An ACI Technical Publication

SYMPOSIUM VOLUME

Eco-Efficient and Sustainable Concrete Incorporating Recycled Post-Consumer and Industrial Byproducts

Editor:
Moncef L. Nehdi

SP-314

American Concrete Institute
Always advancing

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First printing, March 2017

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Printed in the United States of America

Editorial production: Aimee Kahaian

ISBN-13: 978-1-945487-57-6

Preface

With increasing world population and urbanization, the depletion of natural resources and generation of waste materials is becoming a considerable challenge. As the number of humans has exceeded 7 billion people, there are about 1.1 billion vehicles on the road, with 1.7 billion new tires produced and over 1 billion waste tires generated each year. In the USA, it was estimated in 2011 that 10% of scrap tires was being recycled into new products, and over 50% is being used for energy recovery, while the rest is being discarded into landfills or disposed. The proportion of tires disposed worldwide into landfills was estimated at 25% of the total number of waste tires. Likewise, in 2013, Americans generated about 254 million tons of trash. They only recycled and composted about 87 million tons (34.3%) of this material. On average, Americans recycled and composted 1.51 pounds of individual waste generation of around 4.4 pounds per person per day. In 2011, glass accounted for 5.1 percent of total discarded municipal solid waste in the USA. Moreover, energy production and other sectors are generating substantial amounts of sludge, plastics and other post-consumer and industrial by-products. In the pursuit of its sustainability goals, the construction industry has a potential of beneficiating many such byproducts in applications that could, in some cases, outperform the conventional materials using virgin ingredients. This Special Publication led by the American Concrete Institute's Committee 555 on recycling is a contribution towards greening concrete through increased use of recycled materials, such as scrap tire rubber, post-consumer glass, reclaimed asphalt pavements, incinerated sludge ash, and recycled concrete aggregate. Advancing knowledge in this area should introduce the use of recycled materials in concrete for applications never considered before, while achieving desirable performance criteria economically, without compromising the long-term behavior of concrete civil infrastructure.

Moncef L. Nehdi
Editor

TABLE OF CONTENTS

SP-314—1
Recycling Tire Rubber in Cement-Based Materials 1.1
Authors: Mahmoud Reda Taha, Amr S. El-Dieb and Moncef L. Nehdi

SP-314—2
Analytical Modeling of the Main characteristics of Crumb Rubber Concrete 2.1
Authors: Osama Youssf, Mohamed A. ElGawady, Julie E. Mills, Xing Ma

SP-314—3
Dynamic Properties of High Strength Rubberized Concrete 3.1
Authors: A. Moustafa and M. A. ElGawady

SP-314—4
Evaluation of Fly Ash Based Concretes Containing Post-Consumer
Glass Aggregates...4.1
Authors: Colter Roskos, Michael Berry, and Jerry Stephens

SP-314—5
Reclaimed Asphalt Pavement as Aggregate in Portland Cement Concrete 5.1
Authors: Michael Berry, Bethany Kappes, and David Schroeder

SP-314—6
Physical and Mechanical Properties of Mortars Containing Incinerated
Sludge Ash and Silica Fume.. 6.1
Authors: Anant Parghi and M. Shahria Alam

SP-314—7
Characteristics of Concrete with High Volume Coarse Recycled Concrete
Aggregate 7.1
Authors: Anto Sucic and Medhat Shehata

SP-314—8
Fresh, Mechanical, and Durability Characteristics of Self-Consolidating
Concrete Incorporating Recycled Concrete Aggregate... 8.1
Authors: Yasser Khodair and Bhagiratha Bommareddy

SP-314—9
Flexural Strength of Reinforced Concrete Beams Incorporating Coarse
Recycled Concrete Aggregate 9.1
Authors: Ardavan Yazdanbakhsh, Lawrence C. Bank, and Jonathan Rosena

SP-314—10
Behavioral Model for Recycled Aggregate Concrete Under Axial Compression..10.1
Authors: Mohamed Mahgoub, Amin Jamali and Mohamed Ala Saadeghvaziri

SP-314—11
Durability of Recycled Aggregate Concrete: A Review 11.1
Authors: A.M. Said, A. Ayad, E. Talebi and A.C. Ilagan

Recycling Tire Rubber in Cement-Based Materials

Mahmoud Reda Taha, Amr S. El-Dieb and Moncef L. Nehdi

Abstract

The disposal of scrap tires has become an international concern. In Canada and the USA, hundreds of thousands of tires have been stockpiled with some authorities banning its landfill. The construction industry can beneficiate substantial volumes of shredded and crumb tire. This article is an overview of recycling tire rubber in concrete. It is shown that concrete with 20-30 *MPa* incorporating crumb and chipped tire rubber particles can be produced with a tire rubber aggregate replacement content less than 20%. Such a rubcrete can have adequate workability and air content, relatively low compressive strength, tensile strength and modulus of elasticity, high impact strength, high ductility and fracture toughness, and reasonable freeze-thaw resistance. The major concern with rubcrete is the significant loss of compressive strength and stiffness at high levels of aggregate replacement with tire rubber particles. However, surface treatments to enhance the bond of tire rubber particles to cement paste represent an efficient approach for enhancing the mechanical properties of rubcrete. Replacing coarse and/or fine aggregate with tire rubber particles results in increasing the strain capacity of concrete. Significant increase in material ductility and ability to absorb energy with increasing tire rubber particle content was reported. It is shown that rubcrete has a clear potential where flexibility and ductility are sought after, for example in tunnel linings, shock barriers, etc.

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Introduction

Recycling waste solid materials has been an international concern considering the unprecedented growth of the world's population, the amount of solid waste generated, and the depletion of waste disposal sites. Scrap tires constitute a large portion of that solid waste and have turned into a worldwide environmental concern. In several countries, scrap tires are being burnt and used as fuel, which is a compromise at best since this practice leads to significant air pollution (Reda Taha et al. 2008). Only a few percentage of scrap tires are being used in or recycled as construction materials.

With the world population exceeding 7 billion people, there are roughly 1.1 billion vehicles on the road, with 1.7 billion new tires produced and over 1 billion waste tires generated each year (Forrest and Rapra, 2014). Specifically, for the fate of scrap tires in the USA, it was estimated in 2011 (Forrest and Rapra, 2014) that about 10% of scrap tires was being recycled into new products, and over 50% is being used for energy recovery (tire-derived fuel (TDF) oil), while the rest is being discarded into landfills or disposed. Worldwide, the proportion of tires disposed into landfills was estimated at 25% of the total number of waste tires (Forrest and Rapra, 2014). Many states (e.g. Ohio) have banned the landfill disposal of whole tires. Scrap tires are sometimes illegally dumped in abandoned buildings and on the landscape (Figure 1) and can present even greater public and environmental health risks. To-date, some of the most important initiatives to reduce the environmental impact of waste tires have been taken in Europe. Other parts of the world are still trying to addressing this issue. For example, in September 2010, China's Ministry of Industry and Information published a new strategic policy document that outlines the future of the country's tire industry (Forrest and Rapra, 2014). In addition to the ever growing shortage of waste disposal sites, stockpiling of scrap tires in landfills can create health and environmental hazards. Possible fires of scrap tires in landfills are an additional reason for banning landfilling of scrap tires (Brown et al. 2001).

Figure 1: Examples of uncontrolled disposal of scrap tires (http://www.edmondok.com/index.aspx?nid=972).

A tire is a composite of plies of rubber elastomer reinforced transversely with steel fibers and cords. Natural rubber, as fabricated in rubber products, combines high strength (tensile and shear) with outstanding resistance to fatigue. Its ability to stick to itself and to other materials makes it simple to fabricate. Rubber has excellent adhesion to brass-plated steel cord, low hysteresis which imparts low heat generation, which in turn maintains new tire service integrity. Thus, tire recycling shall make use of some of these performance attributes.

Some promising options for using scrap tires include incineration of tires for the production of steam and electricity (Fedroff et al. 1996, Siddique and Naik 2004) and the reuse of ground tire in reproducing plastic products. Scrap tires have been used successfully in cement kilns and for artificial reefs (Fattuhi and Clarck 1996). Nehdi et al. (2005) investigated the possible use of tire rubber in flexible mortars used as a lining material for precast concrete tunnels subjected to pressure from time-dependent rock squeeze. It was shown that deformable tire rubber mortar helped to decrease stresses in the tunnel lining system. Possible use of such a material in protective lining systems for underground and buried infrastructure opens a new and wide field. Other successful applications of scrap tires include its use in hot mix asphalt, as a highway construction material in pavements, subgrade insulation, lightweight fill material, and drainage material in flowable fills and road embankments (Bosscher et al. 1992; Hossain et al. 1995, Fedroff et al. 1996, Zhu and Carlson 1999, Pierce and Blackwell 2002, Frantzis 2003, Nehdi et al. 2005).

One of the mature and primary uses of tire rubber is incorporating crumb rubber for modifying asphalt binders in asphalt pavements (Hossain et al. 1995, Navarro et al. 2005). This included the use of tire rubber in pavement crack and joint sealants; binders for chip seals, inter-layers, and hot-mix asphalts; and membranes (Amirkhanian 2001). Similar to conventional asphalt concrete, tire rubber modified hot asphalt mixes are widely influenced by thermal changes (McGennis 1995). Very successful applications of scrap tires in hot mix asphalt were reported in many states in the US including Maryland and South Carolina (Amirkhanian 2001). Experiments and field observations showed that the use of tire rubber particles in hot mix asphalt can enhance the resistance to thermal cracking, rutting, reflective cracking, ageing, and chip retention (Heitzman 1992 and Shuler et al. 1985).

While these fields of applications provided successful areas for recycling tire rubber, this total consumption of scrap tires with respect to the current volumes of scrap tires is still considerably small. It has become obvious that unless tire rubber can be recycled in a systematic way in applications with large production volumes, the suggested methods will have limited effect in helping to reduce the practice of stockpiling scrap tires. The use of ground tire rubber in a variety of rubber products and thermal incineration of waste tires for the production of heat and electricity have also been reported (Nehdi et al. 2005). It was also proposed that the unique properties of tire rubber make it an excellent alternative for applications such as shock absorbers and sound barriers (Topçu et al. 1997). Recent work by Ismail and Assem (2016), showed that full-scale reinforced concrete beams incorporating up to 20% crumb rubber replacement of fine aggregate performed favorably with high deformability and very limited reduction in ultimate strength.

Since cement-based materials (especially concrete) constitute the largest portion of construction materials worldwide, it has been suggested to use tire rubber in concrete. While the use of tire rubber particles in asphalt mixes was successful (Navarro et al. 2005), its use in concrete would be much more challenging due to the absence of heat treatment which allows to enhance bond strength in hot asphalt mixes. This paper discusses the potential use of tire rubber particles in concrete and reviews the major properties of this relatively new type of concrete based on investigations by various researchers. The benefits and challenges of using tire rubber in concrete are discussed.

Tire Rubber in Cement Based Materials

The incorporation of chipped or crumbed tire rubber particles into concrete proved as a promising approach to consume large quantities of tire rubber. The following sections summarize findings on the properties of tire rubber particles used in cement-based materials and the properties of these cement composites. In those investigations discussed below either chipped or crumbed tire particles were used to replace coarse or fine aggregate respectively.

Heitzman (1992), Eldin and Senouci (1993), Siddique and Naiq (2004) and Haung et al. (2004) showed that three types of scrap tire granules can be used as aggregate in concrete: shredded/chipped tires, ground rubber and crumb rubber. Figures 2 and 3 show tire rubber particles at different magnifications.

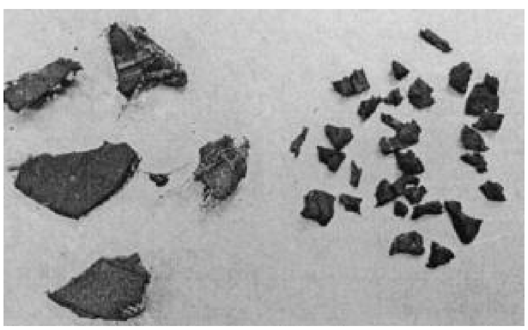


Figure 2: Typical chipped and crumb rubber particles (after Huang et al. (2004) with permission).

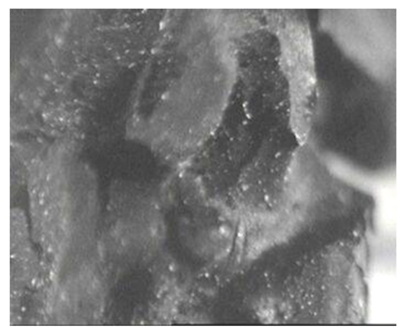


Figure 3: Typical tire rubber particle at 20X magnification (Reda Taha et al., 2008).

The sizes of tire shreds vary between 300 to 450 mm long and 100 to 230 mm wide. Secondary shredding can result in producing chipped tire particles with sizes ranging from 13 to 76 mm, similar to that of coarse aggregates in concrete and mass concrete. Ground rubber is tire particles ranging between 0.15 and 19 mm, combining both coarse and fine aggregate sizes. Finally, crumb tire rubber is analogous to fine aggregate with sizes ranging from 0.075 mm to 4.75 mm. The process of producing these classes of tire particles can be found elsewhere (Heitzman 1992). A typical aggregate size distribution curve for chipped and crumb tire rubber particles are shown in Figure 4.

Al-Akhras and Samdi (2003) discussed the use of tire rubber ash (TRA), which is a significantly fine material to enhance concrete properties. A scanning electron micrograph of typical TRA is shown in Figure 5. In contrast to all other investigations of rubber concrete (rubcrete), TRA was shown to reduce the air content of concrete and increase its mechanical properties. This can be attributed to the extremely small size of TRA that allows it to act as a filler in the cement paste matrix, rather than an aggregate.

Fresh concrete

Slump and flowability

Fedroff et al. (1996), Raghavan et al. (1998), El-Dieb et al. (2001), Nehdi and Khan (2001) and Al-Akhras and Samdi (2003) and others showed that concrete mixtures containing fine crumb tire rubber or TRA produced more workable concrete than mixtures containing either coarse tire chips or a combination of crumb rubber and tire chips. This was attributed to the lower density of crumb tires compared with chipped tires (Nehdi et al. 2005) and the ability of crumb tire particles to significantly entrain air in the concrete mix (El-Dieb et al. 2001). Raghavan et al. (1998) showed mortar with tire rubber to have better workability than conventional mortar mixtures. Similar results were reported earlier by Khatib and Bayomy (1999) with caution on possible decrease of workability with higher tire rubber contents. Karahan et al. (2012) showed the possible production of self-consolidated concrete with acceptable compressive and tensile strength and that incorporates up to 10% replacement of fine aggregate with crumb rubber. No significant interaction of SCC admixtures was reported with crumb rubber particles (Karahan et al. 2012). T

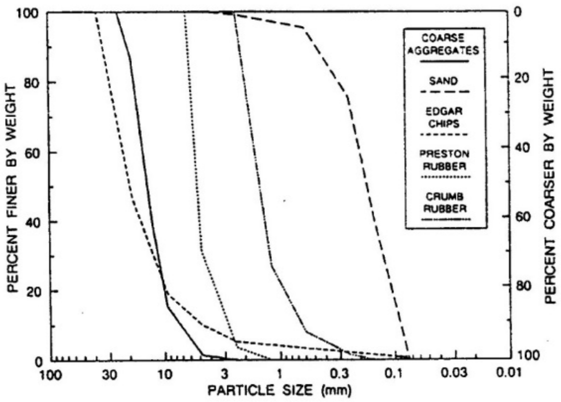
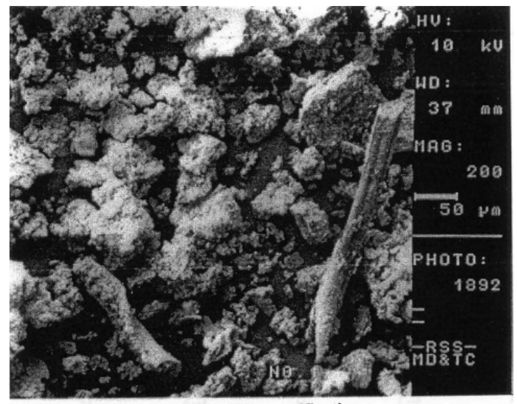


Figure 4: Size distribution of tire rubber aggregate particles (after Eldin and Senouci (1993a) with permission).



(a) ×200 magnification

Figure 5: SEM micrograph showing major structure of Tire Rubber Ash (after Al-Akhras et al. (2003), with permission). Rubber ash is microscale particles.

Unit weight and air content

It was indicated that fresh and hardened concrete produced with chipped or crumbed tire rubber had a relatively lower unit weight than that of ordinary concrete (Fattuhi and Clark 1996, Fedroff et al. 1996, Li et al. 1998b, Khatib and Bayomy 1999, El-Dieb et al. 2001, Nehdi and Khan 2001). The decrease in unit weight was reported to be negligible with a tire rubber aggregate replacement level less than 10-20%. The decrease in unit weight was attributed to the rubber's lightweight and the ability of tire particles to entrain air. Fedroff et al. (1996) and Okba et al. (2001) reported a considerable increase in the air content of fresh cement especially when crumbed tire rubber is used. Siddique and Naik (2004) attributed the increase in the air content to the non-polar nature of tire rubber particles and its tendency to repel water, and thus entrap air in the concrete mixture.

Plastic shrinkage

Raghavan et al. (1998) showed that incorporating tire rubber particles in concrete can help reduce plastic shrinkage cracking. The ability of tire rubber particles (low elastic modulus) to resist early-age plastic shrinkage strains is similar to that of chopped fibers in fiber-reinforced concrete (Beaudoin 1990) since it enhances the ability of limiting plastic shrinkage cracking. Nehdi and Khan (2001) discussed the need for further research to examine the beneficial use of shredded tire rubber particles to limit plastic shrinkage cracking in concrete.

Mechanical Properties

Compressive, tensile and flexural strengths

Experimental investigations showed that incorporating crumb and/or chopped tire particles in concrete resulted in significant changes in mechanical properties. For instance, several investigators (Goulias and Ali 1996, Eldin and Senouci 1993 a/b, Li et al. 1998b, Okba et al. 2001, Nehdi et al. 2005 and Reda Taha et al. 2008) reported significant reduction in compressive strength and splitting tensile strength with increasing tire rubber content. A replacement of the total coarse aggregate with chipped tire rubber resulted in compressive strength reductions in the range of 80% (Eldin and Senouci 1993a, Khatib and Bayomy 1999, El-Dieb et al. 2001) and splitting tensile strength reductions of 50% (Eldin and Senouci 1993b, Khatib and Bayomy 1999, Nehdi et al. 2005 and Reda Taha et al. 2008). Replacing the fine aggregate with crumb tire rubber has resulted in strength reductions in the range of 65% and 50% for