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Density measurement of recycled materials with the nuclear gauge and rubber balloon method in earthworks

Mesure de la densité des matériaux recyclés à l'aide d'une jauge nucléaire et d'un ballon en caoutchouc dans les travaux de terrassement

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ABSTRACT: Large quantities of residual mineral masses are produced annually during construction and demolition works and as industrial by-products. With regard to the sustainable use of natural primary materials, emphasis is being placed in the construction industry on maximising the reuse of these masses as mineral substitute building materials (MSM). Large quantities of MSM are already being used in earthwork construction, where compaction has a decisive importance in ensuring the stability and long-term serviceability. For quality assurance purposes, the compliance of actual achieved in-situ densities with the required density shall be assessed. Two methods widely used for such compaction control in practice are the rubber balloon method and the nuclear gauge. In this paper the results of comparative investigations with these methods are presented, which were carried out on several MSM. The test results show that errors can occur in both test methods and that the material composition must be taken into account especially when using the nuclear gauge. For the case of errors due to the use of the nuclear gauge, simple correction possibilities are presented.

RÉSUMÉ: Chaque année, de grande quantité de masse minérale residuelle est produite pendant des travaux de construction et de démolition, ainsi que comme sous-produits industriels. En ce qui concerne l'utilisation durable des matériaux primaires, le secteur de la construction cherche à maximiser la réutilisation de ces masses en tant que matériaux de construction de substitution minéraux (MSM). Des grandes quantités de MSM sont déjà utilisées dans le terrassement, où le compactage a une importance décisive pour assurer la stabilité et l'aptitude au service à long terme. Afin d'assurer la qualité, une evaluation de la conformité des densités réellement atteintes in-situ avec la densité requise est nécessaire. Dans la pratique, deux méthodes sont principalement utilisées pour ce contrôle de compactage: la méthode du ballon en caoutchouc et la jauge nucléaire. Une étude comparative a été réalisée sur plusieurs matériaux de construction de substitution minéraux en utilisant ces deux méthodes. Les résultats montrent que des erreurs peuvent se produire dans les deux cas et que la composition du matérial doit être prise en compte, surtout lors de l'utilisation de la jauge nucléaire. En cas des erreurs dues à l'utilisation de la jauge nucléaire, des corrections simples sont présentées.

Keywords: density measurement, compaction control, nuclear gauge, rubber balloon method, recycled materials

1 INTRODUCTION

The importance of mineral substitute building materials (MSM) has increased significantly in recent years due to socio-economic reasons. Through their reuse in earthworks, valuable dump space for mineral residual masses can be saved and the usage of limited natural primary building materials can be reduced.

In earthworks, the compaction of fill material used is of particular importance. An increase in the density and the corresponding reduction in the void ratio reduces settlements (increased stiffness) and leads to an increase of the shear strength, which are essential for ensuring the stability and long-term serviceability. An essential component of quality assurance after compaction is the assessment of whether the required degree of compaction has actually been achieved. Common test methods used in practice are the rubber balloon method and the nuclear gauge. This paper shows the discrepencies that exist in the measurment of the density and water content between these methods and to what extent the material properties of MSM can lead to errors. For the case of errors arrising from the use of the nuclear gauge, simple correction possibilities are presented.

2 BASIC PRINCIPLES OF THE TEST METHODS

2.1 Rubber balloon method

The rubber balloon method is a volume replacement method that can be used on both fine and coarse-grained materials (Siedek et al. 1982). For the determination of the density a test hole is excavated manually in the field and it's volume is determined by pressing a rubber balloon filled with water into the test hole. After oven drying and weighing the excavated material the water content and the dry density achieved in the field can be determined.

The rubber balloon method is easy to carry out, but it is time-consuming and laborious. A single test takes about 30 minutes and it can take up to 24 hours to obtain the water content and the dry weight of the excavated material. Furthermore, the correct measurement of the volume of the test hole is difficult. Especially for coarse-grained and angular materials, the excavated test volume is not always representative, since comparatively large cavities in the wall of the test volume, which are difficult to detect with the rubber balloon due to its elasticity, can lead to errors. A possible deformation of the test hole during testing can also result in an incorrect measurement of the volume. The later is understandably more problematic for soft, deformable soils than for MSM, as they are usually relatively stiff after compaction. Further difficulties include the puncturing of the rubber bladder by sharp or angular particles or other components.

2.2 Nuclear gauge

Nuclear gauges determine the density and water content using nuclear radiation and measuring its intensity (e.g. Behr 1988, Regimand & Gilbert 1999, Viyanant et al. 2004). In contrast to the rubber balloon method, the test can be carried out very quickly (approx. five minutes per measurement), with the results being displayed immediately following the testing.

A measuring unit consists of a gamma and a neutron radiation source as well as gamma photon and neutron detectors. The fill material to be tested is irradiated and based on the calibration of the nuclear gauge, the resulting measurement of the radiation intensity can be correlated to the density and water content. The calibration of the nuclear gauge has therefore a decisive influence on the correct determination of the density and water content. Normally, calibration is done by the manufacturer of the gauges on large blocks of materials with defined density and with radiation absorption coefficients that are comparable to the main constituent elements mainly found in soils. (Regimand & Gilbert 1999, Behr 1988). Such a

calibration allows measurement of the density and water content with sufficient accuracy, provided the properties of the elemental composition of the material to be tested corresponds to the properties of the calibration medium. If the material to be tested contains elements whose interaction behaviour with the nuclear radiation differs significantly from that of the calibration standards, errors may occur in the determination of the density and water content (Viyanant et al. 2004, Behr 1988). In order to assess the accuracy of the resulting density and water content measurements, it is necessary to understand the basics of the radiometric measurement.

2.2.1 Determination of water content

The water content is determined using a neutron radiation source. The emitted neutrons are discharged and collide with the atomic nuclei of other elements, whereby the velocity and the energy of the neutrons are reduced. If the energy is reduced to a minimum, the neutrons are called thermalised neutrons (Viyanant et al. 2004). The reduction of the energy of the neutrons during a collision is greater the smaller the difference in mass between the neutron and the respective atomic nucleus (Behr 1988). Since only the element hydrogen has a mass corresponding to the neutron, with the masses of all other atom types contained in natural soil being significantly larger, fast neutrons are therefore almost exclusively decelerated by hydrogen to thermalised neutrons. The number of thermalised neutrons is recorded by the detector of the gauge and is a measure of the number of hydrogen atoms contained in the material to be tested. To determine the water content it is necessary to calibrate the correlation between the number of thermalised neutrons detected and the hydrogen atoms contained in the material to be tested (Regimand & Gilbert 1999).

It must be noted that the detected thermalised neutrons are only a measure of the hydrogen atoms contained in the material and not of the water molecules. If the material to be tested contains other hydrogen-containing compounds besides water, errors in the determination of the water content can occur. Viyanant et al. 2004, for example, have determined significantly higher water contents on recycled asphalt with the nuclear gauge than by oven drying. They attribute this to the hydrogen atoms contained in the bituminous binder. However, if elements that absorb thermal neutrons (e.g. iron and iron oxides) are contained in the material, the water content is determined as too low (Brandl 1977).

For the case that the water content should be determined for materials for which the calibration curve specified by the manufacturer is inapplicable, Behr 1988 proposed the following procedure in practice. First, the water content of the compacted material shall be determined by conventional measuring methods ($w_{conv.}$) as well as by means of the nuclear gauge ($w_{n.g.}$). If both results correspond, i.e. $w_{conv.} = w_{n.g.}$, the calibration curve specified by the manufacturer can be applied. If $w_{conv.} \neq w_{n.g.}$, the radiometrically determined water content $w_{n.g.}$ can be corrected by adding the correction value Δw, which is determined as the mean value of the differences $\Delta w_i = w_{conv.,i} - w_{n.g.,i}$ of several individual measurements. Δw can then be used to correct all further radiometrically determined water contents as long as the dry density of the material at which Δw was determined does not change or only changes by a few percent (Behr 1988).

2.2.2 Determination of density

For determination of the density, a gamma radiation source is used (Behr 1988, Viyanant et al. 2004). The gamma rays emitted by the radioactive isotope interact with the electrons in the shells of the atoms of the irradiated material, deflecting the gamma rays from their original directions and decreasing their energy. For higher densities of the radiated material, more gamma radiation is reduced or even absorbed. Since the energy of gamma rays detected by the

gamma photon detector (count ratio) is inversely proportional to the density of the material, it can be used to determine the materials density. However, since the chemical composition of MSM may differ from natural soils, the use of the nuclear gauge can lead to errors in the measured density due to an inappropriate calibration of the nuclear gauge. Especially in the case of elements with a high atomic number, which can absorb more gamma rays, the use of the nuclear gauge therefore can lead to higher density measurements than what are actually present in-situ (Viyanant et al. 2004).

If materials should be tested with the nuclear gauge for which the calibration given by the producer is not applicable, the problem often arises in practice that the user himself has no possibility of calibrating the gauge. In addition, the user usually does not know the radiation absorption coefficients of the material to be tested and of the material on which the calibration is based, from which a correction factor C_X could be determined (Behr 1988). Behr 1988 therefore proposes to determine C_X experimentally by comparing radiometrically determined densities $\rho_{n.g.}$ of the material to be tested with conventionally determined densities $\rho_{conv.}$. For sufficient accuracy, C_X is determined of more than one density measurements with both test methods. For this purpose the respective correction factor $C_{X,i}$ of each single measurement is first determined from the respective ratio $\rho_{conv.,i}/\rho_{n.g.,i}$. C_X is then determined as the mean value of all $C_{X,i}$ obtained. Once C_X has been determined, all further radiometrically determined densities $\rho_{n.g.}$ can be corrected by multiplying them with C_X without the necessity of conducting any further conventional density checks.

3 FIELD TESTING PROGRAMM

The tests were carried out on a total of ten different MSM. Five recycled building demolition waste mixtures (RC M) with grain sizes 0/56, 0/45, 0/8 and 0/4 mm, a railway ballast (RC RB) and a mixture of crushed concrete and railway ballast (RC C/RB) each with a grain size of 0/45 mm, recycled asphalt (RC A) 0/45 mm as well as electric furnace slag (EFS) with grain sizes 0/32 and 0/4 mm were considered in the investigation. The grain size distribution curves of the materials tested are shown in Figure 1.

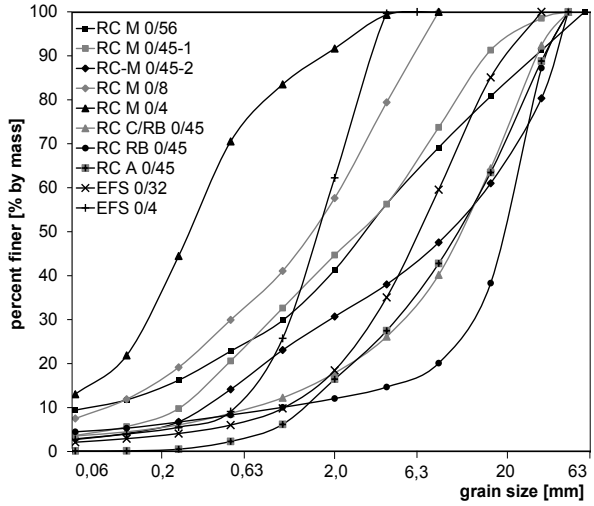

Figure 1: Grain size distribution curves of the materials tested

The materials were placed by a road paver in three layers, each about 25 cm thick and each layer was compacted by a compaction roller, resulting in a total height of about 50 and 60 cm after compaction. The rubber balloon method and the nuclear gauge (type Troxler 3440) were carried out immediately after compaction of the third layer. Before the measurements with the nuclear gauge, its functionality was checked with the reference standard. The density was measured in each case at three measuring depths between 30 cm and 5 cm and subsequently the three individual measurements were averaged. The water contents were determined by the gauge at the surface by the backscattering method. To perform the rubber balloon tests, a hole with a diameter d = 20 cm was excavated to a depth of about 1 to 1,5 times the diameter. As the experimental program was intended to compare densities and water contents measured

with the nuclear gauge to those measured with the rubber balloon method and by oven drying, the tests were carried out in close spatial position within a distance of less than 30 cm.

4 TEST RESULTS AND DISCUSSION

4.1 Determination of the water content

The water contents measured by the nuclear gauge ($w_{n.g.}$) and by oven drying (w_{oven}) are shown in Figure 2. The resulting average ratio $w_{n.g.}/w_{oven}$ of all tests conducted and the standard deviation of the ratio as well as the minimum and maximum ratio are given in Table 1 for each material. In addition, the correction value Δw according to Behr 1988, which was determined from all measured values for a material (cf. section 2.2.1), is given in Table 1.

Especially for the RC M materials, the water contents determined with both methods are in good agreement. Only for the RC M 0/56, distinct lower water contents are determined using the nuclear gauge. However, clear differences can be observed for the other materials. For the electric furnace slags, significantly lower water contents using the nuclear gauge were obtained than by oven drying. This can be attributed to the metal atoms with heavy atom nuclei (e.g. iron) which are contained in the electric furnace slags (Brandl 1977, Viyanant et al. 2004). These absorb more neutrons, so that fewer neutrons are recorded by the detector (Behr 1988), leading to lower water content recordings than are actually present. For the materials RC C/RB, RC RB and RC A, on the other hand, higher water contents were determined with the nuclear gauge than by oven drying. This is particularly noticeable for the RC A, and is probably a consequence of the hydrogen atoms contained in the bituminous binder, a petroleum product consisting of a mixture of hydrocarbon molecules, being misinterpreted by the nuclear gauge as water molecules (Viyanant et al. 2004). For the materials RC RB and RC C/RC, it could not be determined conclusively to what the higher water contents measured with the nuclear gauge can be attributed to. Possibly both materials contain hydrogen atoms within their mineral structure, which are detected by the nuclear gauge, but not by oven drying. For the RC C/RB, which also contains concrete, additional hydrogen atoms can also be contained in the possible admixtures, modifiers and cement content of the concrete (Nagi et Whiting 1999). For these materials, the water contents $w_{n.g.}$ determined with the nuclear gauge can be approximately corrected in practice by adding the correction values Δw given in Table 1.

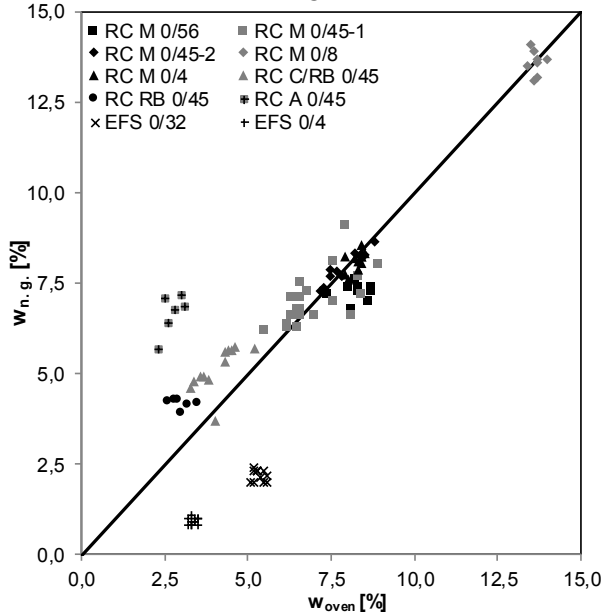

Figure 2: Water contents measured by nuclear gauge ($w_{n.g.}$) and by oven drying (w_{oven})

Table 1: Ratios of water contents ($w_{n.g.}/w_{oven}$) and correction values Δw

	$w_{n.g.}/w_{oven}$			$\Delta w = \frac{\sum_{i=1}^{n}(w_{oven,i} - w_{n.g.,i})}{n}$
	average	std. dev.	Min. to Max.	[%]
RC M 0/56	0,882	0,052	0,814 - 0,973	1,0
RC M 0/45-1	1,017	0,092	0,815 - 1,152	-0,1
RC-M 0/45-2	1,009	0,023	0,976 - 1,053	0,0
RC M 0/8	0,996	0,028	0,963 - 1,044	0,1
RC M 0/4	0,985	0,027	0,950 - 1,044	0,1
RC C/RB 0/45	1,263	0,136	0,925 - 1,412	-1,0
RC RB 0/45	1,411	0,166	1,200 - 1,635	-1,2
RC A 0/45	2,467	0,206	2,210 - 2,840	-4,0
EFS 0/32	0,409	0,033	0,357 - 0,462	3,2
EFS 0/4	0,272	0,024	0,242 - 0,313	2,4

4.2 Determination of the moist densitiy

The moist densities measured with the rubber balloon method ($\rho_{moist,r.b.}$) and the nuclear gauge ($\rho_{moist,n.g.}$) are depicted in Figure 3. The average ratios $\rho_{moist,n.g.}/\rho_{moist,r.b.}$ resulting from all tests conducted as well as the respective standard deviation and minimum and maximum ratios $\rho_{moist,n.g.}/\rho_{moist,r.b}$ are given in Table 2. Moreover, Table 2 contains the average correction factor $C_{x,moist}$ for each material according to Behr 1988, which allows for the correction of the radiometrically determined moist density $\rho_{moist,n.g.}$, if necessary (cf. section 2.2.2).

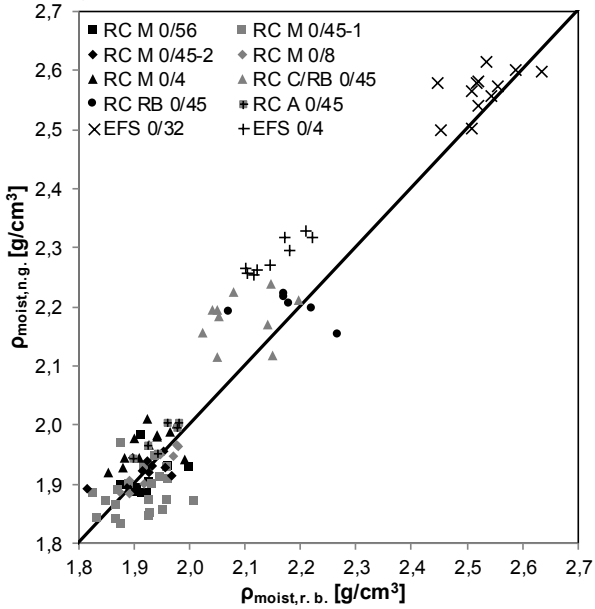

Figure 3: Moist densities measured by nuclear gauge ($\rho_{moist,n.g.}$) and rubber balloon method ($\rho_{moist,r.b.}$)

Again, for the RC M materials the moist densities measured with both test methods are in good agreement. This is also the case for RC A. Clear deviations occur with EFS and RC C/RB, where significantly higher moist densities are determined using the nuclear gauge which are probably again due to the heavy atomic nuclei in the materials EFS and RC C/RB, which absorb an increased amount of gamma radiation. It is noticeable that compared with EFS 0/4 the moist densities determined with the nuclear gauge for EFS 0/32 are only slightly higher than the moist densities determined with the rubber balloon method, despite having the same material composition as EFS 0/4. For RC RB, no clear results could be determined. Although the average ratio $\rho_{moist,n.g.}/\rho_{moist,r.b.}$ shows good agreement for both test methods for RC RB (cf. Table 2), the results show a comparatively large standard deviation and a relatively large difference between the minimum and maximum ratios. It can also be seen in Figure 3 that for the RC RB different moist densities are determined using the rubber balloon method, while the density determined with the nuclear gauge remains relatively constant.

For those materials whose radiometrically determined moist densities $\rho_{moist,n.g.}$ significantly differ from the moist densities $\rho_{moist,r.b.}$ determined using the balloon method, it is possible to make an approximate correction using the correction factors $C_{x,moist}$, given in Table 2, by multiplying the (further) radiometrically determined moist densities $\rho_{moist,n.g.}$ with the correction factor $C_{x,moist}$.

Table 2 Ratios of moist densities ($\rho_{moist,n.g.}/\rho_{moist,r.b.}$) and correction factors $C_{x,moist}$

	$\rho_{moist,n.g.}/\rho_{moist,r.b.}$			$C_{x,moist} = \frac{\sum_{i=1}^{n}(\frac{\rho_{moist,r.b.i}}{\rho_{moist,n.g.i}})}{n}$
	average	std. dev.	Min. to Max.	
RC M 0/56	0,992	0,021	0,964 - 1,037	1,009
RC M 0/45-1	0,988	0,029	0,930 - 1,048	1,013
RC-M 0/45-2	1,003	0,019	0,972 - 1,041	0,993
RC M 0/8	0,996	0,008	0,987 - 1,008	1,004
RC M 0/4	1,021	0,018	0,974 - 1,044	0,980
RC C/RB 0/45	1,035	0,033	0,985 - 1,075	0,967
RC RB 0/45	1,009	0,037	0,949 - 1,058	0,993
RC A 0/45	1,014	0,008	1,004 - 1,022	0,986
EFS 0/32	1,014	0,018	0,986 - 1,053	0,986
EFS 0/4	1,061	0,011	1,043 - 1,078	0,942

4.3 Determination of the dry density

For compaction control, the dry density, which can be determined from moist density and water content, is the decisive criteria. The dry densities resulting from water contents and moist densities of sections 4.1 and 4.2 are illustrated in Figure 4 and Table 3 again contains the average ratios $\rho_{dry,n.g.}/\rho_{dry,r.b.}$, the standard deviations and the differences between the minimum and

maximum ratios $\rho_{dry,n.g.}/\rho_{dry,r.b.}$ as well as the correction factor $C_{x,dry}$, which enables the correction of the radiometrically determined dry densities by multiplication with $C_{x,dry}$.

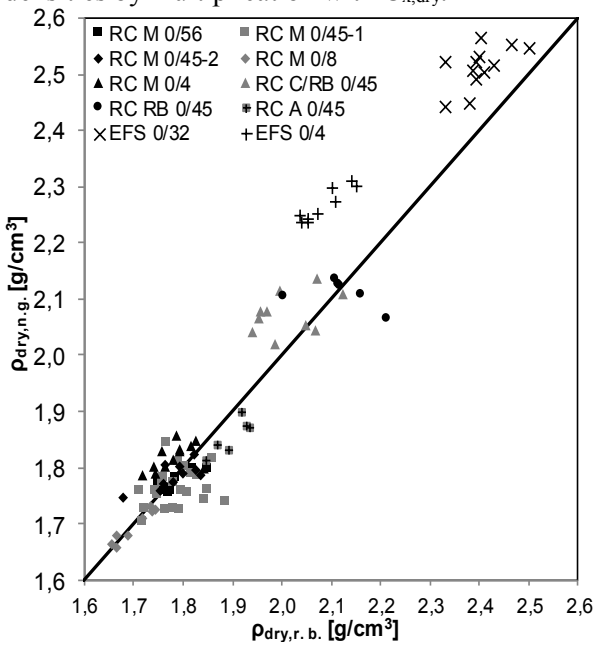

Figure 4: Dry densities measured by nuclear gauge ($\rho_{dry,n.g.}$) and rubber balloon method ($\rho_{dry,r.b.}$)

Like the moist densities and water contents, the dry densities of the RC M materials are in good agreement for both test methods. For RC A, higher moist densities were determined with the nuclear gauge on average, however since the water contents determined using the nuclear gauge were clearly too high, the resulting dry densities are lower than the dry densities determined with the rubber balloon method.

The dry densities of the EFS determined with the nuclear gauge, are contrastingly significantly higher than the dry densities resulting from the rubber balloon method which is attributed to the higher moist density and lower water content recordings. For the RC C/RB the dry densities showed a slightly better agreement between the two methods than the moist densities. Although the average ratio for RC RB is approximately 1 (cf. Table 3), no clear conclusion can be made, since the dry densities determined with the nuclear gauge are both significantly above and below the densities determined with the rubber ballon method.

The dry densities determined with the nuclear gauge can also be corrected by multiplying $\rho_{dry,n.g.}$ with the correction factor $C_{x,dry}$, given in Table 3. While the RC M materials and the RC A show good agreement with both test methods, correction is especially necessary for the EFS and RC C/RB. Since the dry densities of RC RB show a relatively large scattering, correcting the dry densities determined with the nuclear gauge with $C_{x,dry}$ does not necessarily result in correct values.

Table 3: Ratios of dry densities ($\rho_{dry,n.g.}/\rho_{dry,r.b.}$) and correction factors $C_{X,dry}$

	$\rho_{d,n.g.}/\rho_{d,r.b.}$			$C_{X,dry}=\frac{\sum_{i=1}^{n}(\frac{\rho_{dry,r.b.,i}}{\rho_{dry,n.g.,i}})}{n}$
	average	std. dev.	Min. to Max.	
RC M 0/56	1,001	0,020	0,973 - 1,043	1,000
RC M 0/45-1	0,987	0,028	0,922 - 1,045	1,014
RC-M 0/45-2	1,002	0,019	0,972 - 1,040	0,994
RC M 0/8	0,997	0,007	0,989 - 1,009	1,003
RC M 0/4	1,022	0,018	0,978 - 1,041	0,979
RC C/RB 0/45	1,025	0,032	0,982 - 1,063	0,977
RC RB 0/45	0,997	0,039	0,934 - 1,051	1,004
RC A 0/45	0,977	0,009	0,967 - 0,988	1,024
EFS 0/32	1,046	0,018	1,017 - 1,082	0,956
EFS 0/4	1,087	0,011	1,068 - 1,104	0,920

5 CONCLUSION

The suitability of the nuclear gauge and the rubber balloon method for measuring density and water content of MSM was evaluated in a series of field tests. The tests showed that both test methods can generally be applied to MSM and that the results of both test methods for most materials are in good agreement. However, for some materials, systematic differences in the determination of density and water content were found. Therefore, for practical purposes, for both density and water content determination, simple methods were presented, which enable the approximate correction of the the radiometrically determined densities and water contents with the aid of conventionally determined densities and water contents.

The discrepencies in density and water content measured by the two methods can be explained by the elemental composition of the respective materials, which can have a significant influence on the determination of moist density and water content with the nuclear gauge. Since the nuclear gauge measures hydrogen, for materials that have other sources of hydrogen atoms besides water molecules, the water content measurement was found to be significantly higher than that of the conventional method. For example, this was the case for the RC A. In contrast, for materials that contain elements that absorb neutrons (e.g. EFS), the water content measured with the nuclear guage was found to be too low. In the determination of the density, elements with a high atomic number, which absorb a greater amount of gamma radiation can lead to an overestimation of the density determined. This especially was the case for EFS and also for the RC C/RB. The results show that the precision of nuclear gauges depend in particular on the calibration and it's transferability to the material to be tested. For the use of the nuclear gauge on MSM, a separate calibration is therefore necessary. If no specific calibration for MSM is undertaken for the nuclear gauge, the radiometrically determined water contents and densities can be approximately corrected with the methods presented. For this purpose, in addition to radiometric measurements, measurements with conventional measuring methods like the rubber balloon method must also be carried out.

However, when using the balloon method, it must be taken into account that especially with coarse-grained materials the correct determination of the test volume is difficult and the results may be affected by errors. For the rubber balloon method the accuracy of the test method depend heavily on the representativity of the test volume excavated and the accuracy of the test execution.

It is recommended that the users of the nuclear gauge check, by means of comparison measurements with conventional test methods like the rubber balloon method, if the radiometrically measured densities and the water contents are reliable or whether a correction is necessary. However, it should be considered that despite high accuracy in the execution of the conventional testing method, the measurement results obtained are also not free from error.

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