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Performance evaluation of structural concrete using controlled quality coarse and fine recycled concrete aggregate

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ABSTRACT

This paper presents the fresh, mechanical, and durability performance, of a structural concrete mix classified as C-1, by the Canadian Standards Association (CSA) made with controlled quality Recycled Concrete Aggregate (RCA). Five mixes with water-to-cementing material (w/cm) ratio of 0.40 were produced with various RCA contents and tested against two 0% RCA control mixes made with General Use (GU) cement, and General Use Limestone cement (GUL). The RCA contents in the mixes were 10%, 20%, and 30% by coarse aggregate volume replacement, as well as 10% and 20% fine and coarse (granular) aggregate volume replacement. All evaluated mixes met the specifications from the CSA for fresh, mechanical, and durability properties. The coarse RCA mixes performed better than the granular RCA mixes in terms of flexural and splitting tensile strengths, linear drying shrinkage, water sorptivity, and rapid chloride-ion permeability, where the test results were significantly affected by the ultra fines present in the granular RCA.

1. Introduction

The implementation of environmentally friendly construction methods is becoming more widespread as awareness of the need for sustainability in design grows. An ever-increasing rate of construction is occurring with new buildings and thus demanding concrete, as a durable and widely used product in these structures. It is therefore necessary to find ways to make concrete a more environmentally conscious material. Crushing concrete from demolished or deconstructed structures provides Recycled Concrete Aggregates (RCA), which can be used as a partial substitute of virgin aggregates in new concrete production. Not only will recycled concrete aggregates significantly decrease the demand for quarried stone, thus decreasing transportation costs and emissions, but these aggregates will also, in turn, be diverted from landfills. In the United States alone, an estimated 200–300 million tons of construction and demolition waste is created each year [1]. A lot of this waste could be re-used by crushing the concrete waste and using it as RCA.

RCA has already been widely used as granular material in pavement design. However, extensive research has been, and is currently being, conducted in many countries on the performance of RCA in structural applications [2]. The use of RCA in high performance concrete is not widely accepted as of yet, primarily due to a few reductions in mechanical properties as well as durability which may be observed. It has been found that cement paste in RCA contributes to a lowered relative density and higher water absorption than virgin aggregates, while higher shrinkage and creep strains were also observed. However, coarse RCA was shown to provide similar compressive and flexural strength results to virgin aggregates [3]. Tighe and Butler [4] suggest that a good RCA should meet certain criteria in order to be suitable for use in reinforced concrete. The criteria include: an aggregate relative density of 2.3 or higher (to contribute to bond strength), a maximum mortar content of 50%, and a maximum absorption of 3%.

The research presented in this paper is based on experimental results from testing 35 MPa structural concrete with RCA. Two different gradations of RCA were used in this study; one was 20–0 mm RCA (which includes fines) and the other was 20–7 mm RCA, which was used as a substitution for virgin coarse aggregate. These two gradations of RCA were used at various replacement levels to achieve a good understanding of the concrete's fresh, mechanical, and durability performance with varying quantities of RCA.

The objective of this study is to analyze the potential of Recycled Aggregate Concrete (RAC) in structural applications. The use of RAC has been limited to low-risk applications such as sidewalks, residential wall mixes, backfill, and as a granular material

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for pavements as designers are hesitant to include RCA into structural, reinforced concrete mixes. The potential of RAC to be used in structural high-risk applications was studied by comparing the performance of the RAC trial mixes to a control. This study used a commercially produced RCA which is subjected to a high level of quality control thus permitting the use of RCA into structural concrete even further.

2. Research significance

Incorporating RCA in structural concrete applications poses a higher risk factor than the current applications of recycled aggregate materials (i.e. granular base or subbase in roads, granular backfill for retaining walls, etc.). It is therefore important to understand the behavior of a C-1 concrete mix made with coarse and fine aggregates which have been partially substituted with RCA. In many cities, old buildings are being demolished and new ones are being constructed. From an environmental and cost savings standpoint, it is very logical to take waste from one site and re-use it in a new project. Literature discusses various drawbacks of using RCA in concrete, such as increased water demand and decreased strength. By demonstrating the equivalent performance exhibited through replacement of up to 30% RCA (by volume of respective aggregate) into a 35 MPa C-1 structural concrete mix with a water-to-cementing material (w/cm) ratio of 0.40, this study aims to identify the further potential of RCA and reduce the stigma of its commercial feasibility and performance.

3. Experimental program

To properly assess the performance of the controlled quality RAC, a full spectrum of tests were conducted on the fresh, mechanical, and durability properties. The following tests were performed on all mixes; slump, measured air, density, compressive strength, flexural strength, split tensile strength, linear drying shrinkage, Rapid Chloride Permeability (RCP), resistance to freezing and thawing, sorptivity, as well as microscopic analysis. Since the application for this mix is a structural reinforced concrete, a vigorous testing program was performed to test every aspect of the concrete's properties. Five mixes with varying replacement levels of RCA were tested and compared against the control. The type of RCA was a commercially produced controlled quality aggregate, subjected to a very high level of quality control with a deleterious material content much less than 1%.

The concrete mixture's compositions and identification are provided in Table 1. The mix design chosen was a conventional concrete mix with a desired compressive strength of 35 MPa at 28 days. This mix design meets the exposure class of C-1 according to the Canadian Standards Association (CSA) A23.1; reinforced concrete exposed to freezing and thawing, as well as chlorides. Air entraining admixture, as well as mid-range water reducing admixture, was used in all mixes. The CSA A23.1 specifications on the mix state: the w/cm ratio must be limited to 0.4; it must reach a minimum of 35 MPa compressive strength at 28 days, as well as the RCP test must pass less than 1500 C at 56 days. The fresh property specifications according to A23.1 state: the mix must have an air content of 5–8%, as well as a slump of 80 ± 30 mm. The mix design uses Type 10 GU cement as well as a GUL cement equivalent to ASTM Type 1. It also incorporates 35% Ground Granulated Blast Furnace slag (GGBF slag or slag), by mass of the total cementing material content.

The testing program consisted of comparing the results of seven mixes with varying percentage replacement levels of the RCA. Two variations of recycled concrete aggregate were used, a 20–7 mm coarse gradation, and a 20–0 mm granular full gradation. These gradations were tested at different replacement levels and were compared to the control mix. RCA was replaced volumetrically with the virgin aggregate. Coarse RCA replaced only the coarse virgin aggregate at levels of 10%, 20%, and 30%, while the granular full gradation was added to replace the same proportion of coarse and fine aggregates in the control mix at levels of 10% and 20%. The seven mixes used in this study are: (GU) control mix with Type GU cement, (GUL) control mix with Type GUL cement, (C10) 10% coarse RCA, (C20) 20% coarse RCA, (C30) 30% coarse RCA, (G10) 10% granular RCA, and (G20) 20% granular RCA, as listed in Table 1. With the exception of the Type GU benchmark, all mixes incorporated the use of Contempra Portland Limestone Cement (PLC – Type GUL), a product known industry-wide to support sustainable construction practices through its reduced Carbon footprint.

3.1. Materials

Other than the GU cement control mix, all the mixes used GUL cement equivalent to ASTM Type 1, and GGBF slag. The chemical composition and physical characteristics of these cementing materials are presented below in Table 2. Virgin aggregates used in the mixes were 19 mm nominal size, crushed limestone and concrete sand with specific gravities (SSD) of: 2.57 and 2.68, respectively. Coarse RCA and granular RCA were both derived from commercial production and tested for performance characteristics as discussed in Section 3.1.1, and as shown in Table 3. Blends incorporating coarse RCA were tested for physical properties, as can be seen in Table 3. All aggregate gradations are shown in Fig. 1.

3.1.1. Controlled quality recycled concrete aggregates

Recycled concrete aggregates can be of great quality, and meet all the specifications as an aggregate in concrete [5]. What inhibits its use is its variability, and the high risk associated with deficient structures. The type of RCA used in this study is a controlled quality RCA. The RCA is processed on a commercial scale to a high and consistent quality. RCA may usually contain many contaminants such as: metal, asphalt, organics, glass, ceramics, plaster, drywall (gypsum) board, roofing materials, sealants, and wood. The total deleterious material content in the RCA used in this study was less than 1%, which is less than the CSA standards limit; a total of 2% deleterious materials content.

The production process of the RCA used in this study limits the types of concrete being selected for crushing to: returned concrete, concrete wash out material, and waste concrete rubble and blocks. Each load of recycled material is continuously screened for any deleterious materials and unsuitable materials. Gradation, and testing for asphalt coated particles, is performed every 1000 metric tons, while other tests are frequently performed every 25,000 tons during production. This type of RCA has a controlled level of quality and is thus able to produce repeatable, adequate results.

3.2. Test methodology

3.2.1. Fresh properties

Each mix was tested for slump retention up to 45 min, as well as air content. The slump was conducted after 15 min of mixing, while the slump retention was performed at 45 min after mixing to represent actual on-site conditions. Slump testing was performed according to ASTM C143, while the pressure method was used for the measured air content testing according to ASTM C231.

3.2.2. Mechanical properties

The compressive, flexural, and split-tensile strengths were determined for each mix. These three mechanical properties were meant to give a better understanding of the physical interaction of the RCA in the concrete mix. Compressive strength was tested on