DOI: https://doi.org/10.14256/JCE.2572.2018

Građevinar 2/2020

Primljen / Received: 26.11.2018.
Ispravljen / Corrected: 15.5.2019.
Prihvaćen / Accepted: 1.7.2019.
Dostupno online / Available online: 10.3.2020.

Laboratory comparison of roller-compacted concrete and ordinary vibrated concrete for pavement structures

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Research Paper

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Laboratory comparison of roller-compacted concrete and ordinary vibrated concrete for pavement structures

The roller-compacted concrete pavement (RCCP) has the same ingredients as the pavement made of normal vibrated concrete (NVC). Microstructure images show that RCCP has higher pack density compared to NVC specimens. The 28-day compressive, splitting tensile, and flexural strengths of RCCP are by 9%, 4%, and 25% higher than those of NVC. The final water absorption and porosity values are by about 8% and 10.6% lower for RCCP in comparison with NVC.

Key words:

concrete pavement, roller-compacted concrete, vibrated concrete, compressive and tensile strength, elastic modulus, water absorption, porosity

Prethodno priopćenje

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Laboratorijska usporedba valjanog i običnog vibriranog betona kolničkih konstrukcija

Kolnik od valjanog betona (RCCP) sastoji se od istih komponenata kao i kolnik od običnog vibriranog betona (NVC). U radu se analiziraju razlike između RCCP-a i NVC-a. Prikazi mikrostrukture pokazuju da RCCP ima veću gustoću pakiranja u usporedbi s uzorcima NVC. Vrijednosti tlačne čvrstoće nakon 28 dana, vlačne čvrstoće pri cijepanju i vlačna čvrstoća savijanjem RCCP-a veće su za 9 %, 4 % i 25 % od odgovarajućih čvrstoća NVC-a. Konačne vrijednosti kapilarnog upijanja i poroznosti RCCP-a otprilike su za 8 % tj. 10,6 % niže od odgovarajućih vrijednosti NVC-a.

Ključne riječi:

betonski kolnik, valjani beton, vibrirani beton, tlačna i vlačna čvrstoća, modul elastičnosti, kapilarno upijanje, poroznost

Vorherige Mitteilung

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Laborvergleich von walzenverdichtetem und normalem vibriertem Fahrbahnbeton

Eine Fahrbahn aus walzenverdichtetem Beton (RCCP) besteht aus den gleichen Komponenten wie auch eine Fahrbahn aus normalem Vibrationsbeton (NVC). Die Abhandlung analysiert die Unterschiede zwischen RCCP und NVC. Die Ansichten der Mikrostrukturen zeigen, dass RCCP im Vergleich zu den NVC-Proben eine höhere Packungsdichte aufweist. Die Druckfestigkeitswerte nach 28 Tagen, die Zugfestigkeit bei Spaltung und die Zugfestigkeit durch Biegen des RCCP sind um 9%, 4% und 25% höher als die entsprechenden Festigkeiten des NVC. Die endgültigen Kapillarabsorptions- und Porositätswerte des RCCP sind um etwa 8%, d. h. 10,6% niedriger als die entsprechenden NVC-Werte.

Schlüsselwörter:
Betonfahrbahn, walzenverdichteter Beton, Vibrationsbeton, Druck- und Zugfestigkeit, Elastizitätsmodul, Kapillarabsorption, Porosität

1. Introduction

The roller compacted concrete pavement (RCCP) is a concrete compacted by vibrating roller compactors [1]. RCCP is superior with respect to its cost effectiveness, low heat of hydration, and fast and simple application in many construction areas such as dams, airport and highways [1, 2]. The main difference between RCCP and normal vibrated concrete (NVC) is the required consistency [2]. Fresh RCCP is stiffer than normal concrete used in pavement construction [2, 3]. Therefore, due to difference in fresh properties of NVC and the RCCP, most techniques for mixture proportioning of NVC cannot be directly applied to the mix design of RCCP [3].

Although basic materials used for making RCCP are the same as those common to the production of NVC, RCCP has a higher volume of aggregate, and lower binder and water content and, therefore, a reduced paste volume [4-7]. The aggregate content typically ranges from 75 to 85 % of the total volume of RCCP, compared to 60 to 75 % in NVC [8, 9]. The aggregate used in RCCP differs from NVC in its gradation requirements [3].

The use of chemical admixtures in NVC is quite common [7]. On the other hand, Delatte [10] has reported that, with the exception of retarders, admixtures are not often used for RCCP. Mechanical properties of NVC are highly influenced by cement hydration. However, mechanical properties of RCCP are highly influenced by cement hydration and, in addition, by the level of compaction [11]. A study showed that a 3 % decrease in the compaction of RCCP reduces the compressive strength by nearly 30 %, which in turn decreases the durability of concrete [12]. Distribution of paste in RCCP is less homogeneous than in NVC. Nevertheless, the compressive strength of RCCP is comparable to that of NVC [2, 3, 12]. The modulus of elasticity of RCCP is similar to or slightly higher than that of NVC when the mixes have similar cement contents [13]. Test results have shown that the compressive strength, modulus of elasticity, and fatigue strength of RCCP are similar to those of the normal paving concrete [14].

A literature review has shown that limited numerical data on the differences between NVC and RCCP has so far been reported, which may not be sufficient to draw proper conclusions. In most previous studies, researchers conducted qualitative comparative analyses between RCCP and NVC. Therefore, a comprehensive numerical comparison between NVC and RCCP is presented in this study. For this purpose, the differences between NVC and RCCP are investigated with the focus on fresh properties, mechanical properties**,** durability, and thermal properties. Furthermore, the field emission scanning electron microscope (FESEM) is applied to assess microstructure of specimens.

2. Experimental Program

2.1. Materials

2.1.1. Cement

The cement was ordinary Portland cement (OPC), which conforms to MS522, part-1:2003 with a 28-day compressive strength of 48MPa. Specific gravity and specific surface area of cement were 3.14. and 3510 cm^2/g, respectively. Chemical properties of the OPC are shown in Table 1.

2.1.2. Fly ash and ground granulated blast-furnace slag

Millions of tons of Fly ash (FA) are generated across the world annually. India produces 80 million tons of FA per year but only less than 10 % of that quantity is being utilized. It should be noted that the majority of FA is finding its way to landfill [15, 16]. The use of FA in concrete has economic advantages and enhances concrete properties in both the fresh and hardened stages [6]. Due to its pozzolanic nature, FA is used as an admixture in cement and concrete [17]. The ground granulated blast-furnace slag (GGBFS) is a mineral admixture that is a by-product of pig-iron in blast furnaces, and it derives from the minerals contained in iron ore, flux ashes, and foundry coke. It mainly consists of calcium alumina-silicates and is essential for producing hydraulic binder [18]. Chemical properties of the FA and GGBFS used in this study are summarized in Table 1.

Table 1. Chemical compositions and LOI of OPC, FA and GGBFS [%]

Chemical composition	OPC	FA	GGBFS
Cao	63.40	1.00	49.76
Sio_2	19.80	64.60	29.35
Al_2O_3	5.10	20.9	11.72
Fe_2O_3	3.10	4.00	0.52
MgO	2.50	0.66	4.20
SO_3	2.40	0.30	2.09
K_2o	1.00	1.20	0.46
Na_2O	0.19	0.32	-
LOI	1.80	5.10	-

2.1.3. Superplasticizer

The superplasticizer (SP) is in conformity with EN 934-2 and meets the requirements of BS EN 934-2. It is a highly effective liquid SP for the production of free flowing concrete, and it enhances high ultimate and early strengths. The SP used is a modified polycarboxylate type superplasticizer. The SP quantity of 1.5 % by mass of total cement was used in this study.

2.1.4. Aggregate

Local mining sand was used in the concrete mix. Fineness modulus and saturated-surface-dry (SSD) specific gravity of sand was 2.9 and 2.55, respectively. In addition, 24h water absorption of sand was 1.5 %. The maximum nominal size, SSD specific gravity, and 24h water absorption of used coarse aggregate was 12.5 mm, 2.62 and of 0.67 %, respectively. The grading curves of the combined coarse and fine aggregate were within the Portland Cement Association (PCA) standard limits, as shown in Figure 1.

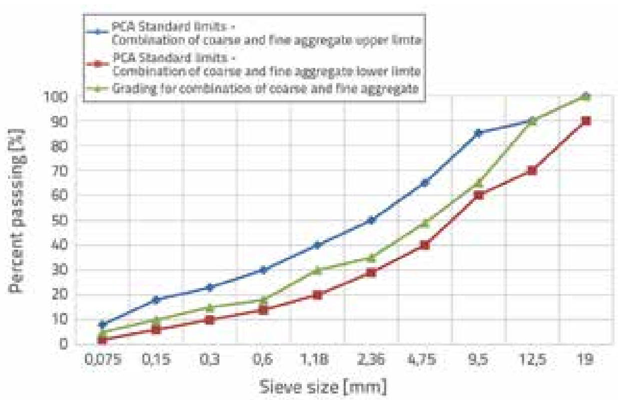

Figure 1. Sieve analysis of combination of coarse and fine aggregate compared to PCA standard limits

2.2. Mix proportions and mixing procedure

In this study, both RCCP and NVC contain 15 % Portland cement (329 kg/m^3) by mass of total dry solids. The cementitious materials in RCCP usually ranges from 250 to 350 kg/m^3 [2, 3]. With the same cement ratio, two RCCP mixtures with Fly ash (FA) and Ground-granulated blast-furnace slag (GGBFS) were made. Then, 1.5 % of superplasticizer was added to RCCP to obtain NVC mixtures with suitable slump. The FA and GGBFS are widely used as a supplementary cementitious material (SCM) for pozzolanic reaction in concrete. The use of FA in RCCP is an effective solution for providing fine particles required for full density [19]. FA and GGBFS usually account for 25 % and 30 % of the total volume of cementitious material in RCCP, respectively [2]. It was also established that the addition of GGBFS to RCCP led to reduced porosity, lower water absorption and permeability [20]. The mix proportions of all concretes are summarized in Table 2. In this table, "NVC1" and " NVC2" stand for normal vibrated concrete with FA and GGBFS, respectively. In addition, "RCCP1" and "RCCP2" stand for roller-compacted concrete pavement with FA and GGBFS, respectively. The water to binder (w/b) ratio is set 0.42 for all mixtures. In different real projects for RCCP application such as "port of Tacoma; intermodal yard" and " Atlanta; RCCP Shoulder" binders are included with 270 kg/m^3 cement and 60 kg/m^3 FA with the w/b ratio of 0.47, and with 300 kg/m3 of cement with w/b ratio of 0.53, respectively [2]. Also, Atis et al [21] reported an RCCP containing 340 kg/m^3 of cement and 60 kg/m^3 of FA, with the w/b ratio of 0.41 and with the 28-day compressive strength of 63 MPa.

The freshly-mixed RCCPs were compacted in cylindrical moulds by electric vibrating hammer according to ASTM C 1435 [22]. In addition, prism moulds were used for the flexural tensile strength test. Prism specimens were prepared by electric vibrating hammer equipped with a shaft and rectangular plate. The prism specimens were cast in three layers, and each layer was fully compacted until mortar

Table 2. Mix proportion details

Mix ID	Cement [kg/m^3]	FA* [kg/m^3]	GGBFS* [kg/m^3]	Water to binder ratio	Aggregate [kg/m^3]		Water [kg/m^3]	Superplasticizer [kg/m^3]
					Coarse aggregate	Fine aggregate		
NVC1	329	50	0	0.42	917	873	159	4.94**
NVC2		0	50					4.94**
RCCP1	329	50	0					0
RCCP2		0	50					0

* Fly ash and ground-granulated blast-furnace slag were added to RCCP mixtures by weight of total cement
** Superplasticizer was added to the RCCP mixtures by weight of total cement

formed on the top surface. The RCCP mixtures used in this study were designed based on the soil compaction concept in accordance with ASTM D1557.

2.3. Test methods and measured properties

The laboratory testing program was aimed at measuring the workability, strength, stiffness, durability, and microstructure of RCCP. The modified Vebe test and slump test were conducted to determine the consistency of RCCP and workability of NVC specimens, respectively. Properties of hardened concrete were measured by compressive strength, splitting tensile strength, and flexural tensile strength tests at 7 and 28 days. The stiffness (or modulus) of concrete was measured by the modulus of elasticity test and ultrasonic pulse velocity (UPV) test. Absorption (at initial and final stages) and porosity of concrete were measured for durability evaluation. The Field Emission Scanning Electron Microscope (FESEM) was used for microstructure assessment.

2.3.1 Consistency and workability

The consistency of conventional concrete was determined by the slump test according to ASTM C143. However, the Vebe test, ASTM C1170 [23], was employed to measure the consistency of RCCP concrete since RCCP is a "zero-slump" concrete. The compactibility, cohesion, and tendency to segregate are quite important properties of no-slump concrete [24].

2.3.2 Water absorption

The absorption test in accordance with ASTM C642 [25] was conducted on 100 × 200mm cylinders. The saturated surface dry (SSD) specimens were oven-dried at 105 ± 5 for 24 hrs. Then the dry weight (A) was recorded. Afterwards, the specimens were immersed in water at 20 until they achieved a constant weight (B). The absorption at 30 min (initial absorption) and at 72 hrs (final water absorption), when the difference between two consecutive weights was almost negligible, was calculated by the eqn. (1):

$$\text{Water absorption [\%]} = \left[\frac{B-A}{A}\right] \cdot 100 \qquad (1)$$

2.3.3. Strength properties

The compressive strength and splitting tensile strength tests were performed according to ASTM C39 and ASTM C496 [26], respectively. The testing was performed at 7 and 28 days on cylindrical specimens measuring 100 mm in diameter and 200 mm in height. On the other hand, the flexural tensile strength test was performed on prism specimens measuring 100 mm in diameter, 100 mm in height and 500 mm in length, according to ASTM C78 [27].

2.3.4. Porosity

RILEM (1984) [28] recommended a test method that involves air evaporation from oven dried samples. In this way, after evaporation of air from the oven dried samples, the water fills the pores under vacuum to reach full saturation. This method has been proposed by many other researchers [29, 30].

2.3.5. Ultrasonic pulse velocity test

The Ultrasonic Pulse Velocity (UPV) is a non-destructive method that is used to check the quality, homogeneity, and compressive strength of concrete [31, 32]. Ultrasonic measurements can be conducted in two ways [33]: a) by direct transmission, and b) by propagation along the surface. The direct transmission procedure was adopted in this study. The UPV test was performed on 100 mm cubes as per BIS 13,311 (Part 1)-1992. The transducer frequency amounted to 54 kHz in this test. The time the pulses take to travel through the concrete specimen was recorded, and then the velocity was computed using eqn. (2):

$$V = \frac{L}{T} \qquad (2)$$

where:
V - pulse velocity [m/s]
L - length of travel [m]
T - effective time [s].

2.3.6. Modulus of elasticity test

The static modulus of elasticity test was conducted in accordance with ASTM C469 [34]. Cylinder specimens 150mm in diameter and 300mm in height were placed in the compression testing machine and uniform load was applied until failure. For strain calculation, dial gauge readings were divided by gauge length and, for stress, the load applied was divided by the area of cross-section of samples. For finding modulus of elasticity of samples, the deformation at different loads was plotted graphically against the stress. In the stress-strain curves, the modulus of elasticity was determined from the slope of the initial tangent modulus. Three cylinders were prepared for each test. The end surface of all specimens was ground to ensure uniform load distribution over the specimen surfaces.

2.3.7. Field emission scanning electron microscope (FESEM) test

Electron microscope can be used as a diagnosis tool for nano- and micro-scale cracking of concrete [35]. The FESEM is an advanced microscope that offers increased magnifications and the ability to observe fine features with a lower voltage compared to the typical scanning electron microscope (SEM)

[36]. In this study, the FESEM test was used to detect entrapped air voids and compaction voids in RCCP and NVC specimens.

2.3.8. Thermal conductivity test

The thermal conductivity test was performed on cylindrical specimens (100mm × 200mm) at the age of 28 days. The samples were oven dried for 24 hours at 100 ± 5°C to remove internal moisture. KD2-PRO analyser with the TR1 needle sensor was used for the testing. The TR1 sensor (2.4 mm in diameter and 100 mm in length) is capable of measuring thermal conductivity in the range of 0.1 W/m.°K to 4 W/m.°K. A pilot pin was inserted in uncured specimens to prepare the hole corresponding to the size of the TR1 sensor. The relatively long read times of sensor (10-minute reading and 15-minute interval) contribute to the reduction of errors caused by the large-diameter needle. The contact between the needle and specimen was ensured by applying thermal grease in the hole (see Figure 2).

Figure 2. a) Preparing a hole to insert TR1 sensor; b) Thermal conductivity measurement by KD2-Pro

Figure 3. a) Surface texture of RCCP1 at Vebe test; b) Surface texture of RCCP2 at Vebe test

The principle of KD2-PRO analyser involves heating the needle for a time and monitoring the temperature during the heating and cooling process. During testing, the ambient temperature is maintained at constant temperature to obtain accurate measurement. In addition, the surface of specimens is wrapped by plastic bag to minimize the effect of ambient temperature. The thermal conductivity can be calculated according to eqn. (3).

$$Q = -kA\frac{\partial T}{\partial x} \qquad (3)$$

where Q is the heat flow (W), K is the thermal conductivity (W/mK), A s the area to the x (m^2), ∂T is the temperature difference (°K) and ∂x is the distance (m).

3. Results and discussion

3.1. Fresh properties

Measured fresh properties of all mixtures are summarized in Table 3. The Vebe time for RCCPs was in the range of 26-29 sec. Based on ACI 325, the Vebe time is limited to 30-40 sec for producing RCCP. Figure 3 shows the RCCP surface texture at the time of Vebe test. RCCP mixes exhibited sufficient workability, which is crucial for RCCP's easy compaction, uniform lift thickness, bonding with previously compacted lift, and for support of compaction equipment [15].

Table 3. Fresh properties of NVC and RCCP specimens

Mix	Vebe time [s]	Slump [mm]	Oven dry density [kg/m³]
NVC1	N/A	239	2287
NVC2	N/A	223	2308
RCCP1	26	0	2339
RCCP2	29	0	2374

High workability of slump 200-240 mm was observed for the NVCs. Based on visual inspection, no segregation or bleeding was observed at all mixes during mixing, placing, and compaction. The slump test for NVC mixtures is shown in Figure 4. The oven dry density values of RCCP and NVC specimens were in the range of 2339-2374 kg/m³ and 2287-2308 kg/m³, respectively. Generally, the density of RCCP ranged from 2340 to 2510 kg/m³ [10]. It can be concluded that compaction with vibrating hammer can provide higher pack density for RCCP, in comparison with normal vibration table for NVC. The heavy compaction applied for RCCP results in a denser structure when compared to the conventionally vibrated concrete [3]. The use

Figure 4. c) Slump test for NVC1; d) Slump test for NVC2

of GGBFS decreased a slump in NVC and increased Vebe time in RCCP. This means that the use of GGBFS decreased the workability in RCCP and NVC.

3.2. Compressive strength

Compressive strength results for various mixes are presented in Figure 5. The strengths measured at 7 and 28 days show standard deviation in the range of 2 % to 6 %. The compressive strengths of NVC1 at 7 and 28 days were found to be 35.2 and 40.1 MPa, and those of NVC2 amounted to 37.2 MPa and 42.4 MPa. However, the 7-day compressive strengths of RCCP1 and RCCP2 showed 7 % and 6 % decrease, respectively, and the 28-day compressive strengths showed 8 % and 10 % increase in comparison with NVC1 and NVC2 specimens, respectively. The compressive strength of RCCP is comparable to that of NVC, typically ranging from 28 to 41 MPa. Compressive strengths higher than 48 MPa have been reported in some projects [2].
The increase in compressive strength for NVC specimens at early age can be attributed to the acceleration of setting time. Early strengths may be somewhat accelerated due to better dispersion of cement particles in water because of the use of superplasticizer [37]. Compared to NVC, it can clearly be noted that the 28-day compressive strength of RCCP mixtures is higher by about 8-10 %. It should be noted that, with the use of FA and GGBFS, the difference of compressive strength between NVC and RCCP is almost constant. Therefore, it can be concluded that, on an average, the compressive strength of RCCP is higher by 9 % than that of NVC.

3.3. Splitting tensile strength

The splitting tensile strength results of various mixes at 7 days and 28 days are shown in Figure 6. The standard deviation for the splitting tensile strength results was 3-7 %. The splitting tensile strength shows the same trend as the compressive strength, with the higher values at 7 days for NVC specimens. Similar enhancement in splitting tensile strength was observed for RCCP specimens at 28 days. The splitting tensile strength for RCCP1 and RCCP2 decreased by about 10.2 % and 9.3 % at 7days and increased by about 4.4 % and 3.9 % at 28 days in comparison with NVC1 and NVC2, respectively. These results revealed that the 28 days splitting tensile strength for RCCP mixture is higher by about 4 % compared to NVC mixture. In addition, it can be concluded that the increment of compressive strength is higher than that of the splitting tensile strength for RCCP mixture at 28

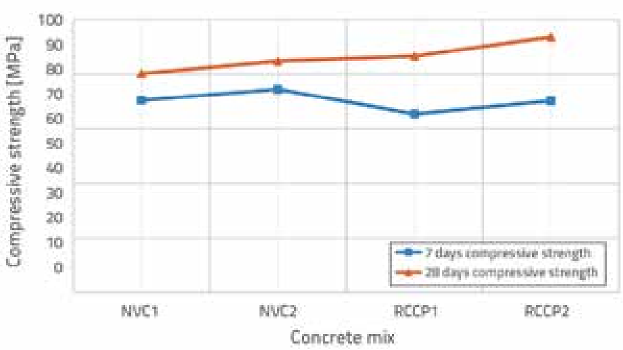

Figure 5. Compressive strength of NVC and RCCP mixes

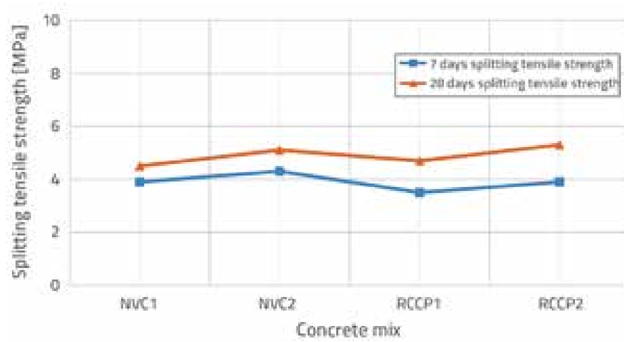

Figure 6. Splitting tensile strength of NVC and RCCP mixes

days, in comparison with NVC mixture. Generally, the splitting tensile strength of conventional concrete corresponds to about 10 % of the compressive strength [38]. This ratio ranges from 7 to 13 % for RCCP [37]. In this study, the splitting tensile strength for NVC and RCCP amounted to about 11.65 % and 11.4 % of the compressive strength, respectively.

3.4. Flexural tensile strength

Flexural tensile strength results are shown in Figure 7. The standard deviation of the flexural tensile strength results ranged between 3-9 %. In spite of the compressive strength and splitting tensile strength, the flexural tensile strength of RCCP mixtures increased by about 11.9 % and 13.3 % at 7 days, and by about 19.6 % and 30.1 % at 28 days in comparison with NVC1 and NVC2, respectively. Flexural strength is directly related to compressive strength and unit weight of concrete mixtures [3]. In properly constructed RCCP the aggregates are densely packed, and so more energy is required for crack propagation and cracking to occur [3]. Typically, the flexural tensile strength of conventional concrete corresponds to about 15 % of compressive strength [38]. Also, it is reported that the ratio between flexural strength and compressive strength in RCCP is about 0.15, as compared to between 0.10 and 0.12 in normal concrete [3]. In this investigation, the flexural tensile strength for NVC and RCCP were about 12.6 % and 14.4 % of the compressive strength, respectively.

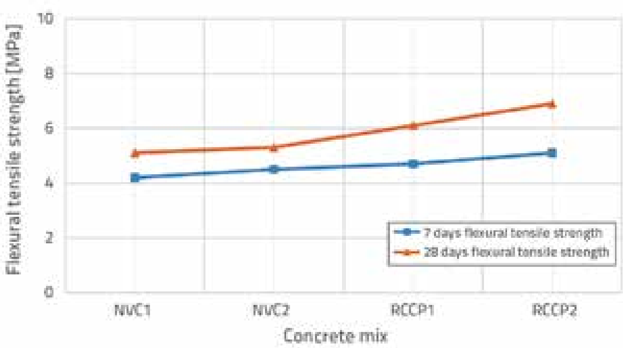

Figure 7. Flexural tensile strength of NVC and RCCP mixes

3.5. Water absorption

Water absorption is usually considered as an important factor for quantifying durability of cementitious systems [39]. Previous studies indicate that decrease in the water to cement ratio and increase in the degree of consolidation could result in decrease of the water absorption value [37]. Comité Euro-International du Béton (CEB) [40] divided concrete into good concrete with water absorption of < 3 %, average concrete with water absorption of 3-5 %, and poor concrete with water absorption > 5 %.
The results for initial water absorption after 30 min and final water absorption after 72 h are shown in Figure 8. As can be seen, the initial surface water absorption of all RCCP and NVC mixtures showed values lower than 3 %. In addition, the final water absorption was lower than 3 % for RCCP1 and RCCP2 mixtures. However, it was 3.2 % and 3.12 % for NVC1 and NVC2 mixtures, respectively. The results revealed that the initial and final water absorption for RCCP is slightly lower than that of NVC. Also, Khayat and Libre (2014) [3] compared water absorptions of RCCP mixtures with that of the conventional concrete. In this study, lower water absorption was observed in the RCCP mixture compared to conventional concrete.
The final water absorption for RCCPs containing FA and GGBFS reduced by about 7 % and about 9 %, respectively. It should be noted that the initial and final water absorption values for NVC and RCCP mixtures containing GGBFS were slightly lower compared to mixtures containing FA.

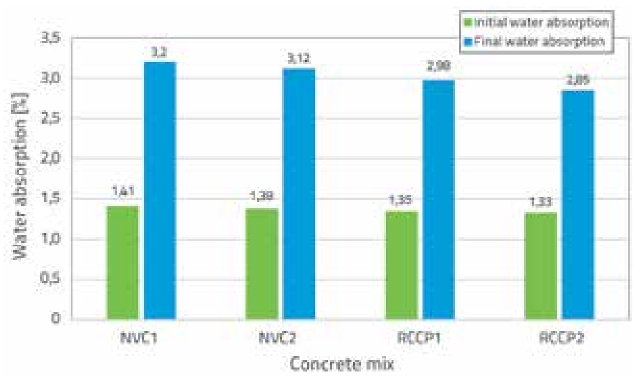

Figure 8. Initial and final water absorptions of NVC and RCCP mixes at 28 days

3.6. Porosity

The total volume of capillary voids in Portland cement paste is known as porosity [37]. The inverse relationship between porosity and strength of solids has been reported by researchers [41]. The porosity and pore size distribution of cement based materials affect their mechanical and durability properties significantly [42]. Porosity results of the RCCP and NVC mixtures are presented in Figure 9.

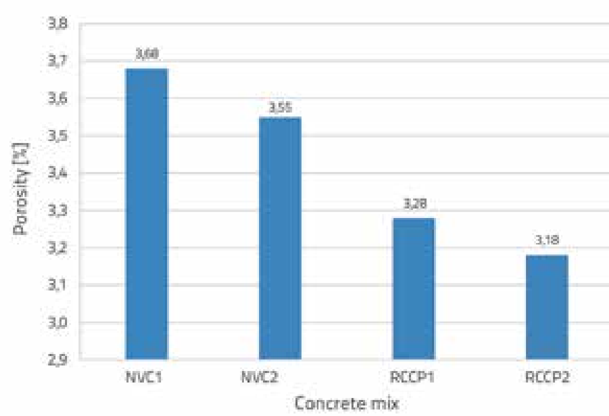

Figure 9. Porosity test results for NVC and RCCP mixes at 28 days

It can be seen that the porosity results are in agreement with the water absorption test results. The percent of porosity for RCCP1 and RCCP2 decreased approximately by 10.8 % and 10.4 % in comparison with NVC1 and NVC2, respectively. It has been observed that the high-pressure compaction applied to RCCP mixture could result in lower porosity of the cement matrix.

3.7. Ultrasonic pulse velocity

The range of ultrasonic pulse velocity (UPV) qualitative rating varies from 3 to 4.5 Km/s [33]. The UPV must be more than 4.5 Km/s for excellent quality concrete, from 3.5 to 4.5 Km/s for good quality concrete, and from 3.0 to 3.5 Km/s for medium quality concrete. In this study, the UPV was about 4.21 and 4.33 Km/s for NVC1 and NVC2, respectively. Therefore, NVC mixtures were in the range of good quality concrete. However, this value was 4.61 and 4.77 Km/s for RCCP1 and RCCP2, respectively, and so they are in the range of excellent quality concrete. A strong correlation between UPV and 28-day compressive strength is shown in Figure 10.

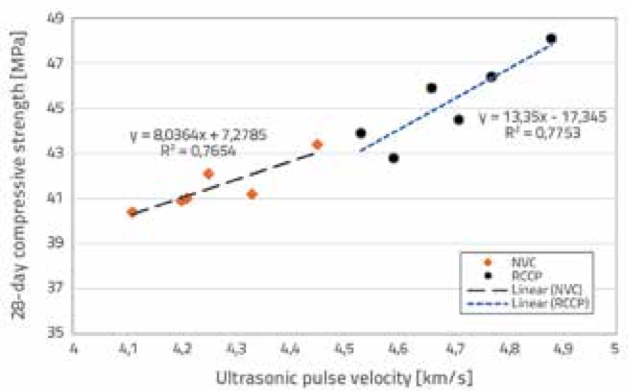

Figure 10. Relationship between UPV and 28-day compressive strength

3.8. Modulus of elasticity

Modulus of elasticity (ME) results for the NVC and RCCP specimens are shown in Table 4. As shown, the modulus of elasticity of the NVCs was between 27 and 29 GPa, while it was between 32 and 35 GPa for RCCPs. The average modulus of elasticity for various RCCP mixes is reported to be about 30 GPa at 28-day [12]. The modulus of elasticity of RCCP1 and RCCP2 is by about 16.2 % and 19 % higher than MOE of NVC1 and NVC2, respectively. These results also show that the behaviour of the modulus of elasticity is similar to that of the compressive strength.

The modulus of elasticity of concrete is affected by the cement paste, nature of aggregate, and the interfacial transition zone [43]. According to European standard [44], the modulus of elasticity of concrete is especially dependent on its aggregates. This result is in agreement with findings previously reported by Yildirim & Sengul [45]. Ouellet [46] illustrates that the elastic modulus of RCCP is influenced by the properties of the two phases in this mixture that are the hydrated cement paste and the aggregates. Therefore, it can be concluded that higher porosity of NVC, and heavy compaction applied on RCCP, may be the reason behind the lower modulus of elasticity of NVC.

The models developed initially for conventional concrete should be applied to estimate the modulus of elasticity of RCCP. ACI 318 developed eqn. (4) to estimate the modulus of elasticity of conventional concrete:

$$E_c = 4700\sqrt{f_c} \tag{4}$$

where E_c is the modulus of elasticity [MPa], and fc is the compressive strength of concrete [MPa]

The measured and estimated values of modulus of elasticity results for NVC and RCCP specimens are compared in Table 4. A comparison between estimated values provided by ACI 318 and the data obtained in this study shows that the measured values for NVC1 and NVC2 are about 7.2 % and 6.9 % lower than estimated values, while the measured values for RCCP1 and RCCP2 are about 3.8 % and 5.6 % higher than estimated values, respectively.

Table 4. Measured and estimated values of MOE for the NVC and RCCP concretes

Mix	Measured MOE [GPa]	Estimated modulus of elasticity by ACI 318 [GPa]
NVC1	27.9	29.9
NVC2	28.8	30.8
RCCP1	32.4	31.14
RCCP2	34.3	32.37

It can be concluded from these results that NVC specimens reached their breaking points at lower stress, without much strain softening in comparison with RCCP specimens.

3.9. Field emission scanning electron microscope test

Microstructural configurations for different NVC and RCCP samples were investigated using field emission scanning electron microscope (FESEM) as shown in Figure 11. The FESEM test was used to detect entrapped air voids and compaction voids in NVC and RCCP specimens. The durability of concrete is dependent on the characteristics of its pore structure [47] and it is obtained when pore structure gets tight and highly impermeable [48].

- The FESEM test results show the following: 1) No compaction voids were observed in NVC and RCCP specimens. An interconnected network could be formed due to the high number of compaction voids which seriously jeopardize durability of concrete and can affect its freeze-thaw resistance [3]. Generally, compaction voids are irregular and large in shape. They are formed due to improper compaction of concrete during casting.

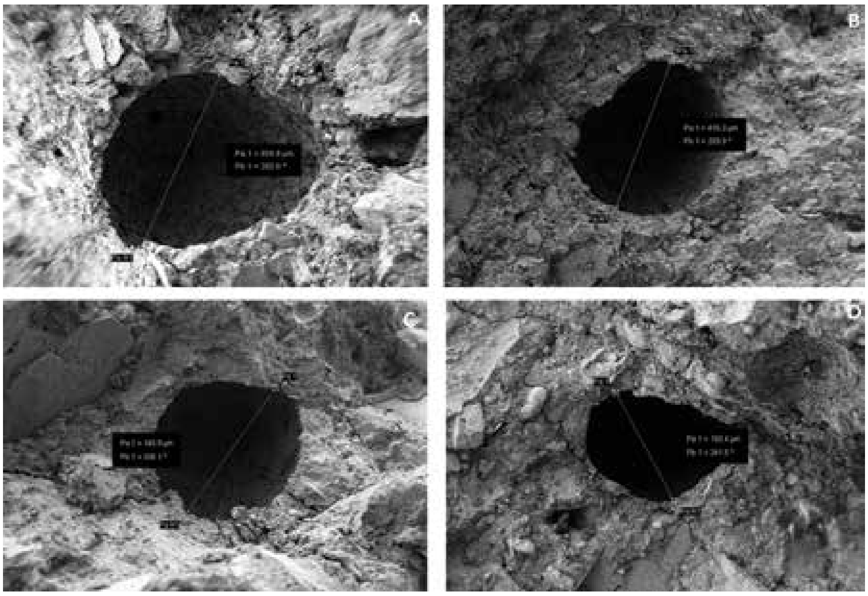

Figure 11. Maximum void size in the paste of NVC and RCCP specimens: a) NVC1; b) NVC2; c)RCCP1; d) RCCP2

- The maximum air voids size found in RCCP mixture was about 192 µm. However, it was about 858 µm in NVC mixture, which makes the microstructure of the paste more porous and results in lower strength. During concrete mixing, a little quantity of air usually gets trapped in the cement paste. Entrapped air voids are generally spherical in shape and may be as large as 3 mm [37]. The strength of concrete is adversely affected by the entrapped air voids [49].

3.10 Thermal conductivity test

Thermal properties of pavement material have a vital role in the formation of Urban Heat Islands (UHI) [50]. At usual operating temperatures, the heat transfer in concrete is mainly operated by conduction. Thermal conductivity is a property of a material that demonstrates its capability of heat conduction [51, 52]**.** An average thermal conductivity and oven dried density of different samples are summarized in Table 5.

Table 5. Average thermal conductivity and density of samples at 28 days

Mix	Density [kg/m³]	Thermal conductivity [W/mK]
NVC1	2287	2.44
NVC2	2308	2.47
RCCP1	2339	2.52
RCCP2	2374	2.69

Sengul et al. [53] revealed that there is a significant relationship between unit weight of concrete and the value of thermal conductivity. Figure 12 shows the relationship between thermal conductivity and density of specimens in oven-dried conditions.

The average thermal conductivity of NVC and RCCP samples is about 2.45 W/m.°K and 2.60 W/mK, respectively. Based on literature, the thermal conductivity of lightweight concrete is in the range of 0.2 to 1.9 W/m.°K, while it is up to 3.3 W/mK for normal weight concrete [54-57]. The results show that the k-value of both NVC and RCCP is in the range of normal weight concrete. However, compared to NVC, RCCP has a greater heat transfer capability providing for a lower surface temperature. This capability is due to its denser structure compared to NVC. Eqns. (5) and (6) could be used to predict the thermal conductivity value of NVC and RCCP:

$$K = 0{,}0015\rho - 0{,}9125 \quad (R^2 = 0.88) \tag{5}$$

$$K = 0{,}0045\rho - 8{,}0712 \quad (R^2 = 0.86) \tag{6}$$

where K s the thermal conductivity (W/mK) and ρ is the density (kg/m³).

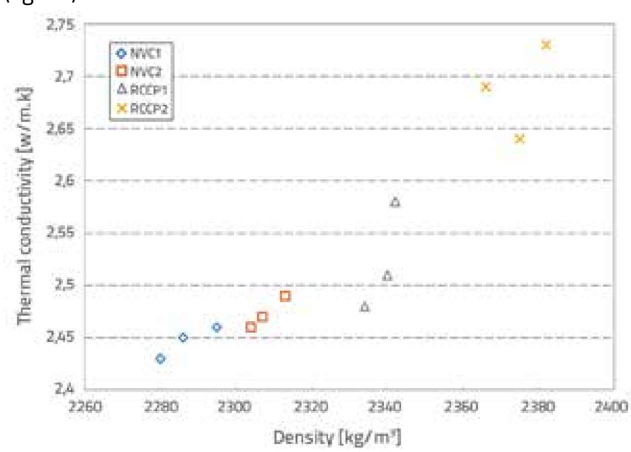

Figure 12. Relationship between thermal conductivity and density

4. RCCP application

The results show that RCCP is an attractive alternative to conventional road structures due to its higher mechanical properties, proper durability, and denser structure. Therefore, ports and heavy industrial facilities, which require high-strength and durable pavement to support heavy loads and where surface appearance is not quite important, would be ideal candidates for RCCP.

5. Conclusions

The following conclusions can be made based on test results obtained in this experimental study:

- The 28-day oven dry density of RCCPs was higher compared to NVCs. This increase may be due to heavy compaction applied on RCCP specimens. Therefore, the compaction with vibrating hammer can provide higher pack density as compared to normal vibration table.
- The 28-day compressive strength, splitting tensile strength, and flexural tensile strength of RCCP were found to be by 9 %, 4 % and 25 % higher compared to NVC specimens.
- The final water absorption and porosity values of RCCP specimens decreased by about 8 % and 10.6 % in comparison with NVCs. This points to better durability performance of RCCP compared to NVC.
- The compressive strength and UPV present a linearly increasing relation curve. Also, a linear relationship between UPV and density of concretes was observed. Higher UPV values were obtained for RCCPs (4.61 and 4.77 km/s for RCCP1 and RCCP2) in comparison with NVCs (4.21 and 4.33 km/s for NVC1 and NVC2).
- On an average, the MOE for RCCPs was about 33.3GPa. However, it was around 28.3 GPa for NVCs. This shows that RCCP specimens can withstand higher stress with lower deflection in comparison with NVC.
- FESEM images of concretes show that the maximum void size of NVCs may be reached at 858 μm. However, it was about 192 μm for RCCPs. This is another reason for concluding that vibrating hammer can provide higher pack density for RCCP in comparison with normal vibration table for NVC.
- Thermal conductivity test results indicate that RCCP is capable of transferring heat faster and that it ensures lower surface temperature compared to NVC due to its higher thermal conductivity.

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