Analyzing Lab and Field Compaction Methods for designing Roller Compacted Concrete Pavements (RCCP) with Different Curing Processes

Hussien Raheem Hassoon
Department of Civil Engineering, University of Baghdad, Baghdad, Iraq
hussein.hassoun2201m@coeng.uobaghdad.edu.iq (corresponding author)

Zena K. Abbas
Department of Civil Engineering, University of Baghdad, Baghdad, Iraq
Dr.zena.k.abaas@coeng.uobaghdad.edu.iq

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ABSTRACT

Roller-Compacted Concrete Pavements (RCCP) display a combination of attributes associated with both asphalt and conventional rigid pavements. However, their broader implementation remains constrained. One of the reasons is the discrepancy between the manner in which the RCCP mixture behaves in a laboratory setting and its performance in the field. In laboratory settings, the RCCP is blended in accordance with the modified Proctor approach. Subsequently, the Vibratory Hammer (VH) technique is employed to create specimens for strength characterization. In contrast, the actual pavement is constructed using a variety of rollers, including static, pneumatic, and vibratory types. Additionally, specimens are extracted from the actual pavements and compared to laboratory values to ensure quality control. The usage of diverse compaction mechanisms and energies throughout these procedures gives rise to discrepancies between field and laboratory behavior, necessitating a comprehensive understanding. This investigation examines the various techniques for designing RCCP, including the VH, Vibratory Table (VT), and Manufactured Roller (MR), which have been developed and utilized by previous researchers. These techniques are then compared to Field Specimens (FS). Furthermore, the RCCP is treated with three distinct curing methods: normal curing, coating the mixture with waterproof material, and spraying with water. The compressive strength of the RCCP has been sensitive to both the compaction method employed and the curing process. Additionally, research has indicated that the MR technique may be a viable option for the RCCP design. However, it is essential to optimize this technique to ensure an accurate simulation of the field conditions.

Keywords-compaction techniques; field compaction; Roller Compacted Concrete Pavements (RCCP); manufactured roller; strength properties

I. INTRODUCTION

In recent decades, Roller Compacted Concrete (RCC) technology has seen considerable advancement across a range of sectors, including highway construction, industrial and heavy-duty applications, airports, dams, and parking lots. This is primarily due to the rapid construction speed and cost-effectiveness of the specific technology [1-3]. RCC is a concrete mixture that can be compressed with a roller while being in a pliable, unhardened state [4-6]. RCC is a zero-slump material that requires roller compaction to attain the desired density, and can be directly exposed to traffic [7-9]. In contrast to conventional slump concrete, RCC requires less water to reach zero slump, thereby necessitating a lesser quantity of cement to achieve an equivalent water-cement ratio (w/c). Furthermore, reducing the quantity of water in the mixture serves to mitigate the occurrence of thermal-induced cracking by limiting the amount of cement required. In contrast to conventional Portland cement concrete, RCCP mixtures include greater quantities of fine aggregate, which allows the achievement of a more homogeneous concrete composition with reduced surface voids [10, 11]. The reduced quantity of water and cementitious ingredients in RCCP results in a cost-effective alternative of traditional concrete [12, 13]. The objective of this study is to identify the most effective laboratory compaction technique for the RCCP design. Three techniques, VH, VT, and MR, will be evaluated to ascertain which is most likely to simulate field compaction under laboratory conditions using field slabs compacted with field rollers. The objective of this investigation is to assist academic researchers and field engineers in selecting reliable compaction techniques from various compactors for the purpose of designing RCCP that can accurately replicate the field behavior under laboratory conditions.

II. MATERIAL PROPERTIES

The RCCP mixture was composed of the following elements:

- Ordinary Portland cement (type I) is characterized by a set of physical and chemical properties, which are outlined in Table I.
- Aggregate: Crushed coarse aggregate with a nominal maximum size of 19 mm was used, while natural sand with a particle size below 4.75 mm was employed as the fine aggregate [14, 15]. In order to compare the grading of fine and coarse aggregates, the ASTM C33 grading standards, specifically the ASTM C33/C33M-16, 2016 standards [16], have been adopted. Tables II and III present the properties of the fine and coarse aggregates, respectively.
- Limestone Filler (LF) refers to fine particles that passed through a sieve with a number 200 mesh.

The ACI 327 standards [17], set limits for the grading of combined aggregates used in RCCP. In this study, these limits were applied to determine the grading of the combined aggregate, as shown in Figure 1.

TABLE I. ORDINARY PORTLAND CEMENT PROPERTIES

Specification	**Chemical composition / Oxide (%)**								**Vicat's setting time(min)**		**Strength(MPa)**	
	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	L.O. I	I.R.	Initial	Final	3- days	7-days
Results-OPC	61.43	20.7	4.4	3.1	2.14	2.08	2.85	0.54	126	255	21.0	25.0
ASTM C150 (ASTM)	-	-	-	-	≤ 3.0	≤ 6.0	≤ 3.0	≤ 1.5	≥ 45.0	≤ 600	≥ 12.0	≥ 19.0

TABLE II. NATURAL SAND AGGREGATE PROPERTIES

Specification	**SO_3 (%)**	**Specific gravity**	**Absorption (%)**	**Sieve size (mm)**						
				10	4.75	2.36	1.18	0.6	0.3	0.15
Cumulative passing (%)	0.09	2.57	1.2	100	95	87	73	48	27	6
ASTM C33	-	-	-	100	95–100	80–100	50–85	25–60	5–30	0–10

TABLE III. COARSE CRUSHED AGGREGATE PROPERTIES

Specification	**SO_3 (%)**	**Specific gravity**	**Absorption (%)**	**Sieve size (mm)**			
				25	19.5	9.5	4.75
Passing (%)	0.06	2.62	0.42	100	98	45	7
ASTM C33	-	-	-	100	90–100	20–55	0–10

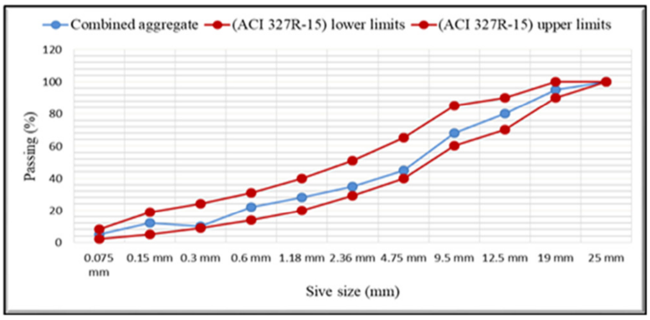

Fig. 1. Combined aggregate graduation with ACI 327R limitation.

III. MIXTURE PROPORTIONING

In accordance with the ACI 327 process design, the cement was selected as a weight percentage of 13% of all dry components. Gradation tests were conducted to determine the proportions of coarse crushed stone, natural sand, and filler, which were 55%, 40%, and 5%, respectively. In order to ascertain the appropriate water content and density for RCCP, the ASTM D1557 standard [18], (ASTM D1557-12, 2012) was employed. The Optimum Moisture Content (OMC) relative to the maximum dry density (max γ dry kg/m^3) was determined by a calculation based on the water content specifications provided by ACI 327 and ACI 211 (ACI 211-3R, 2002 (09)) [19]. This calculation was performed in accordance with the modified Proctor test (Method C), as specified by the ASTM D1557 standard. A modified Proctor curve with five points was constructed by varying the moisture content from 4.5% to 8.5% in increments of 1%. Each Proctor point is composed of a mixture of 5.7 kg of combined aggregates, including 2.4 kg of fine aggregate and 3.3 kg of coarse aggregate. Additionally, 0.3 kg of filler are mixed with the calculated amounts of cement and water. The resulting mix design for 1 m^3 of RCCP is portrayed in Table IV.

TABLE IV. RCCP MIX DESIGN

Materials	**Cement**	**Coarse aggregate**	**Fine aggregate**	**Filler**	**Free water**
Weight (kg)	294.97	1,092.23	799.09	98.72	126.93

A. *Laboratory SPECIMENS' Fabrication*

a) Vibrating Hammer (VH)

The cylindrical specimens, measuring 150 mm in diameter by 300 mm in length, were fabricated in accordance with the ASTM C1435 standard (ASTM C1435/C1435M-14, 2014) [20], which permits testing for compressive strength. Each specimen was compacted in four equal layers using a manufactured vibrating hammer attached to a 149 mm (diameter) cylinder plate until a mortar layer formed around the periphery of the tamping plate, or for a maximum of 20 seconds.

b) Vibratory Table (VT) with Surcharge

Cylindrical specimens (150 mm × 300 mm) were constructed in accordance with ASTM C1176 (ASTM C1176/C1176M, 2008) to ascertain the compressive strength. The cylinders were filled with three equal layers of RCCP and attached to the vibrating table under a locally constructed (9 kg) surcharge until the mortar ring formed either along the periphery of the surcharge or after 20 seconds, that is whichever occurred first.

c) Modified Manufactured Roller (MR)

Authors in [21] indicated that the slab specimens were produced via casting in a steel mold with internal dimensions of 380 x 380 mm, a depth of 100 mm, and a weight of 51 kg. To prevent the escape of water or mixtures and to avoid adhesion to the concrete once it was hardened, nylon sheets were applied to the internal surfaces of the mold. The RCCP slabs were cast using the same aggregate gradation with that employed in the hammer compaction technique. The percentage of aggregate retained on each sieve was maintained, but the total aggregate content was calculated in accordance with ACI 211.3R to accommodate the new slab volume. The specimen was subjected to two concurrent stages of compaction. At the initial stage, the mixture was placed in the slab mold and subjected to initial compaction using a handheld vibrator motor, which consists of a steel handle and a gasoline motor. The vibration was transmitted to the concrete by affixing a rectangular mold with dimensions of 380 mm × 380 mm × 100 mm (length × width × thickness) to the motor via welding an iron pipe with a diameter of 1.5 inches and a thickness of 3 mm along one side of the mold. The steel handle was then inserted inside the pipe. At the second stage, the mixture was compacted utilizing a roller apparatus that was specifically designed to mimic the compaction process of a steel roller, which is typically used in the field for compaction. The apparatus was a solid cylinder, measuring 150 mm in diameter, 330 mm in length, and weighing 15 kg. It was constructed with a steel skeleton and weighted 36 kg. A container was provided in the design to accommodate the additional steel weights. The mold was subjected to three rolling stages in advance of the roller compactor, as depicted in Table V. At each stage, a total of 15 passes were applied, which were sufficient to achieve optimal rolling with minimal effort. The x-x rolling action was followed by the y-y rolling action to ensure the compaction of the slab sides. This particular compaction technique differs from other procedures because it employs a vibrator motor in lieu of the vibrating table deployed in other techniques, prior to the compaction stage. Once the compaction stage was completed, the wet slab was cut into cubes with dimensions of 10 cm×10 cm×10 cm in accordance with ASTM C42/C42M-20. The laboratory compaction methods are presented in Figure 2.

B. Field Slab Fabrication (FS)

An RCCP with dimensions of 1.2 m × 0.9 m × 0.320 m (length × width × thickness) was constructed in accordance with the specifications provided in ACI 309.5 (ACI 309.5R, 2000) [22]. A comparative analysis was conducted using a dual drum vibrating roller (BOMAG 65) with a width of 65 cm, an operating weight of 1,000 kg, and a dynamic force of 7.54 N/mm. The slab was compacted in two layers (0.16 cm for each layer) utilizing this roller. The handle vibration and vibratory frequency of the roller were 5 m/s^2 and 68 Hz (4,080 vibrations per minute, respectively).

TABLE V. THREE ROLLING STAGES OF THE MOLD

Stage	Weights
One	A total load of 6.16 lb/in. (1.1 kg/cm) width (using roller compactor weight) is implemented. The concrete is settled in a level position and completely fills the slab mold. This can represent the initial compaction in the field
Two	The total load is increased to 17.92 lb/in. (3.2 kg/cm) width (using 152.12 lb [69 kg] standard loads + roller compactor weight). This may simulate the intermediate field compaction
Three	The total load is increased to (29.68 lb/in. [5.3 kg/cm] width) (using 304.24 lb [138 kg] standard loads + roller compactor weight). At this stage, the slab surface is smooth and level. This represents the finishing compaction in the field

Fig. 2. Laboratory compaction methods: (a) Vibrating hammer with cylinder mold and tamping plate, (b) vibrating table with cylinder mold and surcharge (9 kg), (c) modified manufactured roller (RCCP specimen in a slab mold).

These specifications are considered to be conducive to achieving favorable outcomes, as outlined in the ACI 309.5R, 2000 guidelines. Additionally, a duplex roller was employed for the compaction of the subgrade and subbase layers situated beneath the slab sample. The slab fabrication process follows ACI 309.5 (ACI 309.5R, 2000) specifications. This means four passes in static mode, four in vibratory mode, and one in static mode to remove roller marks. After construction, the slab was covered to prevent moisture loss. After 28 and 90 days, cylindrical specimens were extracted using a portable core cutter. They were then tested for compressive strength.

Fig. 3. Compaction of field slab with (BOMAG65).

C. Curing

The RCCP specimens were subjected to three distinct curing processes [23]:

- The laboratory specimens are immersed in a water tank with a temperature setting of (23 ± 2) °C continuously from the moment of molding until the time of testing, in accordance with the specifications of ASTM C192 (ASTM C192/C192M, 2016).
- The RCCP laboratory samples and a half of the field slab were treated with Sika Antisol WB IQ, applied over the samples after compaction. On the following day, after the removal of the mold from the laboratory samples, the remaining samples were sprayed and exposed to the atmosphere until the conclusion of the testing phase.
- The specimens were subjected to permanent (continuous) air curing, which entailed the application of water twice on a daily basis at 7:00 a.m. and 2:00 p.m. until the end of the test. The analogous procedure was then applied to the remaining half of the field slab.

IV. ITEMS OF RESEARCH

Figure 4 illustrates the compressive strength tests that were performed on the VH and VT samples, which were manufactured following different curing methods.

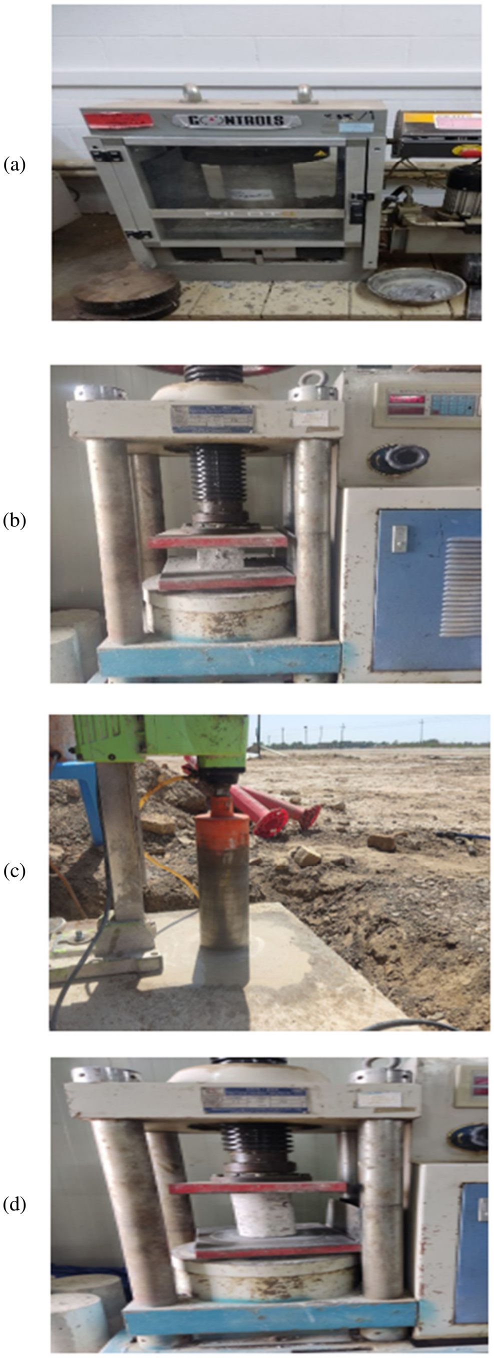

Fig. 4. Compressive strength test for laboratory and field samples: (a) testing of vibrating hammer and table samples, (b) testing of cubes samples for modified manufactured roller, (c) extraction of cylinder sampler from field slab, (d) testing of field slab samples.

Additionally, the tests were conducted on field slab samples extracted from each part, in accordance with the ASTM C39/C39M (2015) specifications. The tests were carried out after 28 and 90 days. In the case of the modified MR, cubes were tested for compressive strength in accordance with the specifications set forth in BS EN 12390:3-19, after 28 and 90 days. For the purpose of comparison, the cubic results of the MR were converted to cylinder results using the factor 0.8. Subsequently, the results of the laboratory compaction techniques were compared to the field slab results.

V. COMPRESSIVE STRENGTH RESULTS

Following the completion of the compressive strength test on the laboratory samples and field slab, the outcomes of the laboratory techniques are presented in comparison to the field slab in Figure 5.

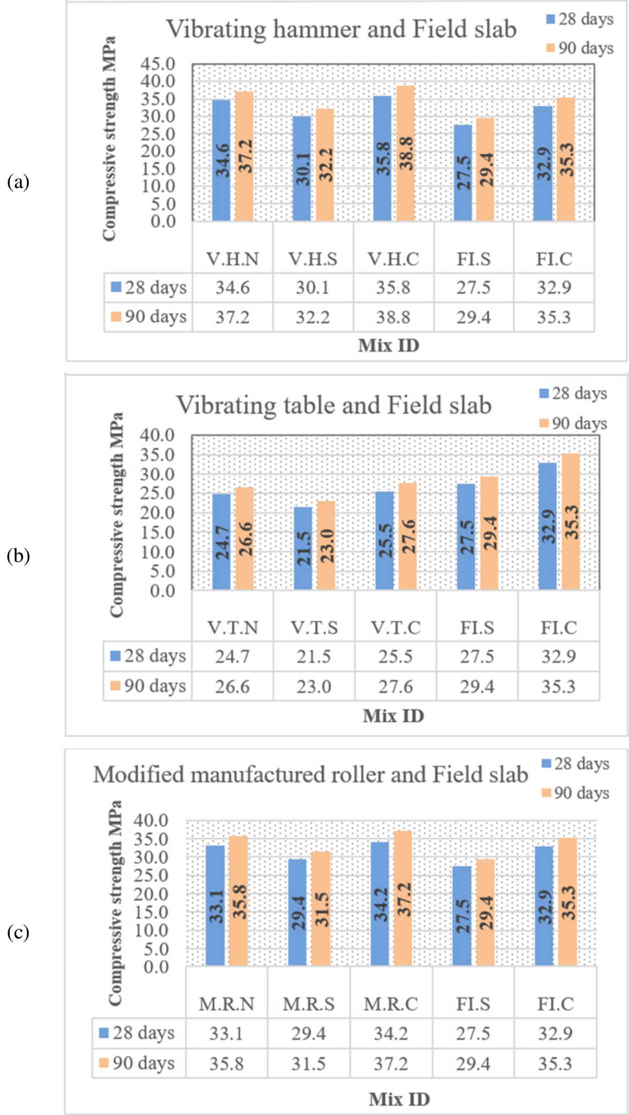

Fig. 5. Compressive strength Results of laboratory samples compared to field slab with different curing methods: (a) VH, (b) VT, (c) modified manufactured roller.

VI. DISSCUSION AND CONCLUSIONS

The objective of the current research was to discuss the results of the production of Roller-Compacted Concrete Pavements (RCCP) using different laboratory compaction techniques and to compare them with Roller-Compacted Concrete (RCC) in field conditions and with different curing processes. A summary of the conclusions drawn from these results is:

- Vibrating Hammer (VH) compared to field slab: The increase in compressive strength of the lab normal curing (V.H.N) was found to be equal to 25.82%, and 26.53% at 28 and 90 days, respectively, in comparison to the Sprayed Field (FI.S). The increase in compressive strength of the lab normal curing (V.H.N) was found to be equal to 5.29%, and 5.35% at 28 and 90 days, respectively, in comparison to the Coated Field (FI.C). The increase in compressive strength of the laboratory normal curing (V.H.N) equals to 5.29%, and 5.35% at 28 and 90 days, respectively, compared to the coated field (FI.C). The percentage increase in the coated lab (V.H.C) compared to the coated field (FI.C) is 8.97%, and 9.78% at 28 and 90 days, respectively. The spray lab (V.H.S) exhibited an increase in compressive strength of 9.34%, and 9.45% at 28 and 90 days, respectively, in comparison to the spray field (FI. S).
- Vibrating Table (VT) compared to field slab: The reduction in compressive strength of the laboratory normal curing (V.T.N) compared to the sprayed field (FI. S) was up to -10.20%, and -9.50% at 28 and 90 days, respectively. The reduction in compressive strength of laboratory normal curing (V.T.N) equals to -24.85%, and -24.65% at 28 and 90 days, respectively, compared to the coated field (FI.C). The compressive strength of the laboratory sprayed (V.T.S) was reduced by -21.69%, and -21.81% at 28 and 90 days, respectively, compared to the sprayed field (FI. S). Finally, the percentage reduction in the coated laboratory (V.T.C) compared to the coated field (FI.C) was up to -22.3%, and -21.71% at 28 and 90 days, respectively.
- Manufactured roller compared to field slab: The increase in compressive strength of the lab normal curing (M.R.N) was found to be equal to 20.36%, and 21.77% at 28 and 90 days, respectively, in comparison to the sprayed field (FI.S). The increase in compressive strength of the lab normal curing (M.R.N) was observed to be equal to 0.72%, and 1.39% at 28 and 90 days, respectively, in comparison to the coated field (FI.C). The percentage of the increase in the coated lab (M.R.C) compared to the coated field (FI.C) was equal to 3.95%, and 5.24% at 28 and 90 days, respectively. Finally the spray lab (M.R.S) compressive strength exhibited an increase of 6.88%, and 7.03% at 28 and 90 days, respectively, in comparison to the spray field (FI.S).

These results allow us to draw the following conclusion:

- The results for the VH indicated that the compressive strength was greater than that observed in the field slab, which may be attributed to the VH compaction mechanisms applied to the RCCP mixture. This is due to the combined effect of vibration and impact forces, which reduce the interparticle distance to a degree that is greater than that achieved by specimens compacted by other methods. This results in greater aggregate mobilization, even in the stiff rheological concrete mix, and leads to improved aggregate-to-aggregate interlocking. In contrast, the compaction mechanism of the VT is based on the combined effect of vibration and static pressure, which is applied by the surcharge (9 kg for cylinder specimens). However, this method did not achieve the requisite degree of compaction and density, resulting in significantly greater spacing between the aggregates in VT specimens and leading to a reduction in compressive strength.

- It is reasonable to anticipate a strong correlation between the outcomes of the MR and the observations made in the field, particularly when using the coated material (FI.C). This is due to the effectiveness of the material in question, in conjunction with the manufacturing process of the device, which closely resembles that of field compactors and employs a combination of impact, pressure from the roller, and added weight. Furthermore, vibration is introduced through modifications to the device, which include the attachment of a handheld vibrator motor to the rectangular mold. This additional component facilitates the rearrangement of aggregate particles during the compaction process. As a consequence, the requisite degree of compaction and density was attained, resulting in compressive strength that was nearly comparable to that achieved by a field compactor.
- The findings demonstrate that all laboratory samples subjected to controlled laboratory conditions (V.H.N, M.R.N) result in a notable and potentially overestimated enhancement in compressive strength when compared to field samples sprayed with water FI.S and subsequently enhanced in V.T.N. The results exhibit a reasonable reduction. The discrepancies in environmental conditions between laboratory and field settings, which are subjected to various weather patterns, have a detrimental impact on the compressive strength of the FS. In contrast, the samples from the other part of the slab (FI.C) displayed enhanced outcomes, approaching V.H.N and nearly matching M.R.N. This provides evidence of the anti-evaporation material's effectiveness in impeding water evaporation and facilitating sufficient hydration, thereby enhancing compressive strength.

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