

IN-LB

Inch-Pound Units

SI

International System of Units

Compaction of Roller-Compacted Concrete— Report

Reported by ACI Committee 309

ACI PRC-309.5-22



American Concrete Institute
Documents
Document Sharing Hub



Compaction of Roller-Compacted Concrete—Report

Copyright by the American Concrete Institute, Farmington Hills, MI. All rights reserved. This material may not be reproduced or copied, in whole or part, in any printed, mechanical, electronic, film, or other distribution and storage media, without the written consent of ACI.

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at <http://concrete.org/Publications/DocumentErrata.aspx>. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided “as is” without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised the ACI Collection of Concrete Codes, Specifications, and Practices.

38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Compaction of Roller-Compacted Concrete—Report

Reported by ACI Committee 309

Eamonn F. Connolly, Chair

Timothy P. Dolen
Christopher John Eagon
Chiara F. Ferraris
Dimitri Feys

John F. Gibbons
Vincent E. Hunt
Paul Jaworski
Hoa Lam

Patrick F. O'Brien Jr.
Larry D. Olson
H. Celik Ozyildirim
Steven A. Ragan

Luke A. Sevcik

Consulting Member

Jerome H. Ford

Roller-compacted concrete (RCC) is an accepted and economical method for the construction of dams and pavements. Achieving adequate compaction is essential to the development of the desired properties in the hardened material. The compaction depends on many variables, including the strength of the subbase, materials used in RCC, mixture design proportions, mixing and transporting methods, discharge and spreading practices, compaction equipment and procedures, and lift thickness. The best performance characteristics are obtained when the concrete is reasonably free of segregation; well-bonded at construction joints; and compacted at, or close to, maximum density.

This report summarizes experience in compaction of RCC in various applications and offers guidance in the selection of equipment and procedures for compaction, as well as for quality control of the work. Compaction equipment and procedures should be appropriate for the work. In dam or massive concrete applications, large, self-propelled, smooth, steel-drum vibratory rollers are most commonly used. The frequency and amplitude of the roller should be suited to the mixture and lift thickness required for the work. Other roller parameters, such as static mass, number of drums, diameter, ratio of frame and drum mass, speed, and drum drive influence the rate and effectiveness of the compaction equipment. Smaller equipment, and possibly thinner compacted lifts, are required for areas where access is limited.

ACI Committee Reports and Guides are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

Pavements are generally placed with paving machines that produce a smooth surface and some initial compacted density. Final density is obtained with vibratory rollers. Rubber-tired rollers can also be used where surface tearing and cracks would occur from steel-drum rolling. The rubber-tired rollers close fissures and tighten the surface.

Inspection during placement and compaction is also essential to ensure the concrete is free of segregation before compaction and receives adequate coverage by the compaction equipment. Testing is then performed on the compacted concrete on a regular basis to confirm that satisfactory density is consistently achieved. Corrective action should be taken whenever unsatisfactory results are obtained. Roller-compacted concrete offers a rapid and economical method of construction where compaction practices and equipment are a major consideration in both design and construction.

Keywords: compaction; consolidation; dams; pavements; roller-compacted concrete.

CONTENTS

CHAPTER 1—INTRODUCTION, p. 2

- 1.1—Introduction, p. 2
- 1.2—Scope, p. 2
- 1.3—Description of RCC construction, p. 2
- 1.4—Importance of compaction, p. 3

CHAPTER 2—DEFINITIONS, p. 3

- 2.1—Definitions, p. 3

ACI PRC-309.5-22 supersedes ACI 309.5R-00(06) and was adopted and published July 2022.

Copyright © 2022, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording or otherwise, without reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

CHAPTER 3—MIXTURE PROPORTIONS, p. 3

- 3.1—General, p. 3
- 3.2—Moisture-density relationship, p. 5
- 3.3—Coarse and fine aggregates, p. 5

CHAPTER 4—EFFECTS ON PROPERTIES, p. 6

- 4.1—General, p. 6
- 4.2—Strength, p. 6
- 4.3—Watertightness, p. 8
- 4.4—Durability, p. 8

CHAPTER 5—EQUIPMENT, p. 9

- 5.1—General, p. 9
- 5.2—Vibratory rollers, p. 9
- 5.3—Rubber-tired rollers, p. 10
- 5.4—Small compactors, p. 10
- 5.5—Paving machines, p. 11
- 5.6—Roller-compacted concrete mixing plants, p. 11

CHAPTER 6—PLACEMENT AND COMPACTION, p. 11

- 6.1—General, p. 11
- 6.2—Minimizing segregation, p. 12
- 6.3—Placement and compaction in dams and related work, p. 12
- 6.4—Grout-enriched RCC placement and consolidation, p. 14
- 6.5—Placement and compaction of pavements, p. 18

CHAPTER 7—CONSTRUCTION CONTROL, p. 20

- 7.1—General, p. 20
- 7.2—Consistency and moisture content, p. 20
- 7.3—In-place density, p. 21
- 7.4—Maximum density, p. 21
- 7.5—Strength, p. 22
- 7.6—Inspection of compaction operations, p. 22

CHAPTER 8—CONCLUSIONS, p. 23**CHAPTER 9—REFERENCES, p. 23**

Authored documents, p. 24

CHAPTER 1—INTRODUCTION**1.1—Introduction**

Roller-compacted concrete (RCC) has become an accepted material for constructing dams and pavements, rehabilitating and modifying existing concrete dams, and providing overflow protection of embankment dams and spillways. The production of RCC provides a rapid method of concrete construction similar in principle to soil-cement and other earthwork construction. Roller-compacted concrete technology developed considerably in the 1980s, after early research by Cannon (1972), Dunstan (1977), and Hall and Houghton (1974), and the development of the roller-compacted dam (RCD) method in Japan in the 1970s. Also in the 1980s, RCC found application in roadways and parking areas, and was developed as a heavy-duty paving material

for log sorting yards, tank hardstands, railroad sorting yards, and other industrial pavements. Detailed information on the use of RCC in mass concrete and paving applications is contained in ACI 207.5R (Report on Roller-Compacted Mass Concrete) and ACI 327R (Guide to Roller-Compacted Concrete Pavements), respectively.

1.2—Scope

This report discusses the equipment and special construction procedures associated with the compaction of RCC, including characteristics of the mixture relevant to compaction and the effects of compaction on the desired properties of RCC. These properties include various strength parameters, watertightness, and durability. Differentiation is made between RCC used in massive concrete work and that used in pavements. The discussion also includes provisions for measurement of compaction. This report does not cover soil-cement or cement-treated base.

1.3—Description of RCC construction

Roller-compacted concrete gets its name from the heavy vibratory steel drum and rubber-tired rollers used to compact it into final form. Fresh RCC is stiffer than typical zero-slump conventional concrete, with a consistency that is stiff enough to remain stable under vibratory rollers, yet plastic enough to permit adequate mixing and distribution of paste and placement without segregation. RCC pavements are usually placed in lifts of 6 to 8 in. (150 to 200 mm) with a 4 in. (100 mm) minimum and 10 in. (250 mm) maximum. For RCC dams, multiple lifts of concrete, generally 1 ft (300 mm) thick, are often continuously placed and compacted to construct a cross section that is a conventional concrete gravity dam. Variations in placing and compaction methodology have evolved in the past 20 years. For example, the sloping layer method (SLM) is to place five to 10 consecutive lifts on slopes ranging as steep as 20 horizontal to one vertical (H:V) to as flat as 50H:1V instead of horizontal lifts. Another RCC placing method, used primarily in Japan, is to spread three or more thin (approximately 9 in. [230 mm]) layers with a bulldozer before compacting them into one thick lift with a vibratory roller. One significant difference between an RCC dam and a conventional concrete dam is RCC dams are continuously placed from one abutment to the other, or within a series of larger (than typical dam) monoliths. A horizontal construction joint is produced between each lift in the RCC dam. In paving applications, individual lanes of concrete are placed adjacent to each other. The procedure is similar to asphalt-paving techniques. In some instances, two or more lifts of RCC are quickly placed and compacted to construct a thicker monolithic pavement section for heavy-duty use. Roller-compacted concrete is an economical, fast construction candidate for many pavement applications (Cannon 1972).

Several steps are required to achieve proper compaction of RCC construction:

1. A trial mixture should be developed to determine the water content necessary for optimal compaction.

(ASTM C1170/C1170M) and density (ASTM C1170/C1170M) for each application.

2. A trial section should be constructed to validate the number of passes and establish the required moisture content and density.

3. The RCC should be placed on freshly compacted material, or if the surface is not freshly compacted, it can have several different lift surface treatments depending on the maturity of the previously placed lift. This can range from simple air-blowing, to vacuum cleaning, to full treatment as a cold joint.

4. For dams, roll from one abutment to the other continuously.

5. Consolidate the dam facing concrete, if used, and the interface between the dam facing and the freshly placed and compacted RCC. Refer to ACI 207.5R for various types of dam facing. For pavements, the top lift should be placed within 60 minutes of the lower lift (although this interval is dependent on the mixture and environmental conditions) to allow for adequate bonding between layers.

6. Roll the proper number of passes before placing the next lift.

7. Use a tamper or small compactor along edges where a roller cannot operate.

8. Record test results and maintain a site quality-control program.

1.4—Importance of compaction

The effect of compaction on the quality of RCC is significant. Higher density relates directly to higher strength, lower permeability, and other important properties. RCC mixtures are generally proportioned near the minimum paste content to fill voids in the aggregate, or at a water content that produces the maximum density when a compactive effort equivalent to the modified Proctor procedure (ASTM D1557) is applied. The use of RCC in either massive structures or pavement construction needs to address the compaction of each lift because of its influence on performance. Failure to compact the concrete properly can lead to greater risk of seepage paths and reduce the stability in RCC dams or reduce the service life of RCC pavements. Using the “maximum density” theory for soils compaction, RCC for dams would have a moisture content that is 1 to 2% “wet of optimal,” whereas RCC pavements are proportioned closer to “optimal” for density. This difference is due to the thicker lifts and larger aggregate common in dams compared to pavements, where segregation of the coarse aggregate and difficulty in compacting thicker lifts is a concern.

In the 1980s, core sampling from RCC dams revealed instances of voids and low density in the lower one-third of lifts of RCC that had been placed and compacted in 1 ft (300 mm) lifts (Drahushak-Crow and Dolen 1988). Although lower density at the bottom of lifts can be attributed to lack of compactive effort, it is more commonly due to insufficient workability for full-depth compaction and segregation of the mixture during the construction process. This causes excessive voids in the RCC placed just above the previously compacted lift. Segregation is a major concern in

dams because it can lead to greater risk of seepage and the potential for a continuous lift of poorly bonded RCC from one abutment to the other, which could affect the sliding stability. Roller-compacted concrete dams constructed in earthquake zones can also require tensile strength across the horizontal joints to resist seismic loading. At Willow Creek Dam, seepage through a non-watertight upstream face and segregation at lift lines required remedial grouting (USACE 1984). This RCC dam was considered safe from a sliding stability standpoint due to its conservative downstream slope of 0.8 horizontal to 1.0 vertical. The construction of RCC arch-gravity dams with very steep downstream slopes necessitates bonding across lift joints and is critical to the stability of these structures. It is now common in RCC dams to have a Vebe consistency ranging from 10 to 20 seconds in accordance with ASTM C1170/C1170M using a 27.5 lb (12.5 kg) surcharge. Some mass mixtures are being placed at higher Vebe consistency and others are being placed with Vebe times less than 10 seconds and may even use internal vibration adjacent to formwork (Dolen et al. 2019).

In pavements, flexural strength is dependent on thorough compaction at the bottom of the pavement section, while durability is dependent on the same degree of compaction at the exposed surface (Amer et al. 2004; Delatte and Storey 2005). Furthermore, construction joints between paving lanes are locations of weakness and are particularly susceptible to deterioration caused by freezing and thawing, unless good compaction is achieved.

CHAPTER 2—DEFINITIONS

2.1—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions.

The terms “compaction” and “consolidation” have both been used to describe the densification process of freshly mixed concrete or mortar. In ACI 309R, “consolidation” is the preferred term used for conventional concrete work. For the purposes of this document on RCC, however, the term “compaction” will be used for all types of RCC mixtures because it more appropriately describes the method of densification.

CHAPTER 3—MIXTURE PROPORTIONS

3.1—General

Roller-compacted concrete (RCC) mixtures should be proportioned to produce concrete that will readily and uniformly compact into a dense material with the intended properties when placed at the design lift thickness. Procedures for proportioning RCC mixtures are provided in ACI 211.3R, ACI 207.5R for mass concrete, and ACI 327R. Also, the mixture design process should consider the desired engineering properties, construction requirements, and economics. This can be completed using several mixture proportioning methods that have been used successfully for roller-compacted concrete pavement (RCCP) structures. However, the most common mixture proportioning methods

Table 3.1—Examples of RCC mixture designs

Mixture	NMSA	Water	CM	Sand	Coarse aggregate	Slump (in.) or Vebe time (s)	Percent air gravity	Percent pozzolan
CS	0.75	250	585	1010	2010	2 to 4 in.	4.6	23
CL	2	225	370	1170	2070	2 in.	4.1	30
CFE	1	235	630	1400	1555	0.5 in.	5.2	40
RCC-D	2	168	428	1150	2205	17 s	1	68
RCC-D-AEA	2	143	300	1285	2190	13 s	5.2	60

are variations of the following two general approaches (Harrington et al. 2010):

1. **Soil compaction approach:** A cement-aggregate approach, with the mixture determined by optimal moisture content and maximum dry density, used primarily in pavement and RCC overtopping protection.
2. **Consistency or workability approach:** A water-cementitious materials ratio (w/cm) approach, with the water content proportioned for optimal consistency and the mixture determined by absolute volume, used primarily in concrete dam applications.

A side-by-side comparison of RCC mixtures proportioned by both methods is given in “Roller Compacted Concrete Density: Principals and Practices” (PCA 2004). Whichever method is employed, the goal is to produce an RCC mixture that has sufficient paste volume to coat the aggregates in the mixture and to fill in the voids between them (ACI 327R). An example of the difference in several RCC mixture proportions is shown in Table 3.1 (Dolen et al. 1988; USBR 2017).

For the purposes of this report, compaction of mass RCC, such as in dams, and RCC pavements must be approached differently. Mass RCC typically has a nominal maximum size aggregate (NMSA) of 1-1/2 to 2 in. (37.5 to 50 mm) and has a stiff to very dry consistency, as discussed in ACI 211.5R and ACI 211.3R, whereas RCC pavement has an NMSA less than 0.75 in. (20 mm) and requires an extremely dry consistency to provide a smooth, flat rolling surface.

For a given ratio of cementitious materials (including cement, fly ash, and silica fume) sand, fines (passing the No. 200 [75 μ m] sieve size), and coarse aggregate, the workability and ability to compact RCC effectively will be governed by the free-water content. As the water content increases from the optimal level, the workability increases until the mixture will no longer support the mass of a vibrating roller. As the water content decreases from the optimal level, sufficient paste is no longer available to fill voids and lubricate the particles, and compacted density is reduced.

Roller-compacted concrete mixtures have no measurable slump; the consistency is usually measured by Vebe consistency time in accordance with ASTM C1170/C1170M. The Vebe time is measured as the time required for a given mass of concrete to be consolidated in a cylindrically shaped mold. A Vebe time of 5 seconds is similar to zero-slump concrete (no-slump concrete), and at such consistency, it is difficult to operate a roller on the surface without weaving, pumping, and sinking. For RCC mixtures used in dam work, a Vebe time of approximately 15 seconds is suitable for compaction in four to six passes with a dual-drum, 9 tonne (10 ton) vibratory roller. A normal range would be 15 to 20 seconds.

At Victoria Dam Rehabilitation, the Vebe consistency of RCC ranged from approximately 15 to 20 seconds in the laboratory (Reynolds et al. 1993). In the field, the water content of the RCC was decreased and the Vebe consistency increased to approximately 35 to 45 seconds (Reynolds et al. 1993). The Vebe consistency test was not as reliable an indicator of workability at these consistency levels. Compaction was achieved by up to eight passes with a 9 tonne (10 ton) dual-drum vibratory roller at this consistency. Roller-compacted concrete mixtures with a high consistency time, up to 180 seconds, have been compacted in the laboratory (Harrington et al. 2010). Roller-compacted concrete of this consistency required two to three times more compactive effort to achieve the equivalent percent compaction than mixtures with a lower consistency (Casias et al. 1988). A Vebe time of 30 to 40 seconds appears to be more appropriate for RCC pavement and overtopping protection mixtures. It is now common to have a Vebe consistency of 10 seconds with a range from 6 to 15 seconds.

Roller-compacted concrete pavement should be designed using well-graded aggregates to optimize paste content; minimize void space; reduce segregation; and provide a dense, smooth, tight surface (Harrington et al. 2010). Roller-compacted concrete mixtures often require a higher proportion of fine aggregate to coarse aggregate than conventional concrete. Roller-compacted concrete aggregates should meet the quality requirements of ASTM C33/C33M or other agency-approved sources. Roller-compacted concrete mixtures can benefit from the addition of nonplastic fines (material passing the No. 200 [75 μ m] sieve) to supplement the cementitious paste volume and reduce internal voids between aggregate particles. Fines generated by aggregate quarry crushing operations ranging from approximately 4 to 6% by mass of total aggregate are now commonly specified in RCC dams. For mixtures with higher Vebe times, the increased fines improve handling and compactability (Schrader 1988). Some RCC mixtures have no measurable consistency, and the optimal water content for compaction is determined by visual inspection during mixing and compaction (Snider and Schrader 1988). If the moisture content is too low or there is insufficient rolling, the density at the bottom of the lifts is reduced and the bond between lifts is usually poor. This problem is corrected by first placing a bonding mortar or thin layer of high-slump concrete on the surface of the previously placed and compacted lift to bond the two together.

Roller-compacted concrete pavement mixtures can be made with any of the basic types of hydraulic cement, blended cements, or a combination of hydraulic cement and supplementary cementitious materials. It is important

to consider the rate of strength gain and heat of hydration when deciding on the type of cementitious material that is to be used in the RCCP mixture. Cementitious materials should meet the requirements of [ASTM C150/C150M](#), [ASTM C595/C595M](#), or [ASTM C1157/C1157M](#).

Fly ash (Class F or C), and water-reducing and set-controlling admixtures such as retarders, can be beneficial in the compaction of RCC mixtures. The effectiveness of these materials, however, depends on the specific mixture composition. Fly ash, when used to replace a portion of the cement, can decrease the water requirement of mixtures having a measurable consistency ([ACI 207.5R](#)). Fly ash can also be used as a mineral filler in low-paste-volume mixtures to increase workability and density of the RCC. At Elk Creek Dam, using water-reducing, set-controlling admixtures reduced the water content of RCC approximately 14% and reduced the Vebe consistency from 20 to 10 seconds compared with mixtures without the admixture. This improved the workability of the mixture and the ease with which the RCC could be consolidated ([Hopman and Chambers 1988](#)). Retarding admixtures are increasingly being used to extend the setting time of RCC and have initial set ranging from 16 to 24 hours or more. Successive lifts can be intimately compacted and bonded without an identifiable lift line.

Chemical admixtures such as water reducers, retarders, accelerators, and high-range water-reducing admixtures (HRWRAs) can be used in RCCP mixtures just like conventional concrete. However, due to the dry nature of an RCCP mixture, these admixtures typically need to be added at higher dosages to achieve the desired performance. Like conventional concrete, any admixture considered for use in an RCC mixture should be tested prior to use to determine its effects on fresh and hardened RCCP properties.

Air-entraining admixtures (AEA) improve both the workability of fresh RCC and resistance to freezing and thawing of hardened RCC in dam applications ([Dolen 1991](#)). Air-entrained RCC from the U.S. Army Corps of Engineers (USACE) test sections at the North Fork Hughes River Dam met the requirements of [ASTM C666/C666M](#) Procedure A for freezing-and-thawing-resistant concrete in water ([McDonald 2002](#)). The dosage of AEA may have to be increased to achieve air-entrained RCC meeting the desirable ranges of air-void parameters found in conventional air-entrained concrete. Air-entraining admixtures were specified in several U.S. Bureau of Reclamation projects. The water content of RCC mixtures with AEA decreased for comparable Vebe consistency. The compactive effort required for these mixtures was comparable to RCC with no entrained air. Entraining a consistent amount of air in RCC is difficult, particularly with mixtures having no measurable slump. Air-entraining admixtures should be tested for effectiveness with project materials, mixing, and placing equipment before being specified. The pressure air content of RCC can be tested using a standard air meter attached to a vibratory table with a surcharge for consolidating the sample. Air-entraining admixtures have not been used extensively in RCCP because acceptable freezing-and-thawing resistance

was achieved without air entrainment ([Ragan et al. 1990](#)). However, some work still needs to be completed because the practicality of producing air-entrained RCC in the field has not yet been demonstrated ([Harrington et al. 2010](#)).

3.2—Moisture-density relationship

Roller-compacted concrete mixtures have also been proportioned using soil-compaction methods that involve establishing a relationship between density and the moisture content of the RCC. The method is similar to that used to determine the relationship between the moisture content and density of soils and soil-aggregate mixtures ([ASTM D1557](#)). This method can result in a mixture that has inadequate paste to completely fill voids between aggregate particles at the optimal moisture content and, consequently, depends more on expulsion of voids through compactive effort. For a given compactive effort, the optimal moisture content of a mixture proportioned using this method is defined as the peak of the moisture-density curve and is dependent on the properties of the aggregates used and the cementitious material content. Strength loss will occur in a mixture that has a moisture content below the optimal moisture content due to the presence of additional entrapped air voids. Strength loss will also occur in a mixture if the moisture content is significantly above optimal due to an increase in the w/cm . The strength loss above the optimal moisture content is not as dramatic as the strength loss below optimal because more paste volume is available for bonding particles ([Reeves and Yates 1985](#)).

3.3—Coarse and fine aggregates

Coarse aggregates meeting [ASTM C33/C33M](#), [AASHTO M 6](#), and [AASHTO M 80](#) standards are recommended for RCC pavement mixtures. Coarse aggregates are often limited to a nominal maximum size aggregate (NMSA) of 3/4 in. (19 mm) to prevent segregation and achieve a tight surface. Typical NMSA varies from 5/8 to 3/4 in. (16 to 19 mm). However, NMSAs larger than 3/4 in. (19 mm) (up to 1-1/2 in. [38 mm]) can be used and, if properly proportioned (with adequate fines), can render a high-quality finish. Larger NMSAs are typically used for nonwearing course or secondary applications where surface appearance is not highly important ([Harrington et al. 2010](#)).

Fine aggregates used in RCC pavement should meet the durability requirements specified in [ASTM C33/C33M](#). The use of aggregate fractions finer than the No. 200 (75 μ m) sieve, if the fines are nonplastic, may help reduce fine aggregate voids in RCC mixtures. The selection of fine aggregates is crucial because it determines the water requirement (and, therefore, the cement consumption), compactibility, surface smoothness, and durability of the RCC. River sand is a good source of concrete sand; however, manufactured sand is also widely accepted and used in RCC production. Screenings from crushed rock may also be used with care taken to ensure the consistency of the product ([Harrington et al. 2010](#)).

The NMSA normally affects the ease of compaction of RCC due to the tendency of large aggregate to segregate from the no-slump mixture and form a thin bed on the construction joints. For class RCC placed in 12 in. (300 mm)

layers, the NMSA in RCC mixtures should not exceed 2 in. (50 mm), and good placing control should be maintained. The NMSA of some RCC mixtures has been increased to 6 in. (150 mm) by placing multiple 8 in. (200 mm) layers by bulldozing and compacting the mass into a 30 in. (750 mm) lift with vibratory rollers followed by pneumatic tire rollers (Japan Ministry of Construction 1984). The current trend is to use 1-1/2 to 2 in. (37.5 to 50.0 mm) NMSA to minimize segregation problems. In RCC pavement mixtures, a 3/4 in. (19.0 mm) NMSA is recommended for producing a relatively smooth surface texture (ACI 327R).

In addition to NMSA, the degree to which the aggregate grading is controlled will have a significant influence on the uniformity of RCC properties, the ease of compaction, and achieving uniform density of the mixture. Where close grading control is desired, coarse aggregate should be produced and batched in separate size ranges, as recommended in ACI 304R. Some facilities have cut costs in stockpiling and batching by using a single-graded aggregate or by increasing the size range of the stockpiled material. This practice, however, can increase the variation in total grading of the aggregate in stockpiles and cause difficulty in producing uniform RCC mixture during construction.

CHAPTER 4—EFFECTS ON PROPERTIES

4.1—General

Proper compaction of roller-compacted concrete (RCC) is essential to achieve the necessary properties intended for performance and design service life. The degree of compaction influences strength, watertightness, and durability of RCC (Delatte and Storey 2005; Amer et al. 2004).

4.2—Strength

The strength properties of RCC depend on the amount of cementitious materials, w/cm , quality of aggregates, and degree of compaction of the concrete. Although the strength of RCC is a function of many variables, the degree of compaction throughout its entire thickness is perhaps the most significant. The densely graded aggregates used in RCC mixtures help the concrete achieve high levels of compressive strength. The low w/cm of RCC mixtures produces a low-porosity cement matrix that also contributes to the high compressive strength of the concrete. Every mixture proportion has an optimal moisture content at which it achieves the maximum dry density. This density most often provides the maximum strength (Harrington et al. 2010), provided it can be fully compacted. Test results from many RCC paving projects indicate that small reductions in pavement density cause relatively large reductions in both compressive and flexural strengths (Rollings 1988). A 5% reduction in the density of cores taken from several Australian pavements resulted in an approximate reduction in compressive strength of 40%. Abrams and Jacksha (1987) reported a 2.3% decrease in RCC pavement density in Oregon that resulted in a 11% decrease in flexural strength. Rollings (1988) also noted that the performance of RCC pavements is adversely affected when adequate compaction is not achieved at the bottom of the lift; the bottom of the pavement section (where the highest flexural stresses from loading occur) was 25% weaker in flexure tests than the top of the pavement. At Galesville Dam, Oregon, USA, the compressive strength of cores from a mixture with a higher cement-plus-pozzolan content than the interior concrete had a lower compressive strength due to lower density in this outer facing zone of RCC (Drahushak-Crow and Dolen 1988). Figures 4.2a and 4.2b show the reduction in compressive strength of RCC

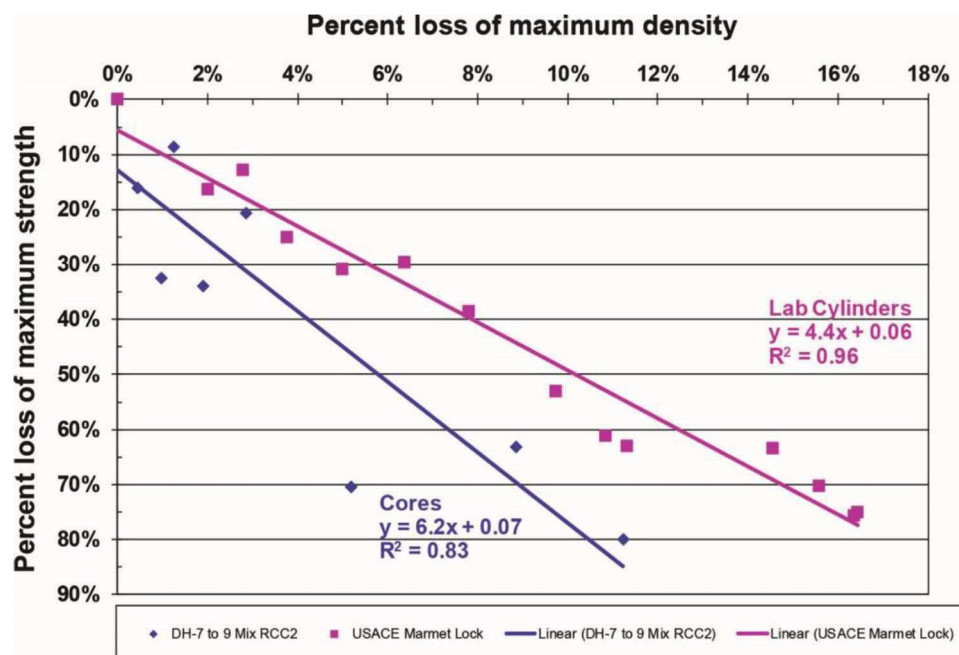


Fig. 4.2a—Reduction in compressive strength due to deduction in density of mass RCC cores and cast RCC cylinders (Dolen 2011).

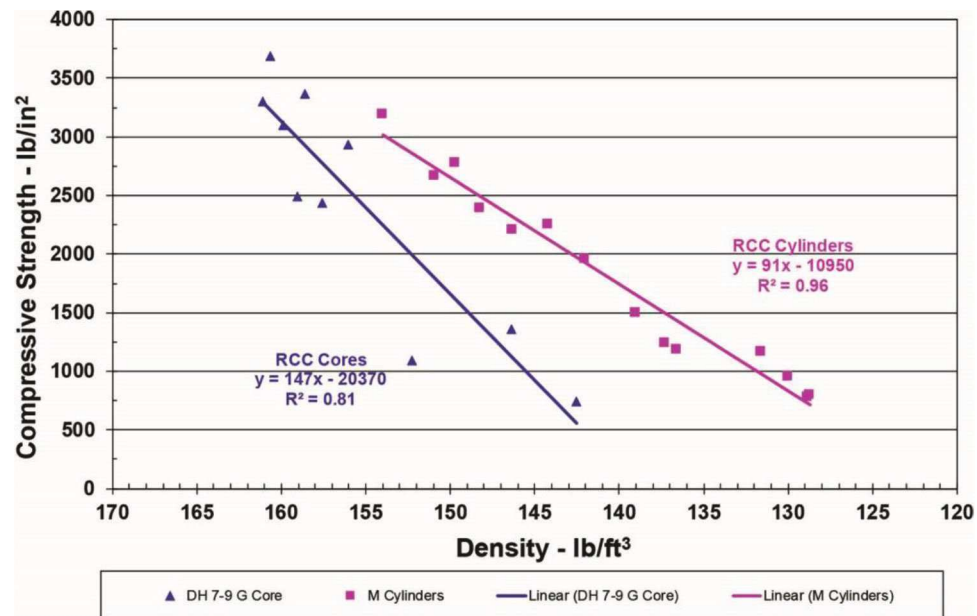


Fig. 4.2b—Relationship between compressive strength and density of mass RCC cores and cast RCC cylinders (Dolen 2011).

Table 4.2—Shear strength properties of RCC cores with and without voids from incomplete compaction (Dolen 2011)

	Parent concrete		Lift lines	
	Cohesion, lb/in. ²	Internal friction, degrees	Cohesion, lb/in. ²	Internal friction, degrees
All tests	500	48	320	60
USD—14 year (90% bond)	595	45	450	54
Lean without voids (50 to 65% bond)	380	33	135	69
Lean with voids (25% bond)			105	41
Lean with bedding (90% bond)			325	57

cores and cast cylinders from two project investigations. For each 1% of entrapped or entrained air that can be removed from any concrete by consolidation that is not removed, the compressive strength is reduced by approximately 5%. Both bond percentage and shear strength properties are also significantly reduced by insufficient compaction at the lift line interface. Table 4.2 shows the shear properties of RCC as affected by compaction. Roller-compacted concrete with full compaction (little or no voids present) achieved approximately 90% bonded lift lines, whereas RCC with voids had 25 to 65% bonded lifts and approximately one-third the shear cohesion values.

Flexural fatigue failure occurs in pavements when the concrete cracks due to continued repetitions of loads that cause stresses less than the static flexural strength of the concrete. The U.S. Army Engineer Waterways Experiment Station conducted flexural fatigue tests on laboratory specimens compacted by external vibration to a density of approximately 98% of the theoretical air-free density. The test results indicated that both the flexural and flexural fatigue resistances of a typical RCC mixture are comparable to those of conventional concrete paving mixtures (Pittman and Ragan 1986). Tayabji and Okamoto (1987b) also found that the fatigue behavior of beams sawn from

a well-compacted RCC test section was similar to that of conventional concrete.

The direct tensile strength or tensile bond strength of RCC lift joints is critical in multiple-lift pavements because it determines whether the pavement will behave as a monolithic section or as separate, partially bonded, or unbonded lifts. The load-carrying capacity of a pavement consisting of partially bonded or unbonded lifts is significantly less than that of bonded lifts of equal total thickness. Joint tensile strength is typically performed on cores drilled normal to the joint using the direct tension test (USBR 1992c) and USACE (1992b). For the pavement to function as a monolithic section, the joint tensile strength should be at least 50% of the parent concrete tensile strength. However, cores taken from RCC test pads at the Tooele Army Depot in Utah and tested for direct tensile strength indicated that 60 to 90% of the parent concrete tensile strength can be achieved if the time between placement and compaction of the lifts is limited to 30 to 50 minutes (Hess 1988). Placing and compaction within the time limits was achieved by using two pavers in echelon. Direct shear test data from cores taken from Conley Terminal in Boston, MA, USA, indicated strength development along edges of longitudinal construction joints was approximately half the strength as that of interior lift locations (ACI 327R). The unconfined edge of an RCC pave-