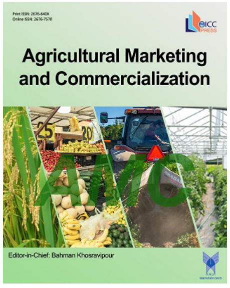

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Original Article

Investigation and Evaluation of Roller-Compacted Concrete Environmentally Friendly Mix with an Emphasis on Rigid Pavement and Compressive Strength

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Abstract:

The RCC constituents are plain concrete including aggregates, water, cement, dispersants, and additives (admixtures). However, some RCC features, such as zero-slump, roller bearing capacity, and RCC placing, have overcome the weaknesses in plain concrete. Despite the similarities between plain concrete and RCC, RCC mix design cannot be achieved by applying a few simple changes to plain concrete mix design, such as reducing water volume, changing the water-cement ratio, increasing the number of fine aggregates, etc. Given the importance of the topic, this paper aims to investigate and evaluate the RCC mix with an emphasis on rigid pavement and compressive strength. To achieve this by using the library (desk research) method, a comparison was first made between concrete (rigid) and asphalt (flexible) pavements. Then, the position of RCC in concrete pavements, the selection of RCC consumables, and the determination of the mix design were investigated. The results showed that one of the most important mechanical properties of concrete is compressive strength which is strongly affected by the concrete mix design. Parameters such as cement grade, water-cement ratio, cement substitutes, etc. affect concrete compressive strength. It is difficult to predict concrete compressive strength due to the existence of many parameters. In mix design proportioning methods, it is attempted to reduce production costs. It is time-consuming and costly to use building code methods for calculating mix design and the building code conditions and assumptions must be met for all concrete components. Hence, artificial intelligence (AI)-based methods such as fuzzy logic and artificial neural networks (ANNs) are being used successfully today. These models have generally been derived from laboratory experiments and investigations.

Keywords: Roller-Compacted Concrete (RCC), Concrete Pavements, Consumables Selection, Mix Design

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INTRODUCTION

The American Concrete Institute (ACI) defines RCC as concrete that can be rolled by a roller when it is fresh, which ultimately results in a compacted concrete, i.e., the roller compaction means. In the flat state, many of the RCC properties are similar to those of plain concrete, except that an RCC can be constructed whose properties in the hardened state is outside the defined range of plain concrete. Roller compaction is the process by which concrete is compacted using vibratory rollers (Ranjbar, 2020).

RCC is used in two completely different contexts whose differences must be taken into account. The first is the use of RCC in dam construction, a low-cement concrete with a compressive strength usually less than that of plain concrete (Mansoori, 2023).

The second area is the use of RCC pavement (RCCP), with high-cement content, compressive strength usually greater than 30 MPa, and mix design with controlled size and material grading over a specified range. The RCC can be used in pavement construction as the main coating for providing the carrying capacity of pavement structures. The RCCP design is similar to the process of designing Jointed Plain Concrete Pavement (JPCP) with contraction joints or non-doweled construction joints. The major difference between RCC and plain concrete is the pavement construction method, joint spacing, and surface (coating) appearance. RCCP is defined as a stiff, relatively dry mixture of aggregates (size: 19 mm maximum), cementitious materials, and water that is dispersed by conventional asphalt paving machines (asphalt pavers) (i.e., finishers) and then compacted and compacted by a vibratory roller and finally, the cement is converted to concrete after hardening as a result of the hydration reaction (Fattahi, 2018). The RCC constituents are transformed into a homogeneous mixture inside the mixer, with similar performance and appearance to that of the wet sand mixture or zero-slump concrete. These mixtures are dispersed and then compacted by asphalt paving equipment (in some cases, with some modifications) into layers of up to 25 cm in thickness as compacted. The layers are compacted by steel vibratory rollers. In some cases, the rubber-tired rollers (rubber-tyred asphalt compactors) are used for the final compaction of the layers to achieve better surface quality. After the concrete has been compacted, the curing surface water retention operation begins to achieve a hard and durable surface pavement. RCCP is commonly used as the final roadway surface. Nevertheless, a hot asphalt coating is used in a few cases to improve surface quality or improve RCC (Kuddus, 2017).

RCCP has been used to execute various projects. Given the difficulties in achieving pavement surface smoothness requirements by this type of pavement, especially in the early years of development, RCCP has been mainly used for road construction or low-speed traffic pavements. Nonetheless, today it can be used at higher speeds with the advancement of technology and the development of more efficient finishers with higher compaction power (Amini, 2025).

RCCP has been mainly used for road construction or low-speed traffic pavements. Nonetheless, today it can be used at higher speeds with the advancement of technology and the development of more efficient finishers with higher compaction power. Until now, RCCP has been mainly used in factory open areas, mine access roads, dockyard surfaces of ports, heavy and military vehicle terminals, parking lots, trucks, and warehouse surfaces, airport parking lots, side roads or low- and medium-speed roads (Shahbazian, 2024). Given the importance of the topic, this paper aims to investigate and evaluate the RCC mix with an emphasis on rigid pavement and compressive strength.

METHODOLOGY

This is descriptive-theoretical research in terms of type and nature. Books and articles related to the research topic were collected using the library (desk research) method.

RESULTS

A Comparison between Concrete (Rigid) and Asphalt (Flexible) Pavements

(Figure 1) compares the RCCP design with an asphalt pavement with equal carrying capacity. The thickness of the RCCP was 356 mm which was placed in two layers and the maximum time span (interval) between layers was limited to one hour. In this project, the flexural strength of the design for RCCP was 4.8 MPa. Contraction cracks were observed at 92m intervals with a maximum width of 6 m, filled with epoxy and sand without any problems (Ghanizadeh et al., 2018).

(Table 1) shows the advantages and limitations of RCC associated with its use in the pavement.

Position of RCC in Concrete Pavements

RCCP is considered concrete pavement, belonging to the first category, i.e., JPCP. The concrete pavement design process is similar to the design of JPCP with expansion joints or non-doweled construction joints. At the same time, it should be noted that there are major differences between RCCP and non-doweled JPCP in terms of pavement construction method, joint spacing, joint performance in terms of load transfer and their appearance and surface properties. It has been attempted to describe the characteristics of RCCPs in different chapters of this report (Asteris, 2019).

RCC Consumables Selection

The selection of the right materials to produce RCC greatly affects the quality of RCC composition. Accordingly, the specifications of the consumables used in the RCC mix design are as follows:

1. Aggregates

Appropriate selection and grading of aggregates for RCCP reduces the probability of detachment and improves pavement strength and durability. In addition, the choice of aggregates affects the amount of water and cementitious materials needed. Aggregate mix with a good and dense grading in RCC is desirable (Ghahari, 2017). In most cases, fine and coarse aggregates are prepared in a blend with a favorable grading. (Figure 2) shows some of the proposed aggregates for this concrete.

For a high-quality RCC, coarse and fine aggregates need to be firm and continuous. The tests listed in the ASTM C33 standard should be performed to evaluate the physical properties of all aggregates used in the RCC mix design to evaluate the aggregate quality (Meftah, 2025).

2. Coarse Aggregates

Coarse aggregates conforming to the ASTM C33 standard are recommended for RCC mix designs. To have a solid surface and to prevent detachment, the nominal maximum aggregate size must be less than 3.4 inches (19 mm). The nominal maximum aggregate size typically ranges from 3.4 to 5.8 inches (16-19 mm). A good quality surface can be achieved also with suitable mix proportions (with

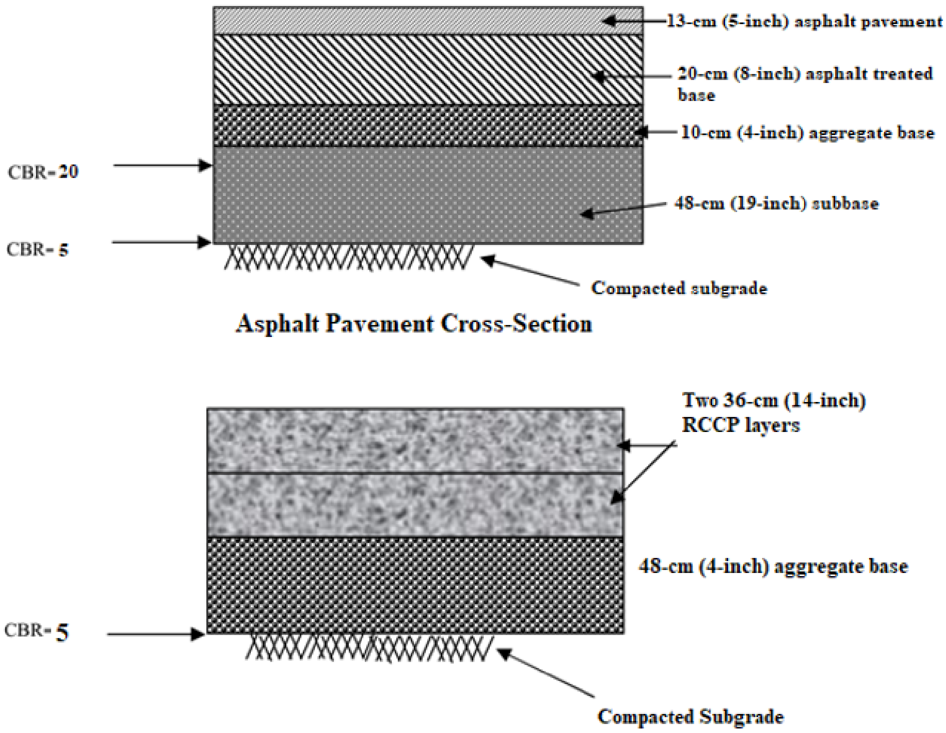

Figure 1. RCCP Cross-Section

Table 1. A comparison between RCCP and asphalt coating (paving)

Advantages	Limitations
It prevents from breaking and rutting.	Compaction of layer edges is very difficult.
It can be used in cold areas.	It needs more care and maintenance in hot seasons.
It is more economical.	There is a lack of sufficient knowledge among contractors.
It can be used easily and implemented quickly due to the lack of bars in its construction.	There is less than an hour difference between layer execution to ensure binding.
There is a decrease in the number of contraction cracks due to low water-cement ratio.	If special tools are not used, the finished surface may not be suitable for high speed.
It is possible to be designed for high flexural, compressive, and shear strength in a location with a heavy passing load	It needs to use a strong mixer because of the dry mixture
It has low permeability due to preventing water from entering the substrates and reducing pavement damage under melt-freeze cycle conditions	There is low production in the mixer and transferred to plain concrete

sufficient fine aggregates) with NMSA over 3.4 inches (19 mm) (up to 11.2 inches (38 mm)). NMSAs smaller than 3.4 inches (19 mm) (down to 1.2 inches (13 mm)) can be used to reduce detachment, increase binding, and improve driving quality. However, the use of small NMSAs leads to an increase in the amount of cement consumed which in turn leads to a decrease in pavement strength. The Los Angeles abrasion test (according to AASHTO T96/ASTM C131 Standard) should also be performed in addition to routine tests on coarse aggregates. It is necessary to perform health tests, alkali-silica reactivity (more commonly known as "concrete cancer") and coefficient of thermal expansion, the necessary durability coefficient in some situations (11 and 12).

3. Fine Aggregates

Fine aggregates shall meet the durability requirements specified in ASTM C33 Standard. Aggregates smaller than sieve 200 (75 µm) are suitable for filling the gaps if they are not plastic. Therefore, the source of high-dust aggregates at their depot location may be useful for use in RCC mix designs if it is not plastic (Kaveh, 2018).

The aggregate skeleton used in RCC, consolidated under compaction, is greatly affected by fine aggregates. The use of more fine aggregates results in a reduction in the amount of cement consumed and the corresponding paste which results in a compressible and durable mixture if mixed with coarse aggregates with appropriate grading. Angular fine aggregates are not of great importance in RCC mixes,

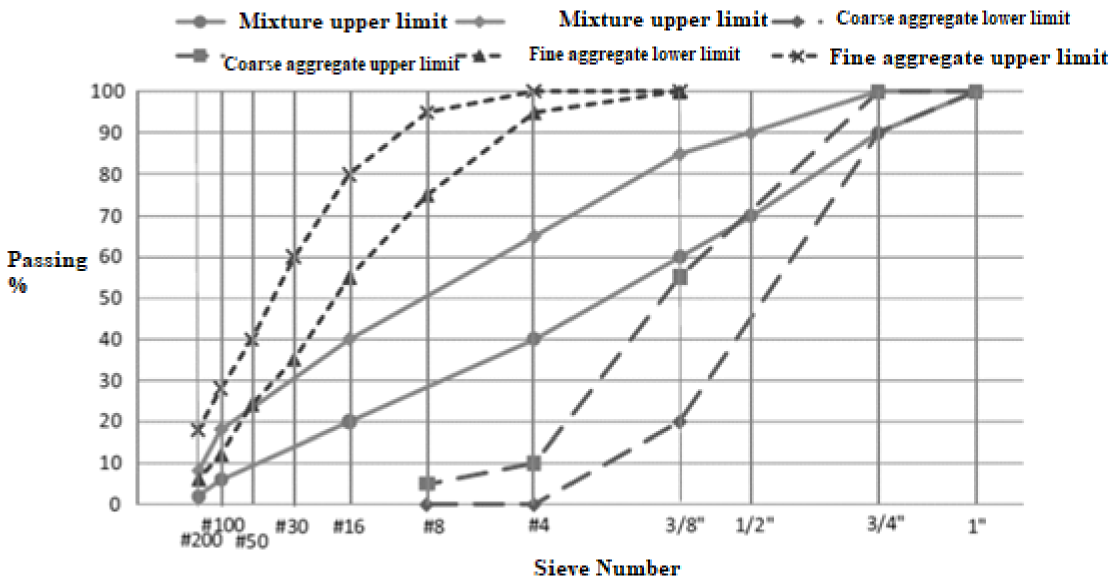

Figure 2. Recommended grading

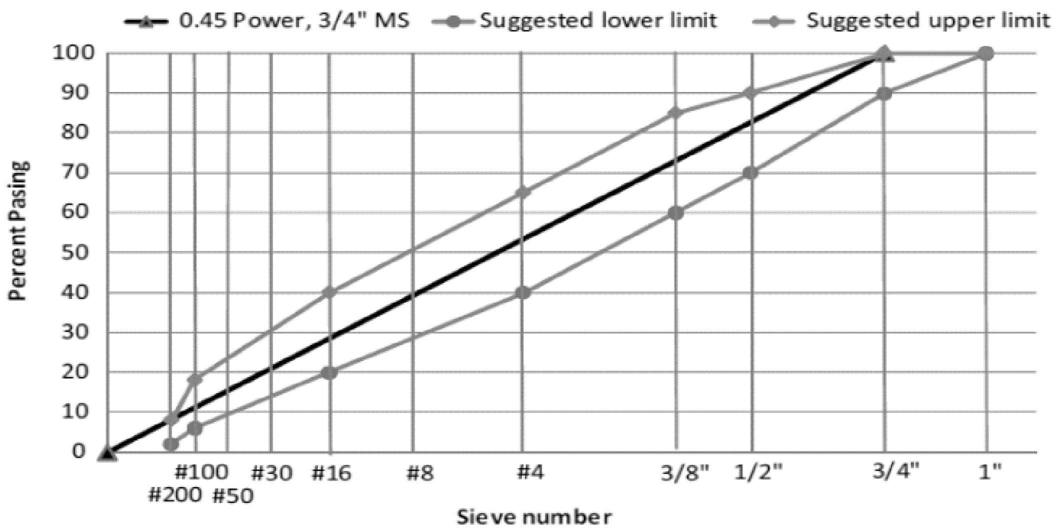

Figure 3. Recommended grading in PCA

as opposed to asphalt mixtures. Obviously, angular fine aggregates have a great impact on the workability and rutting resistance of asphalt mixtures. Natural fine aggregates (i.e., spherical) are very commonly used in RCC mixes to form a strong matrix, unlike asphalt mixtures (Selvam, 2023).

4. Cementitious Materials

Type I and II cement are most commonly used in RCCP. Type III cement can be used for high strength at low ages. Type V cement should be used in areas where the soil is in good condition. Cementitious materials must meet the requirements of ASTM C150 and ASTM C1157 standards (Ram Kumar, 2022).

5. Water

The water needed for chemical hydration in RCC is supplied from two sources, one part through additional water (i.e., free water) in fine and coarse aggregates, and the other part by adding water to the mixer. The water used must meet the requirements of the ASTM C1602 Standard for an approved quality. Water quality needs to be confirmed by experienced engineers prior to project implementation (Rambabu, 2023).

Mix Design Determination

The RCC mix design is generally determined in accordance with the following:

• The soil compaction method is commonly used for RCCPs, which will be described in more detail below.

• The soil compaction method is widely used for the design of the "RCCP mix ratio". According to this method, a relationship is established between the density and moisture content of the RCC mixes to achieve the maximum density of the compacted samples.

Common methods in RCC mix design are discussed below:

1. Compaction Method

The soil compaction method presented in PCA includes the following steps:

1) Selection of the design strength
2) Selection of well-graded aggregates
3) Selection of a medium range of cementitious materials
4) Plotting moisture content-density diagram
5) Preparation of samples to measure compressive strength
6) Testing samples and selecting the required cement grade
7) Calculation of mix proportions

The above steps will be described below.

1.1. Selection of Design Strength

For different materials and different mix and placing conditions, RCC mix designs need to be manufactured in the laboratory to achieve strengths higher than the desired strength. The desired strength is referred to as the "required average strength (f'_{cr}) (f'_{cr})". The determination method is shown for plain concrete in ACI 214R-02. However, no approved determination standard has been inserted for RCC mixes. It is recommended to follow the method outlined in ACI 214R-02 Standard (excluding the $f'_{cr} f'_{cr}$ determination section) (Ashrafian, 2020).

It is recommended that the designer define the required average strength, $f'_{cr} f'_{cr}$, and strength approval criteria for each project. The required average strength (f'_{cr})(f'_{cr}) is equal to the sum of the design strength (f'_{cr}) (f'_{cr}) and the safety factor.

1.2. Selection of Fine Aggregates

First, the aggregates must be optimized in terms of grading, resistance to detachment, and compressibility. Grading of mixed aggregates should give the maximum density. (Figure 3) shows the appropriate RCC grading along with a Fuller's curve for a maximum size of 4.3 inches (19 mm). Fuller's Curve is a method for defining dense grading to achieve a maximum density with any maximum aggregate size (Keleş, 2024).

The range shown in the figure above is based on the grading proposed in PCA 2006 (related to RCC production), except that a slight increase occurred at the maximum percent passing Sieve No. 4. If the aggregates graded within the proposed range are used, manufactured concrete can generally be compacted around a maximum density. Fuller's curve falls within the proposed range except for particles smaller than Sieve No. 100.

1.3. Selection of a Medium Range of Cementitious Materials

Cementitious materials are selected according to project specifications, economic considerations, availability of materials, and production requirements. To get started, 11-13% can be assumed for cement without supplementary cementing materials (SCMs) to cover coarse aggregates. Cementitious materials are expressed as a percentage of the total dry materials, calculated using the following relation:

(Weight of cementitious materials) / (Oven-dried aggregates + Weight of cementitious materials) × 100 = (%) cementitious materials (1)

1.4. Plotting the Moisture Content-Density Diagram

For the percentage of fixed cementitious materials, different moisture contents were selected to plot the moisture content-density diagram. The optimum moisture content is in the range of 5-8% for most aggregates. It is recommended to select different moisture contents within the ranges shown by previous experiments.

The moisture content is calculated according to the following relation:

(Water weight) / (Oven-dried aggregates + Weight of cementitious materials) × 100 = (%) moisture content (2)

Maximum dry density and optimum moisture content can be obtained by performing a modified proctor compaction test (ASTM D1557) for the content of each cementitious material. If weak aggregates are used, the standard proctor compaction test (ASTM D698) should be used to prevent the breakage of aggregates. Another method for determining the moisture content-density relationship is to perform the ASTM C1170 standard test (i.e., the RCC slump and density determination using a vibrating table) (Hassani, 2024).

It is recommended to plot at least three moisture content-density curves for every 3% of the different cementitious materials. For example, 10%, 12%, and 14% can be used for 3% of different cementitious materials.

1.5. Preparation of Samples to Measure Compressive Strength

Cylindrical specimens of compressive strength are prepared using a vibratory hammer (ASTM C1435) or vibrating table method (ASTM C1176) for the content of each cementitious material (Selvam et al., 2024). All specimens should be made at a corresponding optimum moisture content, such as each percent cementitious materials content.

1.6. Testing Samples and Selecting the Required Cement Grade

The specimens are tested to determine the compressive strength in the selected cementitious materials content. The compressive strength curve should be plotted in terms of cementitious materials content. The cement content that meets the predetermined resistance required by the project should be selected using this curve. As stated earlier, the required strength ($f'_{cr} f'_{cr}$) is equal to the sum of the design strength ($f'_c f'_c$) and the safety factor.

1.7. Calculation of Mix proportions

If the content of the cementitious material required is significantly different from all the selected cement contents, a different moisture content-density curve should be formed to determine the optimum moisture content in new cementitious materials content. If the optimum moisture content does not change significantly with a change in the content of the cementitious material, the optimum moisture content in the required cementitious materials content can be obtained by interpolation. Finally, the final mix design ratios for the project can be calculated by selecting the required cementitious materials content and the optimum moisture content. Saturated surface dry (SSD) conditions for aggregates should be used to determine the weight of materials and their corresponding volumes.

2. Slump/Workability Method

The slump/workability method has been developed based on ACI 211.3R Standard to determine the RCC mix design ratios with the largest nominal aggregate size of 37.5 mm. In this method, mix proportions should be designed so that the paste volume is sufficient to cover the aggregates and space between them, as in other methods. In this method, optimum workability and slump are determined by means of a modified test. time is the time when complete bleeding is formed around the mold

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Table 2. Concepts of the terms mentioned in determining RCC mix design by the slump method

P/C	**Pozzolan-cement volume ratio**	V_{MT}	**The total volume of mortar**
P_T	The minimum volume of cement paste	V_m	Non-air-entrained mortar volume
P_v	The ratio of non-air-entrained paste volume to non-air-entrained mortar volume	V_{FA}	Fine aggregate volume
V_{CA}	Coarse aggregate volume	V_W	Water volume
V_A	Mixed air volume	V_C	Cement volume
V_{CA}	Coarse aggregate volume	V_F	Pozzolan volume
C_V	Concrete volume	$W/(C+P)$	The ratio of water volume to total cement and pozzolan
V_P	Non-air-entrained paste volume		

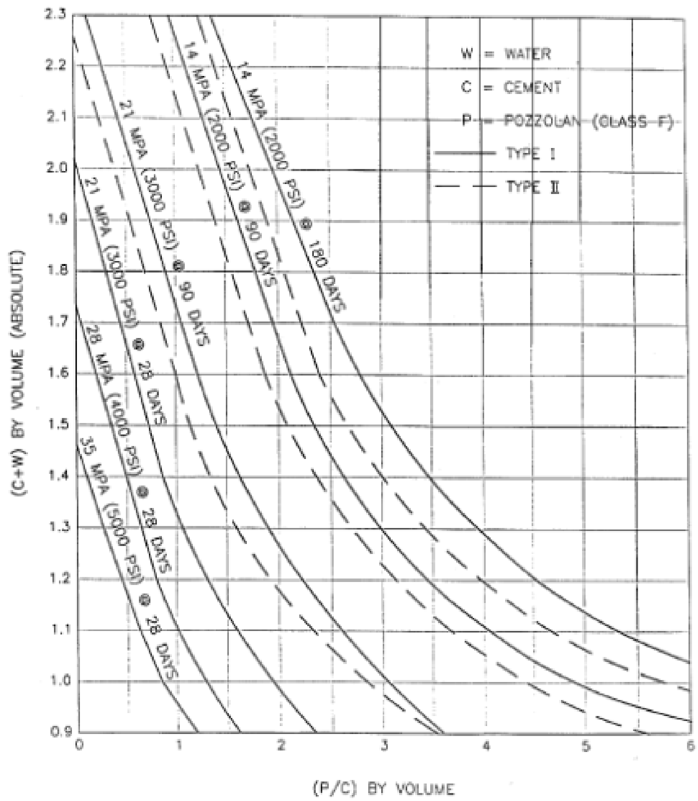

Figure 4. Diagram of determination of the pozzolan-cement volume ratio and the water-(cement+pozzolan) volume ratio

under consolidation. As ACI 211 Standard suggests, the most appropriate time to consolidate is between 30 and 40 seconds (Ali, 2024). See (Table 2) to determine the RCC mix design using the slump method.

The slump method involves the following steps:

Step 1: Select the Pozzolan-Cement volume ratio

According to (Figure 4), the pozzolan-cement volume ratio and the water-(cement+pozzolan) volume ratio should be selected based on the required strength and the type of cement used to produce the test sample.

Step 2: Determine the minimum volume of cement paste

The minimum volume of cement paste can be calculated using two methods:

1) Mortar specimens should be made with different fine aggregate contents according to the selected water-cement ratio. Then, the density of the manufactured mortar specimens should be measured using the ASTM D1557 method (i.e., modified compaction). Then, the paste volume of mortar giving the highest density should be chosen according to the mortar density-paste volume diagram.

2) An approximate method can be used as an alternative to the above method. The ratio of non-air-entrained paste volume to non-air-entrained mortar volume can be selected from 0.38 to 0.46 (Sengun, 2024).

Step 3: Determine the coarse aggregate volume

The coarse aggregate volume can be determined by two methods:

1) In the first method, the coarse aggregate volume is obtained by trial and error, such that different coarse

Table 3. Determination of the coarse aggregate volume percent

Coarse aggregate volume percent	Nominal maximum aggregate size (mm)
63-64	150
61-63	115
57-61	75
52-56	37.5
46-56	19
42-48	9.5

aggregate volume and mortar ratios are combined. Then, the RCC modified time is measured. The above steps are repeated for different ratios to obtain the desired time.

2) (Table 3) can be used to determine the approximate coarse aggregate volume.

Step 4: Determine the mixed air volume

The concrete air content should be selected in the range of 1-2%. The mixed air volume can be calculated by the following relation:

$$V_A = \left(\frac{\text{Air content}}{100}\right) \times C_V V_A = \left(\frac{\text{Air content}}{100}\right) \times C_V \quad (3)$$

Step 5: Calculate the paste volume without air

The non-air-entrained paste volume is calculated in two ways:

Method One:

$$V_p = \left(\frac{P_T}{100} \times V_{MT}\right) - V_A V_p = \left(\frac{P_T}{100} \times V_{MT}\right) - V_A \quad (4)$$

where the total volume of pulp ($V_{MT} V_{MT}$) is calculated using the following relation:

$$V_p = C_V - V_A V_p = C_V - V_A \quad (5)$$

Method Two: If $P_V P_V$ is selected in step two:

$$V_p = V_m \times P_V V_p = V_m \times P_V \quad (6\text{-}2)$$

where the non-air-entrained mortar volume is calculated using the following relation:

$$V_m = C_V - V_{CA} - V_A V_m = C_V - V_{CA} - V_A \quad (7)$$

Step 6: Determine the fine aggregate volume

The fine aggregate volume is calculated based on step 5 as follows:

$$V_{FA} = V_m \times (1 - P_V) V_{FA} = V_m \times (1 - P_V) \quad (8)$$

Step 7: Determine the test water volume

Given the ratio of water volume-cement + pozzolan selected in step 1, we have:

$$V_W = V_P \times \left(\frac{W}{C+P}\right) / \left[1 + \frac{W}{C+P}\right] \; V_W = V_P \times \left(\frac{W}{C+P}\right) / \left[1 + \frac{W}{C+P}\right] \quad (9)$$

Step 8: Calculate the cement volume

The cement volume is calculated as follows:

$$V_C = V_W / \left\{\frac{W}{C+P} \times \left[1 + \frac{P}{C}\right]\right\} V_C = V_W / \left\{\frac{W}{C+P} \times \left[1 + \frac{P}{C}\right]\right\} \quad (10)$$

Step 9: Determine the pozzolan volume

The pozzolan volume is calculated as follows:

$$V_F = V_C \times \frac{P}{C} V_F = V_C \times \frac{P}{C} \quad (11)$$

Step 10: Calculate the weight of the materials

Calculate the density of each aggregate by considering its weight bulk density.

Step 11: Conduct the concrete slump test

According to the standard, the modified test should be performed on the RCC produced with an experimental mix design to obtain the desired slump.

Step 12: Determine the final design and measure the compressive strength

After determining the final aggregate volume, two additional specimens should be made with water-cement ratios lower than and above the selected value. Finally, the compressive strength curve must be plotted in terms of the water-cement ratio to determine the final RCC mix design.

1. High Paste Method:

This mix design proportioning method has been developed by the US Bureau of Reclamation. The RCC produced by this method generally has a high cementitious and pozzolanic materials content with medium grading and high workability. This method aims at producing an RCC with very low permeability that can be achieved using the optimum cementitious materials content.

The amount of water consumed, fine aggregates, and coarse aggregate are determined based on modified time evaluation in the range of 10 to 30 seconds by modified test (ASTM C1176) on experimental concrete mixtures

2. Numerical Method (Solid Suspension Model):

In recent years, a theoretical and numerical method has been introduced to design RCC mix proportions called solid suspension models.

This method is based on optimizing the dry density of RCC mixes to determine the proportions of each dry material (e.g., cement, fly ash, micro-silica, sand, and coarse aggregate). The amount of water needed to cover the empty space between dry materials is calculated using the dry density optimization method. A solid suspension model can be modeled for the RCC mix design using a computer simulator having the characteristics of the materials available (e.g., grading, specific gravity, and contents). The main advantage of a solid suspension model is rapid computation and optimization of mix proportions, without having to perform a large number of laboratory tests (Marjono, 2023).

DISCUSSION AND CONCLUSION

With the advances made in various scientific fields in today's advanced world, the concrete industry has also evolved; the RCC produced is also a result of these improvements. The use of alternative technologies has become necessary due to the high cost of producing bitumen asphalt coatings and the volume of environmental pollutant oils. As one of the types of rigid pavement, RCCP has been of interest to researchers because of its fast construction and low maintenance costs. The lower cement paste content and higher aggregate volume in the RCCP have resulted in its lower slump, which is compacted using rollers and finishers. Longer-term durability of RCCP compared to bitumen asphalt has been considered in tropical and temperate regions due to temperature rise resistance, low water absorption, and good compressive strength; as a consequence, it is less deformed against incoming loads. Furthermore, the concrete coating is safe and resistant to freeze cycles in the face of possible damages in the cold regions. In addition, it does not contain any environmental problems within its scope as a compliant coating for the impermeability of its constituents. Moreover, gray and neutral RCCP has a good temperature absorption coefficient and also helps lower ambient temperature. The use of pozzolanic materials has also been of interest in RCC production due to lower production costs compared to cement and the improvement of its resistive properties. Thus, this study examined the RCCP data containing pozzolan. The pozzolans combine well with the gel produced in the concrete and increase the concrete hydration, resulting in a compacted produced concrete and an increase in the mechanical and chemical properties of RCCP.

One of the most important mechanical properties of concrete is the compressive strength which is greatly affected by the concrete mix design. Parameters such as cement grade, water-cement ratio, cement substitutes, etc. affect concrete compressive strength. It is difficult to predict concrete compressive strength due to the existence of many parameters. In mix design proportioning methods, it is attempted to reduce production costs. It is time-consuming and costly to use mix design proportioning methods to calculate mix design. The conditions and assumptions of the building code must be observed for all concrete components. Hence, different researchers have proposed valuable models for estimating the behavior of concrete using different mathematical techniques. These techniques were mainly based on linear and nonlinear regressions in the past. Nowadays, AI-based methods such as fuzzy logic and ANNs are being used successfully in this field, generally extracted from laboratory experiments and investigations.

Author's contribution
Ali Ranjbar and Nader Barahmand developed the study concept and design. Akbar Ghanbari and Ali Ranjbar acquired the data. Ali Ranjbar and Nader Barahmand analyzed and interpreted the data, and wrote the first draft of the manuscript. All authors contributed to the intellectual content, manuscript editing and read and approved the final manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interest
The authors declare that they have no conflict of interests.

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