

An ACI Technical Publication

SYMPOSIUM VOLUME



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

Editor:
Moncef L. Nehdi

SP-314



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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 benefiting 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

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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 benefit from 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.

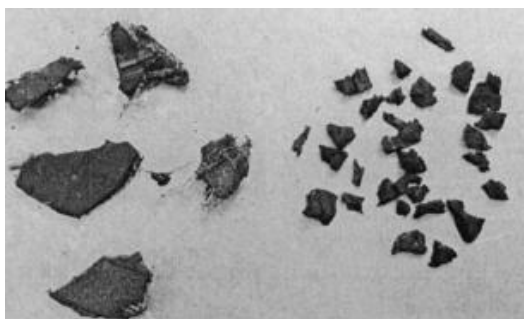


Figure 2: Typical chipped and crumb rubber particles (after Huang et al. (2004) with permission).



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 (Karahana et al. 2012). T

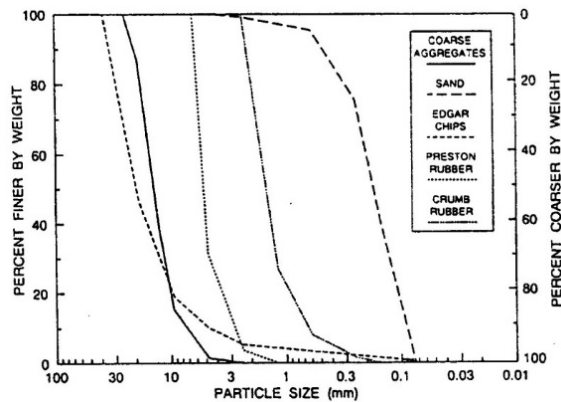


Figure 4: Size distribution of tire rubber aggregate particles (after Eldin and Senouci (1993a) with permission).

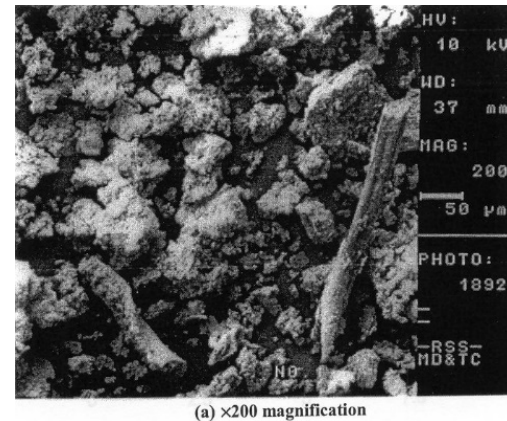


Figure 5: SEM micrograph showing major structure of Tire Rubber Ash (after Al-Akhras et al. (2003), with permission). Rubber ash is microscale particles.

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

compressive and tensile strengths, respectively (Fatuhi and Clarck 1996, Nehdi et al. 2005 and Reda Taha et al. 2008, Hossain et al. 2012, Karahan et al. 2012).

While a reduction in compressive strength of tire rubcrete was commonly reported, the level of this reduction seems to be related to the level of bond between the cement based matrix and the tire rubber particles. Surface treatment of rubber particles varied from washing to using different acidic treatments (Siddique and Naik 2004). The use of water, carbon solvents and sodium hydroxides in surface treatment were also reported by different researchers (Raghavan et al. 1998, Chung and Hong 1999, Segre and Joeques 2000). Treatment of tire rubber particle surface using sodium hydroxide (NaOH) proved capable of developing higher bond strength between cement paste and tire rubber, thus leading to an increase in compressive strength (Segre and Joeques 2000). Raghavan et al. (1998) reported the stability of tire rubber particles in alkaline solutions and an increase in mechanical properties (compressive and flexural strength) with surface treatments using sodium hydroxide (NaOH) and calcium hydroxide ($\text{Ca}(\text{OH})_2$). Chung and Hong (1999) showed that surface treatment of tire rubber particles with silane (tri-ethoxyvinylsilane coupling agent) resulted in an increase in the splitting tensile strength of concrete by up to 50% compared to control rubcretes with a similar level of replacement and without surface treatment.

Moreover, adding styrene-butadiene rubber polymer latex to tire rubber particles was capable of enhancing the bond strength of rubber particles in concrete (Lee et al. 1998). The cement paste-tire rubber bond enhancement resulted in a significant increase in compressive and flexural strengths of rubcrete (Lee et al. 1998). Other investigations by Biel and Lee (1996) also showed that the type of cement can affect the mechanical properties of rubcrete. It has been shown that the use of magnesium oxychloride cement can noticeably enhance the mechanical properties of rubcrete. This was attributed to the ability of magnesium oxychloride to enhance the bond strength of tire rubber particles and the cement paste.

Experimental research showed that the reduction in compressive strength is directly related to the level of aggregate replacement with tire rubber particles (Fattuhi and Clarck 1996). The reduction in compressive strength due to tire rubber particle incorporation was attributed to the ability of the tire rubber to work as a soft aggregate particle resulting in a significant lateral strain development in the cement matrix (Eldin and Senouci 1993a, Topçu 1995). Mechanical models to explain this phenomenon are discussed below.

Elasticity, creep and shrinkage

Fedroff et al. (1996), Toutanji (1996) and El-Dieb et al. (2001) reported a loss of concrete static stiffness with increasing tire rubber content. Goulias and Ali (1997) found that rubcrete has a lower dynamic modulus of elasticity compared to that of normal concrete. This reduction was pronounced with increasing tire rubber content. The reduction of stiffness can be attributed to the significantly low stiffness of the tire rubber phase in the cement paste-tire rubber composite. Figure 6 shows a typical stress-strain curve of rubcrete reported by various researchers (Toutanji (1996), Li et al. (1998), Eldin and Senouci 1993a).

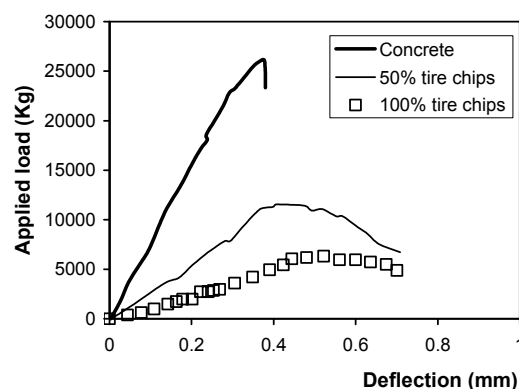


Figure 6: Stress-strain relationship of rubcrete with replacing coarse aggregate with tire chips (Toutanji, 1996).

The reduction in elastic stiffness can be observed by considering the decrease in the slope of the linear elastic region. Nehdi et al. (2005) showed a similar reduction of the elastic stiffness of mortar filled tire rubber with increasing tire rubber content. Such reduction was also observed in other types of concrete including soft materials like polymers

(Chung 2004). Experimental investigations showed conflicting results for the effect of incorporating tire rubber particles on Poisson's ratio. Chung and Hong (1999) showed that rubcrete has a Poisson's ratio similar to that of conventional concrete. Other experiments by (Goulias and Ali 1997) indicated that rubcrete has a higher Poisson's ratio than that of conventional concrete. However, the experiments by Goulias and Ali (1997) also showed that an optimal aggregate replacement percentage might exist beyond which, extensive cracking of the concrete would not allow any growth of Poisson's ratio. Their results indicated that concrete with 20% tire rubber particles was capable of supporting larger lateral strains compared to concrete mixtures incorporating 30% tire rubber particles.

There is a clear paucity on the information of time-dependent deformation, including creep and shrinkage, of rubcrete-based materials. Apart from the results reported by Raghavan et al. (1998) on plastic shrinkage, little related information is accessible in the open literature. Given the viscoelastic nature of rubber materials, time-dependent effects of this material can have a significant effect on its long-term use under sustained stresses. Further research is needed in this area.

Impact strength, toughness, strain capacity and energy absorption

Reports in the literature showed that a significant increase in the impact resistance (toughness) of concrete was observed when tire rubber particles were incorporated (Toutanji 1996, Tantala et al. 1996, Fattuhi and Clarck 1996, Raghavan et al. 1998 and Reda Taha et al. 2008). It has also been shown that shredded and chopped tire rubber particles were more capable of enhancing the impact strength of concrete compared to crumb tire rubber particles. Topçu (1997) reported an increase of the brittleness index of rubcrete with chipped tire rubber particles, which indicates a reduced ability to absorb energy for chipped tire rubber replacement ratio of 15%. Khatib and Bayomy (1999) showed that replacing coarse or fine aggregates with tire rubber particles resulted in increasing the strain capacity of concrete, and thus its ability to absorb energy. Topçu and Vcular (1997) also reported an increase in the concrete ability to absorb impact energy when tire rubber particles are incorporated in the cement matrix. It was shown that replacing fine aggregates with crumb tire rubber particles resulted in a considerable increase in concrete impact strength compared to that of conventional concrete, and this was attributed to the lower modulus of elasticity of the tire rubber particles compared to that of natural fine aggregates, thus increasing the amount of energy that could be absorbed by the concrete (El-Dieb et al. 2001).

Goulias and Ali (1998) reported that concrete incorporating tire rubber particles had much higher strain capacity up to failure compared to that of conventional concrete. The ability of tire rubber particles to enhance concrete ductility has been reported by other researchers (Okba et al. 2001). This ability was attributed to the effect of dispersed tire rubber particles in the concrete matrix, which allowed the new rubcrete composite to have several cracks propagating in the cement paste due to the localized tensile stresses at the tire rubber particles surface. The ability of the tire rubber particles to withstand large deformation prevents the widening of cracks and full disintegration of the specimens. Nehdi et al. (2005) showed a similar reduction of the elastic stiffness of mortar filled tire rubber with increasing tire rubber content. They also showed that increasing the tire rubber content can significantly enhance the ultimate strain capacity of tire rubber filled mortar. A comparison between the strain capacity of the tire rubber filled mortar at 1 and 28 days of age are shown in Figure 7.

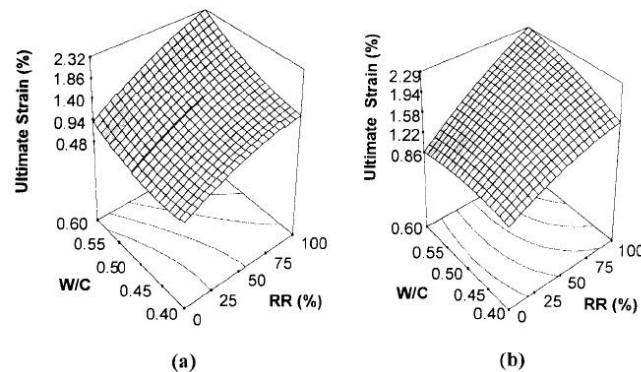


Figure 7: Strain capacity of tire rubber filled mortar after (a) 1-day age (b) 28-day age (after Nehdi et al. (2005), with permission).

Fracture criteria and fracture toughness

The effect of tire rubber particles on fracture criteria of concrete was also examined. Eldin and Senouci (1993a) showed that concrete fracture becomes more ductile with increasing tire rubber particle content. Reda Taha et al. (2008) showed that incorporating tire rubber particle content resulted in a significant increase of the fracture toughness of concrete. Notched and un-notched beams were tested to determine the fracture toughness of rubcrete. Span to depth ratios and specimen geometry were chosen considering limitations for size effect (Bažant and Planas 1998). The results showed that elastic-plastic fracture toughness criteria such as the *J-Integral* are much more capable of capturing this increase rather than elastic fracture toughness criteria such as K_{IC} and G_{IC} (Reda Taha et al. 2008). This finding is in agreement with previous findings with fiber-reinforced concrete, which showed J_{IC} to be a sensitive feature for fracture toughness enhancement (Reda Taha and Shrive 2001; Mindess et al. 1977).

The critical fracture toughness J_{IC} is computed as:

$$J_{IC} = \frac{2}{H_c} \int_0^{\theta_{crack}} M d\theta_{crack} \quad (1)$$

Where M is the applied moment, H_c is the critical un-cracked dimension and θ_{crack} is the cracking angle of the notch. The increase of fracture toughness was attributed to the ability of the tire rubber particles to bridge across cracks and to provide toughening mechanisms in concrete such as those provided by fibers. The change in the critical *J-Integral* (J_{IC}) with increasing tire rubber content in rubcrete is shown in Figure 8.

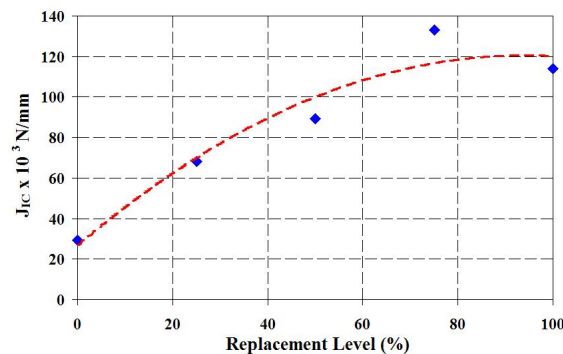


Figure 8: Effect of crumb tire rubber replacement level on the critical fracture toughness J_{IC} of rubcrete (Reda Taha et al., 2008).

Mechanical models

The significant reduction of compressive strength of rubcrete motivated some researchers to investigate mechanical models to explain the mechanisms underlying such a reduction. The common model adopted by several researchers was developed by Eldin and Senouci (1993b). A pictorial representation of the model is shown in Figure 9. The model assumes that tire rubber particles would work as soft granules in the cement matrix resulting in a significant amount of tensile stresses, which leads to multiple longitudinal cracks in the cement paste matrix. The model follows the fundamental findings of stress state at spherical and cylindrical flaws reported by Southwell and Gough (1927) and Goodier (1933), Tomoshenko, Goodier (1951), and adopted relatively recently for explaining multiple cracking of weak concrete under compression by Shrive (1983).

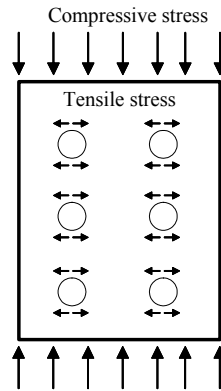


Figure 9: Mechanical model showing the effect of tire rubber on concrete matrix cracking (Eldin and Snouci (1993b), Shrive (1983) and Tomoshenko and Goodier (1951)).

In rubcrete, rubber particles can be perceived as a spherical flaw or void. Therefore, cracks are initiated at the tire rubber particles surface and then propagate in the cement paste matrix. The model can also explain the occurrence of multiple cracking observed in the cement paste matrix in rubcrete (Chung and Hong 1999 and Abd El-Hameed 2002), in contrast to conventional concrete, which is well known to have limited cracking up to 50% of its ultimate capacity (Hsu et al. 1963).

Khatib and Bayomy (1999) suggested that the reduction of compressive strength in rubcrete can be predicted using equations (2) to (3):

$$f_{cR} = SRF f_c \quad (2)$$

$$SRF = a + (1 - a)(1 - R)^m \quad (3)$$

Where f_{cR} is the compressive strength of rubcrete including R tire rubber content volumetric ratio by total aggregate volumetric ratio; f_c is the compressive strength of concrete incorporating no tire rubber particles; and a and m are function parameters. The exponent m reflects the cement based matrix sensitivity to loss of strength with increasing tire rubber content. Some results of the model are shown in Figure 10. Khatib and Bayomy reported values for a to range between 0.1 and 0.18 and m to range between 10 and 7 for rubcrete compressive strengths at 7 and 28 days, respectively, with ultrafine crumb tire rubber. Reda Taha et al. (2008) showed the possible use of a similar model with a change in the coefficients to predict the compressive and flexural strengths of rubcrete.

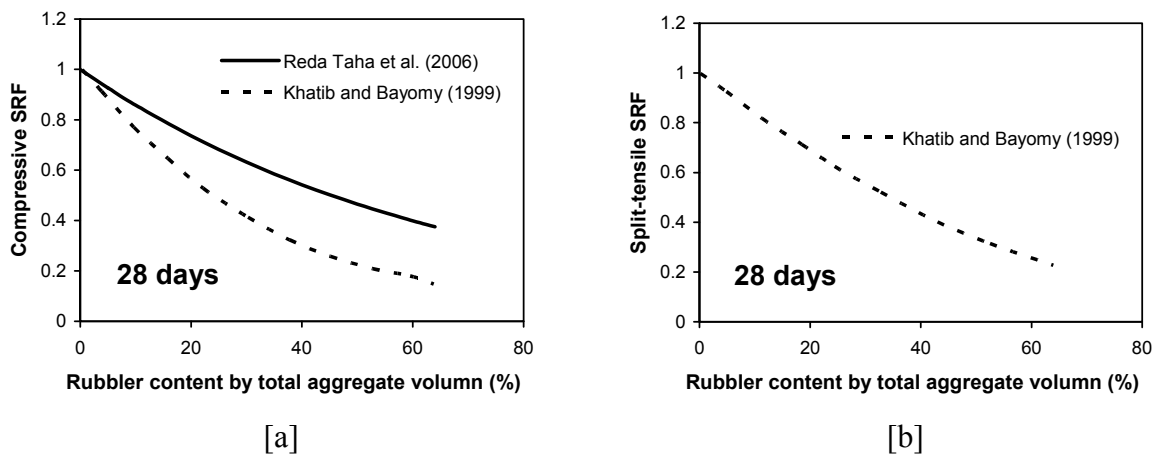


Figure 10: Comparison of compressive and splitting tensile strength results with model predictions (Khatib and Bayomy (1999) and Reda Taha et al. (2008))

Eldin and Senouci (1993) suggested that following the macro-porosity model of Popovics (1985), the compressive strength of rubcrete can be predicted by considering the tire rubber particles to represent the macro-porosity rule in conventional concrete. They suggested that for rubcrete, the compressive strength can be predicted as:

$$f_{rel} = \left(1 - \frac{a}{a_{cr}}\right) \left(\frac{\sigma_0}{0.007}\right)^{0.2 \frac{a}{a_{cr}}} \quad (4)$$

Where f_{rel} is the relative value of compressive strength as a fraction of the strength of pore free concrete, a is the volume of tire rubber in the concrete mass, and a_{cr} is the critical volume of tire rubber at which concrete strength becomes zero, which can be determined experimentally, and σ_0 is the applied stress field. While it was shown that experimental results agreed with the model quite reasonably, the value of the strength model coefficients was not reported.

Another mechanical model based on the composite effect of tire rubber particles and the cement paste and aggregate composite was suggested by Topçu and Vcular (1997). Following the theory of composite materials, the model assumes aggregate and tire rubber to be connected as a series phase model while the aggregate and the tire rubber particles in the cement matrix to be connected in a distributed phase composite. The proposed model and the component cell models are shown in Figure 11. Model 11(d) represents the case of rubcrete.

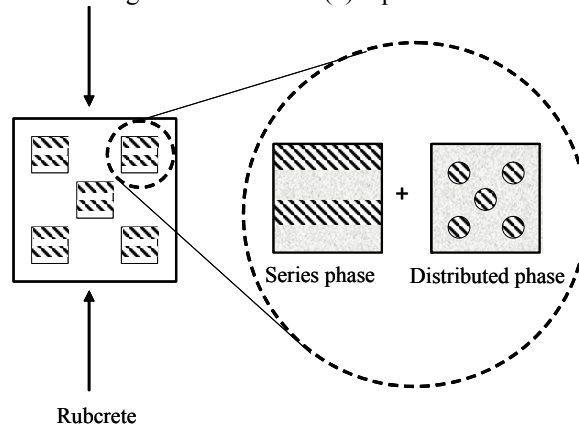


Figure 11: Composite model to predict the stiffness of rubcrete (Topçu and Vcular, 1997).

It was suggested that a theoretical elasticity modulus of rubcrete can be computed using equations (5) to (7) as follows:

$$E_{RC} = E_m \frac{1 + 2V_{ar} \left(\frac{\alpha - 1}{\alpha + 2} \right)}{1 - V_{ar} \left(\frac{\alpha - 1}{\alpha + 2} \right)} \quad (5)$$

$$\alpha = \frac{E_{ar}}{E_m} \quad (6)$$

$$E_{ar} = \frac{E_a E_r}{V_a E_r + V_r E_a} \quad (7)$$

Where E_{RC} , E_a , E_r and E_m are the modulus of elasticity of rubcrete, aggregate, tire rubber and the cement paste matrix, respectively. E_{ar} is a series phase composite modulus of aggregate and tire rubber computed as described by equation (5) and $V_{ar} = V_a + V_r$ where V_a and V_r are the volume proportions of aggregate and tire rubber in concrete, respectively. A fitness modification coefficient ranging between 0.880 and 1.067 was adequate to fit the experimental results.

Huang et al. (2004) proposed a finite element model to accurately model the complexity of stress states in the indirect (Brazilian) tension test of rubcrete due to the interaction between the different material phases including the cement paste phase, the tire rubber particles phase, the aggregate phase and the interfacial transition zone phase. The model, named the modified three-layer built in composite model, follows the basic assumptions for the three-layer concrete model developed by Li et al. (1998a). A pictorial representation of the finite element mesh scheme of the model is

shown in Figure 12. The model showed that the mechanical properties of rubcrete can be enhanced using smaller tire rubber particle size, stiff coarse aggregates with adequate size distribution, and by controlling the cement paste bond and stiffness.

Fire resistance

Fattuhi and Clark (1996) reported that tire rubber particles in external faces of rubcrete elements exposed to fire were burned. However, these tire rubber particles extinguished themselves within 5 seconds when the fire source was removed. Hernandez-Oliavares and Barluenga (2004) reported that the fire resistance of high-strength concrete incorporating small volumes of crumb tire rubber was dependent on the rubber content.

Thermal, acoustic and electrical properties

Mohamed et al. (2012) and Hossain et al. (2012) reported the possible use of crumb rubber in producing hollow concrete blocks. Replacements up to 50% of crumb rubber was shown possible. The produced blocks showed favorable thermal and acoustic insulation properties and acceptable mechanical characteristics.

Durability

During the early hydration of cement, the cement-paste aggregate transition zone is weak and vulnerable to cracking due to differential strains between the cement paste and the aggregate, which are induced by drying shrinkage, thermal deformations and externally applied load. Such micro-cracking would usually enlarge the capillary pore size. However, closed capillary pores were observed in concrete specimens incorporating tire rubber particles. It has been thus argued that rubber particles might be capable of absorbing some of the tensile strains developed during early-age shrinkage, and thus help reduce micro-cracking and capillary porosity size (Sgre et al. 2003).

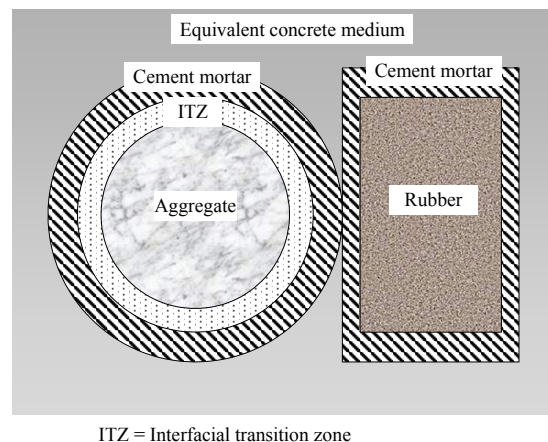


Figure 12: Three-layer built-in composite model for rubcrete (Huang et al., 2004).

Savas et al. (1996) examined the resistance of rubcrete to freezing-thawing cycles. It was found that rubcrete incorporating ground tire rubber up to 20% had acceptable freeze-thaw resistance. On the other hand, rubcrete with a tire rubber particle content in excess of 20% showed poor freeze-thaw resistance. This was represented by both a reduction of elastic stiffness due to freeze-thaw cycles (durability factor) and by microanalysis of the spacing factor. Paine et al. (2002) examined the use of crumb tire rubber as a replacement for air entrainment. Concrete incorporating crumb tire rubber particles showed performance under freeze-thawing cycles higher than or similar to that of air-entrained concrete. Karahan et al. (2012) showed that durability performance of SCC incorporating crumb rubber as replacement of fine aggregate does not get significantly affected until the replacement level passes 10%.

Microstructural characteristics

Lee et al. (1998) showed that polymer latex helped bonding tire rubber particles to cement paste. Crack sizes of rubcrete with polymer latex were observed to be smaller than those of rubcrete without polymer latex. Reda Taha et al. (2008) showed that there might be extensive micro-cracking in the tire particle vicinity in rubber cement-based materials. Figure 13 shows a scanning electron micrograph (SEM) exhibiting significant cracking of rubcrete at the rubber interface. Figure 14 shows the indentations in the cement matrix at locations where tire particles were pulled-

out. These indentations actually play a role in enhancing the bond strength between tire particles and the cement paste. The observations prove that there is reasonable interlocking between tire rubber particles and cement paste. This might contradict with the argument that weak bond strength between the cement paste and tire rubber particles always exists. Moreover, the extensive micro-cracking observed at the particle vicinity supports the hypothesis that the soft-aggregate like behavior of the tire particles generates tensile strains that result in extensive micro-cracking thereafter.

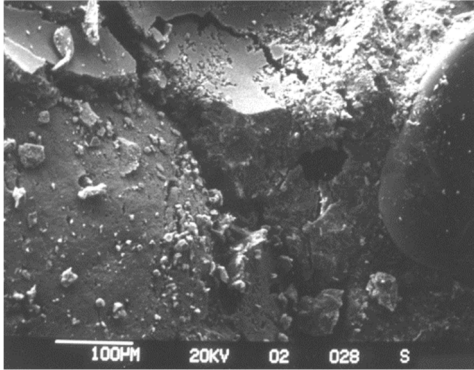


Figure 13: SEM micrograph showing significant microcracking in the cement paste at the tire rubber particle vicinity (Reda Taha et al. 2008).

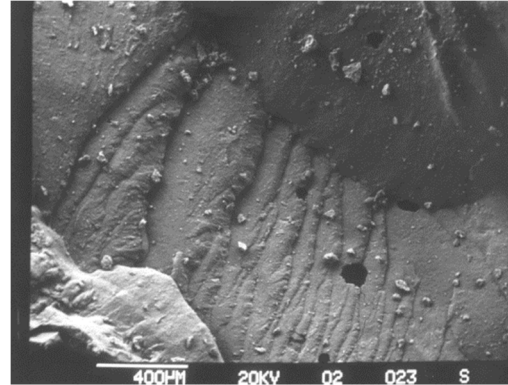


Figure 14: SEM micrograph showing indentation on cement paste as a result of pull-out of tire rubber particles during specimen failure in compression (Reda Taha et al., 2008).

It is evident that the combination of the appreciable bond strength of tire rubber particles in the cement paste and the large lateral strains developed at the surface of tire rubber particles contribute to the low compressive strength of rubcrete.

Summary

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. Researchers reported favorable workability criteria of rubcrete with the possibility of decreasing flowability as the tire rubber content increases. Rubcrete was also reported to be able to reduce plastic shrinkage cracking of concrete.

The major concern with rubcrete is the significant loss of compressive strength and stiffness at fairly high levels of aggregate replacement (up to 50%) 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. Microstructural investigations showed evidence of appreciable bond between tire rubber particles and the cement paste due to particle-paste interlock. Such observations might contradict with the argument that low bond between tire rubber particles and cement paste exists and is responsible for reducing the compressive strength of rubcrete. It is evident that the reduction of compressive strength of rubcrete can be attributed to the significantly large lateral strains developed at the surface of tire rubber particles as a soft aggregate particle as shown by many researchers.

Moreover, it was observed that replacing coarse and/or fine aggregate with tire rubber particles resulted in increasing the strain capacity of concrete. Researchers reported significant increase in the material ductility and ability to absorb energy with increasing tire rubber particle content. This criterion makes rubcrete a good alternative for construction with limited strength requirements and significantly low sustained stress levels but with significant energy absorption need such as bridge traffic barriers.

Researchers showed successful simulation of rubcrete using finite element composite models, such as the modified three-layer built in composite model. Researchers also showed that both strength and fracture criteria of rubcrete can be directly related to its tire rubber contents using simple nonlinear models. Such models can provide reasonable estimate of the tire rubber content limitations to produce rubcrete with specific strength or fracture needs. Finally,

rubcrete has potential where flexibility and ductility are sought after, for example in tunnel linings, shock barriers, etc.

Research needs

- The low stiffness of tire rubber particles and the tendency of tire rubber materials to show significant creep effect warrant the need for experimental and analytical investigations of the time-dependent creep behavior of rubcrete. This investigation is essential before recommending the use of rubcrete in structural applications.
- Little information is available on the shrinkage of rubcrete, especially when special types of cement are used. Therefore, there is a need to evaluate the long-term shrinkage capacity of this relatively new concrete composite.
- There is a fundamental need to examine the permeability of rubcrete since it is a major mechanism governing all durability criteria of concrete.
- There is need for research that further explores the use of rubcrete in engineering applications that do not require high compressive strength, but rather increased durability, and impact resistance.

Acknowledgement

The financial support by the DTRA-University of New Mexico partnership to the first author shall be greatly acknowledged. The financial support by the Faculty of Engineering, Ain Shams University to the second author is greatly appreciated. Finally, the support to the third author by The Lindbergh Foundation, Minnesota, USA is greatly acknowledged. Special thanks to Dr. K. K. Choi for his help in producing some of the artwork used in this document.

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Analytical Modeling of the Main characteristics of Crumb Rubber Concrete
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Synopsis: In recent years, a very important environmental issue all over the world is the disposal of waste tires. One possibility being explored is to use rubber from waste tires to replace part of the natural aggregates in conventional concrete, resulting in a product called crumb rubber concrete (CRC). Recent research on CRC is focusing on using it in structures subject to seismic loads, due to its higher ductility, damping ratio, and energy dissipation compared to conventional concrete. However CRC can have lower compressive strength (f'_{CRC}), tensile strength (f'_{TRC}), and modulus of elasticity (E_{RC}) when compared with conventional concrete. This paper presents empirical models able to predict the CRC characteristics (f'_{CRC} , f'_{TRC} , and E_{RC}). The proposed models are verified through the results of 148 CRC mixes as well as compared with two previous models. The proposed models resulted in predictions of the CRC characteristics with only 10.7%, 12.6%, and 11.3% errors in the predictions of f'_{CRC} , f'_{TRC} , and E_{RC} , respectively. The proposed f'_{CRC} model reduced the mean, standard deviation and maximum error percentages by 24.6%, 5.8%, and 20.2%, respectively, compared with the nearest best predictions by previous models. The proposed models can aid structural engineers who are considering CRC as an environmentally-friendly alternative to conventional concrete in structural applications.

Keywords: CRC characteristics; crumb rubber concrete; rubberized concrete; strength losses; strength prediction; sustainable construction.

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INTRODUCTION

Scrap tires are among the largest and most problematic sources of waste in modern societies, due to their durability and the huge volumes of discarded tires every year. Across the world, one billion tires reach the end of their useful lives every year and 0.5 billion more are expected to be discarded each year by 2030¹. In Australia, forty eight million tires are disposed of each year. Only sixteen percent are recycled with the majority going into landfill, stockpiles, or being exported or dumped². The rubber that is currently dumped to landfill is a significant problem due to its low density, poor degradation, and large volume which means that it cannot be buried in landfills³. When tires are dumped to landfill they can cause numerous environmental problems, such as, becoming breeding grounds for mosquitoes and other pests. In addition, when such tire dumps catch fire it is notoriously difficult and costly to extinguish⁴. The rapid increase in waste tires provides added motivation to find different ways to re-use this waste rubber. One possibility being explored is to use crumbed rubber from waste tires to replace part of the natural aggregates in conventional concrete resulting in a product called crumb rubber concrete (CRC). The recycling of used rubber conserves valuable natural resources and reduces the amount of rubber entering landfill⁵.

Extensive previous research has been undertaken on CRC which shows a common problem, namely that replacing mineral aggregates in concrete with rubber aggregates results in compressive strength loss up to 85% depending on the rubber size and content⁶⁻¹⁴. Because of this, the use of CRC in structural applications has been limited to date. However, compared to conventional concrete, CRC has higher ductility, durability, damping ratio, impact resistance, and toughness^{10, 15-19}. These findings have encouraged the researchers to explore the use of CRC in structural applications, particularly those that are subject to seismic loads.

The reduction in the concrete strength incorporating rubber is attributed to several reasons which can be summarized as follows: 1) rubber has a Poisson's ratio approximately twice as high as that of concrete and has a Young's modulus as low as 1/3 of that of concrete, which results in significantly large relative deformations between rubber and concrete that can lead to early cracking; 2) the low modulus of elasticity of rubber particles produces high internal tensile stresses that are perpendicular to the direction of the applied compression load which cause early failure in cement mortar²⁰; 3) rubber particles act as air voids for crack initiation followed by crack propagation, and then, strength reduction; 4) the low permeability of rubber particles might significantly degrade the interaction between the boundaries of the rubber particles and the cement paste, thus increasing the volume of the voids (weak points) at the interfacial transition zone¹⁰; and 5) rubber has a specific gravity lower than concrete causing rubber migration to the top surface of the concrete due to the vibration process that is used during concrete mixing and placement, resulting in a non-homogeneous mix and reduction in concrete strength²¹.

Determination of CRC characteristics is of great interest to structural engineers. To date, there has been limited research on predicting the CRC compressive strength (f'_{CRC}), tensile strength (f'_{TRC}), and elastic modulus (E_{RC}). Khatib and Bayomy²² (Model-1) proposed a regression analysis model to predict f'_{CRC} and f'_{TRC} . This model had three variable parameters (a , b , and m) which were dependent on rubber type and size. Eqs. 1 and 2 show the proposed models.

$$f'_{CRC} = f'_c[a + b(1 - R)^m] \quad \text{Eq. 1}$$

$$f'_{TRC} = f'_t[a + b(1 - R)^m] \quad \text{Eq. 2}$$

where, f'_{CRC} is the CRC compressive strength, f'_{TRC} is the CRC tensile strength, f'_c is the control concrete compressive strength, f'_t is the control concrete tensile strength, R is the rubber content as a volumetric percentage of the total aggregates volume, and a , b , and m are function parameters.

The assumption in these proposed models was that the control and rubberized concrete mixes must have the same constituents and volumetric contents. In the rubber mixes, rubber should replace the total aggregate by an equal volume. Based on experimental results of 24 CRC mixes, they proposed different values for parameters a , b , and m parameters depending on the size of the used rubber (fine or coarse), the concrete age (7 or 28 days), and the required characteristic to be calculated (f'_{CRC} or f'_{TRC}). Their proposed models were verified against the data published by Eldin and Senouci²³. It was found that the proposed models were less sensitive in predicting the Eldin and Senouci²³'s data than the data used in their model development, although it resulted in high R^2 values. More details about these models and their parameters can be found in Khatib and Bayomy²².

Khaloo et al.²⁴ (Model-2) used the same f'_{CRC} model-form proposed by Khatib and Bayomy²² but proposed new values for the parameters a , b , and m based on regression analysis for experimental results of 10 CRC mixes. In addition, they proposed a new model for E_{RC} predictions. These models are shown in Eqs. 3 and 4.

$$f'_{CRC} = f'_c[0.02 + 0.98(1 - R)^{12}] \quad \text{Eq. 3}$$

$$E_{RC} = E[0.01 + 0.99(1 - R)^{11}] \quad \text{Eq. 4}$$

where, f'_{CRC} is the CRC compressive strength, E_{RC} is the modulus of elasticity of CRC, f'_c is the control concrete compressive strength, E is the modulus of elasticity of control concrete, and R is the rubber content as a volumetric percent of the total aggregates volume.

Their proposed models were verified against the data published by Khatib and Bayomy²² and Li et al.⁵. It was found that the proposed models were over estimating the experimental results. They attributed this over estimation to the lack of the pre-treatment of the tire rubber particles, improper calibration of equations based on concretes with higher tire rubber contents, and tire source.

The limited research on predicting the CRC characteristics and the relatively low number of CRC mixes used to verify the available models indicate the need for further research for more accurate models using a larger experimental database. In this research, three empirical models are proposed to predict the CRC compressive strength, tensile strength, and modulus of elasticity. The proposed models' predictions were compared with the previous models' predictions through comparison with a large experimental database. Sets of 148 data results for compressive strength, 104 data results for tensile strength, and 84 data results for modulus of elasticity were used to verify the proposed models and also for comparison.

RESEARCH SIGNIFICANCE

This research aims to provide direct and easy-to-use formulae to predict the crumb rubber concrete characteristics, f'_{CRC} , f'_{TRC} , and E_{RC} . In addition, this research provides a large crumb rubber concrete database showing the effect of increasing rubber content in concrete on its properties. This can help current researchers and engineers who are interested in the use of rubber waste in concrete subject to seismic loads because of its high ductility, durability, damping ratio, impact resistance, and toughness.

EXPERIMENTAL DATABASE

A total of 336 experimental data results for CRC, including compressive strength, tensile strength, and modulus of elasticity, were collected from the literature as an experimental database in this study, see Table 1. The data in this table were collected from 23 references^{6, 10, 20, 22, 23, 25-42}. Since it has been suggested that rubber content should not exceed 20% of the total aggregate volume because of the negative effect on concrete characteristics²², the collected data was limited to concrete with a maximum of $R_t = 25\%$ to cover the recommended range, where, R_t is the rubber content by total aggregates volume. In this database, the control compressive strength of the conventional concrete (f'_c) ranged between 3336 and 13053 psi (23 and 90 MPa), the cement content ranged between 17.5 and 32.0 lb/ft³ (280 and 513 kg/m³), the water to cement ratio ranged between 0.25 and 0.75, and the size of the rubber particles ranged between 0.006 and 1.000 in (0.15 and 25.4 mm).

The effect of the CRC mix parameters on its compressive strength losses was investigated through the collected database and plotted in Fig. 1. As shown in the figure, there is no correlation between the f'_c of the control mix, the cement content, and/or the water to cement ratio and the losses in the CRC compressive strength, as their

relationships have high scatter and a very low R^2 value, see Fig.1(a to c). However, the rubber content has a relatively stronger correlation with the CRC compressive strength losses, as can be observed from the relatively lower scattering and higher R^2 value in Fig. 1(d) compared to the other parameters. Thus, it was decided in this study to model the CRC strength losses based mainly on the rubber content. The next section will discuss the modelling development and verification.

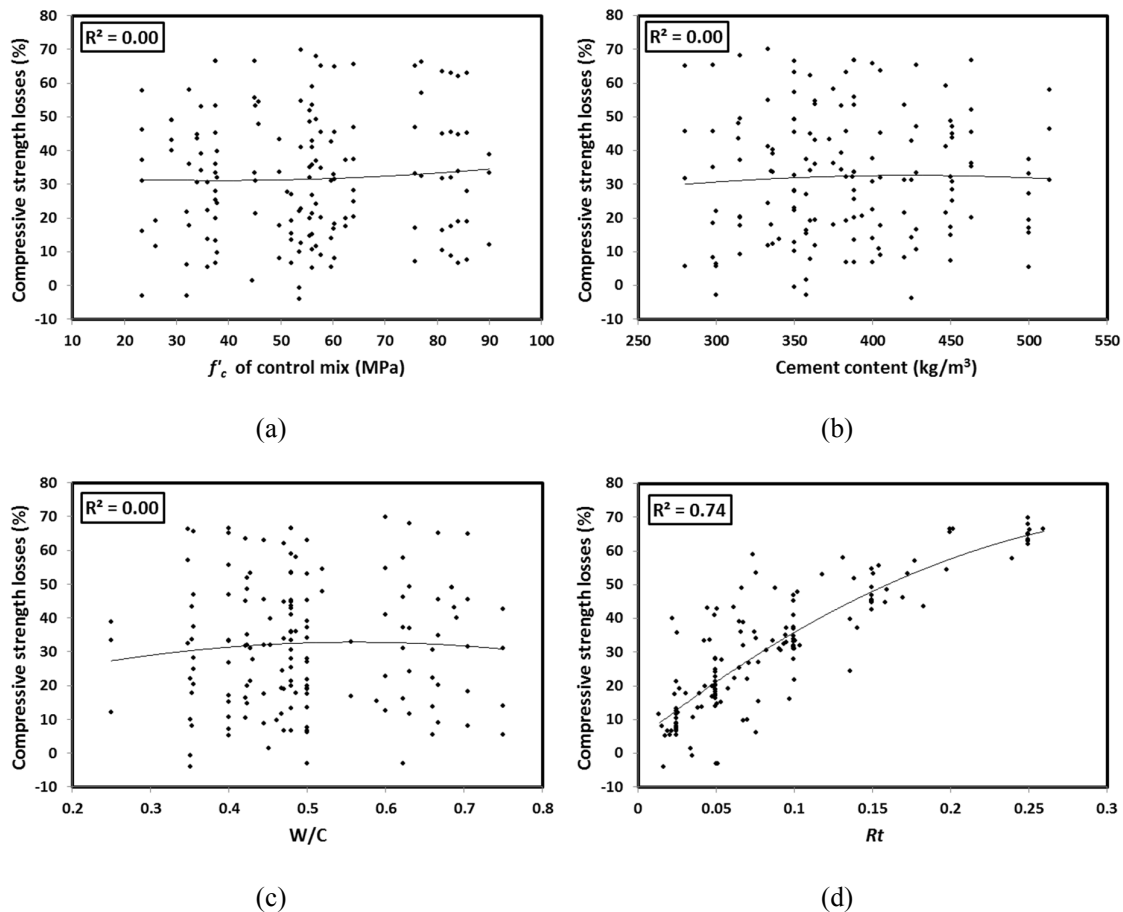


Fig. 1— Effect of: (a) f'_c of control mix, (b) cement content, (c) water to cement ratio, and (d) rubber content on CRC compressive strength losses through the experimental database.

ESTIMATION OF CRC CHARACTERISTICS

Out of the 148 CRC mixes given in Table 1, 103 mixes were used to develop the compressive strength model, and then the rest of the data were used to test the proposed model's predictions. The total data set was used to evaluate the proposed model's predictions compared to the previous models' predictions (Model-1¹¹ and Model-2¹²). The absolute error percentages for the predictions from each model shown in Table 1 were calculated using Eq. 5.

$$\text{Error \%} = \frac{|\text{Experimental results} - \text{Model results}|}{\text{Experimental results}} \quad \text{Eq. 5}$$

The proposed compressive strength model was in an exponential form, which was selected among several forms (e.g. linear, polynomial, logarithmic, exponential, power). The exponential form has an advantage compared to the others that when the rubber content Rt equals zero (no rubber), the concrete compressive strength is not affected ($e^0 = 1.0$). Thus, the proposed model formula was defined as $[f'_{CRC} = f'_c [e^{\alpha Rt}]]$, where f'_{CRC} is the compressive strength of the crumb rubber concrete; f'_c is the compressive strength of the control concrete (without rubber); Rt is the rubber content by volume of the total aggregates; and α is a constant. Since the value of the $e^{\alpha Rt}$ term in this formula has to decrease as Rt increases, the value of the constant " α " was calibrated using a wide range of negative values ranging from -0.1 to -30.0 to select the appropriate value that resulted in the least

root mean square error in the model predictions. A value of -4.2 was found to be the appropriate one, as shown in Fig. 2.

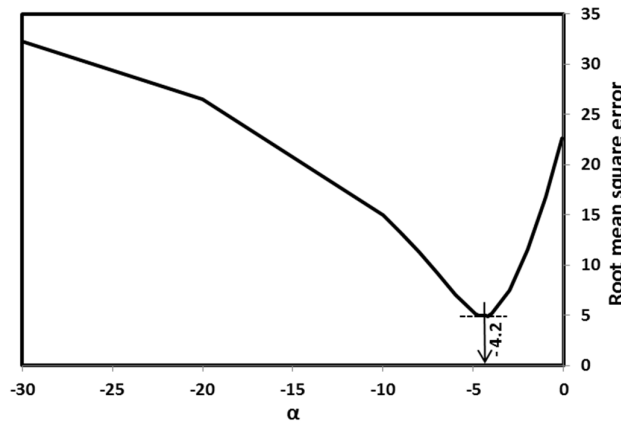


Fig. 2— Effect of constant “ α ” on the root mean square error in the model predictions for compressive strength.

Out of 104 and 84 data results given in Table 1 for the CRC tensile strength and modulus of elasticity, respectively, 72 and 62 data sets were used to develop the tensile strength model and the modulus of elasticity model, respectively. And then, the rest of the data were used to test the proposed models’ predictions. The total data set was used to evaluate the predictions of the proposed models compared with the previous models’ predictions.

The tensile strength and modulus of elasticity models were also proposed in an exponential form like the proposed compressive strength model. Similar procedures were used to find the values of constant α and values of -2.65 and -3.2 were found to be the appropriate ones for the tensile strength and modulus of elasticity models, respectively. Thus, the final forms of the proposed models are presented in Eqs. 6-8.

$$f'_{CRC} = f'_c [e^{-4.2 Rt}] \quad \text{Eq. 6}$$

$$f'_{TRC} = f'_t [e^{-2.65 Rt}] \quad \text{Eq. 7}$$

$$E_{RC} = E [e^{-3.2 Rt}] \quad \text{Eq. 8}$$

where, f'_{TRC} is the tensile strength of CRC, f'_t is the tensile strength of control concrete, E_{RC} is the modulus of elasticity of CRC, and E is the modulus of elasticity of control concrete.

VERIFICATION AND EVALUATION

Table 1 shows the predictions of the proposed model as well as the previous models for the collected database. Figs. 3-5 show comparisons between the predictions of all models. As shown in the figures (left side), compared to other models, the proposed models have the least scattering in the predicted f'_{CRC} , f'_{TRC} , and E_{RC} . In the f'_{CRC} predictions, the proposed model’s error decreased with increasing Rt compared to a continuous error increase using the previous models as shown in Fig. 3, (right side). In the f'_{TRC} and E_{RC} predictions, the proposed models’ errors increased with increasing Rt , similar to the earlier models. However, the proposed models reduced the linear trend slope by 55.6% and 93.6% in the predictions of f'_{TRC} and E_{RC} , respectively, compared to the previous models as shown in Figs. 4 and 5 (right side).

Table 2 shows the statistical parameters for all comparable models in this study. The evaluation of the proposed models was carried out by evaluating each model’s error through calculating the absolute mean (M) and standard deviation (SD) of the each model errors. In addition, the maximum error % calculated for each model, the slope of the liner trend of each model errors, and the ability of each model to predict experimental results within 20% error were also used in this evaluation. As shown in the table, the proposed f'_{CRC} model reduced M, SD, and max. error % by 24.6%, 5.8%, and 20.2%, respectively, compared to Model-1 predictions, and by 75.5%, 46.4%, and 9.3% compared to Model-2 predictions. In addition, the proposed f'_{TRC} model reduced the M, SD, and max. error

% by 24.0%, 18.6%, and 24.7%, respectively, compared to Model-1. Furthermore, compared to Model-2 the proposed E_{RC} model reduced the M and SD by 76.5% and 41.8%, respectively; however, it had a slight increase in the max. error % by 7.8%. When considering the limits of 20% error, Table 2 shows the ability of each model to predict the experimental results in that range. The proposed f_{CRC} model was able to predict 83.1% of the experimental data to be within 20% error compared to 80.4% and 21.6% for Model-1 and Model-2 respectively. In addition, the proposed f_{TRC} and E_{RC} models were able to predict 82.6% and 85.2% of the experimental results to be within 20% error respectively, compared to 76.9% and 14.7% for Model-1 and Model-2 respectively. Fig. 6 summarizes some statistical parameters for the comparable models.

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Table 1—CRC experimental dataabase with all models' predictions.

Source	#	Rt %	Experimental results			Proposed model predictions						Model-1 ²²				Model-2 ²⁴			
			f'_{CRC} , psi	f'_{TRC} , psi	E_{RC} , psi	f'_{CRC} , psi	Error, %	f'_{TRC} , psi	Error, %	E_{RC} , psi	Error, %	f'_{CRC} , psi	Error, (%)	f'_{TRC} , psi	Error, %	f'_{CRC} , psi	Error, %	E_{RC} , psi	Error, %
Valadares et al. 2012 ⁶	1	4.9	6454	377	4960026	6555	1.6	435	14.9	5032541	1.6	5917	8.4	450	19.6	4496	30.4	3423	31.0
	2	9.5	5221	305	4205870	5395	3.5	377	25.9	4350900	3.3	4409	15.6	406	35.6	2538	51.3	2001	52.3
	3	13.9	3872	276	3640253	4496	16.0	348	23.9	3770780	3.7	3350	13.5	377	37.3	1479	61.9	1189	67.4
	4	5.1	6860	435	4916517	6497	5.3	435	1.0	5003535	1.8	7005	2.0	450	3.2	4380	36.2	3336	32.1
	5	10.4	5482	363	4611954	5207	5.1	377	3.2	4220373	8.5	6019	9.7	406	11.9	2277	58.5	1798	60.9
	6	15.9	4133	334	4481427	4119	0.3	319	3.1	3538732	21.1	5105	23.6	363	8.8	1146	72.4	928	79.4
Guneyisi et al. 2004 ²⁵	7	2.5	10210	580	5946230	9906	3.0	551	4.1	6149272	3.4	9819	3.8	566	2.0	8180	19.9	5062	15.0
	8	5.0	9108	551	5453128	8905	2.2	522	5.5	5670673	4.0	8760	3.9	537	1.6	6048	33.6	3814	30.0
	9	10.0	7353	464	4278385	7222	1.8	450	1.7	4829499	13.0	6947	5.6	493	6.2	3263	55.6	2132	50.1
	10	15.0	5845	406	3625750	5859	0.2	406	1.6	4118852	13.6	5497	6.1	450	9.9	1755	70.0	1175	67.7
	11	25.0	3829	290	2538025	3843	0.5	305	5.7	2987618	17.9	3452	10.0	363	24.3	566	85.3	348	86.4
	12	2.5	10515	595	6091260	10573	0.6	580	1.8	6163775	1.1	10486	0.2	595	0.2	8731	17.0	5062	16.8
	13	5.0	9833	566	5801200	9528	3.2	551	3.4	5685176	2.0	9354	4.9	566	0.6	6454	34.3	3829	34.1
	14	10.0	8020	493	4437918	7716	3.8	479	3.0	4844002	9.2	7411	7.5	522	4.8	3481	56.5	2146	51.8
	15	15.0	6454	421	3683762	6251	3.1	421	0.4	4133355	12.1	5859	9.1	464	11.2	1871	71.0	1175	68.2
	16	25.0	4293	305	2683055	4104	4.2	319	5.6	3002121	11.7	3684	14.2	377	24.1	595	86.0	348	87.1
	17	2.5	10935	609	6236290	10805	1.2	609	0.3	6352314	2.0	10718	2.1	624	2.4	8919	18.5	5236	16.1
	18	5.0	9891	580	5946230	9717	1.7	566	1.5	5873715	1.3	9557	3.4	595	2.6	6599	33.3	3945	33.6
	19	10.0	8165	508	4524936	7875	3.5	508	1.4	5003535	10.6	7571	7.2	537	6.6	3553	56.4	2204	51.2
	20	15.0	6541	435	3843295	6381	2.3	435	0.8	4263882	10.9	5990	8.4	493	12.5	1914	70.8	1204	68.5
	21	25.0	4423	334	2755570	4191	5.1	334	0.9	3089139	12.3	3756	15.0	392	18.6	609	86.2	363	87.0
	22	2.50	11356	638	6308805	10964	3.4	638	0.0	6294302	0.3	10877	4.2	653	2.1	9050	20.2	5178	17.9
	23	5.00	9862	595	5583655	9877	0.1	595	0.4	5815703	4.0	9703	1.6	624	4.6	6700	32.1	3901	30.0
	24	10.0	8064	522	4669966	8006	0.7	522	0.2	4945523	6.0	7687	4.6	566	8.2	3611	55.2	2190	53.2
	25	15.0	6729	450	3988325	6483	3.6	464	1.9	4220373	5.8	6077	9.6	508	13.7	1943	71.1	1204	70.0
	26	25.0	4612	363	2799079	4264	7.6	348	3.1	3060133	9.4	3814	17.2	406	14.0	624	86.5	348	87.4
	27	2.5	11472	638	6453835	11196	2.5	638	0.0	6352314	1.5	11095	3.2	653	2.1	9238	19.5	5236	18.9
	28	5.0	10065	609	6134769	10080	0.1	595	2.0	5873715	4.3	9906	1.6	624	2.1	6831	32.1	3945	35.6

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	29	10.0	8948	522	4611954	8165	8.7	522	0.2	5003535	8.5	7846	12.3	566	8.2	3684	58.8	2204	52.1
	30	15.0	6816	464	4060840	6613	2.9	464	1.3	4263882	5.0	6207	8.9	508	10.2	1987	70.9	1204	70.2
	31	25.0	4612	363	2900600	4351	5.7	348	3.1	3089139	6.7	3901	15.5	406	14.0	638	86.2	363	87.7
	32	2.5	6816	406	4698972	7019	3.1	421	3.6	4437918	5.7	6961	2.2	435	5.8	5801	14.9	3640	22.4
	33	5.0	6019	392	4205870	6323	5.1	392	0.6	4089846	2.7	6207	3.2	406	4.7	4293	28.8	2756	34.6
	34	10.0	4612	363	3770780	5134	11.2	348	4.9	3480720	7.6	4931	6.8	377	2.8	2320	49.8	1537	59.2
	35	15.0	3524	305	2915103	4162	17.9	305	0.8	2973115	1.9	3901	10.6	334	10.8	1247	64.7	841	71.1
	36	25.0	2349	232	1856384	2727	16.2	232	0.1	2160947	16.2	2451	4.1	276	17.5	392	83.0	247	86.6
	37	2.5	7281	464	4989032	7411	1.9	479	2.4	4684469	6.1	7353	1.0	479	4.5	6120	15.9	3858	22.7
	38	5.0	6251	435	4350900	6671	6.8	450	2.2	4321894	0.6	6555	5.0	464	6.4	4525	27.6	2915	33.1
	39	10.0	5192	406	3988325	5410	4.3	392	4.1	3683762	7.6	5207	0.2	421	3.6	2451	52.9	1624	59.2
	40	15.0	4177	319	3234169	4394	5.0	348	6.9	3147151	2.9	4119	1.5	377	19.4	1320	68.6	885	72.4
	41	25.0	2640	247	1885390	2886	9.2	261	6.1	2276971	21.0	2582	2.1	305	24.8	421	84.1	261	86.0
	42	2.5	7614	479	4931020	7542	1.0	493	2.1	4727978	4.2	7469	1.9	493	4.2	6222	18.3	3887	21.2
	43	5.0	6686	464	4423415	6787	1.5	464	1.5	4365403	1.4	6671	0.3	479	2.6	4597	31.2	2930	33.7
	44	10.0	5453	406	4060840	5497	0.8	406	1.4	3712768	8.5	5279	3.1	435	6.6	2480	54.5	1639	59.6
	45	15.0	4554	363	3408205	4452	2.1	348	3.2	3161654	7.0	4177	8.2	392	8.0	1334	70.7	899	73.6
	46	25.0	2915	290	2073929	2930	0.5	276	7.2	2305977	10.9	2625	10.0	319	9.1	421	85.3	261	87.2
	47	2.5	8035	508	5003535	7875	2.0	508	1.1	4814996	3.7	7817	2.8	508	1.0	6497	19.1	3959	20.7
	48	5.0	7150	479	4495930	7092	0.8	464	1.8	4452421	1.0	6961	2.6	493	2.3	4800	32.8	2988	33.4
	49	10.0	5990	421	4002828	5743	4.1	406	2.1	3785283	5.3	5526	7.8	450	5.8	2596	56.7	1668	58.2
	50	15.0	4757	377	3364696	4655	2.1	363	4.4	3234169	4.0	4365	8.2	406	6.8	1392	70.7	914	72.7
	51	25.0	3075	290	2030420	3060	0.4	276	4.6	2349486	15.6	2741	10.8	319	12.2	450	85.5	276	86.7
	52	2.5	8180	537	4974529	7803	4.7	508	6.4	4960026	0.4	7730	5.5	508	4.4	6439	21.3	4075	18.1
	53	5.0	7440	493	4553942	7019	5.7	464	4.7	4568445	0.4	6903	7.3	493	0.7	4757	36.0	3075	32.4
	54	10.0	5975	464	4046337	5685	4.8	406	11.3	3901307	3.7	5468	8.5	450	4.1	2567	57.0	1726	57.5
	55	15.0	4960	392	3248672	4612	7.0	363	7.9	3321187	2.2	4322	12.8	406	2.8	1378	72.2	943	71.0
Ganjan et al. 2009 ²⁶	56	5.1	4786	290	3480720	3742	21.9	377	30.9	3451714	1.0	4032	15.8	392	36.5	2509	47.6	2291	34.2
	57	7.6	4351	261	3190660	3379	22.5	363	36.3	3190660	0.2	3756	13.6	377	44.7	1856	57.4	1726	45.9
	58	10.0	3626	218	2900600	3046	16.0	334	53.3	2944109	1.6	3510	3.3	363	65.7	1378	62.2	1291	55.3
Dong et al. 2013 ²⁷	59	6.8	3727	377	652635	4133	10.7	464	21.8	609126	7.8	4554	22.1	493	28.6	2422	35.0	348	46.5
	60	13.6	3307	319	638132	3104	6.2	392	23.8	493102	23.5	3742	13.0	435	37.0	1044	68.4	160	75.3

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	61	6.8	4960	464	725150	4133	16.8	464	1.5	609126	16.3	4554	8.3	493	7.1	2422	51.1	348	51.5
	62	13.6	4148	334	652635	3104	25.2	392	17.8	493102	25.2	3742	9.9	435	30.4	1044	74.8	160	75.9
Youssf et al. 2013 ¹⁰	63	1.7	8064	711	6395823	7237	10.3	638	10.2	5844709	8.6	6976	13.4	653	8.9	6367	21.0	5134	19.7
	64	3.5	7817	696	6105763	6700	14.3	609	12.7	5511140	9.7	6222	20.5	624	10.1	5120	34.6	4191	31.4
	65	7.0	6976	609	5946230	5787	17.1	551	9.0	4931020	17.1	4975	28.6	580	3.8	3336	52.1	2814	52.7
	66	7.0	6048	696	5279092	5787	4.3	551	20.4	4931020	6.8	4975	17.7	580	15.8	3336	44.8	2814	46.8
	67	2.4	7469	--	6569859	8209	9.9	--	--	6134769	6.7	7803	4.5	--	--	6845	8.4	5091	22.4
	68	4.7	7252	--	6801907	7426	2.4	--	--	5685176	16.5	6715	7.5	--	--	5134	29.2	3901	42.7
	69	9.5	5685	--	6279799	6077	7.0	--	--	4873008	22.2	4960	12.7	--	--	2857	49.6	2248	64.1
	70	4.7	7252	--	6975943	7135	1.5	--	--	6294302	9.8	6454	11.0	--	--	4931	31.9	4322	38.1
	71	9.5	5845	--	6671380	5845	0.1	--	--	5409619	18.9	4771	18.4	--	--	2756	52.9	2495	62.6
	72	7.6	3321	--	2915103	3669	10.6	--	--	3074636	5.5	4293	29.1	--	--	2480	25.4	1668	42.7
Li et al. 2011 ²⁸	73	6.5	3075	--	2799079	3843	24.8	--	--	3176157	13.5	3597	16.8	--	--	2654	13.8	1885	32.7
	74	11.8	2364	--	2247965	3075	30.0	--	--	2683055	19.3	2712	14.5	--	--	1537	35.2	1015	55.0
Skripkiunas et al. 2007 ²⁹	75	3.4	6352	--	4292888	5598	12.0	--	--	4307391	0.6	5207	18.2	--	--	4307	32.3	3307	23.0
Adam G. Bowland 2011 ³⁰	76	2.2	2524	--	3103642	3829	51.8	--	--	3727271	20.2	3655	44.8	--	--	3234	28.1	3133	1.0
	77	4.4	2393	--	2755570	3495	45.8	--	--	3466217	26.1	3176	32.6	--	--	2466	3.3	2437	11.2
	78	6.7	2146	--	2654049	3176	48.1	--	--	3234169	21.9	2756	28.4	--	--	1885	12.2	1900	28.6
	79	8.8	2146	--	2044923	2901	35.4	--	--	3016624	47.2	2407	5.0	--	--	1450	36.8	1479	27.9
Turatsinze and Garros 2008 ³¹	80	10.1	4351	--	3190660	4278	1.8	--	--	4640960	45.3	4917	13.1	--	--	1914	56.0	3713	16.4
	81	15.4	2901	--	2755570	3408	17.7	--	--	4423415	60.8	4206	45.0	--	--	986	66.0	3162	14.9
	82	20.2	2175	--	2175450	2799	28.6	--	--	4234876	94.6	3640	67.4	--	--	566	74.3	2698	23.9
Son et al. 2011 ³²	83	1.3	3336	--	3002121	3568	6.9	--	--	3147151	5.1	3466	3.9	--	--	3220	3.5	2843	5.3
	84	2.7	3046	--	2799079	3365	10.6	--	--	3016624	8.2	3176	4.5	--	--	2741	9.9	2451	12.2
Balaha et al. 2007 ³³	85	2.1	4931	421	--	4786	2.9	406	2.0	--	--	4583	7.0	421	0.3	4090	17.0	--	--
	86	4.1	4496	392	--	4394	2.3	392	2.2	--	--	4017	10.5	406	1.2	3191	28.9	--	--
	87	6.2	4061	377	--	4032	0.9	363	2.1	--	--	3524	13.2	392	2.9	2480	38.9	--	--
	88	8.3	3626	363	--	3684	1.8	348	3.6	--	--	3089	14.7	377	2.9	1929	47.0	--	--
	89	1.9	7034	609	--	6961	1.1	624	0.6	--	--	6671	5.1	624	2.2	6004	14.7	--	--
	90	3.9	6526	595	--	6410	1.7	595	0.9	--	--	5903	9.5	609	2.3	4757	27.1	--	--
	91	5.8	6091	566	--	5917	2.9	566	1.0	--	--	5221	14.3	580	3.7	3756	38.3	--	--
	92	7.7	5511	537	--	5453	1.1	537	2.2	--	--	4612	16.2	566	3.9	2959	46.2	--	--

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	93	7.7	6381	--	--	5453	14.6	537	--	--	--	4612	27.6	566	--	2959	53.5	--	--
	94	1.8	7687	667	--	7542	2.0	667	0.5	--	--	7252	5.6	667	1.0	6570	14.4	--	--
	95	3.6	7252	638	--	6990	3.6	638	0.8	--	--	6483	10.6	653	2.2	5308	26.8	--	--
	96	5.4	6889	609	--	6483	5.9	609	0.8	--	--	5787	16.0	624	3.6	4278	38.0	--	--
	97	7.1	5946	595	--	6019	1.2	580	3.1	--	--	5163	13.2	609	2.6	3437	42.3	--	--
Topcu 1995 ²⁰	98	5.0	3510	319	--	2756	21.6	406	29.4	--	--	2466	29.6	421	34.8	1856	47.1	--	--
	99	9.7	2857	218	--	2262	20.8	363	62.1	--	--	1842	35.7	392	74.8	1044	63.4	--	--
	100	14.1	2146	160	--	1885	12.0	319	95.6	--	--	1407	34.7	363	117.1	609	71.6	--	--
	101	9.1	2349	218	--	2320	0.9	363	68.2	--	--	2640	12.7	392	80.6	1131	51.7	--	--
	102	17.0	1827	160	--	1668	8.8	290	93.1	--	--	2088	14.4	334	118.1	421	76.8	--	--
	103	23.9	1436	116	--	1247	13.2	247	107.6	--	--	1682	17.6	290	143.0	189	86.5	--	--
Karahan et al. 2012 ³⁴	104	5.0	5163	479	--	5308	2.9	450	7.1	--	--	4771	7.5	464	3.2	3597	30.2	--	--
	105	10.0	4525	450	--	4307	4.9	392	13.4	--	--	3466	23.3	421	6.4	1943	57.1	--	--
	106	15.1	3060	392	--	3481	13.8	334	13.0	--	--	2538	17.1	377	2.9	1030	66.1	--	--
Aiello and Leuzzi 2010 ³⁵	107	10.2	3466	421	--	4322	24.7	392	8.7	--	--	4989	43.9	421	1.2	1914	44.8	--	--
	108	19.8	3031	363	--	2901	4.3	305	17.5	--	--	3756	24.0	348	5.4	595	80.3	--	--
Najim and Hall 2012 ³⁶	109	2.5	5221	435	--	7310	39.9	595	37.2	--	--	6918	32.6	609	40.1	6019	15.2	--	--
	110	5.1	4641	479	--	6570	41.5	551	16.6	--	--	5888	27.0	580	21.5	4438	4.5	--	--
	111	7.6	3771	363	--	5903	56.6	522	43.9	--	--	5018	33.1	551	52.9	3249	13.8	--	--
	112	2.5	6381	537	--	7324	14.8	595	11.4	--	--	7600	19.0	609	13.7	6062	5.0	--	--
	113	4.9	4786	464	--	6599	38.0	566	20.7	--	--	7092	48.2	580	25.6	4496	5.9	--	--
	114	7.4	3336	348	--	5946	78.4	522	50.7	--	--	6613	98.3	551	59.8	3321	0.3	--	--
Eldin and Senouci 1993 ²³	115	9.2	3423	406	--	3350	1.9	392	3.7	--	--	2756	19.4	421	3.4	1624	52.5	--	--
	116	18.3	2785	334	--	2291	18.0	305	9.4	--	--	1566	43.6	348	3.1	522	81.2	--	--
	117	15.8	2727	305	--	2538	7.0	319	6.9	--	--	3133	15.1	363	20.0	711	74.0	--	--
Grinys et al. 2012 ³⁷	118	5.0	6671	537	--	7527	12.8	435	17.2	--	--	6758	1.4	464	13.7	5105	23.5	--	--
	119	10.0	4931	450	--	6106	23.7	392	13.3	--	--	4917	0.1	421	6.3	2756	44.1	--	--
	120	5.0	6961	508	--	7527	8.1	435	13.2	--	--	6758	2.9	464	9.6	5105	26.7	--	--
	121	10.0	5801	537	--	6106	5.1	392	28.6	--	--	4917	15.1	421	22.9	2756	52.5	--	--
	122	20.0	3191	450	--	4003	25.6	290	33.5	--	--	2683	16.0	348	23.6	812	74.6	--	--
	123	5.0	7397	537	--	7527	1.7	435	17.2	--	--	6758	8.6	464	13.7	5105	31.0	--	--
Olivares and Barluenga 2004 ³⁸	124	2.6	11457	--	--	11718	2.3	--	--	--	--	12415	8.4	--	--	10515	8.2	--	--

Analytical Modeling of the Main characteristics of Crumb Rubber Concrete

	125	4.2	8702	--	--	10921	25.5	--	--	--	--	12008	38.0	--	--	9079	4.4	--	--
	126	6.7	7977	--	--	9833	23.3	--	--	--	--	11414	43.1	--	--	7281	8.7	--	--
Tian et al. 2011 ³⁹	127	5.4	5381	--	--	5946	10.4	--	--	--	--	5294	1.6	--	--	3916	27.3	--	--
Khatib and Bayomy 1999 ²²	128	2.2	5076	--	--	4960	2.1	--	--	--	--	4742	6.5	--	--	4206	17.0	--	--
	129	4.3	4351	--	--	4539	4.3	--	--	--	--	4133	4.9	--	--	3249	25.4	--	--
	130	6.5	4061	--	--	4148	2.0	--	--	--	--	3611	11.2	--	--	2495	38.6	--	--
	131	8.6	3626	--	--	3785	4.3	--	--	--	--	3147	13.3	--	--	1914	47.3	--	--
	132	17.3	2538	--	--	2625	3.6	--	--	--	--	1842	27.5	--	--	653	74.2	--	--
	133	25.9	1813	--	--	1827	0.9	--	--	--	--	1146	37.0	--	--	247	86.0	--	--
	134	2.5	4713	--	--	4902	3.9	--	--	--	--	4859	3.0	--	--	4046	14.2	--	--
	135	5.0	3916	--	--	4409	12.6	--	--	--	--	4336	10.6	--	--	2988	23.7	--	--
	136	7.5	3481	--	--	3974	14.0	--	--	--	--	3858	10.9	--	--	2204	36.8	--	--
	137	10.0	2973	--	--	3568	20.2	--	--	--	--	3437	15.5	--	--	1610	45.7	--	--
	138	20.0	1813	--	--	2349	29.5	--	--	--	--	2146	18.5	--	--	479	73.8	--	--
Azevedo et al. 2012 ⁴⁰	139	9.4	7542	--	--	7527	0.2	--	--	--	--	6149	18.4	--	--	3582	52.6	--	--
	140	17.7	4786	--	--	5308	10.8	--	--	--	--	3684	23.1	--	--	1276	73.4	--	--
	141	25.1	3771	--	--	3887	3.2	--	--	--	--	2451	35.2	--	--	566	85.0	--	--
Issa and Salem 2013 ⁴¹	142	3.9	3872	--	--	3988	3.1	--	--	--	--	3669	5.2	--	--	2944	24.0	--	--
	143	6.6	3017	--	--	3568	18.5	--	--	--	--	3104	2.9	--	--	2132	29.3	--	--
	144	13.1	1972	--	--	2712	37.6	--	--	--	--	2059	4.1	--	--	943	52.1	--	--
Liu et al. 2012 ⁴²	145	1.5	6628	--	--	6758	2.0	--	--	--	--	6541	1.3	--	--	6004	9.3	--	--
	146	3.1	5932	--	--	6338	6.8	--	--	--	--	5932	0.0	--	--	5004	15.7	--	--
	147	4.6	4786	--	--	5946	24.1	--	--	--	--	5381	12.5	--	--	4148	13.2	--	--
	148	6.1	4075	--	--	5569	36.6	--	--	--	--	4888	19.8	--	--	3437	15.5	--	--

Note: 1 MPa = 145.03 psi

Table 2—Evaluation of the proposed models.

Model	Data Used *	Compressive strength, f'_{CRC}			Tensile strength, f'_{TRC}		Modulus of Elasticity, E_{RC}	
		Proposed Model	Model-1 ²²	Model-2 ²⁴	Proposed Model	Model-1 ²²	Proposed Model	Model-2 ²⁴
M (%)	Derive	8.4	--	--	6.8	--	8.2	--
	Verify	15.8	--	--	25.7	--	18.6	--
	Total	10.7	14.2	43.7	12.6	16.6	11.3	48.1
SD (%)	Derive	10.6	--	--	7.7	--	6.3	--
	Verify	16.1	--	--	30.6	--	22.0	--
	Total	12.9	13.7	24.1	20.1	24.7	13.9	23.9
Max. error (%)	Total	78.4	98.3	86.5	107.6	143.0	94.6	87.7
Linear trend slope	Total	-7.0	+39.9	+333.2	+46.3	+104.4	+20.8	+328.1
Predictions $\leq 20\%$ error (%)	Total	83.1	80.4	21.6	82.6	76.9	85.2	14.7

* The data subset used to derive the proposed model, verify the proposed model, or the total data set.

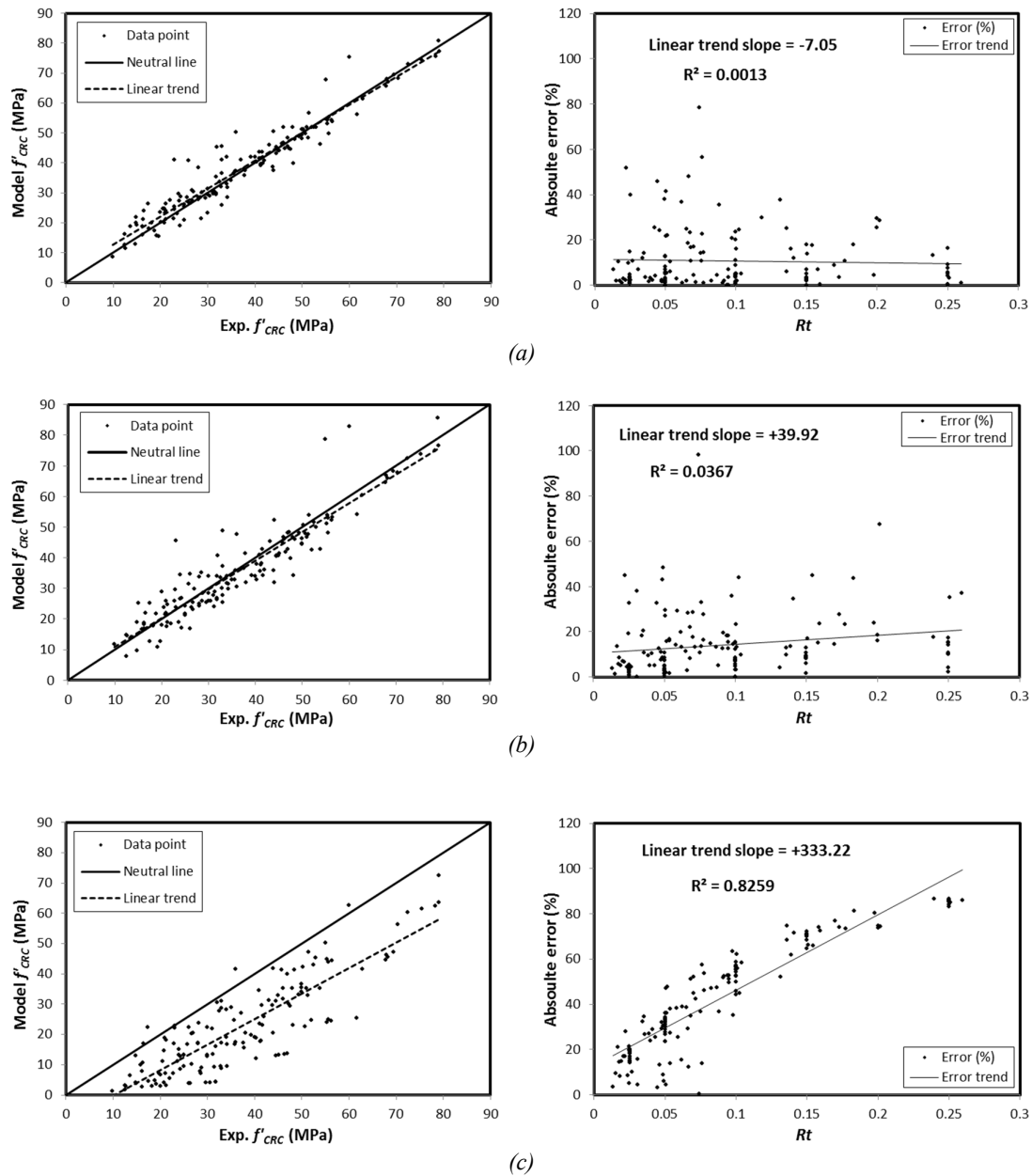


Fig. 3— f'_{CRC} predictions versus experimental results (left) and model errors versus R_t (right) of the total data set for: (a) proposed model, (b) model-1, and (c) model-2.

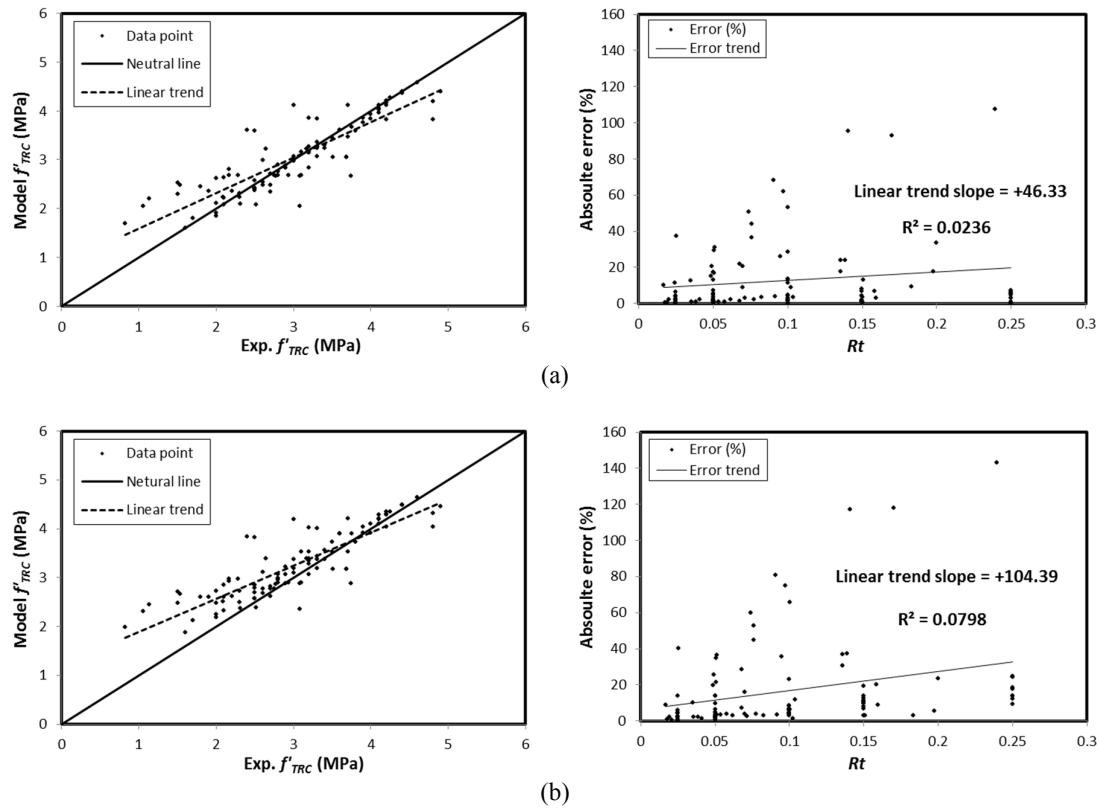


Fig. 4— f'_{TRC} predictions versus experimental Results (left) and model errors versus Rt (right) of the total data set for: (a) proposed model and (b) model-1.

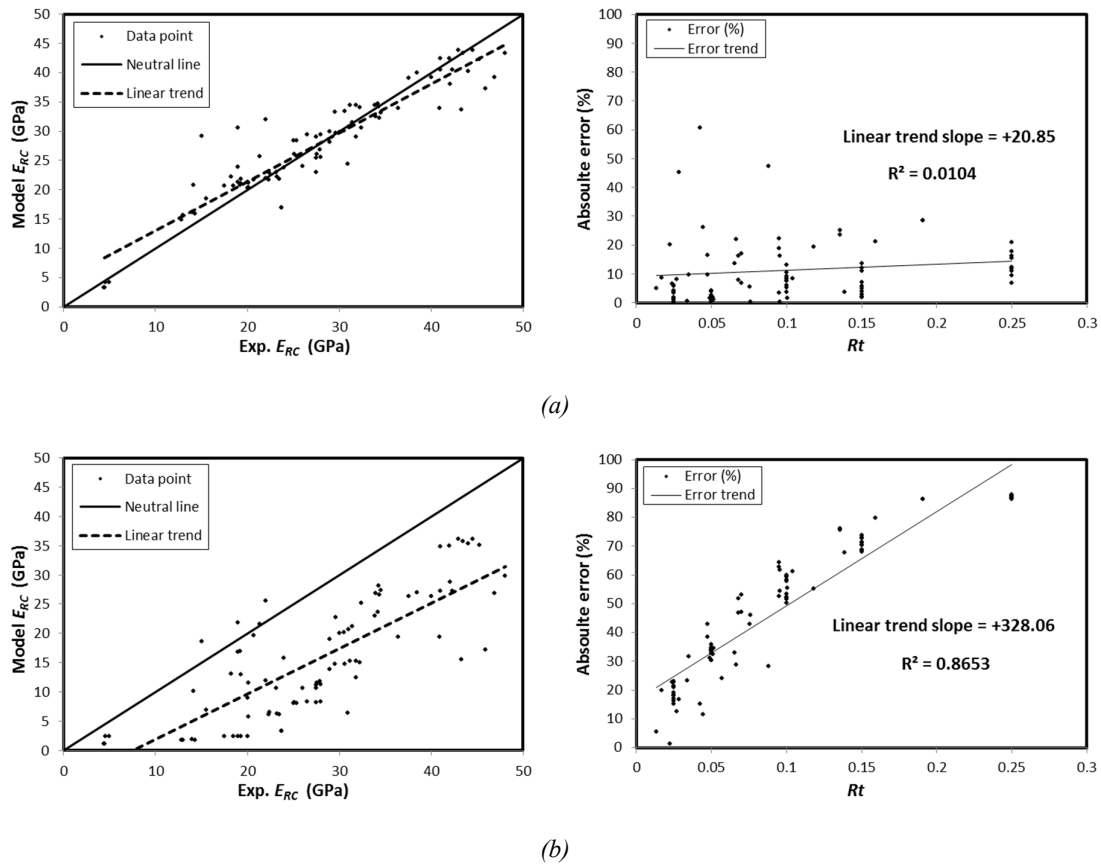


Fig. 5— E_{RC} predictions versus experimental results (left) and model errors versus Rt (right) of the total data set for: (a) proposed model and (b) model-2.

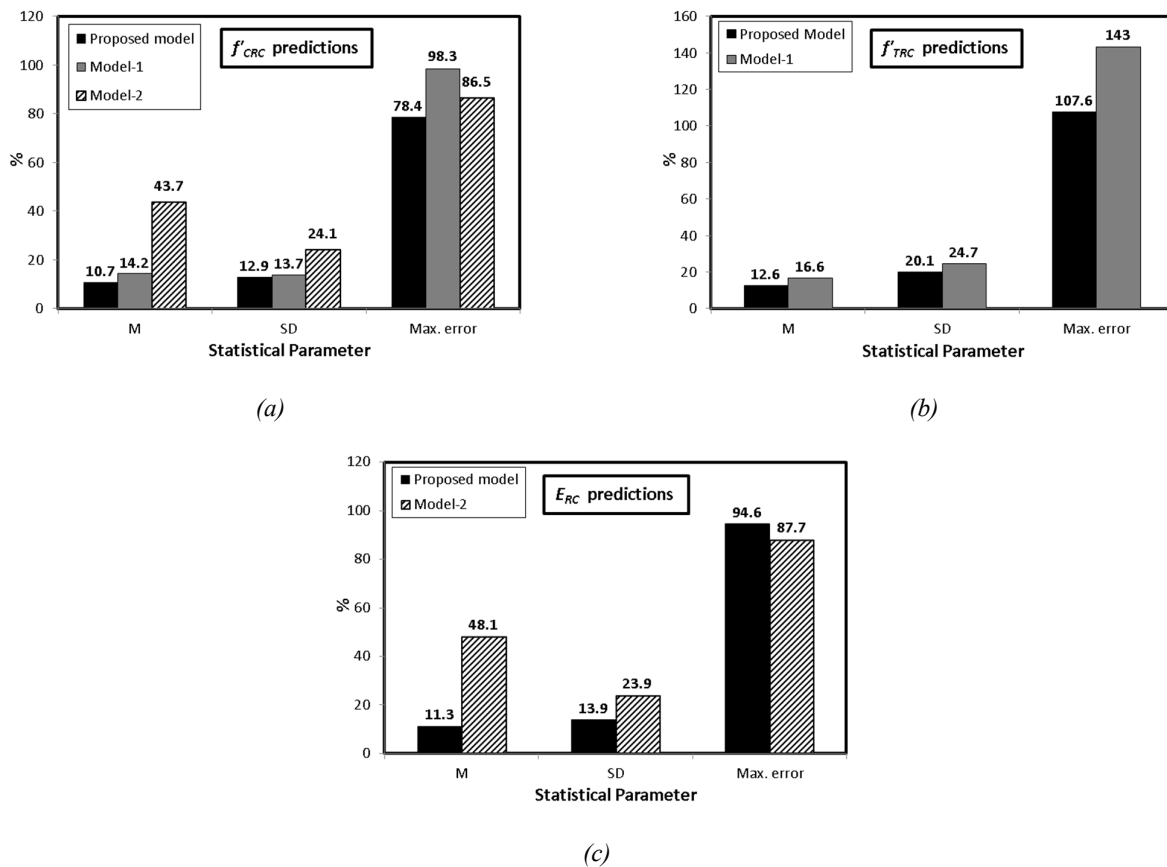


Fig. 6— Statistical parameters of the total data set for all comparable models: (a) f'_{CRC} predictions, (b) f'_{TRC} predictions, and (c) E_{RC} predictions.

SUMMARY AND CONCLUSIONS

This paper presented empirical models that can be used to predict CRC compressive strength, tensile strength, and modulus of elasticity. Sets of experimental data results, 148 data results for f'_{CRC} , 104 data results for f'_{TRC} , and 84 data results for E_{RC} were used to verify the proposed models' predictions.

The proposed models had the least scattering in the predicted f'_{CRC} , f'_{TRC} , and E_{RC} compared to the previous models. The f'_{CRC} model reduced M, SD, and max. error % by 24.6%, 5.8%, and 20.2%, respectively, compared to the Khatib and Bayomy (Model-1) predictions, and by 75.5%, 46.4%, and 9.3% compared to Khaloo et al. (Model-2) predictions. In addition, the f'_{TRC} model reduced the M, SD, and max. error % by 24.0%, 18.6%, and 24.7%, respectively, compared to the Model-1 predictions. Furthermore, compared to Model-2, the proposed E_{RC} model reduced the M and SD by 76.5% and 41.8%, respectively; however, it had a slight increase in the max. error % by 7.8%. Within the error range of 20%, the f'_{CRC} model was able to predict 83.1% of the experimental data compared to 80.4% and 21.6% for Model-1 and Model-2 respectively. In addition, the f'_{TRC} and E_{RC} models were able to predict 82.6% and 85.2%, respectively, of the experimental data compared to 76.9% and 14.7% for Model-1 and Model-2, respectively.

The proposed CRC model can help structural engineers who are considering using CRC as a promising alternative to conventional concrete in structures that need to resist earthquakes in seismic zones.

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Dynamic Properties of High Strength Rubberized Concrete

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Synopsis: Green construction has been a very important aspect in the concrete production field in the last decade. One of the most problematic waste materials is scrap tires. The use of scrap tires in civil engineering is increasing. This article investigates the dynamic properties of concrete with replacement of fine aggregate with scrap tire. Two different rubberized concrete mixtures were designed. The first set; variable slump (VS) was designed to keep the mix proportions constant with rubber replacement as the only variable. The other set; constant slump (CS) was designed to keep the workability the same using superplasticizer. The compressive strength of the concrete was reduced by the use of rubber. The viscous damping ratio was investigated using free vibration tests with impact hammer on simply supported beams and drop weight tests. The replacement of up to 20% of sand with rubber resulted in an increase in damping with the increase being more in the CS beams as well. Beyond 20%, the effect on damping was insignificant. The average hysteresis damping was found to increase with the increase of rubber content. The fracture energy was found to increase with the increase of rubber content up to 20%. Microstructure investigation was also performed on the two mixes. It is concluded that the choice of the rubber content and the mixing process can have a significant effect on the dynamic properties of rubberized concrete. Recommendations for these two aspects were provided.

Keywords: Damping ratio; fracture energy; high strength concrete; microstructure; rubberized concrete; scrap tires

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INTRODUCTION

Green construction has been an important aspect in the concrete production field in the last decade or so. The use of waste products in concrete manufacturing is beneficial both economically by replacing some of the components with waste materials and environmentally by clean disposal of waste materials. Scrap tires are mostly dumped in landfills. However, this can result in environmental hazards and contamination. Around 300 million scrap tires per year are added to the existing piles in the United States according to reports [Rubber Manufacturers Association (2014)]. Only a small amount of these tires are being recycled. Of this small amount, only 4% of the scrap tires are used in civil engineering applications [Rubber Manufacturers Association (2014)].

The addition of shredded scrap tires to concrete provides some favorable characteristics for concrete and alters some of concrete properties. The ordinary cement-based concrete is generally brittle. However, the addition of rubber to concrete, producing rubberized concrete, can increase its ductility and impact resistance [Eldin and Senouci (1993); Topcu (1995); Toutanji (1996); Youssf et al. (2014); Moustafa and ElGawady (2015); Moustafa and ElGawady (2016)]. Rubberized concrete is used in many applications such as concrete pavements, sidewalks, and road barriers where concrete is subjected to dynamic loading from moving vehicles or people walking on sidewalks.

The mechanical properties of rubberized concrete have been investigated extensively under static loading. Past research concluded that replacing up to 5% of mineral fine aggregates with rubber has insignificant effects on concrete strength and workability. However, increasing the rubber content beyond this percentage reduces the compressive strength and workability of fresh concrete. The amount of reduction depends on the percentage and type of aggregate to be replaced (either coarse or fine aggregate) as well as the size and distribution of the rubber particles [Eldin and Senouci (1993); Topcu (1995); Khatib and Bayomy (1999); Hernandez-Olivares et al. (2002); Siddique and Naik (2004); Youssf et al. (2014); Youssf et al. (2016)]. Moustafa and ElGawady (2015) investigated the mechanical properties of high strength rubberized concrete with replacement of fine aggregate of up to 30% and found a reduction of compressive strength of up to 32%.

The dynamic properties of rubberized concrete have not yet received the attention it deserves. Hernandez-Olivares et al. (2002) reported an increase of 23% to 30% of the dissipated energy of rubberized concrete having low rubber contents of 3.5% and 5% compared to conventional concrete. Zheng et al. (2008) measured viscous damping values ranging from 0.68% to 1.67% on small rubberized concrete cubes compared to viscous damping values ranging from 0.45% to 0.74% measured on conventional concrete cubes, i.e., rubberized concrete displayed about 75% higher viscous damping than that of the corresponding conventional concrete. Bowland (2011) tested two full-scale footbridges; one with conventional concrete and the other with 15% replacement of fine aggregate with ground rubber. No significant change in damping between the two footbridges was reported. This may be attributed to the very low imposed excitations of only 0.05g. Reda Taha et al. (2008) investigated the fracture properties of rubberized concrete under impact loading and reported significant enhancements in the impact resistance and fracture toughness of rubberized concrete. Youssf et al. (2015) investigated the behavior of a rubberized concrete column with 20% rubber replacement of fine aggregate under reversed cyclic loading. The rubberized column had an increase of 13% in hysteretic damping while the viscous damping was decreased by 49% compared to the conventional column.

Microstructure investigations of rubberized concrete have been investigated with high variation of conclusions [Hernandez-Olivares et al. (2002); Benazzouk et al. (2007); Emiroğlu and Yıldız (2008); Reda Taha et al. (2008)]. Hernandez-Olivares et al. (2002) recorded a high concentration of calcium oxides of the surface of the rubber particles. They concluded that this means that hydrated cement reacts with the rubber fiber exterior surface and a diffusion of the hydrated products happens, especially the ones with high calcium oxides content. Emiroğlu and Yıldız (2008) concluded that the interfacial transition zone in the rubberized concrete is poor compared to the conventional concrete. They reported that the bond between rubber and cement paste is very weak and resistance is resulting from the roughness of the interface instead. Reda Taha et al. (2008) concluded that the reduction of compressive strength is attributed to the behavior of the tire rubber as a soft aggregate, rather than to the reduction of bond between the tire particles and the cement paste.

Research significance

While there have been some investigations of the dynamic properties of normal strength rubberized concrete, the dynamic properties of high strength concretes with scrap tires have not been thoroughly investigated. In this manuscript, the dynamic properties of high strength concrete (concrete with compressive strength of greater than 69 MPa [10,000 psi]) having scrap tire rubber as a substitution for fine gravel were studied. Furthermore, past research on dynamic properties of normal strength rubberized concrete either focused on measuring viscous damping [Zheng et al. (2008)] or hysteretic damping [Hernandez-Olivares et al. (2002); Bowland (2011)]. The fracture behavior of rubberized concrete also lacks focus [Reda Taha et al. (2008)]. This study represents a comprehensive evaluation of the dynamic properties of high strength rubberized concrete, including viscous, hysteretic damping, and fracture energy under different loading conditions ranging from static cyclic loading to impact hammer testing to drop weight testing. Different percentages of replacement of sand ranging from 0 to 30% by volume were investigated. The microstructure features of high strength rubberized concrete were also investigated.

EXPERIMENTAL INVESTIGATION

Material characteristics

To study the effects of mixture design on the dynamic properties of rubberized concrete, two sets of rubberized concrete mixtures were designed. The first set, hereafter called variable slump (VS), was used to test the dynamic properties of rubberized concrete with the replacement of sand by crumb rubber as the only variable. Replacements of 0%, 5%, 10%, 15%, 20%, and 30% by volume of sand with crumb rubber were investigated. The second set, hereafter called constant slump (CS), is similar to VS set but with variable amounts of superplasticizer to maintain the same workability of the fresh concrete regardless of the rubber percentage. The materials used for sets VS, and CS are shown in Tables 1 and 2, respectively. The mixture nomenclature in Tables 1 and 2 consists of mixture set (VS or CS) followed by the percentage of sand replacement with rubber by volume.

Type I Portland cement meeting ASTM C150 specifications was used in all mixtures. Limestone washed coarse aggregate with nominal maximum size of 1 in was used. Missouri river sand was used. The rubber used was crumb rubber with three different sizes of 8-14, 14-30, and 30- where the first number represents the sieve number of the passing particles and the second number represents the sieve number of the retained particles. Figure 1 shows the grading of the sand, coarse aggregate and ground rubber used during the course of this research.

Concrete mixing

Dry mixing of the coarse aggregate, sand, and rubber was performed for about 1 minute to insure distribution of the aggregates. The cement and fly ash were then added and the concrete was dry mixed for another minute. The superplasticizer was mixed with the water and the water was then added to the mixture. The concrete was mixed for 2 minutes and then let stand for 1 minute; then, mixed for another two to three minutes until consistency was observed. For the CS mixtures, the slump test was performed after the mixing and superplasticizer was carefully added if the target slump was not achieved.

Table 1. Mixture proportions for the control concrete and for VS set

Materials (kg/m ³)	Water	Cement	Fly Ash	Coarse aggregate	Super-Plasticizer	Sand	R(8-14)	R(14-30)	R(30-)
Normal Concrete	142.40	336.39	112.13	1057.22	1.07	576.66	-	-	-
VS 05	142.40	336.39	112.13	1057.22	1.07	544.63	10.09	3.20	0.70
VS 10	142.40	336.39	112.13	1057.22	1.07	519.00	20.18	6.41	1.41
VS 15	142.40	336.39	112.13	1057.22	1.07	490.16	30.27	9.61	2.11
VS 20	142.40	336.39	112.13	1057.22	1.07	461.33	40.37	12.81	2.82
VS 30	142.40	336.39	112.13	1057.22	1.07	403.67	60.55	19.22	4.23

Table 2. Mixture proportions for the control concrete and for CS set

Materials (kg/m ³)	Water	Cement	Fly Ash	Coarse aggregate	Super-Plasticizer	Sand	R(8-14)	R(14-30)	R(30-)
Normal Concrete	142.40	336.39	112.13	1057.22	1.12	576.66	-	-	-
CS 05	142.40	336.39	112.13	1057.22	1.33	544.63	10.09	3.20	0.70
CS 10	144.17	336.39	112.13	1057.22	1.33	519.00	20.18	6.41	1.41
CS 15	144.17	336.39	112.13	1057.22	1.55	490.16	30.27	9.61	2.11
CS 20	144.17	336.39	112.13	1057.22	1.65	461.33	40.37	12.81	2.82
CS 30	144.17	336.39	112.13	1057.22	1.76	403.67	60.55	19.22	4.23

1 kg/m³ = 16.02 lb/ft³

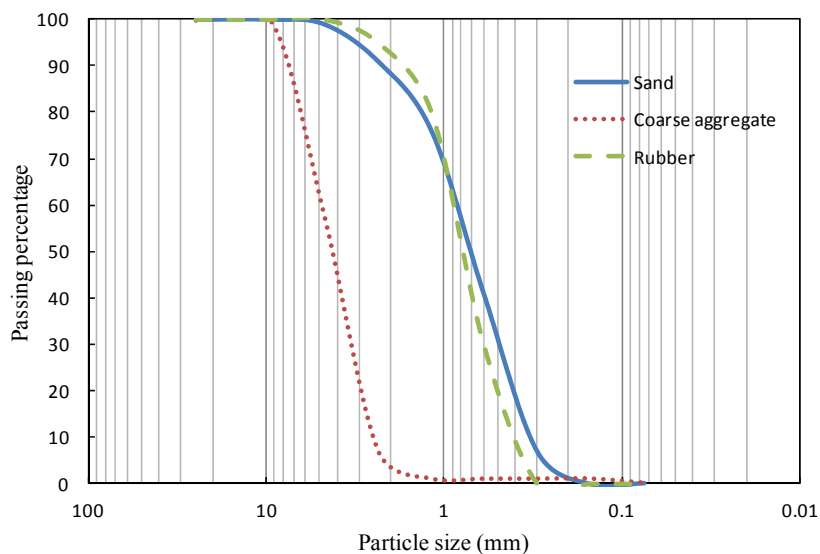


Figure 1 – Grading of used materials

Test specimens

Six concrete beams of each set, VS and CS, were cast with nominal dimensions of 150 mm x 150 mm x 900 mm (6 in x 6 in x 36 in); one for each percentage of rubber replacement. Mechanical vibration was performed for all the beams to insure proper placement and filling of the concrete. A total of thirty-six 100 mm x 200 mm (4 in x 8 in) cylinders for each set were cast in the same day with the beams. The cylinders were used to determine the compressive strength of the concrete at 56 days. These cylinders were tested under axial cyclic loading to determine the hysteretic

damping of the different concrete mixtures. The beams and cylinders were demolded after 24 hours and were moist cured in a controlled moisture room for 7 days. Then, they were removed from the curing room and left in the ambient temperature in the High-bay Lab at the Missouri University of Science and Technology.

Test setups

Compressive strength and hysteresis damping setup

The compressive strengths of the concrete cylinders were determined using an MTS machine. The cylinders were grounded to assure the leveling of the surface and the two surfaces are parallel to each other. To determine the average axial strain of the concrete, two string potentiometers were placed on two opposite sides of each cylinder at a gauge length of one-third of the cylinder height. The average axial strains along a full specimen height were also measured using a Linear Variable Displacement Transducer (LVDT). The test setup for the compressive strength is shown in Figure 2.

The cylinders were tested to determine the concrete compressive strength at 56 days. One group of the concrete cylinder specimens was monotonically loaded in a displacement control and another group was cyclically loaded using displacement control up to failure. The loading rate for both sets was 5 mm/min (0.2 in/min). The cyclic axial compressive loading, including loading/unloading cycles, was applied based on a prescribed pattern of progressively increasing levels of axial displacements until failure occurred. Three cycles of loading/unloading were applied at each axial displacement level. Finally, the cylinders were tested for compressive strength at 56 days to represent the actual compressive strength of the beams on the test day. Three cylinders for each test were tested and the average of the three readings was used.



Figure 2 -- Compression test setup

Instrumented impact hammer setup

The dynamic properties of the rubberized concrete were determined using simply supported beams excited by an instrumented impulse hammer with a capacity of 22.5 kN (5000 lb). Figure 3 shows the dynamic test setup. Four accelerometers were mounted on the surface of the beam. The beam was excited by hitting the beam at mid-span using the impact hammer. The accelerations were recorded using data acquisition system called Synergy box along with the instrumented hammer reading.

Drop weight test setup

Falling weight impact tests were conducted on the rubberized concrete beams used in the impact hammer tests by dropping a 70 mm (2.8 in) diameter, 23 kg (50 lb) steel cylinder from prescribed heights into the mid span of the beams. The beams were simply supported and the uplift was prevented at the supports while allowing rotations, as

illustrated in Figure 4. The weight was dropped inside a guiding PVC pipe to ensure the impact occurred in the mid span and perpendicular to the beams. A 13-mm (0.5 in) thick neoprene plate with the same diameter of the cylinder was attached to the end of the cylinder to reduce the amount of vibration after the impact with the beams. The weight was held in position prior to each drop by a pulley system at the required drop height. The tests were performed on the two beams sets using three different drop heights. The weight was first dropped from a height of 75 mm (3 in) to measure the dynamic response with the attached accelerometers; similar to the impact hammer tests. The drop height was then increased to 150 mm (6 in) and 225 mm (9 in), at which the beams failed, to measure the fracture energy of the beams. The data was collected using the synergy box with a high sampling rate of 500,000 samples per second to ensure adequate representation of the impact.

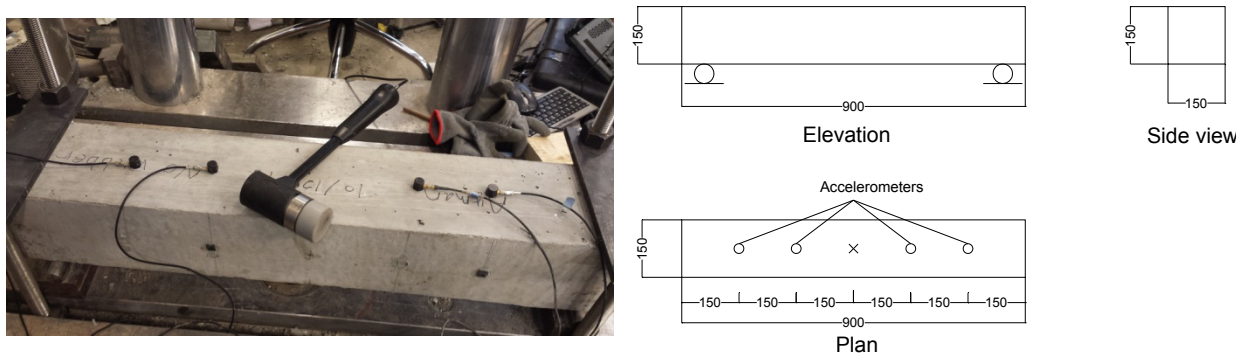


Figure 3 – Impact hammer test setup (dimensions in mm: 1 inch = 25.4 mm)

To measure the deflection of the beams, a linear potentiometer with a 50-mm (2 in) stroke was secured at the bottom of the beam. To obtain the impact force on the beams, the data from the load cell incorporated by Tabatabaei et al. (2014) using the same test setup used in the current study. This load cell consisted of four individual dynamic load cells built by “PCB Piezotronics”, each capable of measuring up to 89 kN (20,000 lb) in compression under dynamic load. The combined load cell was constructed using machined steel discs; allowing a total capacity of 359 kN (80,00 lb). The impact loads are dependent on the height of drop under free fall and are normally not affected by the impact objects [Banthia et al. (1989); Fujikake et al. (2009)]. This assumption was verified by examining all the impact loads at the same heights performed by Tabatabaei et al. (2014) and differenced of less than 5% were found; mainly due to the friction between the weight and the guiding PVC tube.

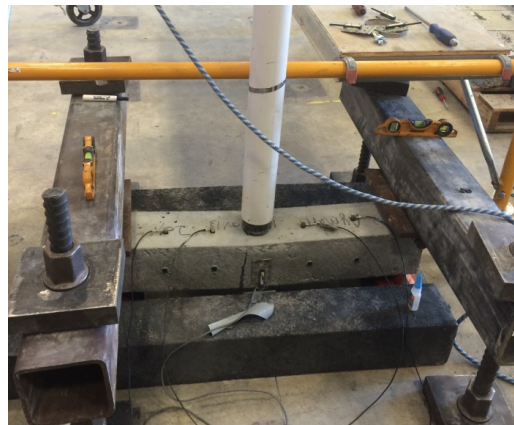


Figure 4 – Drop weight test setup

Microstructure features test setup

Scanning electron microscope (SEM) was employed to investigate the microstructure features of rubberized concrete. The SEM was used to analyze the crystal structure of Calcium Silicate Hydrate (C-S-H) and Calcium Hydroxide (CH)

in the interfacial layers of the aggregate to cement paste and rubber particles to cement paste. A thin disk with a thickness of 12.5 mm was cut from rubberized concrete cylinders and was broken down into smaller pieces to fit inside the SEM machine, as shown in Figure 5. The specimens tested represented the 20% rubber replacement for both the CS and the VS mixes. The specimens were prepared according to ASTM C1723 (2010). The specimens were air dried for 24 hours before the test. The oven drying was avoided because it can have a destructive effect that includes dehydration of hydrous phases and micro cracking. Specimen surface was coated by Edwards S150 sputter coater to get high quality interface images. Elemental analyses were performed on the samples using energy-dispersive X-ray spectroscopy (EDX) attached in the SEM. The EDX uses X-ray source to quantify the elements of the selected areas.



Figure 5 -- Test specimen for SEM analysis

EXPERIMENTAL RESULTS AND DISCUSSION

Compressive strength

The compressive behavior of VS and CS mixtures was determined at 56 days according to ASTM C192 (2013), as illustrated in Figure 6. The Figure shows the average and range of compressive strength of concrete cylinders subjected to axial monotonic loading and cyclic loading at 56 days (six cylinders for each rubber content). The figure shows higher compressive strengths for the CS mix compared to the VS mix. For CS series and unlike the 7 days stress, replacing any percentage of sand resulted in a significant reduction in strength. Replacing up to 15% of sand with rubber resulted in a strength reduction of approximately 10%. At 30% replacement, the strength reduction was approximately 32%. Three cylinders were used for determination of the compressive strength of each rubber content. The standard deviation for the VS mix was higher than that of the CS mix. This difference was caused by the non-uniform distribution of the rubber particles in the VS mix compared to the CS mix. A model to predict the compressive strength of the high strength rubberized concrete (f'_R) based on the concrete compressive strength and the rubber content was developed as:

$$f'_R = f'_c - 1.20R - 0.012R^2 \quad (1)$$

where f'_R is the rubberized concrete compressive strength, f'_c is the compressive strength of concrete without rubber, and R is the replacement percentage by volume of the fine aggregate with rubber. The same model was used for both mixes as it provided good agreement with the experimental results.

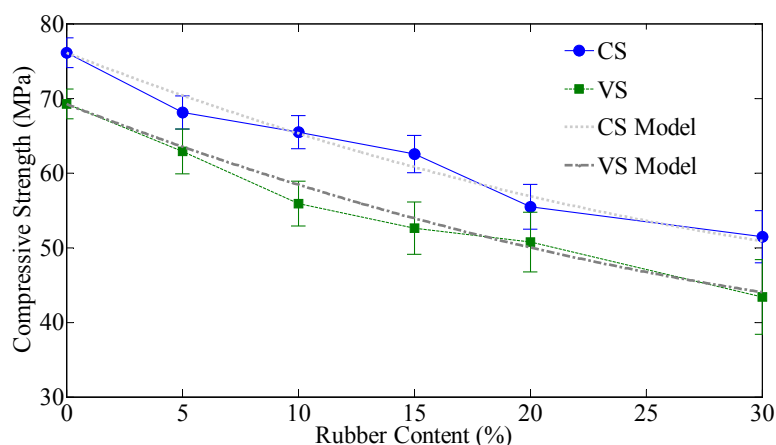


Figure 6 – Compressive stress for VS and CS cylinders (1 MPa = 145 psi)

Hysteresis damping results

The hysteresis is the property of systems to follow different loading and unloading paths. The hysteresis damping for the cyclic testing is calculated from the specific damping capacity (Y), which is the ratio between the energy dissipated per unit volume of the material, E_D , and the strain energy per unit volume stored in a linear elastic system, E_{S0} , as shown in eq. 2.

$$Y = \frac{E_D}{E_{S0}} \quad (2)$$

A graphical representation of E_D and E_{S0} is shown in Figure 7.

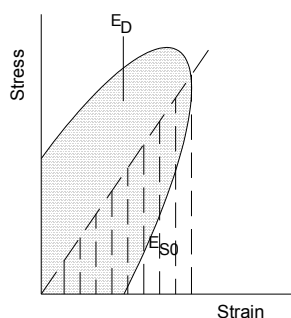


Figure 7 -- Dissipated energy per unit volume of the material, E_D and elastic strain energy, E_{S0}

The energy dissipated per cycle per unit volume, E_D , is measured as the area enclosed by a hysteresis loop drawn on axes of stress and strain. This area can be obtained as the integral of the area under the curve and it can be calculated mathematically using eq. 3.

$$E_D = \sum_{i=1}^{n-1} \left(\frac{F_{i+1} + F_i}{2} \right) (\Delta_{i+1} - \Delta_i) \quad (3)$$

Where, E_D is the dissipated energy (J), n is the total number of stress or strain points, F_i is the force at point i (N), and Δ_i is the displacement at point i (m).

The hysteresis damping can be expressed as the equivalent viscous damping and is calculated from the specific damping capacity using eq. 4.

$$\zeta_{eq} = \frac{1}{2\pi} Y \quad (4)$$

Samples of the stress-strain curves for the normal concrete and the rubberized concretes are illustrated in Figure 8. The energy dissipated per cycle per unit volume, E_D , can be calculated for each of the stress-strain curves using eq. 3. Since the loading was displacement controlled, it is more representative to plot E_D versus the strain of the test specimen. Figure 9 shows the cumulative energy dissipation of the different mixtures. As shown in the figure, the cumulative energy dissipation for the rubberized concrete is much higher than the normal concrete, especially for 20% and 30% replacements.

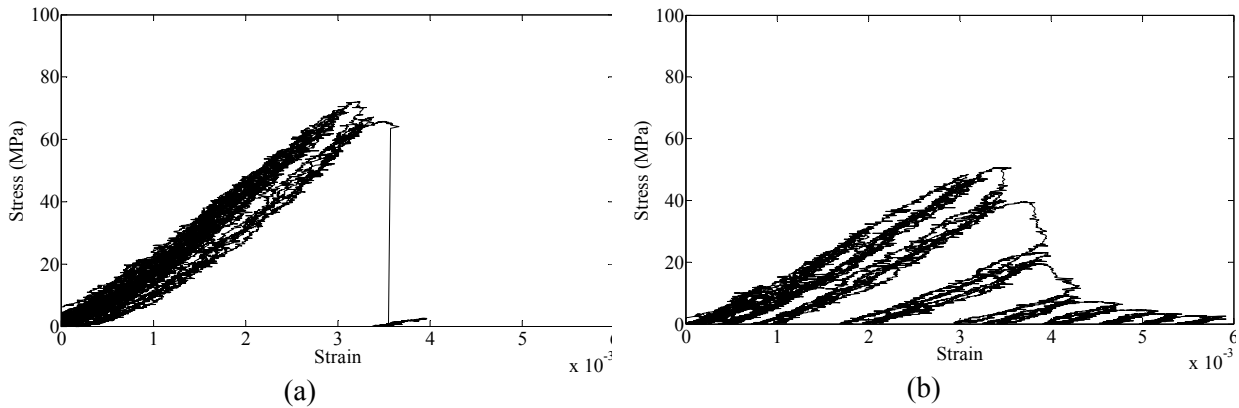


Figure 8 -- Sample stress-strain curves of a) normal concrete, b) rubberized concrete (1 MPa = 145 psi)

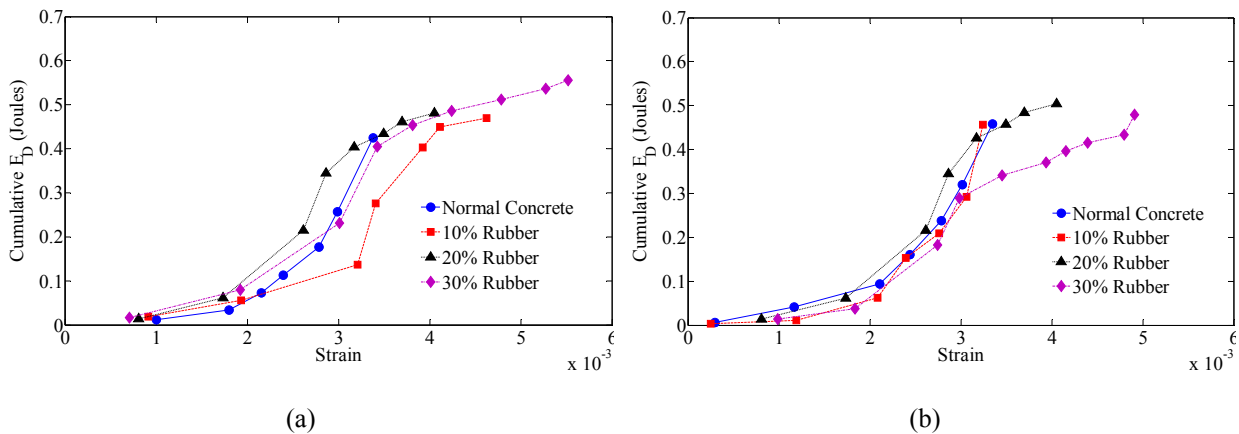


Figure 9 -- Cumulative dissipated energy for a) VS and b) CS (1 J = 8.85 lb.in)

The hysteresis damping is calculated using eq. 4 for each cycle. Figure 10 shows the hysteresis damping vs. axial compressive strain for each mixture for both sets. The figure shows that the average hysteresis damping increases with the increase of rubber content. For 20% and 30% rubber replacement the equivalent viscous damping reach approximately four times the equivalent viscous damping of normal concrete. The increase in damping is higher than that observed by Hernandez-Olivares et al. (2002) and Bowland (2011) because of the higher replacement ratios.

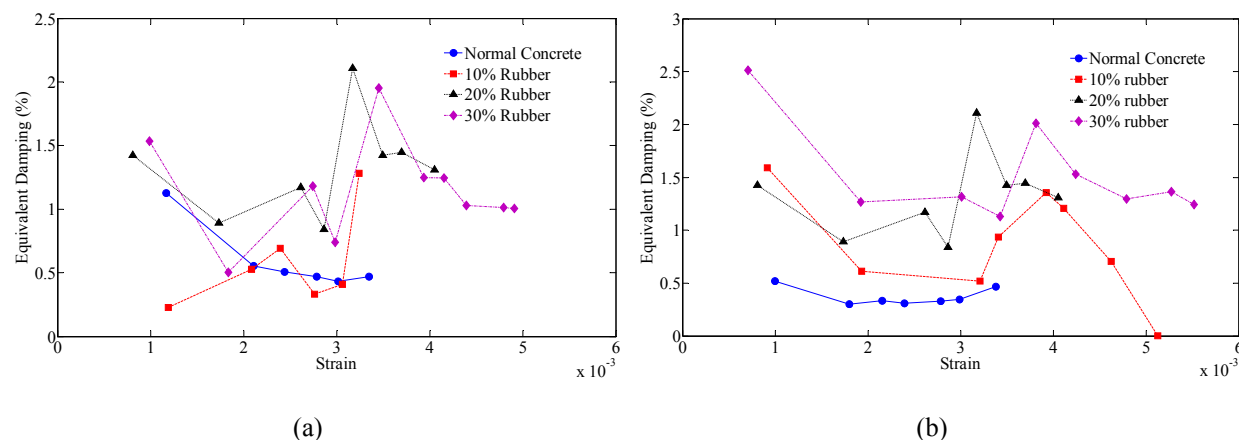


Figure 10 -- Hysteresis damping for different rubber contents for a) VS and b) CS

Impact hammer results

Damping ratio

The viscous damping ratio can be calculated using free vibration tests of structural elements using the logarithmic decrement method [Yan et al. (2000)]. The accelerations amplitudes were recorded for the impact hammer and drop weight tests and the values of the damping ratio can be calculated using eq. 5.

$$\xi = \frac{1}{2n\pi} \ln \left(\frac{A_0}{A_n} \right) \quad (5)$$

Where, A_0 is the initial amplitude and A_n is the amplitude after n cycles.

A typical damping curve is shown in Figure 11 for the measured signals. The figure shows that the actual response of the beams is not strictly exponential; hence, variation in the value of damping ratio occurs with the change in the number of cycles used to calculate the damping. In the current study, a base of 10 cycles is used to define the damping ratio and is denoted by ξ_{10} .

The change in ξ_{10} with the rubber content is shown in Figure 12. The figure shows an increasing trend of the damping ratio with the increase in rubber content for both CS and VS mixes. The increase in the damping ratio for VS mixture was 5.3%, 19.8%, and 22.9% for 10%, 20%, and 30% replacement, respectively. For the CS mixture, the increase was 12.5%, 29.4%, and 32.5% for 10%, 20%, and 30% replacement, respectively. The larger increase in the CS mix can be attributed to the higher workability of CS leading to a uniform distribution of the rubber particles as opposed to concentration of rubber in some places like the bottom surface and the corners. The results of the viscous damping are of good agreement with the results by Zheng et al. (2008) for normal strength concrete.

Effect of number of vibration cycles

It has been shown by several researchers that the calculated damping value depends on the number of cycles used in the calculations, i.e. n parameter in eq. 5. Figure 13 shows the change in damping ratio with changing the number of vibration cycles. As shown in the figure, the damping calculations are sensitive to the number of vibration cycles up to 10 cycles, beyond that the results are independent of the number of vibration cycles.