Construction and Building Materials 98 (2015) 832–845

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Strength, durability, and environmental properties of concrete utilizing recycled tire particles for pavement applications

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HIGHLIGHTS

- This research investigated the replacement of fine aggregate with recycled crumb rubber from waste tires.
- The compressive strength, modulus of rupture, split-tension strength, modulus of elasticity, rapid chloride ion penetrability, and freeze–thaw durability were evaluated for concrete mixtures containing up to 50% replacement of sand with crumb rubber.
- In addition, the leaching potential for hazardous contaminants from the recycled tire was investigated.
- The results indicate that a replacement level up to 30% is acceptable for concrete mixtures used in pavement applications.

ARTICLE INFO

Article history:
Received 29 March 2012
Received in revised form 27 July 2015
Accepted 9 August 2015
Available online 5 September 2015

Keywords:
Recycled materials
Concrete
Tire derived aggregates (TDA)
Crumb rubber
Recycled concrete aggregate (RCA)
Rubberized concrete

ABSTRACT

The Rubber Manufacturers Association reported that approximately 230.7 million tires were disposed in the United States in 2011. Over 197.5 million of these disposed tires are recycled as tire derived fuel, lightweight fill, retaining walls, erosion protection as well as many other marketable uses. The primary objective of this study was to examine an alternative use for the 33.2 million remaining waste tires land disposed throughout the United States. This study used recycled tires in the form of crumb rubber as a fine aggregate replacement in concrete mixtures. Sustainable concrete mixtures for pavement applications that incorporated waste-stream materials such as fly ash, crumb rubber, and recycled concrete aggregate were evaluated for their performance. Fresh and hardened concrete properties were measured on mixtures containing 15% cement replacement with fly ash and sand volume replacements with crumb rubber of 10%, 20%, 30%, 40%, and 50%. The effects of the crumb rubber inclusion were determined by comparing mixtures containing the crumb rubber to a control mixture with only sand as the fine aggregate. Recycled concrete aggregate was included as a 50% coarse aggregate replacement by volume in two mixtures containing 20% and 30% crumb rubber content. The mixtures were tested for fresh concrete properties including slump, air content, unit weight and temperature, and hardened concrete properties including compressive strength, split-tensile strength, modulus of rupture, modulus of elasticity, permeability, and freeze–thaw durability. In addition, tests were conducted to determine whether any volatile organics leached from the crumb rubber concrete. As the crumb rubber content increased, the compressive strength, split-tensile, modulus of rupture, and the modulus of elasticity decreased. The crumb rubber concrete's permeability increased within acceptable levels up to a 40% replacement of sand. The results of this study determined that a 30% replacement of sand with crumb rubber (approximately 5.5% of the total mixture volume) was optimum and produced the necessary fresh and hardened properties for concrete pavement.

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1. Introduction

1.1. Study objectives

Disposed tires have been recycled or used in various ways for several decades. The need to discover additional ways to utilize disposed tires is more important than ever because of the growing number of used tire stockpiles in the United States. Governmental concerns have led to initiatives to fund the development of new technologies to utilize recycle waste tires and slow the growth of these stockpiles. New uses for disposed tires have brought about various refinements or derivatives that are used in a variety of applications. The civil engineering industry has made a large contribution to this effort by providing a means of using old tires in various refinements. In 2007, approximately 12% of the disposed

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http://dx.doi.org/10.1016/j.conbuildmat.2015.08.065
0950-0618/Published by Elsevier Ltd.

tires used as crumb/shredded rubber were used in civil engineering projects such as filtration systems for water treatment, speed bumps, road base or fill for highway projects and modified asphalt concrete pavement [1].

The recycled tire market for a particular region has typically defined the rubber particle size used in past research studies. Early research was completed primarily using shredded rubber particles because of the availability of the material. The crumb rubber (CR) industry has broadened the range of available products to service a broader market. Recent research has used recycled waste tire particles in concrete mixtures with the majority of tire particles larger than one millimeter [3–5]. As refinement practices are changed and modified for the production of recycled tire products to supply the consumer markets, the availability of a broader range of particle sizes will be available to further refine the science of rubberized concrete.

Incorporating waste-stream materials, such as recycled tires, concrete aggregates, and fly ash, into concrete infrastructure can provide quantifiable environmental life-cycle impact and direct cost reductions when compared with ordinary Portland cement concrete. The primary environmental savings comes from the avoided impacts of cement manufacturing, disposal of waste tires and concrete debris in landfills, and reduced transportation distance. The economic benefits of fly ash are evident; either the material is disposed of at a cost or sold for an economic gain. However, the economics of recycled aggregates (recycled waste tire and recycled concrete aggregate) are not found in direct costs, but in the reduced transportation costs due to the lesser distance from source to placement.

This study examined the use of recycled waste tires for use in concrete pavements. Specifically, the effects on the concrete properties were determined using low and high volume sand replacements with CR particles smaller than 0.09 in. (2.36 mm). The sand component within concrete was replaced in 10% increments up to 50% (replacement rates of 10%, 20%, 30%, 40% and 50% CR). The objective of this study was to determine the maximum amount of sand replacement with CR in concrete mixtures while minimizing the effect on the structural integrity of the concrete. Once a maximum replacement rate was determined, additional mixtures were evaluated that incorporated partial replacement of the cement and rock with fly ash and recycled concrete aggregate (RCA), respectively. The RCA had a maximum aggregate size of 1 in. (25.4 mm). The fresh and hardened concrete properties were tested for all mixtures. The concrete mixtures were tested by the standards and procedures set by ASTM for fresh concrete properties including slump, air content, unit weight and temperature, and hardened concrete properties including compressive strength, split-tension strength, modulus of rupture, modulus of elasticity, freeze–thaw durability, and rapid chloride ion penetrability (permeability). Recommendations were made for the development of concrete mixtures used for highway pavement incorporating waste-stream materials as partial replacements for cement, rock and sand.

The primary differences between this study and past research include the replacement of sand with only recycled waste tire particles based on volume in the concrete mixtures and in combination, the replacement of 50% of the coarse aggregate with recycled concrete aggregate. In addition, the study aimed to evaluate CR concrete mixtures containing fly ash. The specific gravity of sand is typically found to be twice that of recycled waste tire particles. Sand replacement with CR should not be performed using a weight basis for sand replacement. A practice, such as this, would consume approximately twice the volume of CR within the concrete mixture. The recycled waste tire particles used for this study meet ASTM C33 requirements necessary to fulfill specified gradations for the Colorado Department of Transportation (CDOT) Class P pavement requirements, as opposed to past research [3–5] where the particle sizes had little focus on a particular field application.

1.2. Background

A literature review was performed to investigate past uses and effects of recycled waste tires used in concrete mixtures. This review covers the various topics researchers have investigated and the rubberized concrete trends that have been discovered that facilitated the current utilization of rubber tire chips/CR in civil engineering applications.

The civil engineering industry has made a large contribution to this effort by providing a means of using old tires in various refinements shown in Table 1.

The performance of any concrete mixture is affected by its constituents. Rubberized concrete has been tested with the typical components used in traditional concrete mixtures, but with portions of the coarse and fine aggregates substituted with recycled waste tire particles of various sizes. Replacement quantities (1–100% by volume) and particle gradations (No. 60 to cut strips of tire 3 in. (76 mm) long) have been used to replace virgin aggregates normally used in concrete [3,4]. "Crumb rubber consists of particles ranging in size from 4 mesh (4.75 mm) to 30 mesh (0.60 mm) and powdered recycled waste tire are particles of maximum size 35 mesh (0.50 mm) but not less than 200 mesh (0.075 mm)" [5]. The majority of markets define ground tire particles passing the #30 sieve, as crumb rubber [5]. All research, that was reviewed, had replaced some portion of either fine or coarse aggregate, or both, with rubber tire chips/CR for use in concrete mixtures. Special considerations in the concrete mixture design must be given since the SG of natural aggregates is more than twice that of recycled waste tire particles. "Crumb rubber can be considered a lightweight aggregate source due to its low specific gravity" [4].

The choice for material size in the majority of past research projects used a rubber chip size typically greater than 0.19 in. (4.75 mm) and with a reported specific gravity between 1.12 and 1.16 [5,6]. Wong and Ting reported crumb rubber as having a specific gravity approximately 0.83–1.20, which is significantly lower than the aforementioned values [7]. It is believed that the presence of steel tire cord in the rubber tire chips would be the potential cause of higher specific gravity values than that of the recycled waste or variations in the type of tires that were refined and then sampled. Another noteworthy consideration in determining the specific gravity for recycled waste tire particles is that two different ASTMs' have been used to determine the SG of recycled waste tire particles. The standards used for coarse and fine aggregates were ASTM C128 and ASTM C127, respectively [8,9]. These two standards were used in all literature involving rubberized concrete research. The other standard was ASTM D854 [10]. The ASTM D854 is a standard primarily used in geotechnical research involving recycled waste tire applications to stabilize soil. Determining

Table 1
Terminology for recycled waste tire particles [2].

Term name	Upper limit, in (mm)	Lower limit, in (mm)
Chopped tire	Cut into relatively large pieces of unspecified dimensions	
Rough shred	$30 \times 1.97 \times 3.94$ ($762 \times 50 \times 100$)	$1.97 \times 1.97 \times 1.97$ ($50 \times 50 \times 50$)
Tire derived aggregate (TDA)	12 (305)	0.47 (12)
Tire shreds	12 (305)	1.96 (50)
Tire chips	1.96 (50)	0.47 (12)
Granulated rubber	0.47 (12)	0.017 (0.425)
Ground rubber	<0.47 (<12)	<0.017 (0.425)
Powdered rubber	–	⩽0.017 (0.425)

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