Strength and durability of roller compacted concrete with different types and addition rates of polypropylene fibers

Ismail Kilic (Main and Corresponding Author)
Kirklareli University, Faculty of Engineering, Department of Civil Engineering
39100 (Turkey)
ismail.kilic@klu.edu.tr
https://orcid.org/0000-0001-5556-512X

Saadet Gokce Gok
Kirklareli University, Faculty of Engineering, Department of Civil Engineering
39100 (Turkey)
saadet.gokce.gok@klu.edu.tr
https://orcid.org/0000-0002-7879-1610

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Abstract
Roller compacted concrete (RCC) is a relatively new alternative construction material that can be used in road and dam constructions by allowing rapid use after production and the use of conventional building materials in production. RCC, which can be produced with low water/cement ratio, is one of the rigid road pavement types and shows similarity to flexible road pavements with the production technique. Different types of fibers such as steel and polypropylene (PP) are used in concrete roads with the aim of preventing cracks, reducing the pavement thickness and increasing the permissible joint gap. In this study, flexural strength, compressive strength, unit weight, water absorption, ultrasonic pulse velocity, modulus of elasticity and freeze-thaw resistance were determined in roller compacted concretes produced by using two different polypropylene-based fibers. In RCC design, fiber addition was insufficient to improve concrete properties in terms of strength and durability. It has been observed that there was a 14.4% reduction in compressive strength with 0.20% fiber inclusion, and a 46.8% reduction in compressive strength with 0.50% fiber inclusion. Polypropylene fiber inclusion increased the water absorption percentages and decreased the specific weights of fiber reinforced roller compacted concretes. However, roller compacted concretes produced with PP-fiber exhibited a good performance under freeze-thaw attack.

Keywords: concrete road, durability properties, fiber, mechanical properties, roller compacted concrete.

Introduction

Roller compacted concrete (RCC) roads are one of the alternative pavement types and provide economic benefit with rapid opening of the road to use after production. RCC roads have the same material content as conventional concrete roads but also have the advantages of both concrete and asphalt as they can be produced with machines used in asphalt road production. The use of roller compacted concrete pavements instead of asphalt pavements using petroleum derivatives, contributes to the efficient evaluation of resources in terms of accessibility and cost of the raw materials used. RCC production is achieved by mixing the components used in conventional concrete in different ratios, and the workability of RCC is different from conventional concrete, but RCC can be transported, laid and compacted with the machines used in bituminous hot mix asphalt. One of the important differences between RCC and conventional concrete mixtures is the use of a higher proportion of fine aggregate in RCC production than in conventional concrete for providing better compaction of concrete (Yaman & Ceylan, 2015).

The slump value of the fresh RCC is zero and the mixture is in a very dry form compared to conventional concrete. The dry mixture is transported by dump trucks, laid in layers and compacted with vibratory roller compaction equipments. RCC offers advantages as the materials used in the production stage are similar to those used in conventional concrete production. In fresh state, roller compacted concretes have decreased workability when compared to conventional concrete and appear to be a filler material in soil. However, roller-compacted concretes have the same characteristics with conventional concrete when solidified. The advantages of RCC in application have enabled the studies on this subject to increase in recent years (Adamu, Mohammed, & Shahir Liew, 2018; Chi & Huang, 2014; Mardani-Aghabaglou, Andic-Cakir, & Ramyar, 2013; Meddah, Beddar, & Bali, 2014; Modarres & Hosseini, 2014; C. Wang et al., 2018; X. hua Wang, Zhang, Wang, Liu et al., 2018).

The most important advantage of RCC roads is that they can be constructed much faster and more economically than concrete pavements and multi-layer asphalt pavements. In addition, molds are not used on RCC roads, extra finishing is not generally needed and the cost decreases as no steel reinforcement is used such as shear reinforcement (Yaman &

Ceylan, 2015). It can be produced with lower cement content and allows reuse of pozzolanic by-products such as fly ash, or waste aggregates and waste fibers in concrete. By choosing the right aggregate and optimizing the aggregate combination, cement content can be reduced, workability can be improved and RCC performance can be enhanced (Khayat, Wu, & Fellow, 2019). Considering the disadvantages and limitations of application of roller compacted concrete, the production volume in the mixer is low compared to conventional concrete due to their dry consistency (Topličić-Ćurčić et al., 2015). Also, a planned organization is required in the production, transportation, laying and compacting stages of roller compacted concrete.

While fiber utilization is more common in concrete roads, studies on use of fiber in roller compacted concrete are more limited. The use of macro-synthetic fibers in roller compacted concrete increases the water requirement of the mixture, does not significantly affect the compressive strength but provides an increase in splitting tensile strength (Algin, Mermerdas, & Zeynepli, 2019). In roller-compacted fast-curing concrete, permeability is reduced, chloride ion permeability is decreased, abrasion resistance and impact resistance are increased by the use of macro-synthetic fibers (Lee, Jeon, Cha, & Park, 2017). Ozturk et al. stated that the maximum flexural strength decreased but the remaining bending strength after cracking increased with the addition of fiber to roller compacted concrete, and despite the increase in the positive moment capacity in fiber-reinforced sample, they found the pavement thickness values of fiber-reinforced and fiber-free samples close together due to the decrease in bending strength of fiber-reinforced samples (Ozturk, Ozyurt & Atahan, 2019). In roller compacted concrete produced using macro-fibers, it has been stated that structural performance depends on fiber type, geometry and dosage and fiber usage improves the compressive strength and splitting tensile strength (LaHucik et al., 2017). Based on fatigue life, fiber inclusion reduces pavement thickness, and additional fiber costs are compensated when material and construction costs are considered (Nanni, 1989).

Fiber addition reduces the compressive strength of roller compacted concrete but significantly improves the post-peak bending behavior (Neocleous, Angelakopoulos, Pilakoutas, & Guadagnin, 2011). Although polypropylene fiber reduces the compressive strength of concrete, it is beneficial for fire resistance by providing higher thermal insulation, controlling internal pressure and hindering heat transfer with increased amount of voids in the structure (Manica, Bolina, Tutikian, & Valadares, 2019). Karahan et al. stated that mortars containing PP fiber exhibit better performance at elevated temperatures up to 400°C in terms of relative residual strengths (Karahan, Durak, Ilkentapar, Atabey, & Atis, 2019).

In roller compacted concretes, steel fibers can be used as well as polypropylene fibers (Kumar, KrishnaRao, & Panduranga Rao, 2013; Lin, Karadelis, & Xu, 2013; Neocleous, Pilakoutas, Graeff, & Koutselas, 2011; Sukontasukkul et al., 2019). The combination of short steel and macro-polypropylene fibers in roller compacted concrete has a synergistic effect in modifying fracture toughness, while steel fibers have been more effective in bridging macro cracks (Rooholamini, Hassani, & Aliha, 2018). Both polypropylene fibers and steel fibers create more thermal stress in roller compacted concrete than fiber-free samples, increase flexural strength and increase thermal cracking resistance of the structure (Hejazi, Abtahi, & Safaie, 2016). Kolase and Desai studied the monotonic and fatigue behavior of polypropylene fiber compacted concrete containing fly ash and stated that the addition of polypropylene fiber provides an improvement on the repeated load cycles and the energy spent to complete a single cycle (Kolase & Desai, 2019). Because of their low density, polypropylene fibers reduce the concrete density when added to roller compacted concrete, affect workability negatively, may cause segregation, increase water absorption but increase mechanical strength and reduce free shrinkage development (Benouadah, Beddar, & Meddah, 2017).

In this study, two different polypropylene fibers were added to the roller compacted concrete and flexural strength, compressive strength, unit weight, water absorption, ultrasonic pulse velocity, modulus of elasticity, and freeze-thaw resistance of fiber reinforced roller compacted concrete (FRRCC) were investigated.

Materials and methods

Portland cement, water, crushed stone I, crushed stone II, stone dust, natural sand and polypropylene fiber were used in the production of roller compacted concrete. The aggregates used were dolomitic limestone and natural sand.

Materials

CEM I 42.5R portland cement was used in the experimental study. Table 1 shows the chemical analysis and the physical properties of the cement. Four different sizes of aggregates were used in the production and the sieve analysis of the aggregates is given in Table 2. Maximum aggregate size (d_{max}) was selected as 19 mm. The granulometric curve of the aggregate mixture remains between the upper and lower limits proposed in the literature (Harrington et al., 2010). The specific gravity values of the aggregates used were 2.80, 2.80, 2.81 and 2.76 g/cm^3 for crushed stone II, crushed stone I, stone dust and natural sand, respectively.

Table 1. The chemical analysis and the physical properties of the cement. (Self – Elaboration).

Chemical analysis												
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Cl^-	Loss on ignition	Insoluble residue	Total alkali
%	19.15	4.78	3.25	63.98	1.18	2.90	0.64	0.24	0.0128	3.43	0.35	0.66

Physical tests		
Setting time (min)	Initial	140
	Final	200
Specific gravity (g/cm^3)		3.11
Specific surface (Blaine) (cm^2/g)		3712
Total volume expansion (Le Chatelier) (mm)		1.00
Residue on 45 µ sieve		2.35
Residue on 90 µ sieve		-

Compressive strength (MPa)		
Mechanical characteristic-day	Early strength (2 day)	30.6
	Early strength (7 day)	47.1
	Standard strength (28 day)	59.5

Table 2. The sieve analysis of the aggregates. (Self – Elaboration).

Sieve No. (mm)	Percentage passing (%)				
	Crushed stone II	Crushed stone I	Stone dust	Natural sand	Mixture
19	100.00	100.00	100.00	100.00	100.00
16	42.46	100.00	100.00	100.00	85.62
12.50	1.05	90.97	100.00	100.00	73.01
9.50	0.00	71.32	100.00	100.00	67.83
8	0.00	51.73	100.00	100.00	62.93
4	0.00	5.06	93.37	98.93	49.34
2	0.00	0.00	66.20	96.01	40.55
1	0.00	0.00	43.71	86.22	32.48
0.50	0.00	0.00	29.37	57.26	21.66
0.25	0.00	0.00	22.30	20.97	10.82
0.125	0.00	0.00	17.31	3.46	5.19
0.075	0.00	0.00	10.99	1.13	3.03
0.063	0.00	0.00	6.25	0.80	1.76

The properties of the polypropylene fibers used are given in Table 3. In this table, the material, size, strength, elasticity modulus, width and length values of the fibers are available. Since the diameter and modulus of elasticity values of the Fiber-2 are not included in the product information catalogue provided by the manufacturer, this information is not included in the table. As can be seen in Table 3, the fibers comply with the ASTM C 1116 (ASTM, 2015) standard.

Table 3. Fiber properties (Url-1, 2019). (Self – Elaboration).

Fiber	Fiber-1 (BF)	Fiber-2 (MM)
Type	PP (100% Polypropylene)	PP/PE (99% Polypropylene)
Standard	ASTM C1116 CE, EN 14889-2BBA 92/2830	ASTM C1116, TS EN 14889-2:2006
Appearance	Natural white fibers	Twisted, deformed
Specific gravity	0.91 g/cm^3	0.91 g/cm^3
Length	19 mm	54 mm
Profile and diameter	Circular, 18 µm-20 µm	-
Tensile strength	450-700 MPa	550-750 MPa
Modulus of elasticity	3000-3500 MPa	-
Melting point	162ºC	160-170ºC
Ignition point	593ºC	400ºC

Fiber reinforced RCC production

As specified in the Technical Specification for Roller Compacted Concrete (RCC) roads, the minimum characteristic compressive strength class of roller-compacted concrete should be C30/37 (TCMA, 2017). The flexural strength of roller compacted concrete should be minimum 4.2 MPa for C30/37 concrete class (TCMA, 2018). RCC was designed by using TS 802 (TS 802, 2016) standard for the concrete class C30/37 and the amount of each material in 1 cubic meter of concrete for each production is given in Table 4. The moisture content of the aggregates was taken into account when determining the mix proportions. Mix proportions were determined by using dry surface water-saturated aggregates. The amounts of water and cement were kept constant, and fiber was added to the mixture. With the change of water amount, the water/cement ratio will also change and will affect the RCC properties.

Therefore, the amount of water was kept constant and the RCC properties were investigated based on the fiber content only. The consistency with zero slump was taken into consideration in concrete mix design. Cement content was selected as 429 kg/m^3 which is higher than the minimum dosage (340 kg/m^3) specified in the technical specifications of concrete pavement (KGM, 2016). Although this dosage is known to be a high value for roller compacted concretes, the cement content used in many RCC road projects in North America ranges from 300 kg/m^3 to 500 kg/m^3 (Harrington et al., 2010). The cement ratio of the mixture was calculated in terms of cement weight/dry material weight (cement+aggregate) as given in ACI 327R (2014) and determined as 18%.

This value is high for roller compacted concrete (12%) and is higher than the cement used in conventional concrete pavements (15%) (LaHucik et al., 2017). In the production of roller compacted concrete, two different fibers were used as shown in Figure 1 and Figure 2. While the fiber volume ratio in the samples produced with Fiber-1 (BF) is 0.10%, 0.15% and 0.20%, the fiber volume ratio in the samples produced using Fiber-2 (MM) varies as 0.10%, 0.30% and 0.50%. These ratios are determined based on the recommended amounts for the fibers in question. In the ASTM C 1116 (2015) standard, it is stated that a fiber reinforced concrete must contain at least 0.1% fiber by volume. While determining the fiber amounts, this standard and the manufacturer's recommendation were taken into consideration.

Figure 1. Fiber-1 (BF). (Self – Elaboration).

Figure 2. Fiber-2 (MM). (Self – Elaboration).

Table 4. The amount of each material in 1 cubic meter of roller compacted concrete. (Self – Elaboration).

Specimen	Fiber volume ratio (%)	W/C	Water (kg)	Cement (kg)	Crushed stone II (kg)	Crushed stone I (kg)	Stone dust (kg)	Natural sand (kg)
Reference	0.00	0.35	150	429	488.25	488.25	488.25	488.25
BF0.10	0.10	0.35	150	429	488.25	488.25	488.25	488.25
BF0.15	0.15	0.35	150	429	488.25	488.25	488.25	488.25
BF0.20	0.20	0.35	150	429	488.25	488.25	488.25	488.25
MM0.10	0.10	0.35	150	429	488.25	488.25	488.25	488.25
MM0.30	0.30	0.35	150	429	488.25	488.25	488.25	488.25
MM0.50	0.50	0.35	150	429	488.25	488.25	488.25	488.25

The production of roller compacted concrete was carried out according to ASTM C 1435 (ASTM C 1435, 2014). After the preparation of aggregate mixtures, different concrete mixtures containing water, cement, aggregate and polypropylene fiber were produced and compaction process was made with a vibratory hammer. As preparing the specimens, BOSCH GBH 12-52 DV Professional brand vibrating hammer was used in accordance with the requirements of ASTM C 1435 (2014) standard. The impact energy used while preparing the specimens was 19 J. For cylinder specimens, the compaction process was carried out in three layers and each layer was compressed for twenty seconds. In the beam sample production, compression process was performed in two layers. Compaction operations were carried out with vibratory hammer in accordance with the standard. 146 mm diameter circular head end was used with vibratory hammer for cylinder samples, and square head with 146 mm edge length was used as fitted to vibratory hammer for beam samples. Samples with BF in the sample code contained Fiber-1, while samples with MM were produced with Fiber-2.

Experimental stage

The flexural strengths of FRRCC beams at 28 days and compressive strengths of FRRCC cubes at 90 days were determined. The specimens were demolded 24 hours after casting and water-cured until the day of testing. Three specimens were tested and the average of the three values were determined for each production. Compressive strengths were determined according to TS EN 12390-3 standard (TS EN 12390-3, 2003). Concrete cube specimens of 150 mm × 150 mm × 150 mm were used to determine the compressive strength at the age of 90 days. In order to determine the flexural strengths at the age of 28 days, 150 mm×150 mm×750 mm sized unnotched prismatic specimens were tested. Four-point bending test was carried out in accordance with TS EN 12390-5 standard (TS EN 12390-5, 2002) and the flexural strengths were determined.

Prismatic specimens with 150 mm × 150 mm × 750 mm dimensions produced to determine the flexural strength were also used in experiments to determine the ultrasonic pulse velocity and modulus of elasticity, and measurements were taken from three points on each beam surface. Proceq brand Pundit PL200 ultrasonic tester was used in the experiments. The S-wave transducers used to determine the modulus of elasticity have a bandwidth of 250 kHz and the aperture size is Φ41 mm×32 mm. The P-wave transducers have a bandwidth of 54 kHz and an aperture size of Φ50 mm × 46 mm. 54 kHz P-wave transducers with a wavelength of 68.5 mm were used for determining ultrasonic pulse velocity. In order to determine the modulus of elasticity, first measurement was taken by using 54 kHz P-wave transducers with wavelength of 68.5 mm, and then these transducers were removed and replaced with 250 kHz S-wave transducers with a wavelength of 10 mm, and the second measurement was made. After the measurements using S and P wave transducers, the modulus of elasticity of the concrete was determined by reading from the digital display of the device. A pulse velocity of 3700 m/s (longitudinal wave) and 2500 m/s (shear wave) were used in the calculation of wavelengths (Url-2, 2019).

In order to determine freeze-thaw resistance of the PP-fiber reinforced roller compacted concretes, the presaturated cube specimens at the age of 90 days (before exposure to freeze-thaw) were tested. A 24 h freeze-thaw cycle was applied starting at +20°C, and then the temperature was lowered in one hour to -20°C, the temperature was kept constant for 11 h at -20°C. After every 25 cycles, the weight of the specimens and the ultrasonic pulse velocity were monitored and the changes were recorded. As reference, a group of RCC was kept in laboratory conditions during test period. After 75 cycles, axial compression test was applied and the changes in compressive strength after freeze-thaw cycles were determined. The water absorption percentages of the RCC specimens were determined in accordance with BS EN 772-11 (BSI, 2011). In order to calculate the unit weight, the weight and the volume of the hardened specimens were determined. Modulus of elasticity was determined by using the unit weight and the ultrasonic pulse velocity data.

Results and discussion

Slump test was carried out to determine the consistency of roller compacted concrete and the slump values were determined as zero for all RCC mixes. Dry or semi-dry mixtures with zero slump are designed for RCC. Although determination of consistency by measuring the slump is difficult, slump value was measured as zero for each RCC mixture in the experimental study. In order to determine the slump value, TS EN 12350-2 (2019) standard was used. According to TS EN 12350-3 (2019), the allowable time interval for the Vebe test to be performed is given as 5 s ≤ Vebe time ≤ 30 s. This method was not used because the produced RCC mixtures were very dry and the Vebe time was more than 30 s. Zero slump despite the high water content may be due to the excess amount of stone dust used.

Unit weight, water absorption, flexural and compressive strength, ultrasonic pulse velocity and modulus of elasticity values of RCC specimens are given in Table 5. It shows the flexural strengths at 28 days obtained from the four-point bending test of prismatic fiber reinforced RCC, and compressive strength values of 150 mm×150 mm×150 mm sized cube RCC specimens at 90 days. As the fiber content increased, the water absorption percentages increased. The unit weights of FRRCCs decreased with increasing fiber content. This result is related to the low unit weight of polypropylene fibers.

Table 5. Unit weight, water absorption, flexural and compressive strength, ultrasonic pulse velocity and modulus of elasticity values of RCC specimens. (Self – Elaboration).

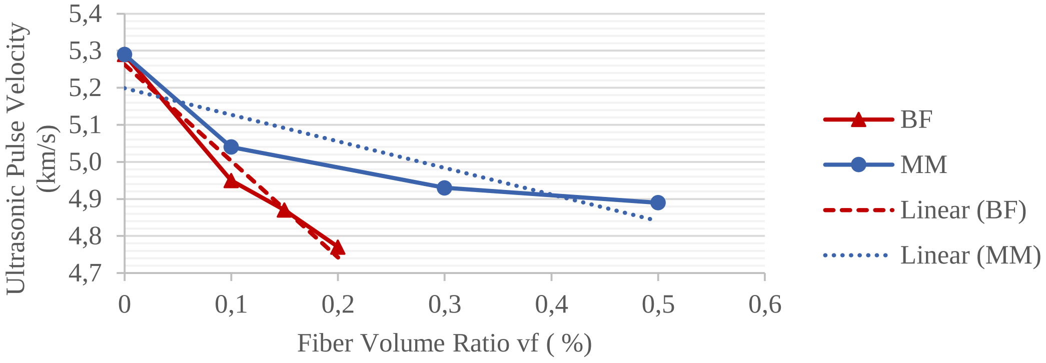
Specimen	Unit weight (g/cm^3)	Water absorption (%)	Flexural strength values of RCC beams at 28 days (MPa)	Compressive strength values of RCC cubes at 90 days (MPa)	Ultrasonic pulse velocity (km/s)	Modulus of elasticity (GPa)
Reference	2.53	2.1	8.96	67.9	5.29	35.21
BF0.10	2.47	2.4	8.03	59.4	4.95	45.84
BF0.15	2.44	2.6	7.47	58.7	4.87	44.63
BF0.20	2.13	2.7	7.97	58.1	4.77	38.24
MM0.10	2.27	2.9	6.43	48.3	5.04	41.93
MM0.30	2.07	3.7	5.89	45.6	4.93	40.98
MM0.50	2.06	3.8	5.46	36.1	4.89	34.23

While specimens which did not contain any fiber had the highest flexural strength, flexural strength decreased with increasing fiber content. The use of low amounts of fiber was insufficient to improve mechanical properties. With higher amounts of fiber inclusion, problems in placement of concrete were experienced and a structure having voids was obtained. The addition of 0.50% Fiber-2 was found to cause a 39.1% reduction in flexural strength compared to the reference sample. However, flexural strength values of all samples exceeded the minimum value of 4.2 MPa required for RCC which is stated in the literature (TCMA, 2018). With the addition of fibers, it was expected that there would be an increase in flexural strength, but a decrease in strength values occurred. Unlike conventional concrete, specimens were compacted in RCC production. It is thought that the compaction is unidirectional and the fibers remaining horizontally between the aggregates during compaction negatively affect the compaction. This effect was more evident in larger fibers (Fiber-2). In RCC specimens, the increase in water absorption rates with the increase in fiber volume ratios supports this view.

As the fiber amount increased, the compressive strength of concrete decreased. While the reference sample containing no fiber had a compressive strength of 67.9 MPa, there was a 14.4% reduction in compressive strength with 0.20% fiber addition, and a 46.8% reduction in compressive strength with 0.50% fiber addition. Although the targeted strength values were provided, the higher strength values which was expected due to the high cement content could not be reached. The high amount of stone dust used had an effect on this result. The use of high amount of stone dust will increase the cement requirement in the mixture and reduce the effect of the existing cement amount. For this reason, it is thought that the use of high amounts of stone dust will affect the strength values. In addition, it can be also affected by the gaps formed between the layers during the compaction of the cylindrical specimens. According to ASTM C 597 (ASTM C 597, 2002), the quality of the concretes with ultrasonic pulse velocity above 4.5 km/s is given as very good. This value was exceeded in all the samples produced.

The variation of the ultrasonic pulse velocity depending on the fiber volume ratio is shown in Figure 3. As seen from the graph, ultrasonic pulse velocity decreases with the increasing fiber content. It can be said that this situation is due to the voids formed at the fiber-concrete interface as the amount of fiber increases. These voids were also effective on decreasing the strength values. However, in all samples, adequate strength values were obtained for roller compacted concrete roads.

Figure 3. Ultrasonic pulse velocity of FRRCCs depending on the fiber volume ratio. (Self – Elaboration).



The highest modulus of elasticity value was obtained as 45.84 GPa with the BF0.10 specimens. Fiber inclusion of 0.10% increased the modulus of elasticity by 30.2%. However, it should be considered that the results can be affected by fiber distribution. Table 6 shows the freeze-thaw test results. Based on the obtained data, it can be said that the strength gaining of the roller compacted concrete cubes continued during freeze-thaw cycles due to the increased age. However, the specimens exposed 75 cycles of freeze-thaw had smaller compressive strength values than the specimens kept in laboratory conditions during test period. There was no significant damage after 75 cycles, the weights of the specimens and ultrasonic pulse velocity values, which can be affected by fiber distribution, were determined after each 25 cycles. According to UPV data, freeze-thaw cycles were not sufficient to deteriorate the RCC specimens, the UPV values were higher than 4.5 km/s in all the specimens after 75 freeze-thaw cycles, and the concrete quality remained the same in accordance with ASTM C 597 (ASTM C 597, 2002).

Table 6. Freeze-thaw test results. (Self – Elaboration).

		Change in weight (%)			UPV (km/sec)				Compressive strength (MPa)	
Number of cycles		25	50	75	0	25	50	75	0	75
Specimens kept in laboratory conditions	BF0.10	-	-	-	4.95	4.79	4.66	4.70	59.4	80.6
	BF0.15	-	-	-	4.87	4.98	5.00	4.97	58.7	71.5
	BF0.20	-	-	-	4.77	4.81	4.75	4.70	58.1	58.9
	MM0.10	-	-	-	5.04	5.03	5.05	5.07	48.3	69.4
	MM0.30	-	-	-	4.93	5.02	4.97	4.98	45.6	63.0
	MM0.50	-	-	-	4.89	4.95	4.93	4.92	36.1	52.7
Specimens exposed to freeze-thaw cycles	BF0.10	-0.73 (0.10)	-0.84 (0.04)	-0.94 (0.22)	4.95	4.93 (0.04)	4.91 (0.07)	4.91 (0.06)	59.4	76.3 (1.7)
	BF0.15	-0.77 (0.30)	-0.98 (0.25)	-0.99 (0.29)	4.87	4.94 (0.04)	4.89 (0.00)	4.91 (0.02)	58.7	70.5 (1.3)
	BF0.20	-0.76 (0.01)	-0.98 (0.05)	-1.00 (0.03)	4.77	4.80 (0.12)	4.73 (0.01)	4.80 (0.02)	58.1	58.2 (1.7)
	MM0.10	-1.00 (0.35)	-1.13 (0.56)	-1.20 (0.28)	5.04	4.95 (0.11)	4.95 (0.10)	4.95 (0.15)	48.3	69.1 (0.7)
	MM0.30	-1.53 (0.42)	-1.76 (0.36)	-1.78 (0.33)	4.93	4.90 (0.14)	4.82 (0.16)	4.88 (0.12)	45.6	60.8 (0.5)
	MM0.50	-1.73 (0.06)	-1.97 (0.13)	-1.98 (0.33)	4.89	4.96 (0.14)	4.91 (0.14)	4.88 (0.19)	36.1	48.4 (0.4)

*Standard deviation was given in parentheses

After 75 freeze-thaw cycles, the weights of the specimens coded BF0.10, BF0.15 and BF0.20 decreased 0.94%, 0.99% and 1.00%, respectively. In addition, the weights of the specimens coded MM0.10, MM0.30 and MM0.50 decreased 1.20%, 1.78% and 1.98%, respectively. The changes in weights were more significant for the specimens produced with Fiber-2 after freeze-thaw cycles, and increased with increasing fiber amount. Also, the increased amount of polypropylene fiber decreased the compressive strength. The concrete compressive strengths decreased slightly under freeze-thaw attack. The decrement on compressive strength values varied between 1.19% and 5.33% for the specimens produced with Fiber-1, where it varied between 0.43% and 8.16% for the specimens produced with Fiber-2. In concretes containing excess fiber amount, the lower reference values in concrete compressive strength increased this rate.

The fibers used in the study are polypropylene fibers that are popular materials with promising contribution to the quality of concrete and particularly on microcracking. The results of freeze-thaw attack and modulus of elasticity support well this contribution. On the other hand, probably mainly due to compaction difficulties, air content can increase and cause problems for some properties. The extent of degradation is dependent on the type and volume concentration of fibers as shown by the results of the study. Another important issue is the development of strength at later ages as indicated by the results at the end of freeze-thaw cycles for exposed and unexposed specimens. This shows the capacity of concretes for strength recovery. Consequently, the unconventional and original use of high powder material content in RCC mixes leads to two different findings: on one hand, this may make difficult the incorporation of polypropylene fibers and on the other hand, this makes possible strength recovery at later ages by the potential of continuous hydration. The experimental study emphasizes the benefits of using rich mixes incorporating fibers and the need for efficient consolidation.

Conclusions

The following conclusions could be drawn from this experimental study:

- For both fibers, flexural strengths of FRRCCs decreased with the increasing fiber content.
- As the fiber amount increased, the compressive strength decreased. While the small amounts of fiber inclusion were insufficient for improving the mechanical properties, the strength values decreased with increasing fiber content due to the problems in the placement of FRRCC. The workability of FRRCC decreased as the fiber volume ratio increased.
- Water absorption percentages increased as the amount of polypropylene fiber used in RCC increased.
- As the fiber amount increased, the unit weight values of roller compacted concretes decreased.
- As the fiber amount increased, the ultrasonic pulse velocity decreased and a structure having more voids was obtained. It can be said that this result is due to the voids formed at the fiber-concrete interface as the amount of fiber increases. The resulting voided structure also had an effect on the strength results, and both the flexural strength and compressive strength decreased.
- In all of the RCC specimens produced, ultrasonic pulse velocity was greater than 4.5 km/s. Based on this result, it can be said that the concrete quality of the specimens produced was very good in accordance with ASTM C 597 (ASTM C 597, 2002).
- In this study, the highest modulus of elasticity was obtained by using polypropylene fibers with a length of 19 mm and with the fiber volume ratio of 0.10%. It should be noted that the results obtained are specific to the material properties used and mix design, and cannot be generalized.
- Under freeze-thaw attack, the weights and compressive strengths of the FRRCCs decreased slightly. However, for all the specimens produced, ultrasonic pulse velocity was higher than 4.5 km/s and the concrete quality remained the same after 75 freeze-thaw cycles.

In order to build concrete roads more quickly and economically, to open the road to traffic earlier than the alternatives and to reduce the dependence on petroleum products, it is recommended to use roller compacted concrete in production of concrete roads.

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