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Influences of mixture composition on properties and freeze–thaw resistance of RCC

Chetan Hazaree [a,*], Halil Ceylan [b], Kejin Wang [b]

[a] Civil, Construction and Environmental Engineering, Iowa State University, 136 Town Engineering Building, Ames, IA 50011-3232, USA
[b] Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA, USA

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ABSTRACT

The paper reports a series of lab investigations carried out on roller compacted concrete (RCC) mixtures containing a wide range of cement contents (100 and 450 kg/m^3). The key objectives were to appreciate the effects of variations in the cement content and air entrainment on basic physical, mechanical properties and freeze–thaw (F–T) resistances of RCC mixtures. The Vebe consistency, moisture–density relations, water absorption, permeable voids, compressive strength, and F–T resistances of comparable mixes were evaluated. Physical and mechanical properties indicated a significant deviation from the behavior shown by conventional concrete. Air entrainment was found to be affecting the strength and F/T durability of the mixes. Further analysis shows wide range applications of RCC in various pavement applications.

1. Introduction

Roller compacted concrete (RCC) is a stiff, zero-slump mixture that is transported, placed, and roller-compacted utilizing conventional earth and rock fill construction equipment [1]. RCC can be manufactured with various types of aggregates (natural gravel, crushed, recycled), cementitious materials (Type I OPC, blended cements, fly ash, lagoon ash, slag, etc.) using relatively lower water and binder contents. As a construction practice, RCC provides high rates of production, and speedy construction at much less labor cost. Moreover, RCC requires no forms, surface finishing, texturing, and jointing. RCC can be mixed using either batch-type or continuous flow mixers and can be placed using either asphalt pavers (with or without modifications) or concrete pavers (without needle vibrators). It is reported that RCC construction could lead to savings in the range of 15–40% over conventional concrete [2,3].

As the economic pressures on high-speed construction and concern on environmental impacts of concrete construction are increasing, alternative methods and materials are gaining more importance. RCC is one such material, which is primarily applied as wearing course in North America. Apart from its application as a wearing course, RCC has been applied as pavement sub-base under asphalt concrete and portland cement concrete, crushed rock bases, full depth pavement with sprayed bituminous surface treatment, high- and low-volume roads, widening, overlays, concrete inlays, low-speed traffics, shoulders, etc. around the world [4–6]. For a dry lean concrete (DLC) pavement base (used in concrete pavements) the cement content may range only from 90 to 170 kg/m^3 to gain a specified compressive strength of 10 MPa at 7 days [7]. Using an optimized packing density model, RCC mixtures can be designed to have cement contents ranging from 175 to 225 kg/m^3 to yield compressive and flexural strengths of as high as 50 MPa and 5.7 MPa respectively at 7 days. Such RCC mixtures are suitable for wearing course [8]. Conventionally proportioned RCC mixes have typical cement content of 300 kg/m^3 and posses relatively higher strength at the age of 7 and 28 days than the conventionally compacted concrete (CVC) for pavements.

When RCC is utilized in cold regions, prediction of its freezing–thawing (F–T) resistance becomes difficult yet inevitable. The difficulties are often attributed to the heterogeneity in the concrete matrix and non-availability of satisfactory test methods and/or prediction tools (like ASTM C457 [9]). These may also result from the disparity between the samples cast in lab and extracted from

Abbreviations: A/C, aggregate to cement ratio by weight; AEA, air entraining admixture; ASTM, American society for testing and materials; CVC, conventionally compacted concrete, other than roller compaction; DLC, dry lean concrete; F–T, freezing and thawing; ITZ, interfacial transition zone; LPI, limestone aggregate, phase-I, without AEA; LPII,limestone aggregate, phase-I, with AEA; MDD, maximum dry density; MSA, maximum size of aggregate; NOMC, nominal optimum moisture content; OPC, ordinary portland cement; RCC, roller compacted concrete; UUCS, uniaxial unconfined compressive strength; VebeT, Vebe consistency or time; w/c, water to cement ratio, by weight.

* Corresponding author. Tel.: +1 515 294 2140; fax: +1 515 294 8216.
E-mail address: chazaree@iastate.edu (C. Hazaree).

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field. Contradictory results related to F–T performance are reported by many researchers and are summarized in the literature [3]. In addition, it is not clear how compaction voids influence RCC's F–T performance and whether or not air entrainment is necessary for RCC. Because of the dry and lean nature of mixtures, air entrainment in RCC has been a challenge.

Although growing in its importance as a sustainable construction material, the speed of RCC research seems not to match up with the speed of the application. The aim of this study was to comprehend answers to some of these intriguing questions. As such, the study focused on the investigation of effects of cement content and air entrainment on physical and mechanical properties and F–T durability of RCC. Samples with cement contents ranging between 100 and 450 kg/m^3 were formulated with and without air entrainment. The Vebe consistency (or Vebe time), dry moisture–density relations, water absorption, permeable voids, specific gravity, strength, and F–T resistances of the concrete mixes were evaluated. Based on the results, quantitative responses and qualitative evaluations are obtained in understanding an internally heterogeneous material. The influence of matrix composition on these properties was examined, analyzed and is reported in the succeeding sections.

2. Experimental work

2.1. Objectives

The objectives of the presented investigations are four-fold:

i. Generate an initial database for exploring assorted applications of RCC in pavements.
ii. Comprehend the variations in bulk properties with cement content.
iii. Assess the possibility of entraining air.
iv. Understand the responses to hydro-thermal (F–T) loading.

Table 1 represents the goal-variable matrix for the experiments.

2.2. Materials and mixture proportions

The matrix constituents included ASTM Type I cement, 19 mm MSA crushed limestone coarse aggregates, siliceous fine aggregate (river sand), tap water, ASTM C494 Type D [10] water reducing admixture and ASTM C260 [11] air entraining agent (AEA). The physical properties and chemical composition of cement has been summarized in Table 2. The specific gravity and 24-h water absorption of coarse and fine aggregates were 2.537 and 2.642 and 3.4% and 1.05% respectively. Limestone had a Los Angeles abrasion value (ASTM C131) [12] of 44%. The water reducing admixture was used in all the mixes to enhance cohesiveness.

Table 1
Goal-variable-test method matrix.

Objective no.	Variables	Characterizing test	Relevant standard
i	Cement content	Vebe time, moisture–density plots and characteristic compressive strength	IS 1199 [13]; ASTM D1557 [14], C1435 [15]; C39 [16]
ii	Cement content	Permeable voids content, water absorption	ASTM C642 [17]
iii	Air entraining agent (AEA)	All of the above	–
iv	Cement content and AEA	Accelerated Freeze–thaw	ASTM C666 [18]

Table 2
Physical properties and chemical composition of cement.

Property	Unit	Value	ASTM C150 [19]
Physical properties			
Blaine fineness	(m^2/kg)	374	Min. 280
Vicat initial setting time	(min)	94	Min. 45
Vicat final setting time	(min)	198	Min. 275
Normal consistency	(%)	25.7	–
Air	(%)	7.4	Max. 12
Compressive strength			
7-days	(MPa)	37.03	19.00
28-days	(MPa)	47.10	–
LOI	(%)	1.72	Max. 3
Chemical composition (%)			
SiO_2	(%)	20.35	
Al_2O_3	(%)	5.13	
Fe_2O_3	(%)	2.14	
CaO	(%)	64.34	
MgO	(%)	1.93	Max. 6
SO_3	(%)	2.95	Max. 3
Na_2O	(%)	0.21	
K_2O	(%)	0.44	

To realize the decided objectives, this research was divided into two phases. Phase I (designated by LPI) consisted of eight non-air entrained mixtures with cement contents ranging between 100 and 450 kg/m^3 (4.5% to 19.6% by weight of total dry materials). Phase II (designated by LPII) consisted of four comparable air entrained mixtures with similar cement contents (alternate) as those used in LPI. The 0.45 Power curve was used for deciding the aggregate grading and all the combined aggregate gradations met the requirements laid down by ACI 325 [2]. Mixes were proportioned for a constant consistency of 40 ± 10 s Vebe time [20] after a lapse of 60 min. The nominal optimum moisture content (NOMC) and maximum dry density (MDD) values were obtained by developing moisture–density plots. Table 3 summarizes the mixture proportions used along with the NOMC–MDD values and VebeT.

2.3. Specimen preparation and test methods

Two types of laboratory specimens were prepared for testing. Per mix – 15 nos. 100 mm diameter-200 mm height cylinders and one 600 mm × 300 mm × 150 mm beam. Cylindrical specimens were used for testing the compressive strength, boiling voids, water absorption and other tests, not reported in this paper; samples were extracted from beams for evaluating F–T resistances. The cylinders were cast using the procedure laid out in ASTM C1435 [15] with a compaction time of 45 ± 5 s per lift. In the absence of clear guidelines for achieving comparable densities between the cylindrical and beam specimens, the concept of taking equivalent weight of concretes and matching the compaction energies for either specimen was used in specimen formulation. To validate the method of compaction of cylinders and beam specimens, similar set of tests were repeated for cores extracted from the beams. Comparable results were obtained for density, water absorption and permeable voids. Hence, the method was justified. These specimens were cured in a curing room for different ages depending on the tests to be carried out and were further processed before actual testing. It should be noted that no-field tests or in-place studies were conducted.

One of the objectives of this study was to understand the variation of some of the properties of concrete with depth and to understand the effects of the compaction process on the bulk properties. To achieve this, the cylindrical specimens were saw-cut into three sections as top (T) 50 mm, middle (M) 100 mm and bottom (B) 50 mm. These chopped specimens were used for measuring the boiling voids content, specific gravity and 24 h water absorp-