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Experiences in compaction control of secondary building materials in Germany

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ABSTRACT

Sufficient compaction of the fill materials used in earthworks is essential for the stability and long-term serviceability of the earthworks constructed. To ensure sufficient compaction, the German earthworks regulations therefore contain application-related requirements for the minimum degree of compaction D_{Pr} to be achieved, which must be verified after compaction in the course of compaction control (end-product specification). This can be done by means of direct test methods or by using relationship testing. In the case of secondary building materials (SBM, i.e. recycled materials, industrial by-products), however, difficulties and differences in comparison to natural primary building materials (PBM) can occur in earthworks practice both in the determination of the Proctor density in the laboratory and during compaction control in the field. These can be related to material-specific properties of SBM. In order that these do not represent an exclusion criterion for the use of SBM in earthworks, the special properties of the SBM must be taken into account during testing in the laboratory and in the field. This paper aims to highlight the special features of SBM that can occur in connection with the determination of Proctor density in the laboratory and compaction control in the field and - if possible - to explain causes. Finally, suggestions are presented on how the material-specific differences of SBM can be taken into account in practice during the compaction test in the laboratory and compaction control in the field.

Keywords: secondary building materials, recycled materials, industrial by-products, compaction control, plate load tests, volume replacement methods, nuclear gauge

1 INTRODUCTION

To ensure stability and long-term serviceability in earthworks, the sufficient compaction of the fill material is essential. During compaction, the compaction energy supplied leads to rearrangement of the individual grains of the fill material into a denser packing. This is equivalent to an increase in the number of grain-to-grain contacts and leads to a reduction of the void volume and to an increase in shear strength as well as stiffness of the fill material. This is fundamental to ensure stability and long-term serviceability. To ensure sufficient compaction in Germany, application related requirements for the minimum degree of compaction D_{Pr} must be met (end-product specification). The degree of compaction D_{Pr} gives the ratio between the dry density determined in the field and the Proctor density determined in the laboratory in percent. The compaction requirements in Germany are contained in the so called ZTV E-StB (FGSV, 2017) ("**Z**usätzliche **T**echnische **V**ertragsbedingungen und Richtlinien für **E**rdarbeiten im Straßenbau", in english: "Additional technical conditions of contract and directives for earthworks in road construction"). If these application-related requirements can be verified on the construction site, sufficient compaction of the fill material can be assumed. The conformity of the achieved compaction quality with the required one must be proven within the framework of self-monitoring and control tests. The test and measurement methods available for this differ in terms of their informative value, accuracy, handling and cost-effectiveness and must be selected carefully accordingly (Floss, 2019).

For natural primary building materials (PBM), extensive experience is already available in earthworks practice, both in connection with the determination of the Proctor density as a reference value for compaction in the field and with the test methods for verifying the compaction requirements in the field. In the case of recycled materials from processed construction waste and industrial by-products, which have meanwhile gained enormous importance as secondary building materials (SBM) in earthworks due to economic and ecological requirements and legal regulations (cf. Heyer & Huber, 2019; Heyer & Henzinger, 2016), differences can occur in the determination of the Proctor values in the laboratory and during compaction control. If these differences are not taken into account they can contribute to reservations about the use of SBM and can also lead to their rejection for reasons related to the construction contract.

The following explanations are intended to contribute to the increased use of SBM as a sensible alternative to PBM in earthworks. First, the possibilities for proof of the compaction requirements in Germany are presented. Then, on the basis of extensive results from laboratory and field tests, the differences that can occur with SBM compared to PBM in the determination of the Proctor values and in the context of control tests in the field are shown. Finally, suggestions are presented on how to proceed in earthworks practice with regard to the difficulties presented.

2 PROOF OF COMPACTION ACCORDING TO GERMAN EARTHWORKS REGULATIONS

The compaction requirements formulated in ZTV E-StB 17 (FGSV, 2017) are application-related requirement values for the degree of compaction D_{Pr} in percent. The size of the required degree of compaction D_{Pr} depends on the area of application of the fill materials, the associated design loads and the settlement sensitivity of the earthworks construction. For water-sensitive mixed and fine-grained fill materials, additional requirements on the maximum permissible air void ratio must be considered. This is to limit the penetration of water into the compacted fill material and thus to prevent a loss of load-bearing capacity due to softening. Requirements on the load-bearing capacity and stiffness properties in earthworks according to ZTV E-StB 17 only exist for the planum and for road shoulders.

The required degree of compaction D_{Pr} can be proven by means of direct test methods or by relationship testing. In direct test methods, the dry density achieved in the field is determined directly as a test characteristic and is set in relation to the Proctor density determined in the laboratory as the reference value for the degree of compaction D_{Pr}. Direct test methods are, for example, volume replacement methods according to DIN 18125-2 (DIN, 2020) or radiometric measurement methods according to TP BF-StB B 4.3 (FGSV, 1999). In the case of relationship testing, the degree of compaction is proven on the basis of an indirect test characteristic, which has a close technical relationship with the degree of compaction (e.g. modulus of deformation). Relationship testing usually is done using static or dynamic plate load tests according to DIN 18134 (DIN, 2012a) respectively TP BF-StB B 8.3 (FGSV, 2012) or by continuous compaction control.

In general, it should be noted that the test results determined with the different test methods are subjected to method-related and subjective errors during sampling and testing, and that the magnitude of the error is influenced by the type and nature of the fill materials to be tested. In the case of volume replacement methods, for example, difficulties in correctly determining the excavated test volume lead to errors in the determination of the dry density. In addition, their execution is associated with a considerable interruption of the working process on the construction site. In the case of radiometric test methods, which enable much faster testing than volume replacement methods, unsuitable calibration of the radiometric probe can lead to systematic errors in density and water content determination (Huber & Heyer, 2019; Viyanant et al., 2004; Regimand & Gilbert, 1999; Behr, 1988). It should also be noted that, due to their radioactivity, special care is required when handling the radiometric probe and special legal regulations must be considered (FGSV, 1999).

Due to the mentioned difficulties in connection with the direct test methods, compaction control of coarse and mixed-grained soils with a fines content d < 0.063 mm of less than 15 % by mass is often carried out using the static or dynamic plate load test. For such materials, the stiffness of the layer to be tested depends only subordinately on the water content. The stiffness is determined as static or dynamic modulus of deformation, which may correlate with the degree of compaction D_{Pr} as the direct test characteristic and thus can be used for relationship testing. The respective correlation between the static or dynamic modulus of deformation and the degree of compaction D_{Pr} must be determined in advance within the scope of calibration tests according to ZTV E-StB 17, taking into account the specifications according to TP BF-StB Part 4 (FGSV, 2003). In the case of coarse-grained fill materials with a fines content d < 0.063 mm of less than 5 % by weight, calibration between the degree of compaction D_{Pr} and the static or dynamic modulus of deformation is not required in accordance with ZTV E-StB 17. Instead, use can be made of guideline values (see Table 1), which, depending on the soil group of the fill material according to DIN 18196 (DIN, 2011), assign a static or dynamic modulus of deformation (E_{V2} or E_{Vd}) to a degree of compaction of D_{Pr} = 100 % or D_{Pr} = 98 %.

Table 1. *Guideline values according to ZTV E-StB 17 (FGSV, 2017) for the assignment of the degree of compaction D_{Pr} to the static and dynamic modulus of deformation E_{V2} respectively E_{Vd}*

Soil group according to DIN 18196 (DIN, 2011)	**D_{Pr} [%]**	**E_{V2} [MN/m²]**	**E_{V2}/E_{V1} [-]**	**E_{Vd} [MN/m²]**
GW, GI	≥ 100	≥ 100	≤ 2.3 2)	≥ 50
	≥ 98	≥ 80	≤ 2.5 2)	≥ 40
GE, SE, SW, SI	≥ 100	≥ 80 1)	≤ 2.3 2)	≥ 50 1)
	≥ 98	≥ 70 1)	≤ 2.5 2)	≥ 40 1)

GW: wide graded gravel, GI: gap graded gravel, GE: equally graded gravel
SW: wide graded sand, SI: gap graded sand, SE: equally graded sand
1) For soil groups GE and SE, confirmation by test compaction is required.
2) If the E_{V1} value already reaches 60 % of the required E_{V2} value, higher E_{V2}/E_{V1} ratios are also permitted

3 INVESTIGATIONS CARRIED OUT

The following results from proctor tests and tests for compaction control stem from three investigation campaigns that were carried out in July 2017, June 2018 and August 2020. A total of 12 different SBM (recycled concrete [RC C], mixed recycled materials [RC M], recycled railway ballast [RC RB], recycled railway ballast and concrete [RC C/RB], electric furnace slag [EFS]) and three PBM (pit gravel, a PBM with rounded grains and a PBM with angular grains) were investigated. The test materials were classified in the laboratory and their compaction properties were determined using Proctor tests according to DIN 18127 (DIN, 2012b). Some of the soil mechanical parameters of the materials tested are listed in Table 2.

Table 2. *Soil mechanical properties of the materials tested*

Material / Property	**RC C 0/56**	**RC C 0/16**	**RC M 0/56**	**RC M 0/45_1/2**	**RC M 0/45_3**	**RC M 0/22**	**RC M 0/8**	**RC M 0/4**	**RC RB 0/45**
Soil group 1)	GW	GW	GU	GI	GI	GU	GU	SU	GI
Max. Grain size 2) [mm]	56	16	56	45	45	22	8	8	45
≤ 31.5 mm 2) [%]	93.4	100.0	91.2	98.5	80.3	100.0	100	100	87.2
≤ 2 mm 2) [%]	30.9	24.0	41.2	44.6	30.6	33.9	57.6	83.5	12.0
≤ 0.06 mm 2) [%]	4.9	3.8	9.3	3.5	2.8	8.4	7.4	10.3	4.4
C_U 3)	26.4	19.0	60.5	18.5	42.8	48.3	22.4	-	21.2
C_C 3)	1.8	2.3	2.7	0.6	0.6	3.5	1.2	-	8.3
ρ_S [g/cm³]	2.672 4)	2.629 4)	2.698 4)	2.621 4)	2.585 4)	2.647 4)	2.645 5)	2.628 5)	2.850 4)
ρ_{Pr} 6) [g/cm³]	1.879	1.801	1.839	1.833	1.800	1.809	1.743	1.844	2.142

Material / Property	**RC C/RB 0/45_1/2**	**Pit Gravel 0/22**	**PBM, round 0/45**	**PBM, angular 0/32**	**EFS 0/32**	**EFS 0/4**
Bodengruppe 1)	GW	GU	GI	GU	GW	SE
Max. Grain size 2) [mm]	45	22	45	32	32	4
≤ 31.5 mm 2) [%]	92.3	100.0	90.0	100	100	100
≤ 2 mm 2) [%]	17.8	56.7	17.2	22.6	18.4	62.2
≤ 0.06 mm 2) [%]	3.4	6.7	4.9	6.5	2.0	2.6
C_U 3)	21.2	24.0	48.6	56.6	7.8	3.6
C_C 3)	2.6	0.2	6.6	4.6	1.4	1.2
ρ_S [g/cm³]	2.740 4)	2.646	2.705 4)	2.653 4)	3.676 4)	3.598 5)
ρ_{Pr} 6) [g/cm³]	2.043	2.099	2.301	2.047	2.300	2.120

1) Soil group according to DIN 18196 (DIN, 2011a)
2) Grain size distribution according to DIN EN ISO 17892-4 (DIN, 2017)
3) according to DIN EN ISO 14688-2 (DIN, 2018)
4) determined with the air pycnometer according to TP BF StB Teil B 3.3 (FGSV, 1988)
5) determined with the gas pycnometer according to DIN EN ISO 17892-3 (DIN, 2016)
6) Proctor density according to DIN 18127 (DIN, 2012a), mean value of the three highest dry densities determined in the Proctor test

With each of the test materials a test field was also constructed (cf. Figure 1). Density determinations were carried out on each test field using the balloon replacement method according to DIN 18125-2 (DIN, 2020) and the radiometric probe according to TP BF-StB B 4.3 (FGSV, 1999). In addition, static and dynamic plate load tests were carried out according to DIN 18134 (2012a) and TP BF-StB B 8.3 (FGSV, 2012), respectively.

Figure 1. *Example of a test field during the investigation campaign in June 2018*

4 DETERMINATION OF THE PROCTOR DENSITY IN THE LABORATORY

The Proctor test (in Germany standardised in DIN 18127 (DIN, 2011b)) is carried out in the laboratory to determine the Proctor density as a reference value for compaction in the field. In this test, the dry density that can be achieved with a standardised compaction work is determined as a function of the water content. The test was originally developed for cohesive soils (cf. Proctor, 1933a, b, c, d), but it is also applied in Germany for coarse and mixed-grained soils. For most PBM, the dry density increases with increasing water content due to the initially compaction-favouring effect of the pore water until an optimum is reached. With a further increase in water content, the dry densities fall again roughly parallel to the saturation line. In contrast, the compaction curves of SBM usually show no clear dependence of the dry density on the water content. Instead of the familiar parabolic curve, they show linear, concave or convex curves of the relationship between water content and dry density. As a result, the derivation of a clear optimum for the determination of the Proctor density as well as the derivation of an optimum compaction water content is no longer possible according to the common procedure (see also Huber & Heyer, 2018; Huber et al., 2018, Krass & Kollar, 2004). The described material behaviour is illustrated in Figure 2 using the example of the compaction curves of the test materials listed in Table 2.

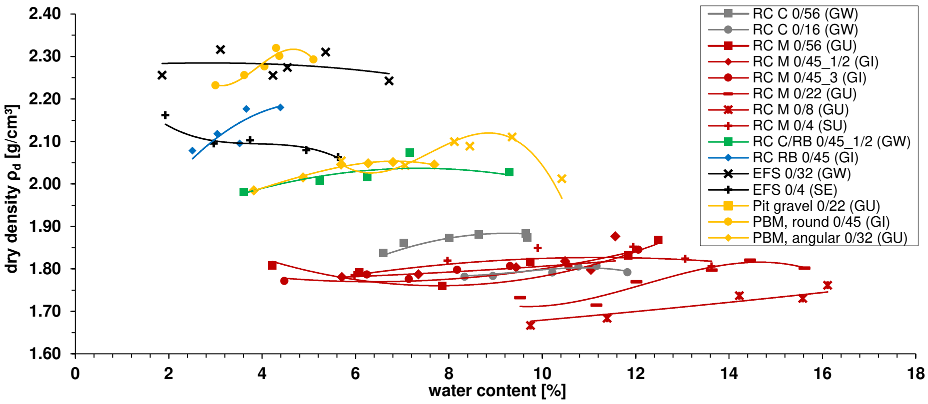

Figure 2. *Compaction curves of the materials tested*

The shape of the compaction curves of SBM is primarily caused by the porosity of the individual grains and their associated water absorption capacity (cf. Huber & Heyer, 2018; Diedrich et al., 2001). Only a part of the pore water present in the test specimen is available at the surface of the individual grains to facilitate compaction, while another part is stored in the water-accessible pores within the individual grains. The amount of water stored within the individual grains depends on the type and natural water content of the material to be tested as well as the homogenisation time after the addition of water. In order to ensure repeatability of the Proctor test with SBM and other fill materials containing porous single grains, at least these three parameters must be taken into account.

5 PROOF OF THE REQUIRED COMPACTION IN THE FIELD

5.1 Direct testing methods

5.1.1 Determination of water content

Figure 3 illustrates the water contents determined during the investigation campaigns in the field. It compares the water contents determined using the radiometric probe with the water contents determined by oven drying. The values obtained with both methods agree when they lie on the straight line also shown in Figure 3. The results in Figure 3 show that for mixed recycled materials (RC M) comparable values are achieved with both test methods. Only for RC M 0/56 slightly lower values were achieved with the radiometric probe than by oven drying. For recycled concrete RC C 0/16, on the other hand, systematically slightly higher water contents were determined with the radiometric probe than by oven drying. In the case of PBM, the water contents determined with the radiometric probe and by means of oven drying also agree relatively well. Only in the case of pit gravel 0/22 slightly larger deviations occur in single tests.

In the case of electric furnace slags (EFS 0/4, EFS 0/32), however, systematically lower water contents are determined with the radiometric probe than by oven drying. This is probably due to metal atoms contained in the electric furnace slags (e.g. in solidified steel droplets, iron oxides). The metal atoms absorb disproportionately more neutrons, which are used by the radiometric probe to determine water content (Behr, 1988; Brandl, 1977). This means that the manufacturer's calibration of the radiometric probe for water content determination cannot be applied to the electric furnace slags without systematic test errors. If such systematic test errors occur as a result of the calibration of the radiometric probe, the radiometrically determined water contents can be corrected by means of a correction factor Δw. For this purpose, the correction factor Δw is added to each determined measured value. The correction value Δw is material-specific and is obtained as the mean value of the differences $\Delta w_i = w_{oven,i} - w_{radiometric,i}$ from at least five individual measurements i (cf. Huber & Heyer, 2019; Behr, 1988). The applicability of the correction factor Δw is illustrated in Figure 3 using the example of electric furnace slag EFS 0/4.

In contrast to the electric furnace slags, slightly higher water contents were determined with the radiometric probe for the materials consisting (proportionally) of railway ballast (RC C/RB 0/45, RC RB 0/45). The reason for this could not be definitively clarified.

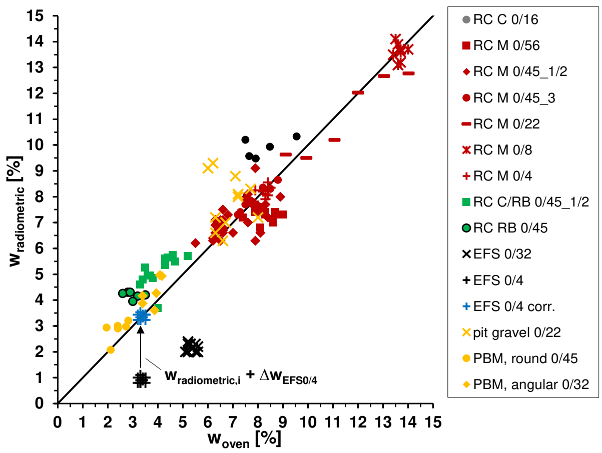

Figure 3. *Water contents determined by oven drying (w_{oven}) and by the radiometric probe ($w_{radiometric}$)*

5.1.2 Determination of wet and dry density

The wet and dry densities determined by the balloon replacement method are compared to the wet and dry densities determined by the radiometric probe in Figure 4. Even if individual measured values show slight differences, the wet and dry densities of both measurement methods for the mixed recycled materials, the recycled concrete and the PBM largely agree well. Systematic deviations occur in the case of electric furnace slags, where the wet and dry densities determined by the radiometric probe are above the values determined using the balloon replacement method. The deviations are probably due to heavy atoms with a high atomic number (e.g. iron). These absorb disproportionately more gamma radiation, which is used by radiometric probes for density determination, and thus lead to the overestimation of the wet and dry densities (Huber & Heyer, 2019; Viyanant et al., 2004; Regimand & Gilbert, 1999). In case of systematic test errors in the radiometric determination of wet and dry density due to the calibration of the radiometric probe, the radiometrically determined wet and dry densities can be corrected by multiplication with the correction factor $C_{x,f}$ or $C_{x,d}$, respectively. The correction factor $C_{x,f}$ or $C_{x,d}$ is determined as the mean value of the ratios $C_{x,f,i} = \rho_{f,balloon,i}/\rho_{f,radiometric,i}$ respectively $C_{x,d,i} = \rho_{d,balloon,i}/\rho_{d,radiometric,i}$ from at least five individual measurements i (cf. Huber & Heyer, 2019; Behr, 1988). The applicability of both correction factors is illustrated in Figure 4 using the example of EFS 0/4.

In the case of RC C/RB 0/45_1/2, predominantly higher wet and dry densities were determined with the radiometric probe than with the balloon replacement method. In the case of RC RB 0/45 no clear tendency can be identified. This is probably due to comparatively large test errors when using the balloon replacement method for such coarse grained materials (max. grain size 45 mm, soil group GI).

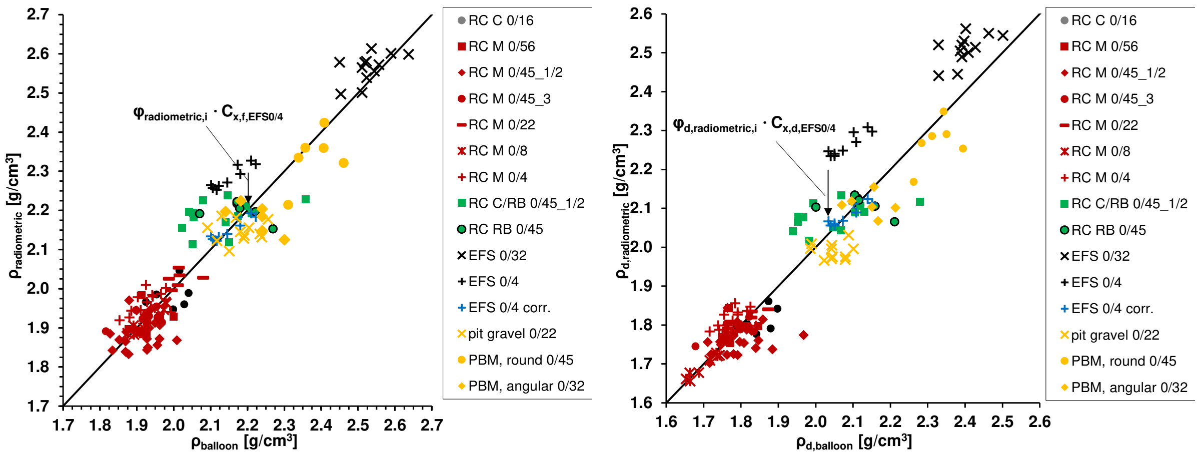

Figure 4. *Wet densities (left) and dry densities (right) determined by balloon replacement method and radiometric probe*

5.2 Relationship testing using plate load tests

5.2.1 Static plate load tests

The static moduli of deformation E_{V1} and E_{V2} determined during the investigation campaigns are plotted against the degree of compaction D_{Pr} in Figure 5. The relationships between the degree of compaction D_{Pr} and the moduli of deformation E_{V1} and E_{V2} are shown using linear regression lines (coefficients of determination R^2 are listed in the legends in Figure 5). The regression lines show increasing moduli of deformation E_{V1} and E_{V2} for all materials with increasing degree of compaction D_{Pr}, whereby the results show a scatter typical for testing with the static plate load test.

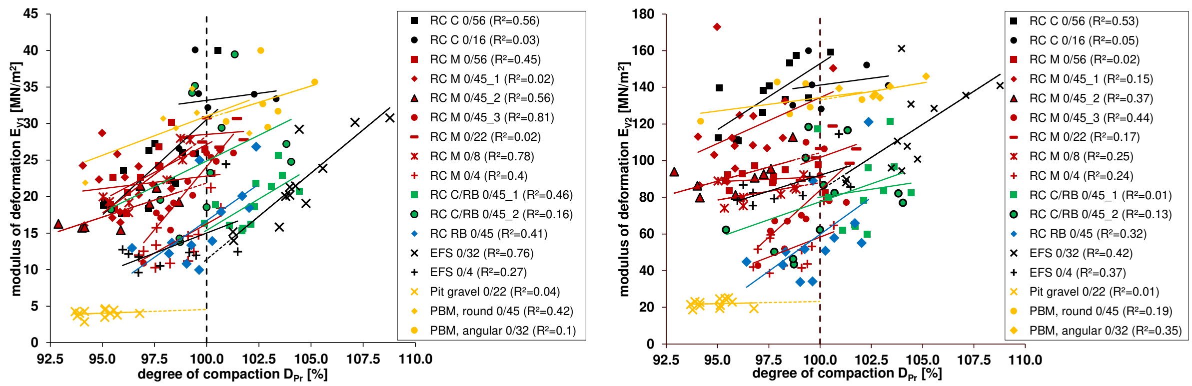

Figure 5. *Static moduli of deformation E_{V1} (left) and E_{V2} (right) over the degree of compaction D_{Pr}*

If compaction control is to be carried out with the static plate load test for coarse-grained earthworks materials (soil groups GW, GI, GE, SW, SI, SE according to German standard DIN 18196) using the guideline values of ZTV E-StB 17 (cf. Table 1), the ratio E_{V2}/E_{V1} must be taken into account in addition to the value of the modulus of deformation E_{V2}. From a soil mechanical point of view, the ratio E_{V2}/E_{V1} indicates which part of the deformations occurring during the initial loading remains as plastic deformations and which part can be regarded as elastic deformations. Low ratios E_{V2}/E_{V1} indicate that the deformations occur predominantly as elastic deformations. According to ZTV E-StB 17, a maximum ratio E_{V2}/E_{V1} of 2.3 is permissible to verify a degree of compaction of $D_{Pr} \geq 100$ % when using the guideline values shown in Table 1 (or $E_{V2}/E_{V1} \leq 2.5$ for $D_{Pr} \leq 98$ %), unless the E_{V1} value is already 60 % of the required E_{V2} value (cf. section 2). In Figure 6, the ratios E_{V2}/E_{V1} determined in the test fields are plotted over the degree of compaction D_{Pr}. For the tested SBM of the soil groups GW, GI, GU, SU and SE, the linear regression lines (for the coefficients of determination R^2 see legend in Figure 6) give E_{V2}/E_{V1} ratios between values of 3.1 and 6.5 at a degree of compaction of $D_{Pr} = 100$ %. The ZTV E StB 17 requirements for the maximum permissible ratio of 2.3 do not apply to mixed-grain fill materials of soil groups GU and SU. However, the SBM of soil groups GW, GI and SE are required to meet the permissible ratio ($E_{V2}/E_{V1} \leq 2.3$ for $D_{Pr} = 100$ % or $E_{V2}/E_{V1} \leq 2.5$ for $D_{Pr} \leq 98$ %), and this requirement is not met. The PBM of soil groups GI also do not meet the required ZTV E-StB 17 ratio (see linear regression lines shown in Figure 6).

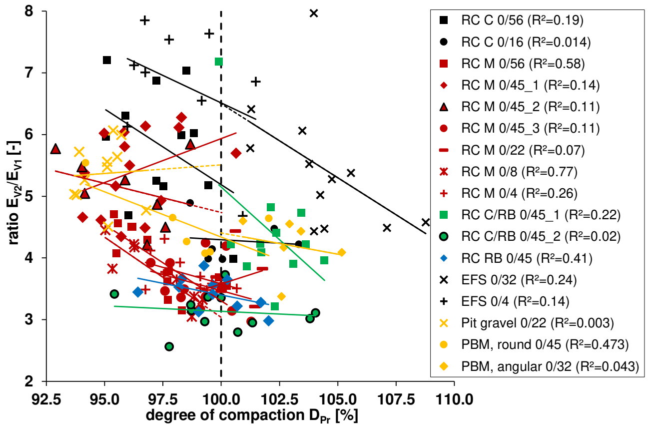

Figure 6. *Ratio E_{V2}/E_{V1} over the degree of compaction D_{Pr}*

5.2.2 Dynamic plate load tests

The dynamic moduli of deformation E_{Vd} determined during the investigation campaigns are plotted against the degree of compaction D_{Pr} in Figure 7. The relationship between E_{Vd} and the degree of compaction D_{Pr} again is shown by means of linear regression lines for each testing material (coefficients of determination R^2 see legend in Figure 7). The data show that the moduli of deformation E_{Vd} of the test materials increase with increasing degree of compaction D_{Pr}, with the exception of RC M 0/56 mm. The results of the dynamic plate load tests in Figure 7 show that the moduli of deformation E_{Vd} are in part significantly below the requirements of the guideline values of ZTV E-StB 17 ($E_{Vd} \geq 50$ MN/m² for $D_{Pr} \leq 100$ % or $E_{Vd} \geq 40$ MN/m² for $D_{Pr} \leq 98$ %, cf. Table 1), despite a sufficient degree of compaction $D_{Pr} \geq 100$ %. This concerns both the PBM and SBM of the soil groups GW, GI and SE, for which the table values of ZTV E-StB 17 are applicable.

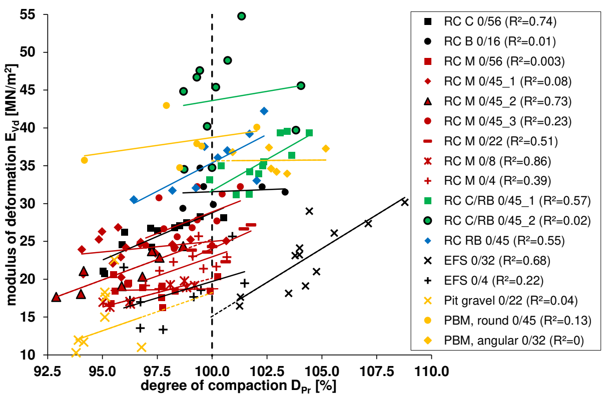

Figure 7. *Dynamic moduli of deformation E_{Vd} over the degree of compaction D_{Pr}*

5.2.3 Applicability of the table values of ZTV E-StB 17

The results of the static and dynamic plate load tests have shown that the correlation between the degree of compaction D_{Pr} and the moduli of deformation E_{V1} or E_{V2} or E_{Vd} depends strongly on the properties of the respective material and cannot be generalised even for comparable material types (e.g. recycled materials) and identical soil groups. This is clearly shown by the summary of the moduli of deformation of the materials tested at a degree of compaction of $D_{Pr} \geq 100$ % in Table 3.

The values in Table 3 also show that compaction control of coarse-grained SBM, but also PBM, is not possible on the basis of the table values of ZTV E-StB 17 shown in Table 1:

- For recycled materials from processed mineral construction waste (RC C and RC M) of soil groups GW and GI, the table values of ZTV E-StB 17 for the static plate load test provide estimates for the degree of compaction D_{Pr} that are on the unsafe side. Some of these materials exhibit very high moduli of deformation E_{V2} above 100 MN/m² even with a degree of compaction $D_{Pr} \leq 100$ %. In this case, a degree of compaction of $D_{Pr} \geq 100$ % would be assumed when applying the table values of ZTV E-StB 17 due to the achieved modulus of deformation E_{V2}. Moreover, the ratio values E_{V2}/E_{V1} of the recycled materials of soil groups GW and GI are clearly above the maximum permissible ratio value of $E_{V2}/E_{V1} \leq 2.3$ despite sufficient degrees of compaction. This also counts for the PBM with rounded grains of soil group GI.

- For the recycled railway ballast (RC C/RB and RC RB) as well as for the electric furnace slags (EFS), moduli of deformation $E_{V2} \leq 100$ MN/m² were determined at a degree of compaction of $D_{Pr} \geq 100$ %. As these materials are assigned to soil groups GW, GI and SE, the table values of ZTV E-StB 17 apply for these materials. The ZTV E-StB 17 provides safe (but uneconomical) estimates of the degree of compaction D_{Pr} based on the modulus of deformation E_{V2}. However, the ratio values E_{V2}/E_{V1} are also significantly above the maximum permissible ratio of $E_{V2}/E_{V1} \leq 2.3$.

- With regard to the dynamic plate load test, the moduli of deformation E_{Vd} determined for all SBM of soil groups GW, GI and SE are below the table values of ZTV E-StB 17, despite degrees of compaction of $D_{Pr} \geq 100$ %. The table values of ZTV E-StB 17 thus provide a safe estimate of the degree of compaction D_{Pr}, but their application is not economical and it can be assumed that the required values cannot be achieved in practice.

Table 3. *Summary of the moduli of deformation of the materials tested at a degree of compaction of $D_{Pr} \geq 100$ %.*

Material	Soil group[1)]	E_{V1} [MN/m²]	E_{V2} [MN/m²]	E_{V2}/E_{V1} [-]	E_{Vd} [MN/m²]	E_{V2}/E_{Vd} [-]	Type of material
RC C 0/56	GW	≥ 31	≥ 153	≤ 5,2	≥ 29	5,3	Recycled concrete
RC C 0/16	GW	≥ 33	≥ 142	≤ 4,2	≥ 32	4,4	
RC M 0/56	GU	≥ 27	≥ 91	≤ 3,3	≥ 19	4,8	Mixed recycled materials
RC M 0/45_1	GI	≥ 23	≥ 134	-[2)]	≥ 25	5,4	
RC M 0/45_2	GI	≥ 22	≥ 104	≤ 4,7	≥ 25	4,2	
RC M 0/45_3	GI	≥ 26	≥ 90	≤ 3,4	≥ 30	3,0	
RC M 0/22	GU	≥ 28	≥ 102	≤ 3,6	≥ 24	4,3	
RC M 0/8	GU	≥ 28	≥ 88	≤ 3,0	≥ 20	4,4	
RC M 0/4	SU	≥ 16	≥ 58	≤ 3,6	≥ 23	2,5	
RC C/RB 0/45_1	GW	≥ 15	≥ 80	≤ 5,3	≥ 31	2,6	Recycled railway ballast
RC C/RB 0/45_2	GW	≥ 24	≥ 76	≤ 3,1	≥ 44	1,7	
RC RB 0/45	GI	≥ 16	≥ 56	≤ 3,4	≥ 35	1,6	
EFS 0/32	GW	≥ 11	≥ 84	≤ 6,5	≥ 15	5,6	Electric furnace slag
EFS 0/4	SE	≥ 15	≥ 92	≤ 6,5	≥ 20	4,6	
Pit gravel 0/22	GU	≥ 5	≥ 22	≤ 5,5	≥ 18	1,2	PBM
PBM, round 0/45	GI	≥ 31	≥ 135	≤ 4,2	≥ 39	3,5	
PBM, angular 0/32	GU	≥ 31	≥ 134	≤ 4,3	≥ 35	3,8	

1) according to DIN 18196 (DIN, 2011)
2) No specification, since the ratio E_{V2}/E_{V1} increases with increasing degree of compaction D_{Pr}

6 SUMMARY AND CONCLUSIONS REGARDING PRACTICE

In this paper, it was shown that with SBM, in connection with the compaction test in the laboratory (Proctor test) and the compaction control in the field according to the German earthworks regulations, material-characteristic peculiarities can occur, which must be taken into account.

In contrast to most PBM, the compaction curves of SBM with porous particles in the compaction test according to Proctor usually do not show a pronounced dependence on the compaction water content and do not exhibit a distinctive optimum. Instead, the compaction curves show linear increases or concave and convex curvatures. As a result, the derivation of a Proctor density as a reference value for compaction control in the field and the specification of an optimum compaction water content is no longer clearly possible. If no clear optimum is found, alternative possibilities must be used to determine the reference density for compaction control in the field. In this work, for example, the reference density was determined as the mean value of the three highest dry densities determined in the Proctor test. It would also be conceivable to average all dry densities achieved in the compaction test and to apply the standard deviation to this mean value. This assumes that the test results actually do not reveal any systematic trend for the correlation between the dry density and the water content. Since the compactability of SBM usually does not show a pronounced dependence on the water content, it is also not possible to specify an optimum compaction water content. For practical purposes, however, it would be useful to specify water content ranges for SBM within which good compactability can be expected.

With regard to compaction control, the investigations in the field have shown that volume replacement methods can be used as direct test methods to prove the degree of compaction D_{Pr}, taking into account method-specific uncertainties. In contrast, the applicability of the radiometric probe is not equally given for all SBM, and systematic test errors can occur with some SBM (e.g. electric furnace slags). These systematic deviations are due to the elementary composition of the respective SBM, for which the calibration of a radiometric probe is not applicable. If compaction control for SBM is to be carried out with the radiometric probe, it is recommended to first check the applicability of the calibration of the probe by means of comparative tests with a suitable volume replacement method. If the test values of both test methods match, the radiometric probe can be used for density and water content determination without further ado. If, on the other hand, the radiometric measured values systematically deviate from the values determined using the volume replacement method, compaction control can still be carried out using the radiometric probe. However, it is necessary to correct the values determined with the radiometric probe. Possibilities for correction were suggested in sections 5.1.1 and 5.1.2.

Since the moduli of deformation E_{V2}, E_{V1} and E_{Vd} increase with increasing degree of compaction D_{Pr}, relationship testing by means of static or dynamic plate load tests is possible in principle. Due to the discrepancies mentioned in section 5.2.3, however, it is recommended to determine the correlation between the respective modulus of deformation (E_{V2} or E_{V1} or E_{Vd}) and the degree of compaction D_{Pr} in advance in calibration tests, instead of using the table values provided in the ZTV E-StB 17. The procedure for carrying out such calibration tests is specified in Germany in TP BF-StB Part E 4 (FGSV, 2003). With regard to the practical usability of the correlation between the degree of compaction D_{Pr} and the respective modulus of deformation, a coefficient of determination of $R^2 \geq 0.65$ is requested according to TP BF-StB Part E 4. Since the results of the field tests have shown that a coefficient of determination of $R^2 \geq 0.65$ is difficult to achieve, we suggest to carry out compaction control by means of direct determination of the dry density achieved in the field.

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