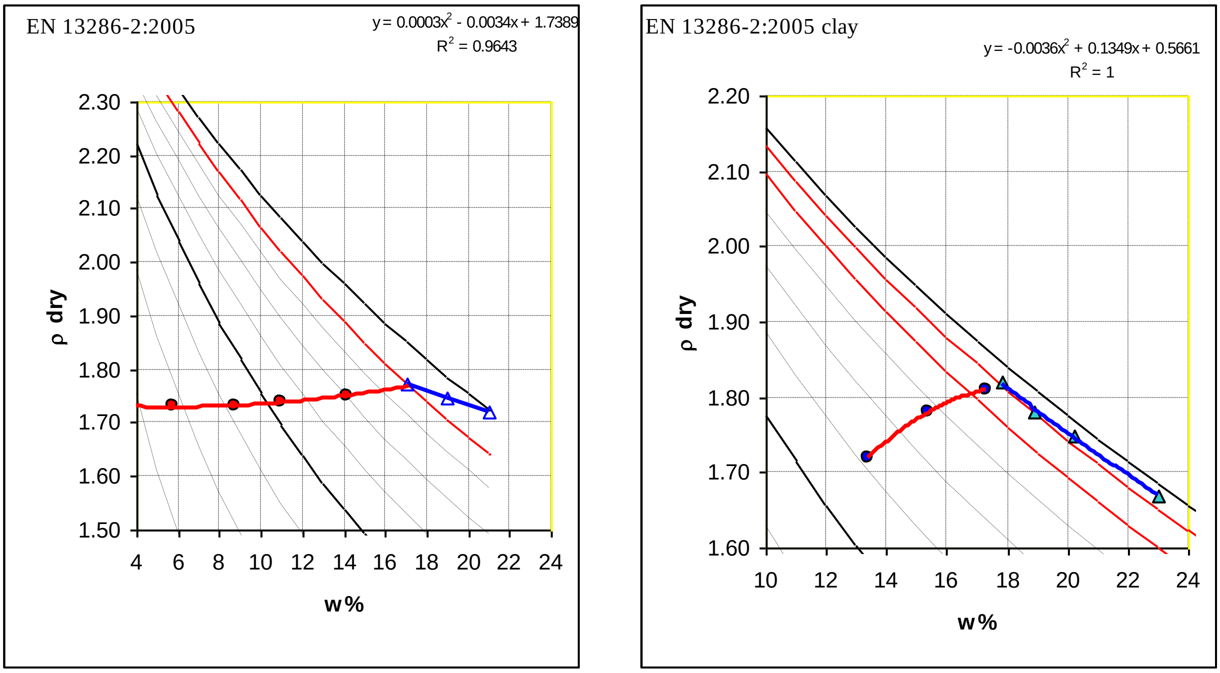


Figure 3 Proctor points measured by different accredited laboratories from one soil sample

5 New interpretation of the Proctor curve

We processed the half thousands of available Proctor points, as data of the round tests (2006 Phong – Subert). We could state that the Proctor curves that were considered as typical and used so far have not been relevant for the most part. The plotting of the saturation lines turn out to be important and left from the saturation line S=0.9 it features the "dry" material behaviour, while right from the saturation line S=0.9, which is well separable, the wet behaviour.



(a) gravel (b) clay

Figure 4 Proctor curve processed with the new two-branch method

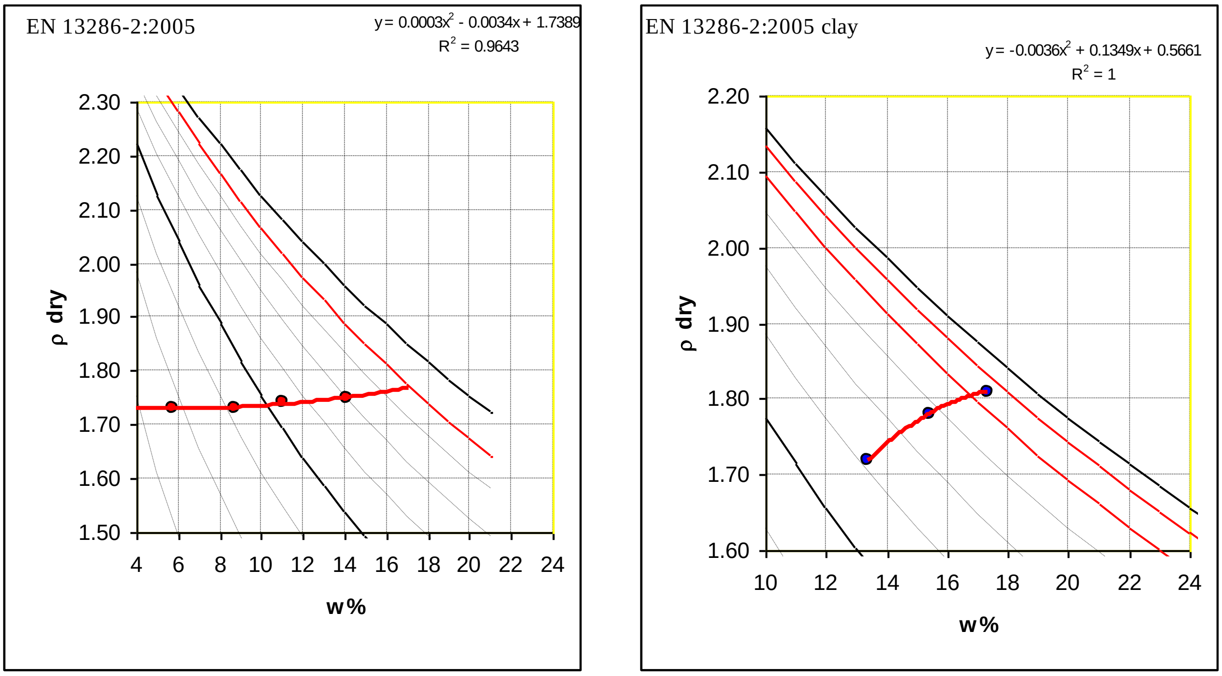
Dry behaviour

The dry behaviour shall be determined on the basis of the regression test of the Proctor points left from saturation line S=0.9 (i.e. we eliminate the other measured Proctor points from the calculation). Generally, this is a convex or rarely concave curve; and it coincides only sometimes to the foregoing curves that were generally formed. Even though this new interpretation brings about the smallest change in the values around w_{opt} in comparison with the previous interpretation, it is yet regarded as a significant theoretical consideration (Figure 5). The allowed range of the dynamic compactness measurements is in this dry branch, from which the moisture correction coefficient can be calculated as well.

Wet behaviour

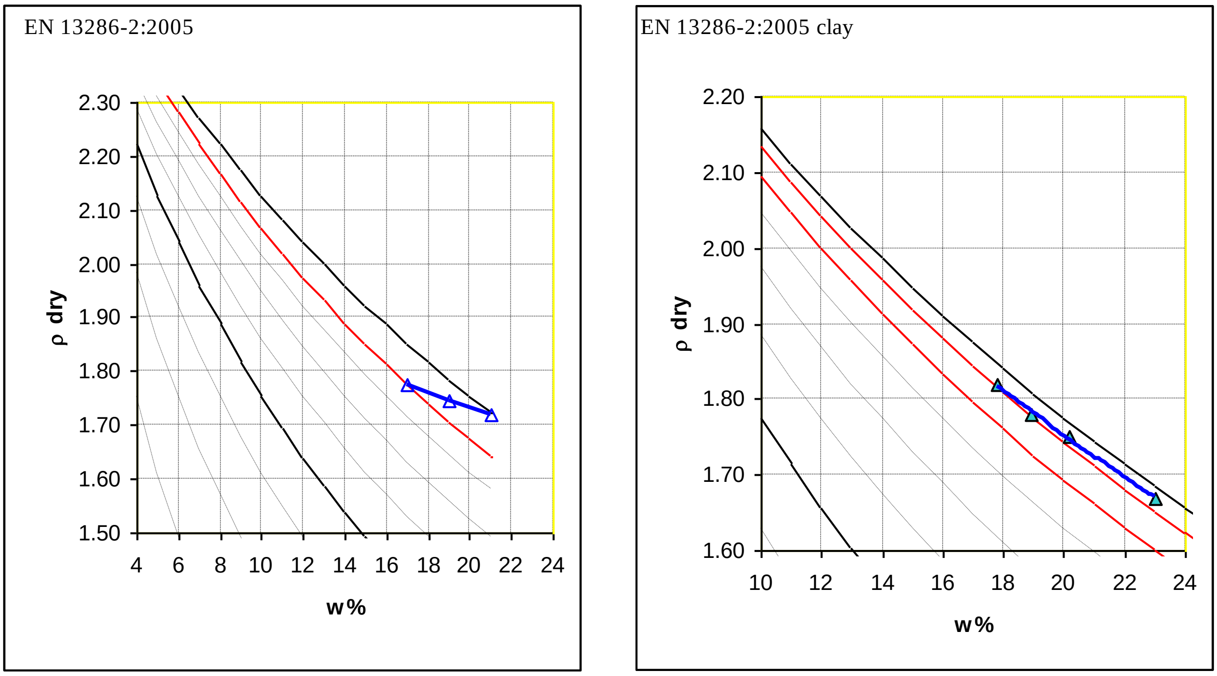
By examining the curve of the wet behaviour at water contents above the saturation S=0.9 we found that it always typically osculates to the saturation lines and finally approaches the saturation curve S=1 (Figure 6).

As far the compaction on the site above the saturation S=0.95-0.98 is not possible, and nor there is reason for dynamic measurements, therefore the processing of this curve can be only occasionally important. In means in this period there is insufficient air in the system to effect the compaction, and the *water can not be compressed*. This is the reason why the regulations do not allow measurements (and also compactions) on full-saturated soils.



(a) Gravel (b) Clay

Figure 5 Proctor curve of the dry branch with the new method



(a) Gravel (b) Clay

Figure 6 Proctor characteristic curve of the wet branch with the new method

Complex Proctor curve

It clearly comes from that mentioned above that the Proctor curve specifying the compactibility, which depends on the moisture content, consists of not one, but two curves, actually, which cross (touch) each other at one point and *have mathematically nothing to do with each other*. The right branch osculates the saturation lines and it can be calculated far simpler and more accurate than it can be measured. On this section (far from w_{opt}) yet *virtual Proctor points* can be taken, by determining their values via calculations.

The dry-branch curve can be calculated from the measured Proctor points by regression analysis and that gives the CWA 15846 moisture correction coefficient curve ($T_{rw}=\rho_{di}/\rho_{dmax}$) at the same time. From the cases examined by us those sands shall be highlighted where the conventional shape of the Proctor curve was wavy (Sinus-curve-like). These curves were generally typical below w_{opt}, for the dry range. In the present processing this is also obvious since the linking of the point results in far simpler concave curves which are closer to reality. (Figure 7, Figure 8)

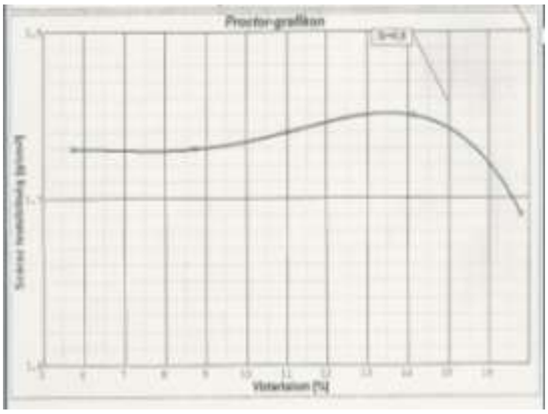


Figure 7 Proctor „sinusoidal" curve processed conventionally (w_{opt} = 13.5%)

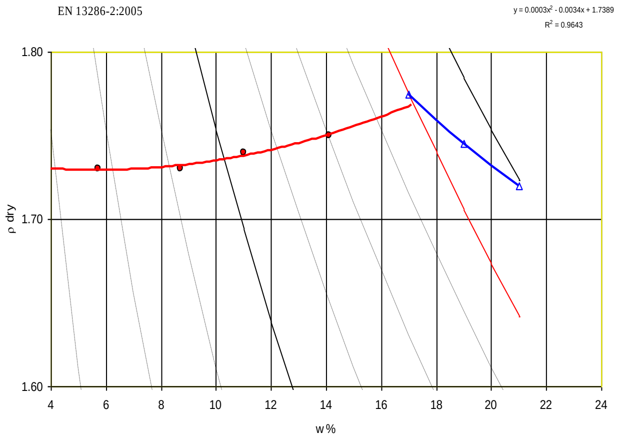


Figure 8 the same Proctor curve processed with the new method (w_{opt} = 17.0%)

6 The air content and the saturation belonging to the optimal water content

We found the relationship between the air content and the saturation belonging to the optimal water content for 8 different materials. These relationships are linear and nearly coincide each other except in our case the grail dolomite.

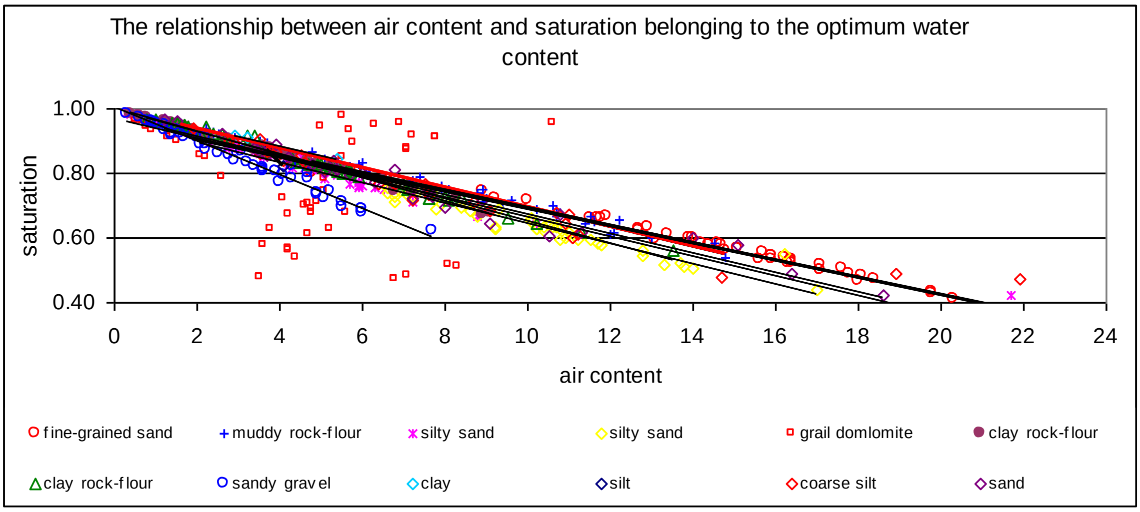


Figure 9 Relationship between the air content and the saturation belonging to w_{opt}

By the processing of the 8 very different materials and all our 566 Proctor results we fixed the relationship between the air content and the saturation belonging to the optimal water content, which is the following:

$$S_r = 1 - 0.03a$$

where is: a the air content, S_r the relevant saturation.

It is typical to have fare lower pores than 12 volume% at the optimal water content (at the highest dry density).

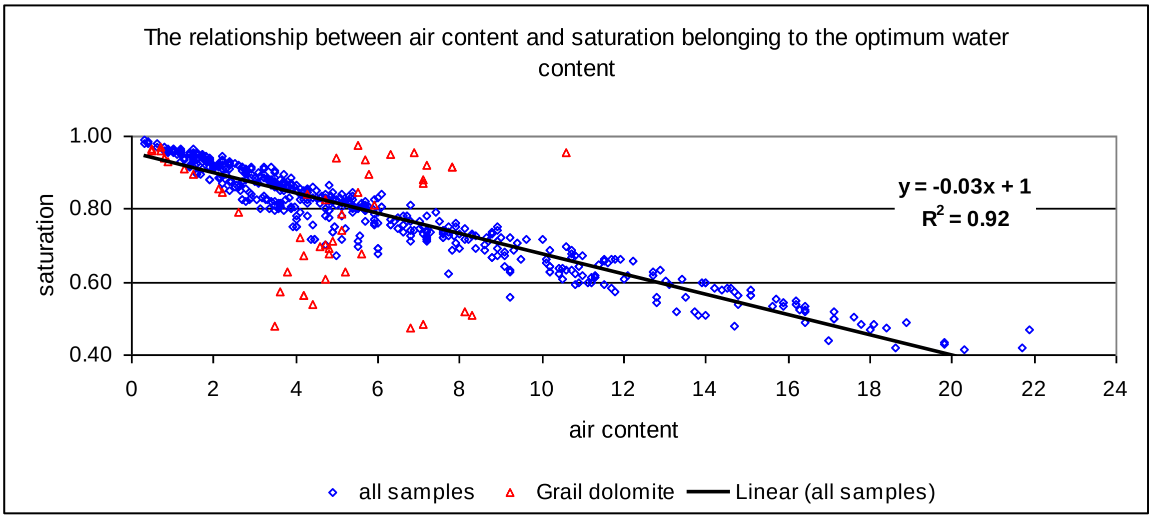


Figure 10 General relationships between the air content and the saturation belonging to w_{opt}

The distribution of the available Proctor-test results is lognormal and can be seen on figure 11. The air content defined at w_{opt} is very frequently, typically in range 1-6 volume% Using the relationship of the regression-analysis is the saturation correctly between **S=0.88 – 0.94**, which accords to the experiences and is practically determinant for the adaptation of the B&C dynamic compactness measurement. By saturations above 0.95 are the dynamic measurements (large plate LFWD, small plate LFWD, and KUAB) to void, because the water can not be compressed by dynamic hits.

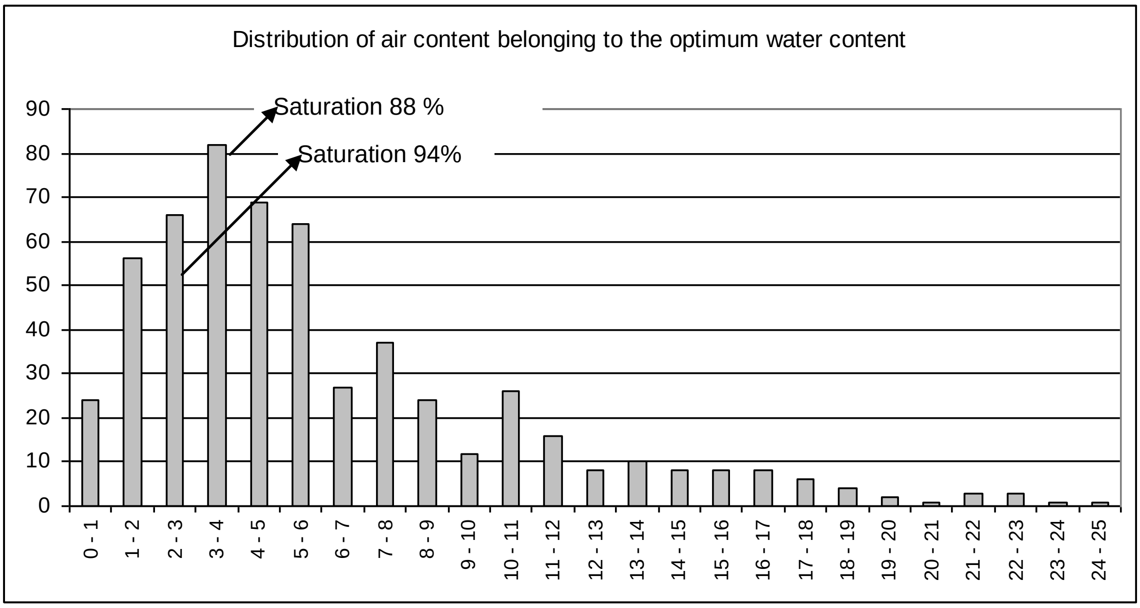


Figure 11 Frequency distribution of the air content belonging to the optimal water content

7 Conclusions

Based on the theory of the Complex Proctor Curve (CPC) next ultimate conclusions can be made:

- $\rho_{d\max}$ and w_{opt} have typically a range of air content between 2-6 % (i.e. far lower than 12 %) and saturation was between 0.88-0.95 in the analysed range
- That's why the determination of the Proctor curve must not be accepted together by regression analysis with the left dry and the right wet branch because the dry branch and the wet branch are *mathematically completely diverse*, but they feature also physically a completely different behaviour. If we do not take this into account then we get a deformed curve that does not indicate the *real* compactibility behaviour.
- The *uncertain zone* between the two characteristic Proctor-curves is relatively small and can be taken as representative between the saturation lines S=0.88-0.95
- The regression analysis of the Proctor-points located left from the saturation lines S=0.88-0.95 is typical for the dry branch, according to the conditions of construction, but gives a far more precise, reliable curve as the former evaluation method. In the dry – very dry range, for example, the new CPC processing method removed the earlier, "wavy" Proctor curves, causing several discussions
- With the new method the compactibility of points located far from the optimal water content can be estimated more exactly, contrary to the method used earlier
- The separate regression-mathematical analysis of the wet (right) branch is possible, but practically without any sense. On the one hand it is determinative that it lies close between the saturation lines, on the other hand it is important, that by this saturation neither real compaction, nor dynamic compactibility test can be done
- On the wet branch it is possible to take *virtual Proctor points* that are calculated, for the regression test. The precision of these is far higher than the real measurable values because of water effluence. By these distant points we can make the fitting of the right-side curve more precise
- The maximal value of the normalized Proctor curve ($T_{rw}=\rho_{di}/\rho_{d\max}$) is 1.0 and it specifies the compactibility behaviour of the material upon the effect of a change in the moisture. This is the so-called T_{rw} moisture correction coefficient curve, which is used to convert the relative compactness degree to a dynamic one by dynamic compactness measurements. The moisture correction coefficient can be calculated by such a calculation method in wider range of water content, with higher reliability
- Finally, the new method helps in the more accurate evaluation of the results of the other (EN 13286-3-4-5) laboratory compactibility tests and in the comparison thereof, since the interpretation of the wet branch above w_{opt} can be the same in all cases. In this way, the comparison shall be limited to the compactibility at water content levels below w_{opt}, and to the curvature thereof, as well as to the comparison of the intensity of the compaction
- The method facilitates the development of "On Site – Proctor test" with the CWA15846 - B&C falling weight, by on site compaction work, in the test of trial constructions. In several cases it is a good help if problems owing to the varying material quality can be cleared yet on site

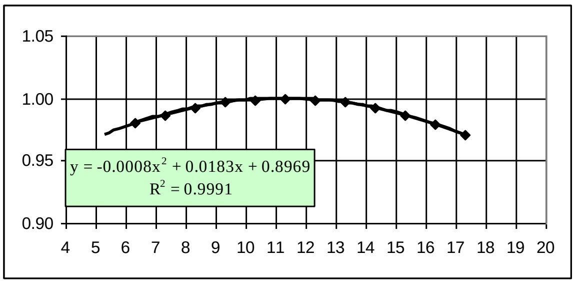
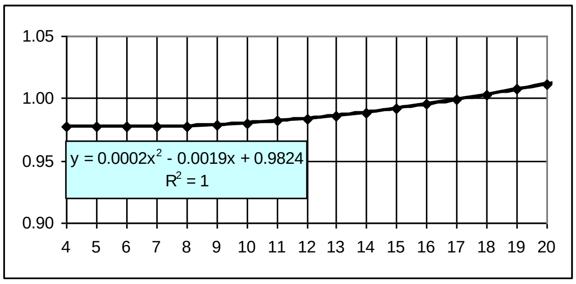


Figure 9 Calculation of the moisture correction coefficient from the Proctor curve with the old method



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8 Summary

The CWA15846 and the BC dynamic compactness test applies on-site compaction method at all test points on the site, by performing the complete compaction by 18 drops on the plate. From the calculated compaction curve, the initial on-site relative compactness degree belonging to the given water content can be calculated. Therefore, the compaction method (as well as the deformation behaviour of the test points) is very similar to the laboratory Proctor test, by coming to a relative compactness of 100% on all points of the laboratory Proctor test, that are examined at all moisture contents, and by doing "one unit" of compaction work.

The role of compactibility tests is decisive in qualifications of the base material. Until now the compactness degree was calculated from the measured dray densities and from the ratio of the reference density. This is the maximum of the Proctor curve, the maximum measured dry density is the reference density, and therefore its definition method, precision and reliability affect decisively the correctness of the measurement.

The role of the Proctor test as regards the dynamic compactness degree is less significant since we take only the curve reflecting the dry behaviour of the material and its curvature in consideration. By this method the curvature of the Proctor curve, not the absolute value of the density is important. Yet, in case of moistures being far from w_{opt}, results that deviate from the reality can cause inaccuracy or a larger error, therefore the new method is a method to *increase the accuracy* of the CWA 15846 dynamical compaction measurement.

The analysis of the results of Proctor tests with a large number of data clearly highlighted the general similarities and the allowable consequences. A significant result in increasing the accuracy includes that method by which we analyse the separated points characterised by S=88–95 % range separately. In this way, the values of $\rho_{d\max}$ are *divided into two curve sections specified for wet and dry behaviour* of a kind that conforms with the real behaviour. These are examined separately, and the formula of the curve is determined by calculation and regression analysis.

The new method of the valuation of the Proctor curve basically changes the accuracy of the estimation of $\rho_{d\max}$, the reliability of the reference density, providing by this better accuracy for all compactness measurements, including the new CWA 15846 B&C dynamic measurement, as well as a more accurate determination of the T_{rw} moisture correction coefficient and curve.

Literature

- FGSV 516:2003 Merkblatt für die Verdichtung das Untergrundes mit Unterbaues im Straßenbau.
- Measuring Method for Dynamic Compactness & Bearing Capacity with SP-LFWD
  CWA 15846, WS33
- MSZ EN 13286 – 2 Unbound and hydraulically bound mixtures. Part 2: Test methods for the determination of the laboratory reference density and water content. Proctor compaction.
- MSZ EN 13286 – 3 Unbound and hydraulically bound mixtures. Part 3: Test methods for laboratory reference density and water content. Vibrocompression with controlled parameters.
- EN 13286 – 4 Unbound and hydraulically bound mixtures. Part 4: Test methods for laboratory reference density and water content. Vibrating hammer.
- ÚT2-2.124 Measuring of dynamic compactness and dynamic bearing capacity with small plate light falling weight deflectometer.
- Dr József Pusztai– Dr Emőke Imre– Dr János Lőrincz– István Subert – Trang Quoc Phong: Development of large surface dynamical compactibility measurements with location identification and the continuous on site measuring of the sinking of the compacting cylinders. Report of COLAS R+D in year 2007.
- Subert: Method for measuring Compactness-rate with New Dynamic LFWD. XIII. Danube-European Conference on Geotechnical Engineering Ljubljana, Slovenia, 2006
- Subert: „Dynamical compactibility measurements on Hungarian highways and reconstruction in cities" Geotechnical Conference 2006 in Ráckeve, Hungary (17-18. of October 2006.)
- Subert I.: „Dinamikus tömörségmérés aktuális kérdései. A dinamikus tömörség mérés újabb tapasztalatai" Geotechnika Konferencia 2005 Ráckeve. (2005. október 18-20.)
- Subert I.: „Új, környezetkímélő, gazdaságos mérőeszközök a közlekedésépítésben" Geotechnika Konferencia 2004 Ráckeve. (2004. október 26-27.)
- Subert I.: „A dinamikus tömörség- és teherbírásmérés újabb paraméterei és a modulusok átszámíthatósági kérdései" Közúti és mélyépítési szemle 55. évf. 2005. 1. sz.
- Subert I.: „B&C Dynamic Compactness Test" Mélyépítés 2004 October - December (p.:38-39).
- Subert I.: "B&C – a useful partner" Magyar Építő Fórum 2004/25.