Analysis of laboratory compaction methods of roller compacted concrete

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Abstract. Roller-Compacted Concrete (RCC) is an ordinary concrete poured and compacted with machines typically used for laying of asphalt road layers. One of the problems connected with this technology is preparation of representative samples in the laboratory. The aim of this work was to analyse two methods of preparation of RCC laboratory samples with bulk density as the comparative parameter. The first method used dynamic compaction by pneumatic hammer. The second method of compaction had a static character. The specimens were loaded by precisely defined force in laboratory loading machine to create the same conditions as during static rolling (in the Czech Republic, only static rolling is commonly used). Bulk densities obtained by the two compaction methods were compared with core drills extracted from real RCC structure. The results have shown that the samples produced by pneumatic hammer tend to overestimate the bulk density of the material. For both compaction methods, immediate bearing index test was performed to verify the quality of compaction. A fundamental difference between static and dynamic compaction was identified. In static compaction, initial resistance to penetration of the mandrel was higher, after exceeding certain limit the resistance was constant. This means that the samples were well compacted just on the surface. Specimens made by pneumatic hammer actively resisted throughout the test, the whole volume was uniformly compacted.

1. Introduction
Roller-Compacted Concrete (RCC) is an ordinary concrete poured and compacted with machines typically used for laying of asphalt road layers. RCC is not significantly different from conventional concrete. Aggregates, cement and water are basic components. Concrete should be sufficiently dry to support the weight of the roller and to avoid excessive deformation of the concrete layer, but moist enough to ensure good placement of cement paste.

Roller-compacted concrete is able to resist severe climatic conditions up to certain degree. In 1999, Pigott [1] made a visual study of RCC structures in Canada and the United States, the age of examined surfaces was from 4 to 20 years. In general, he found that the structures lacked the finest particles, surface scaling reached to the depth of 2 mm. However, the structures were compact and no substantial damage was visible. Therefore he came to a conclusion that RCC can be used for the construction of road infrastructure structures such as parking lots, airfields, temporary roads or landings.

The aim of this study was to assess the suitability of production of RCC samples in laboratory by globally recognized compaction procedure using a pneumatic hammer. This dynamic compaction
method was compared with the results of samples obtained by static compaction in loading machine that tried to simulate the same conditions as during rolling without vibratory mode (in the Czech Republic, only static rolling is commonly used).

Samples produced by pneumatic hammer were manufactured in accordance with standards (ASTM C1435 [2], ČSN EN 13286-4 [3]). However, the standards only define the process for the production of laboratory samples, they do not take into account the compliance with the manufacturing process at a construction site. Samples then may have significantly different characteristics than the material produced by rolling and as such they cannot be considered to be representative samples.

The results obtained on both types of laboratory samples were compared with core drills from the construction site.

2. Calculation of compaction parameters

Numerical expression of the degree of compaction can be done using the energy expended during compaction. Various methods use different test specimens and various principles of compaction. It was necessary to normalize the overall compaction energy applied to test specimens.

The first option was to relate the energy to the volume of the specimen. The second option was to relate the energy to the surface area of the tamping plate. As a reference test for determining the energy of compaction has been selected Proctor standard test (ČSN EN 13286-2 [4]). Equations (1) and (2) represent the calculation of the amount of compaction energy relative to the volume of the test specimen and the surface of the tamping plate. Weight of the hammer was 2.5 kg \( (m) \), hammer was dropped from the height of 0.305 m \( (h) \). Compaction was performed by 56 strikes \( (i) \) per layer in each of the three layers \( (n) \) in which the sample was compacted.

Energy related to the volume of the test sample (Proctor standard test):

\[
E_p = \frac{m \cdot g \cdot h \cdot n \cdot i}{V} = \frac{2.5 \cdot 9.81 \cdot 0.305 \cdot 3 \cdot 56}{0.002121} = 0.59 \, \text{MJ m}^{-3}
\]

Energy related to the surface of the tamping plate (Proctor standard test):

\[
E_p = \frac{m \cdot g \cdot h \cdot n \cdot i}{S} = \frac{2.5 \cdot 9.81 \cdot 0.305 \cdot 3 \cdot 56}{0.00196} = 0.64 \, \text{MJ m}^{-2}
\]

The objective was to calculate the time of compaction by pneumatic hammer \( (t) \) so that the energy introduced into the sample \( (E) \) was the same as in the Standard Proctor test. Equations (3) and (4) represent the calculation of the amount of compaction energy relative to the volume of the test specimen and relative to the surface of the tamping plate, respectively. Used pneumatic hammer had the impact energy of \( w = 5.9 \, \text{J} \) and impact frequency of \( o = 48 \, \text{impacts per second} \). The sample was compacted in three layers \( (n) \).

Energy related to the volume of the test sample (pneumatic hammer):

\[
E = \frac{w \cdot n \cdot o \cdot t}{V} = \frac{5.9 \cdot 3 \cdot 48 \cdot 2.5}{0.15 \cdot 0.15 \cdot 0.15} = 0.63 \, \text{MJ m}^{-3}
\]

Energy related to the surface of the tamping plate (pneumatic hammer):

\[
E = \frac{w \cdot n \cdot o \cdot t}{S} = \frac{5.9 \cdot 3 \cdot 48 \cdot 17}{0.15 \cdot 0.15} = 0.64 \, \text{MJ m}^{-2}
\]

Table 1 compares the amount of energy stored according to compaction methods. The aim was to get the same amount of energy for both methods.
Table 1. The amount of energy divided according to compaction methods.

|                          | Energy related to the volume of the test specimen (MJ/m$^3$) | Energy related to the surface of the tamping plate (MJ/m$^2$) |
|--------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Standard Proctor test    | 0.59                                                        | 0.63                                                        |
| Pneumatic hammer         | 0.64                                                        | 0.64                                                        |

When the compaction energy was related to the volume of the specimen, 2.5 s compaction time was necessary, when energy was related to the surface area of the tamping plate, 17 s compaction time was required. The results were different. Therefore, the compaction time of cubic samples for the selected pneumatic hammer was determined as an average of both times: 10 s.

For the static compaction method, the same approach could not be used as it would lead to unrealistic compaction force (approximately 240 kN – the molds would not withstand such a force). Therefore, the compaction force was determined according to the stress under the roller ($F$ is the force created by one drum of the roller, $A$ is the estimated contact area between the roller and the surface of RCC layer, both parameters were calculated from the data provided by the manufacturer of the roller):

$$\sigma = \frac{F}{A} = \frac{36.05}{0.045} = 802 \text{ kPa} \quad (5)$$

Equation (6) calculates the required force for the static compaction method:

$$F = \sigma \cdot A = 802 \cdot 0.0225 = 18.045 \text{ kN} \rightarrow 19 \text{ kN} \quad (6)$$

3. Production of the samples
The composition of RCC mixture used for the production of samples is given in Table 2.

Table 2. RCC mixture composition.

| Compound                      | kg/m$^3$ |
|-------------------------------|----------|
| Cement - CEM I 42.5 R         | 325      |
| Aggregates 0 – 4              | 1019     |
| Aggregates 4 – 8              | 631      |
| Aggregates 8 – 16             | 386      |
| Water                         | 105      |
| Air entraining admixture      | 0.2      |
| Water retarder                | 0.35     |

3.1. Static loading machine
Cubic samples were produced in plastic forms with dimensions of 150x150x150 mm. Total of 21 test samples were produced. Each sample was compacted in three 6 cm thick layers. In the end, final layer was created to receive smooth surface of the sample. The loss of thickness in each layer during compaction was around 1 cm.

For the compaction of test samples in the static loading machine, special compression tool was created (Figure 1) to simulate the same conditions as during rolling without vibratory mode in the laboratory. Basic acting force was $F = 19$ kN, which was derived in equation (6).
3.2. **Pneumatic hammer**

Production of test samples using a pneumatic hammer is addressed in detail in ASTM C1435 [2]. The standard specifies the requirements for the form and shape of the compaction tamping plate including tolerances. Standard specifies the requirements for the type of the hammer. Minimum power inputs should be 900 W, frequency at least 2000 impacts/min. These important parameters are not listed in the Czech standard ČSN EN 13286-4 [4]. Pneumatic hammer (Figure 2) was chosen to meet the parameters of ASTM C1435 [2].

Cubic specimens were produced in plastic forms in three layers, with the creation of the final layer by tamping plate (Figure 3) Time of compaction for one layer was determined as 10 s, see the explanation in section 2. A total of 21 samples were produced.

To compare the effect of the degree of compaction, another set of samples was produced. In this set, the samples were compacted to the maximum possible degree of compaction; these samples were compacted until no further compaction was possible.
3.3. Core drills
Core drills from the parking lot and driveway to the department store were extracted to compare the results of the laboratory samples with the material from the real structure. Weight of dual-drum rollers used during the construction was 7.5 tons, the rollers passed the concrete layer 4 times. The structure was compacted in one layer 20 cm thick. Roller worked only in static mode. The RCC mix composition was the same as in case of the laboratory samples. A total of 14 core drills were extracted.

4. Test results and discussion of results

4.1. Bulk density and compressive strength
For comparison of the various methods of compaction, bulk density was the main evaluation parameter, as an additional aspect the compressive strength was measured. The measured values of bulk density and compressive strength for the different methods are given in Table 3.

| Method                          | Bulk density (kg/m³) | Compressive strength (MPa) |
|---------------------------------|----------------------|-----------------------------|
| Standard Proctor test           | 2208                 | (-)                         |
| Pneumatic hammer t = 10s        | 2212                 | 40.2                        |
| Pneumatic hammer-max            | 2400                 | 61.9                        |
| Static loading machine F=19 kN  | 2042                 | 14.4                        |
| Core drills                     | 2181                 | 32.3                        |

Core drills had lower compressive strength and lower bulk density compared to the samples compacted by pneumatic hammer. Better result would be probably achieved with the use of dynamic compaction mode or in case that the structure was compacted in more layers [5], but only static rolling in one layer was used by the construction company due to economic reasons.

Static loading machine had the worst results of all the methods of compaction. Basic applied force was low. This confirms the assumption that to achieve comparable results, the acting force would have to be larger, which excludes this method from practical use.

Pneumatic hammer (time of compaction 10 s): The results show almost identical results of bulk density as the standard Proctor test and core drills, which was chosen as the target for verification.

Pneumatic hammer (maximum compaction): The measured results show that it is necessary to determine the parameters of the pneumatic hammer and subsequently to modify the compaction time accordingly. Samples had different characteristics than the material produced on site and samples cannot be considered as representative, which should be their purpose.

4.2. Immediate bearing index (IBI) test
Immediate bearing index expresses the ratio of the force required to push the mandrel by prescribed constant rate to a specified depth of the test sample to the force required to push the mandrel into a reference material [6]. It is therefore a comparative method. The test is used to measure the resistance of the base layers in road construction.

IBI was measured shortly after compaction. The diameter of the penetration mandrel was 50 ± 0.5 mm. The mandrel was pushed with the constant speed of 1.27 ± 0.2 mm / min into the test sample. As reference material was selected crushed limestone located in California (CBR = 100 %).

The test was carried out on three specimens of fresh concrete (immediately after compaction) compacted by different methods. The first specimen was compressed by the force of F = 19 kN in static loading machine. The second specimen was compressed by the force of F = 80 kN in static loading machine. Force was increased four times, because the basic applied force (F = 19 kN) was insufficient. Force of F = 80 kN was chosen due to the stability of forms. The last specimen was compacted by the pneumatic hammer with 10 s compaction time.
The main purpose of the test was to determine the quality of compaction through the sample height, which the bulk density cannot detect.

Sample compacted by static loading machine by the force of $F = 19 \text{ kN}$ resisted the worst against the penetration of the mandrel (Figure 6).

Sample compacted by static loading machine by the force of $F = 80 \text{ kN}$ led to a surprising result. After crossing the second point (5 mm penetration), the sample had a constant resistance to the penetration of the mandrel. This behaviour of the specimen can be explained by large compaction just below the surface of the compression tool, where the strongly compacted layer is located. After
breaking the surface of the sample and the formation of shear surfaces (Figure 5), the sample had constant resistance to the penetration of the mandrel.

The sample created by pneumatic hammer didn’t have the best result of IBI in compared points. However, sample had the best and longest resistance to penetration of the mandrel. This means that the sample was compact throughout the whole depth. Top of the curve was not reached even after 12 mm penetration.

5. Conclusions
The results confirmed the fact that the exact conditions of compaction by pneumatic hammer have crucial influence on the final properties of the sample. Parameters of pneumatic hammer must be taken into account, the time of compaction strongly influences the results. The time of compaction has to be exactly defined in order to obtain representative samples. If the compaction energy introduced into the sample is not regulated, the samples do not correspond to the material produced on the construction site.

The comparison of the results of core drills and samples produced by pneumatic hammer with exactly defined compaction time (10 s) showed that the parameters that influence the compaction were correctly selected. Core drills had similar results of bulk density and compressive strength as samples produced by pneumatic hammer, which confirms the correctness of the calculation.

Static loading machine is unsuitable for practical use. However, the results of samples produced by static loading machine clearly showed the difference between the static and dynamic compaction of RCC. Therefore it can be stated that the production of RCC structures by mere static compaction is unsuitable.

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