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Dmytro Rozmus, Khrystyna Sobol, Mykola Loik, Oleksii Hunyak

MIX DESIGN AND LABORATORY COMPACTION METHODS OF RCCP – A REVIEW

Lviv Polytechnic National University,
Department of Highways and Bridges
dmytro.i.rozmus@lpnu.ua

This article analyzes the difficulties in reproducing the actual circumstances of concrete compaction with rollers in the laboratory and mix design afeatures of RCCP (Roller Compacted Concrete Pavement). While quick and straightforward, the Proctor compaction test may not adequately reflect the field compaction achieved with rollers. Gyratory compactors simulate the movement of the rollers, providing a more realistic situation with greater accuracy. However, they are expensive and require specialized knowledge. Due to the Vibratory hammer limited application and unrealistic vibration pattern compared to rollers, it is mostly used in laboratories for sample preparation rather than compaction. A vibrating table is effective for less rigid RCC mixture combinations and provides good compaction, although it does not perfectly simulate the action of a roller. The paper also underlines the need to create a link between density and moisture content to achieve maximum RCC performance.

Key words: roller-compacted concrete, pavement, compaction methods, gyratory compactor, moisture content, aggregate grading.

Introduction

As a result of the full-scale Russian-Ukrainian war, there is a need to replace the already classic technology of asphalt concrete pavement. Due to the constant terrorist attacks by the aggressor country, the Ukrainian market suffers from a shortage of bitumen due to the destruction or damage to bitumen plants, and logistics problems as a result of the fighting. To circumvent this problem, it is proposed to use the roller compacted concrete pavement technology, which is already known in Western countries and the United States and has proven itself over the years.

Roller-compacted concrete (RCC), which takes its name from the construction method used to place it, is a slump-free concrete in the uncured state. It is defined as «concrete compacted by a roller» according to (ACI 207.5R) or "A super-stiff or stiff mixture of materials of the selected composition, obtained by mixing coarse and fine aggregate, binding material, batching water, and, if necessary, chemical and mineral additives and fiber, which is used for arranging rigid layers of pavement, using an asphalt paver and road rollers" as described in newly proposed project of Ukrainian standard (USS XXXX:202X "Compacted concrete mixes and rolled concrete. Technical characteristics").

This ensures effective consolidation, which is critical to achieving satisfactory density, strength (compressive strength can be greater than 60 MPa), smoothness, and surface texture. RCCP is placed without joints, formwork, finishing, steel reinforcement, or dowels. These properties make compacting concrete with rollers simple, fast and economical. Roller compacted concrete owes much of its cost-effectiveness to high-speed construction methods.

RCC began its journey in the 1930s in Sweden, where it was used to make paving stones. In the construction of dams, compacted roller concrete began its initial development with the construction of the Alpe Gera dam near Sondrio in Northern Italy between 1961 and 1964. The concrete was placed in a similar shape and method but was not rolled. RCC was touted in engineering magazines during the 1970s as a revolutionary material (U. A. C. O. Engineers, 2000). Initially, RCC was primarily used for backfill, foundations, and concrete sidewalk construction.

In general, RCC has been used for heavy-duty pavements such as tank hardstands, log handling yards, intermodal yards, freight depots, and other special applications. However, in the past ten years, RCC has also been proven to be a cost-effective pavement for many conventional pavement applications, including warehouse facilities, industrial access roads, large commercial parking areas, intersection replacements, roadway inlays, and residential streets. Two of the most significant RCC paving projects in the USA have been for the auto industry: the Saturn automobile plant in Tennessee was completed in 1989, with Approximately 500 000 m^2 of a 180-mm-thick pavement was placed for parking areas and access roads. Approximately 830 000 m^2 of 175-mm-thick pavement was placed in 2003 for the Honda manufacturing facility in Alabama.

Today, RCC is used when strength, durability, and cost-effectiveness are paramount. It is used for the construction and rehabilitation of dams, roads, airfields, parking lots, power plants, roadsides, storage facilities, military installations, and other industrial complexes. Depending on the desired thickness and width of the installation, concrete can be placed very quickly – from 60 to 120 meters per hour.

The use of RCC in public and private construction programs has steadily increased in recent years, especially in the construction of low-traffic roads and parking lots (Larson, 2008).

However, one of the biggest challenges of using RCC is the lack of laboratory compaction methodologies that can simulate actual field conditions well. There are a limited number of laboratory studies and field experiences in the literature that indicate significant differences between field and laboratory results. For example, LaHucik and Roesler conducted a study that showed that samples of the same size when determining compressive strength between a laboratory and a field core were statistically different by 95 % at the confidence interval. While this can be attributed to the lower density and more significant variation obtained in the field, it was specifically noted that a 4 % decrease in density compared to the laboratory resulted in a 45 % loss of strength in the field. Another study reported that a 1–2 % loss in RCC density could result in a 10–17 % reduction in strength (Adaska, 2006).

Features of RCC pavement and its differences from conventional cement concrete

The use of RCC is characterized by the technical, economic, and environmental advantages of rigid pavements compared to non-rigid ones (Harrington et al., 2010; LaHucik, Roesler, 2017). Among these advantages of rolled concrete are a 15–20 % reduction in the cost of pavement using it compared to asphalt concrete or monolithic cement concrete pavement; increased durability and lack of rutting compared to asphalt concrete pavement; paving without the use of formwork, production without the use of imported materials and radical re-equipment of the road enterprise. The main advantages of the technology include the absence of metal reinforcement. The material is 25–30 % cheaper than cast concrete. Compared to asphalt concrete, the cost per 1 m^2 is 15–18 % less, and the service life is more than 25 years.

Roller Compacted Concrete has the same basic ingredients as conventional concrete: cement, water, sand, and aggregates. But unlike conventional concrete, it is a drier mix–stiff enough to be compacted by vibratory rollers. Typically, RCC is constructed without joints. It needs neither forms nor finishing nor does it contain dowels or steel reinforcing. Nevertheless, RCCP can be reinforced with fibers in order to improve durability, flexural strength, load transfer capacity, and so on (Amer, Storey & Delatte, 2004).

If well designed, the RCC will develop high compressive strength and good durability, i.e., 40 N/mm^2 at 3 days for a cement content of 300 kg/m^3 and a W/C ratio of 0.35. Moreover, this type of concrete is less sensitive to cracking in relation with drying shrinkage. In road construction, RCC is generally laid down 20 cm thick by means of motor graders, which will ensure the flatness and uniformity of the surface. Compaction is assured by pneumatic tire rollers and finishing rollers. Belgian Guidelines define the minimum requirements for such a type of concrete used in road foundations: BSC 20 and BSC 30 samples (100 cm^2 cores), with a cement content of minimum 200 kg/m^3 and 250 kg/m^3, respectively, must reach an average compressive strength of 20 and 30 N/mm^2, respectively, at the age of 90 days. Today, RCC is used for any type of industrial or heavy-duty pavement. The reason is simple. RCC has the strength and performance of conventional concrete with the economy and simplicity of asphalt.

Also, in cold areas, the concrete pavement is resistant to frost cycles in the face of possible damage. In addition, due to the impermeability of the constituting materials, as consistent pavement, there is no environmental problem in its application range. The gray and neutral color of the RCCP also has a good temperature absorption coefficient and helps lower the ambient temperature (Tolmachev, 2017).

In addition, due to the high stiffness of the rolled compacted concrete mix, traffic can be opened faster than with a conventional monolithic pavement.

The dense structure of the RCC made it possible to reduce the use of binder in the composition without losing strength. Limit requirements for the properties of the mixture allow the use of local materials and production waste (ACI 207.5R-11; Semenenko & Smirnova, 2019).

Other advantages of RCC include the ability to use equipment that contractors already have. For example, a grader can be used for paving in small areas, and an asphalt paver can be used for large volumes of concreting.

The cost of pavement construction when RCCP is used can be 15–30 % lower than if conventional rigid pavement or asphaltic pavement. In terms of environmental sustainability, RCCP requires lower cement content to achieve the desired cement, which greatly reduces cement consumption, CO_2 emission during cement production, and heat of hydration during mixing. On the other hand, some of the deficiencies of RCCP include lower tensile strength, high stiffness, and the possibility of cracking due to drying shrinkage. In addition, due to no reinforcing bar used, all applied loads on the RCCP are transferred through aggregate interlock to the lower courses, with the corresponding effects such as tensile cracks, fatigue cracks, fatigue damage, expansion and contraction, thermal and shrinkage cracks are all resisted by the RCC concrete strength alone.

In addition to economic benefits, the RCC is considered a "green" concrete because the cement consumption in the RCC is lower as the RCC mixtures are normally designed with leaner binder content. Mineral admixtures are used extensively in RCC mixtures. The use of large amounts of mineral admixtures improves durability and reduce adiabatic temperature rise of concrete, construction costs, and greenhouse gas emission accompanied by the manufacturing of cement clinker. Class F and Class C fly ashes, slag, and natural pozzolan have been used as mineral admixtures in the RCC (Mishutin, Solonenko & Leonova, 2018).

RCC mixtures typically contain a lower volume of cementitious materials, coarse aggregate, and water than conventional concrete mixtures and a higher volume of fine aggregates that occupy air voids (pores) in the pavement system (Fig. 1). Fine aggregates in RCC are more densely distributed than in conventional concrete.

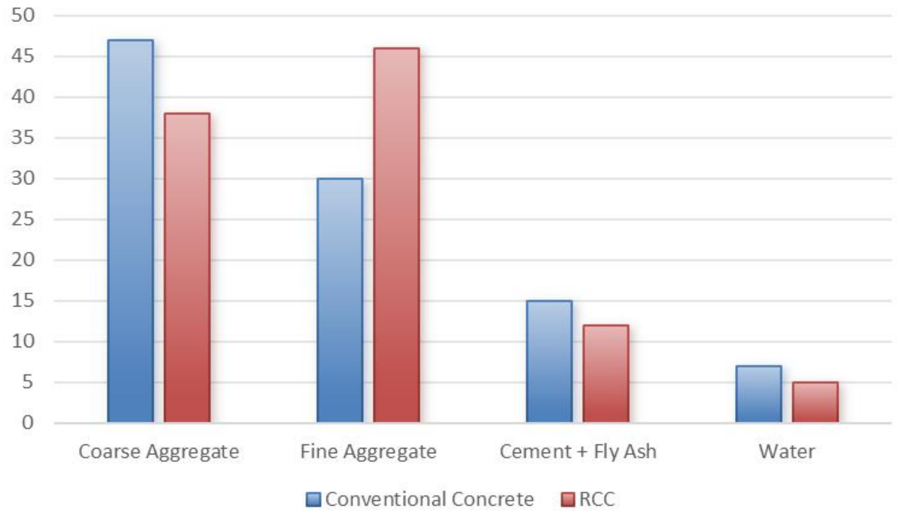

Fig. 1. Comparison of the quantity of materials of conventional concrete and RCC, wt. %

This type of compaction initially provides high friction (adhesion of aggregates) between the particles and contributes to the initial load-bearing capacity of the pavement. The design of all concrete pavements involves mechanical (compaction) and chemical (hydration) processes. As for conventional asphalt pavement and RCC pavement, compaction is carried out by roller or pneumatic wheeled rollers with the sequential use of light, medium, and heavy rollers (Courard, Michel & Delhez, 2010). As with conventional concrete, the mixture hardens through hydration to bind the aggregate particles in the RCC mixture. The result is a dense pavement that has properties similar to those of conventional concrete pavement. Immediately after placement, conventional concrete is in a plastic state until hydration begins, and the mixture hardens and binds all aggregates together. A conventional concrete pavement does not have sufficient load-bearing capacity to support the occasional traffic of light vehicles until the necessary minimum tensile strength is reached or passed (Larson, 2008).

RCC compaction methods

All RCC compaction methods involve establishing a relationship between the density and moisture content of the RCC mixture to obtain maximum density by compacting samples over a range of moisture contents.

Different moisture contents are selected for a fixed percentage of cementitious materials to produce a moisture density plot similar to the one shown in Figure 2. For most aggregates, the optimum moisture content is 5 % to 8 %. It is recommended that the moisture content be varied within this range or within a range selected based on previous experience with the aggregates under test (Larson, 2008).

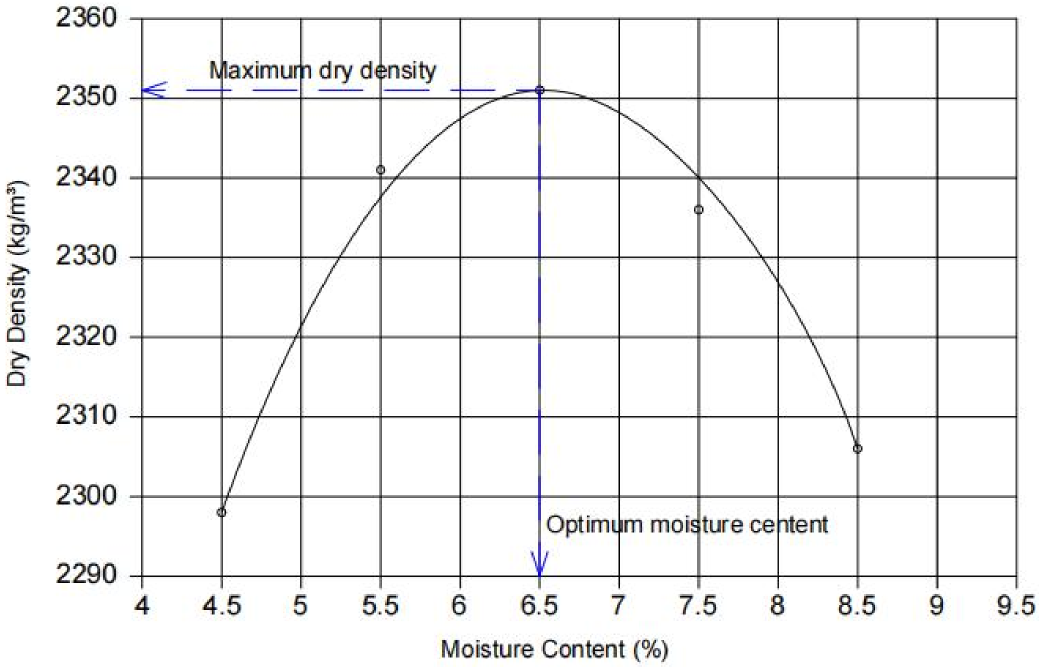

Fig. 2. Moisture-density curve of RCC

There are the following compaction methods:

- proctor method (manual/semiautomatic);
- gyratory compactor (Super Pave);
- vibration with a load (Vibrating Hammer);
- vibrating table.

The Proctor compaction test is a laboratory method for determining the optimum soil moisture at which the soil becomes the most dense. The test is named after the American engineer Ralph Roscoe Proctor (Courard, Michel & Delhez, 2010). Soil compaction is performed for different moisture contents, and in each case, the dry density is determined. Next, a graphical dependence of the dry density on the moisture content (compaction curve) is plotted (Rooholamini, Hassani & Aliha, 2018) This will make it possible to estimate the density of the mixture that can be obtained on construction sites and provide a reference parameter for assessing the compaction of the mixture layer. It was chosen to display the results of the study because the main advantage of this test is that the results of the maximum density test become available faster since there is no need to dry the compacted sample, and it also displays the most accurate results for a given granulometry.

This method is used for mixtures with a maximum aggregate size of 63 mm and larger, up to 25 % by weight. The laboratory setup includes cylindrical molds, a tamper, and a steel plate.

In Ukrainian regulatory documents, there are no standards for compaction methods performed using a vibratory hammer, vibrating table and a gyratory compactor, but they also need to be given special attention since each of the proposed methods has its advantages and disadvantages.

The Gyratory compactor (SUPERPAVE method) is used to compact concrete mixtures in the laboratory. This method simulates the compaction process that occurs when the concrete mixture is placed on the road using vibratory rollers. Unlike other systems that rely on impact compaction, the gyratory compactor employs a mix of vertical consolidation pressure and gyratory kneading effort to achieve optimal laboratory conditions. Furthermore, gyratory compactors provide significant advantages by obtaining the necessary density and compaction rates with varying kneading numbers (Ashrafian,Gandomi, Rezaie-Balf & Emadi, 2020; Semenenko & Smirnova, 2019).

In the study by Şengün et al., 60 compaction cycles were used because the reference density that can be achieved with 50-60 compaction cycles corresponds to the desired density for RCC (Şengün, Alam, Shabani, & Yaman, 2019).

Gyratory compactors offer several benefits over other laboratory compaction methods. They simulate the compaction process that occurs on the road, which results in more accurate results. Additionally, they provide a high level of accuracy when compacting concrete mixtures. Furthermore, this method allows for the study of various compaction parameters, such as the inclination angle and rotation speed, and their effects on the properties of the concrete mix.

While gyratory compactors have several advantages, they also have some drawbacks. One of the main disadvantages is the cost of the equipment, which can be expensive. Additionally, this method can be complex and should only be used by qualified personnel. Finally, the compaction process can be time-consuming and labor-intensive.

The Vibrating Hammer is not a common way of compacting concrete mix for goods on building sites. Rather, laboratories utilize it for reasons other than the primary compaction process.

When sampling concrete to assess its strength or other qualities, a vibratory hammer can be used to compact the mix. It can be an alternative to a manual or internal vibrator, particularly for mixes with a high crushed stone content that are difficult to compact using conventional methods. Also, a vibratory hammer may be used to examine the impact of various vibration modes on concrete characteristics. This can help optimize compaction procedures on building sites. The disadvantage of this method is that it does not simulate real compaction, as the vibration from the hammer is different from that of the roller used on the construction site. As a result, this approach does not provide fully reliable information about the behavior of concrete during compaction. Also, a limited application must be considered - a vibratory hammer is designed for tiny samples, not for compacting vast volumes of concrete on a construction site (Mohammed & Adamu 2018; Omran, Harbec, Tagnit-Hamou & Gagne, 2017).

In conclusion, vibratory hammers cannot replace traditional methods of compacting concrete mix on construction sites, as shown above. However, it can be an effective tool for laboratory testing and the production of concrete samples.

Compacting concrete using a vibrating table involves using a vibrating table, an external vibrator that causes the upper part of the table to vibrate. One or two appropriately dimensioned unbalanced motors generate this vibration, which can vary in frequency and centrifugal force depending on the concrete being compacted. The centrifugal force can be adjusted to the optimum compaction parameters for compacting concrete. The vibrating table is typically used for stiff to extremely dry concrete mixtures commonly used in roller-compacted concrete construction, as it is more efficient than rodding or internal vibration for these types of mixes. The process is carried out by filling cylindrical molds with concrete and then compacting it to a predetermined density using the vibrating table. The compaction process continues until the concrete is fully compacted, as indicated by the surface texture of the concrete, which should appear closed and bright after compaction (USS XXXX:202X; Day, 2001).

Conclusions

Regardless of the compaction process employed, determining the link between density and moisture content is critical for getting the highest RCC density. Most aggregates have an ideal moisture content of 5–8 %. While the Proctor method can be considered to offer simplicity and speed, gyratory compactors provide the most realistic simulation of field compaction and high accuracy for RCC. Vibratory hammers have niche applications in laboratory testing, and vibratory tables are helpful for specific RCC mixtures. The choice of method depends on factors such as project requirements, budget, and experience.

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Д. І. Розмус, Х. С. Соболь, М. М. Лоїк, О. М. Гуняк
Національний університет “Львівська політехніка”,
кафедра автомобільних доріг та мостів

РОЗРАХУНОК СКЛАДУ СУМІШІ ТА ЛАБОРАТОРНІ МЕТОДИ УЩІЛЬНЕННЯ УКОЧУВАНОГО ЦЕМЕНТОБЕТОННОГО ПОКРИТТЯ – ОГЛЯД

Здійснено огляд сучасних методів проєктування сумішей для укочуваного бетонного покриття (Roller compacted concrete pavement - RCCP) та особливостей їх складу. Досліджено різні підходи до вибору компонентів бетонної суміші, зокрема вміст цементу, водоцементне співвідношення, використання мінеральних добавок і додаткових в’яжучих матеріалів для досягнення оптимальних характеристик міцності та довговічності. Підкреслено, що оптимальне співвідношення між вологістю та щільністю є критичним фактором, який впливає на міцність і довговічність бетонного покриття, а вивчення впливу складу суміші на її кінцеві властивості є важливим напрямом подальших досліджень. Вказано на необхідність розроблення та впровадження нових лабораторних підходів і методів ущільнення RCCP, оскільки це особливо важливо для покращення методів проєктування бетонних сумішей, оптимізації процесів ущільнення та забезпечення високої якості дорожніх покриттів.

Основну увагу звернено на оцінювання ефективності та доцільності використання різних методів ущільнення бетону, таких як метод Проктора, гіраторне ущільнення та вібраційне ущільнення. Зазначено, що традиційний метод Проктора, хоча й широко використовується завдяки простоті та швидкості, не завжди здатен адекватно відтворювати реальні умови ущільнення, що виникають під час укочування бетону в польових умовах. Метод гіраторного ущільнення є однією з найперспективніших технологій для лабораторного моделювання реальних умов ущільнення бетону, здатності імітувати обертовий рух котків. Методи вібраційного ущільнення не повністю відображають реальні технологічні умови влаштування укочуваних бетонних покриттів на будівельних майданчиках. Також зроблено висновки щодо подальших досліджень для підвищення ефективності використання RCCP у дорожньому будівництві.

Ключові слова: укочуваний цементобетон, дорожнє покриття, методи ущільнення, гіраторний компактор, вологість, гранулометричний склад заповнювача.