Chapter 9

Tire-Derived Aggregate Cementitious Materials: A Review of Mechanical Properties

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Abstract

This chapter presents an overview of tire-derived aggregate concrete, also known as rubberized concrete, a cementitious-based material with some or all of its mineral aggregates replaced with rubber particles. Typical source of rubber materials is scrap tire. Tire-derived aggregate concrete has practical applications as safety barriers, sound barriers, and architectural features among others. General observed trends include a decrease in compression strength, a decrease in flexural strength, and an increase in energy absorption and damping capacities with an increase of rubber content. These characteristics are modifiable by application of lightweight aggregates, fiber-reinforcement, admixtures, and other common techniques. The chapter also includes discussions on handling, design, and analysis of tire-derived aggregate concrete.

Keywords: tire-derived aggregate (TDA), rubberized concrete (RuC), mixture proportioning (mix design), strength, modulus of elasticity, toughness, lightweight aggregate (LWA)

1. Introduction

Investigation of rubberized concrete has received considerable attention since late twentieth century, when exploration of the idea of adding rubber particles to the concrete matrix began. The intriguing idea for many has been the combination of an ultra-flexible material to an ultra-rigid material to enhance ductile performance of the composite material. In addition, the idea of incorporating a waste material that may otherwise end up in a landfill is attractive for sustainable development. The main constituent of rubberized concrete is tire-derived aggregate (TDA), incorporated in a cementitious matrix through replacement of fine or coarse aggregate as a percentage of volume or weight. This application redirects a significant amount of waste rubber from landfills to infrastructure industries.

The idea of repurposing a waste material for use in concrete has roots in concerns regarding the amount of waste tires in landfills. The United States alone generates 289 million scrap tires on an annual basis as of 2006 [1]. The Environmental Protection Agency (EPA) identifies stockpiled tires as an "ideal incubator for mosquito larvae" and connects this to the spread of the West Nile Virus from 1999 to 2005 [1]. As of 2012, tires were being recycled at a rate of 44.6% with rubber and leather contributing 6.18 million tons of waste after accounting for recycling and recovery [2]. The idea of reducing the number of waste tires that accumulate in landfills through recycling rubber for use in concrete has continued to attract the attention of researchers.

The general focus of research on rubberized concrete is the evaluation of mechanical properties of the concrete. The basic properties include compressive, tensile, and flexural strengths. The performance of TDA concrete subject to dynamic loading is another essential property of TDA concrete. In addition, application of supplementary cementitious materials and admixtures, such as silica fume and fly ash, has potentials to enhance various characteristics of TDA concrete. Research seems to be in support of the fact that the lower strength and enhanced dynamic properties of the TDA concrete mixtures are valuable in certain practical applications such as traffic barriers and other impact-resistant systems.

2. An overview of constituent materials

Other than the inclusion of the rubber particles, the rubberized concrete mix is virtually the same as most other concrete including cement, fine aggregates, coarse aggregates, and water. Some researchers have incorporated super plasticizers, in order to achieve better workability. Others have experimented with the use of silica fume and fly ash in order to achieve enhanced strengths. Further, researchers have experimented with pretreating the rubber particles using chemical washes in attempts to develop better bonds between the rubber particles and the cementitious matrix. Following sections discuss individual components making up the rubberized concrete matrix.

2.1. Tire-derived aggregate materials

TDA refers to the rubber particles, processed from multiple types of tires differing in composition and fiber type, used for replacing the mineral or rotary kiln expanded lightweight aggregates in many mixtures (**Figure 1**). Descriptive classification of rubber particles relies on the size and manufacturing processes of materials [3]. The first and largest classification of TDA is shredded tire chips, which are typically results of mechanical shredding. Resulting tire chips may be as large as 460 mm long by 230 mm wide to as small as 150 mm long. A combination of both primary and secondary shredding processes is also common to produce smaller shredded chips. The next classification is ground rubber; with a typical range of 19–0.1 mm in size. Ground rubber is subject to two stages of magnetic separation and

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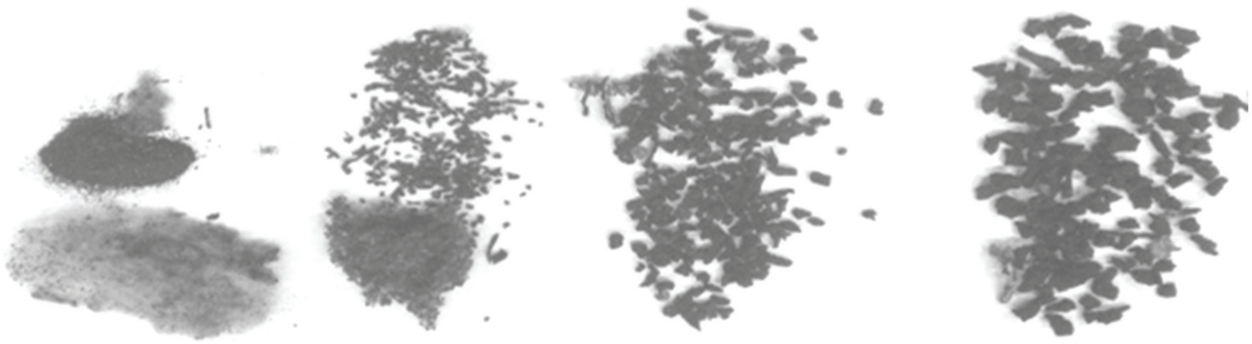

Figure 1. Crumb rubber manufactured through mechanical shredding of recycled tires.

screening to remove the steel fibers from the rubber particles. The smallest classification of TDA is crumb rubber, obtained through micro-milling, cracker-milling, and granular processes. Crumb rubber particle sizes range from 4.75 to 0.075 mm. Another method is a cryogenic method, in which the rubber is frozen using nitrogen and then shattered [3].

2.2. Mix design constituents

The common fine aggregate used in most research studies on rubberized concrete is natural sand with a gravel coarse aggregate. The cement used is either Type 1 or Type 2 cement, with no significant evidence suggesting one type of cement performing better. Other admixtures incorporated into rubberized concrete include the addition of silica fume and fly ash by replacement of cement. This enhances the strength of rubberized concrete and bond between the rubber and cement. Further, rubber particles may also replace lightweight aggregates (LWA), such as rotary kiln expanded shale, clay, and slate, in various lightweight concrete materials, where, the similarity between the volume weights of TDA and LWA enhances the ease of mixing and placing operations [4].

3. Mechanical properties

3.1. Compressive strength

Table 1 lists selected research projects and their characteristics. Existing literature indicates that an increase in rubber content results in a systematic decrease in the compression strength of the concrete material (**Figure 2**). The substitution of mineral aggregates with TDA is generally between 0 and 100% of the total aggregate volume in increments of 20%. The relationship between the compressive strength and rubber content in the mix is not linear [22]. Further, the size of the particles has an impact on this relationship. While, inclusion of 100% crumb rubber may reduce the compressive strength by more than 90% [8], substitution of fine aggregates by less than 25% appears to have no significant impact on this strength [13]. In particular, research has shown that application of fine crump rubbers has less negative impact on the compressive strength of the mix [5, 6, 15, 20]. A comparison between applications of coarse rubber particles

Reference	Rubber aggregate	Replaced conventional aggregate	Specimen type/ size
Aiello and Leuzzi [5]	Tire shreds 20 mm w/ Steel Fibers Included	Coarse aggregate 12.5–20 mm	Cube 150 mm Beams 250 × 250 × 900 mm
Al-Tayeb et al. [6]	Crumb rubber 1 mm	Sand fine aggregate	Cylinder 100∅ × 200 mm Beams 100 × 50 × 400 mm
Atahan and Sevim [7]	Shredded tire chips 11–22 mm	Crushed limestone coarse aggregate 4–16 mm	Cylinder 150∅ × 300 mm Full Scale Barriers 1000 × 450 × 250 mm
Atahan and Yucel [8]	Large rubber 13 mm and crumb rubber #10-20	Crushed Stone 19 mm and Sand	Cylinder 100∅ × 200 mm
Bignozzi and Sandrolini [9]	Scrap and crumb tires 0.05–2 mm	Fine aggregate sand 0–4 mm	Cube 150 mm
Ganjian et al. [10]	Chipped rubber 25 mm	Crushed siliceous coarse aggregate	Cube 150 mm Beams 100 × 100 × 500 mm
Guneyisi et al. [11]	Crumb rubber similarly graded to sand and tire chips 10–40 mm	Natural sand 4 mm and crushed limestone 20 mm replaced equally	Cube 150 mm Cylinder 150∅ × 300 mm (90-day strength)
Hernandez-Olivares et al. [12]	Rubber strip fibers 8.5–21.5 mm	No material removed	Cylinder 150∅ × 300 mm Beams 150 × 150 × 600 mm
Issa and Salem [13]	Crumb rubber (similar to sand used)	Crushed sand	Cylinder 150∅ × 300 mm
Khaloo et al. [14]	Coarse tire chips	Crushed stone gravel 20 mm	Cylinder (50-day strength)
Khatib and Bayomy [15]	Tire chips from mechanical shredding 10–50 mm	Coarse aggregate gravel	Cylinder 150∅ × 300 mm Beams 152 × 152 × 50 mm
Li et al. [16]	Truck & car tire chips and fibers with and w/o steel belt 25–51 mm	Coarse aggregate gravel	Cylinder 150∅ × 300 mm
Liu et al. [17]	Crumb tire rubber 0.178 mm	River sand fine aggregate 5 mm	Cubes 150 mm Cylinders 35∅ × 70 mm (SHPB Impact)
Miller and Tehrani [4]	Crumb rubber	Coarse lightweight expanded shale aggregate	Cylinder 150∅ × 300 mm Beams 152 × 152 × 50 mm

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Reference	Rubber aggregate	Replaced conventional aggregate	Specimen type/ size
Mohammed et al. [18]	Crumb rubber 600 μm	River sand fine aggregate	Cube 100 mm
Son et al. [19]	Crumb rubber particles 1 mm	Total aggregate weight (coarse & fine)	Cylinder 100∅ × 200 mm
Topcu [20]	Rubber particles from mechanical grinding 6 mm	Crushed limestone coarse aggregate 4–16 mm	Cylinder 150∅ × 300 mm
Topcu and Avcular [21]	Large rubber particles 2.2 mm	Limestone coarse aggregate	Cylinder 150∅ × 300 mm
Toutanji [22]	Tire chips 12.7 mm	Crushed stone coarse aggregate 19 mm	Cylinder 100∅ × 200 mm Beams 100 × 100 × 350 mm
Xue and Shinozuka [23]	Crumb Rubber 6 mm	Gravel coarse aggregate 12 mm	Cylinder 100∅ × 200 mm Lumped Mass Columns
Zheng et al. [24]	Crushed rubber with steel belt wires 4–15 mm	Crushed stone coarse aggregate 31.5 mm	Cube 150 mm 60-day Beams 100 × 160 × 1000 mm
Zheng et al. [25]	Ground rubber 2.6 mm and crushed rubber with steel belt wires 4–15 mm	Crushed stone coarse aggregate 31.5 mm	Cylinder 150∅ × 300 mm

Table 1. Summary of selected research on rubberized concrete.

versus fine rubber particles indicate that coarse and fine rubber particles are more effective at substitution ratios of less and more than 25%, respectively [14]. Using larger sizes of TDA, also known as tire chips, provides an opportunity to keep the steel belt wires after shredding in order to lower the costs, even though, they may not provide any specific advantage for the mix [25]. On the same line, application of fiber reinforcement by adding polypropylene fibers has shown to be effective in reducing crack propagation due to shrinkage [12].

Similar to conventional concrete, application of supplementary cementitious materials such as silica fumes has shown to be effective on increasing the compressive strength of TDA concrete containing high water-to-cement ratios [11]. Replacing 7% of cement with silica fume has shown to increase the compressive strength between 3 and 7 MPa [23]. Tire-derived aggregates are also applicable to self-compacting concrete, which utilizes fine filler materials, admixtures such as superplasticizers, and viscosity modifying agents. Combination of shredded tire and crumb rubber has the potential to replace nearly 20–30% of the sand with a similar grain size [9]. Further, it is also possible to replace cement with ground rubber. Substitution of 5% of cement has shown to reduce the compressive strength by 5% [10]. Tire-derived aggregate concrete with enhanced characteristics due to admixtures and supplementary cementitious materials has

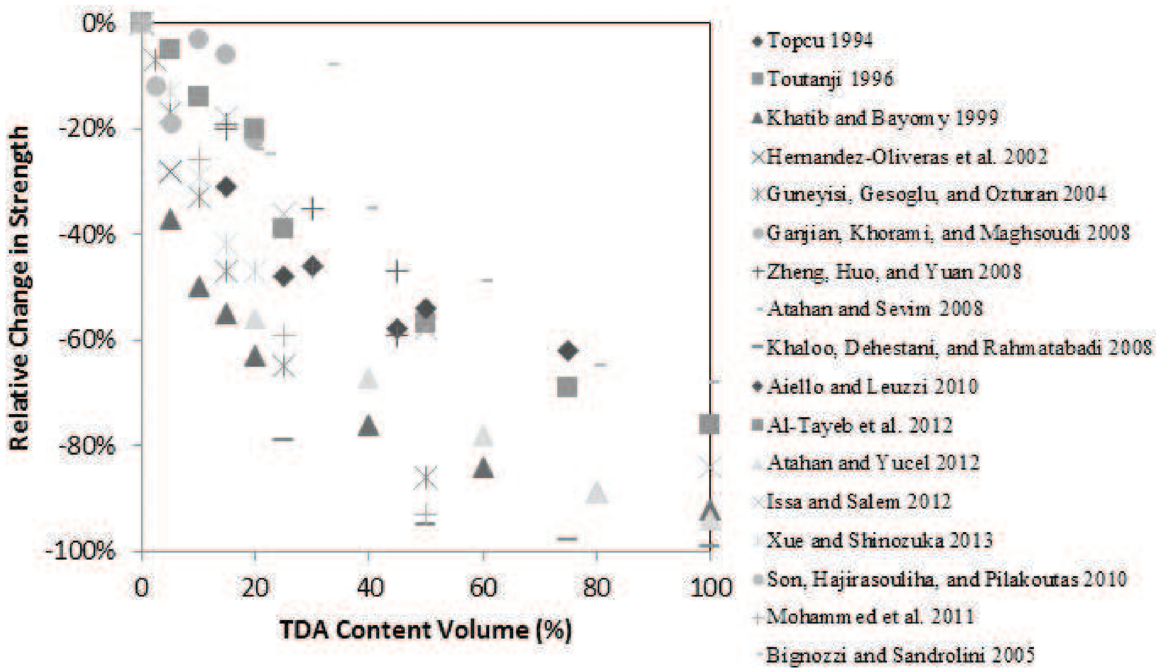

Figure 2. Selected reported relative changes in the compressive strength of rubberized concrete.

applications in hollow concrete blocks. The recommended rubber contents for loadbearing and non-loadbearing systems are 6.5 and 40.7%, respectively [18].

3.2. Modulus of elasticity - static

Research shows that increasing the rubber content in concrete decreases the static modulus of elasticity [6–8, 19]. However, there is not much agreement on the amount of reduction at high rubber contents (**Figure 3**). Generally, Tire-derived aggregates influence the stress-strain relationship and enhance the ductility of the concrete [14]. Some comparative studies on the size of

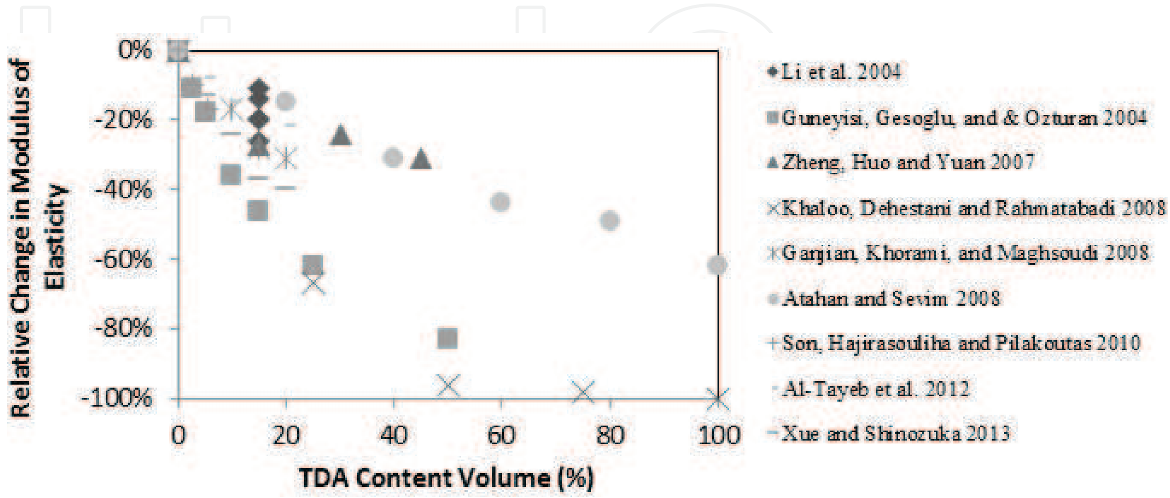

Figure 3. Selected reported relative changes in the static modulus of elasticity of rubberized concrete.

rubber aggregates suggest that using tire chips have more impact on the reduction of elastic modulus than using waste tire fibers do [16]. However, there are also evidences that the reduction of modulus of elasticity is only a function of the rubber content [10].

Further, using tire chips containing steel belts increases the stiffness of TDA concrete [16, 24, 25]. In addition, application of fly ash and silica fume can also enhance the modulus of elasticity [11, 23].

3.3. Split-tensile strength

Figure 4 indicates how increasing the rubber content reduces the splitting tensile strength. However, existing research agrees that capacity of rubber in absorbing energy enhances the toughness of the TDA concrete [6, 16, 20]. Application of fiber reinforcement using polypropylene fibers has shown to improve the toughness further [12]. Comparison of results for compressive and tensile strengths suggests that the rate of reduction for split-tensile strength is less than the same rate for compressive strength [11]. Further, there are reports indicating that specimens with ground tires perform better in tension than specimens containing large tire chips [10].

3.4. Flexural strength

The relationship between flexural strength and TDA content is similar to other mechanical properties (**Figure 5**). However, there are variations in this relationship. Studies generally indicate that reduction of flexural strength parallels an increase in the ductility of specimens [22]. Some research indicates that the rate of reduction for the flexural strength is much steeper than other mechanical properties, particularly at lower rubber contents [15]. Application of smaller rubber particles improves the observed flexural strength [5, 10]. Adding polypropylene fibers has also shown to be effective in crack control, but not necessarily in enhancement of the strength [12].

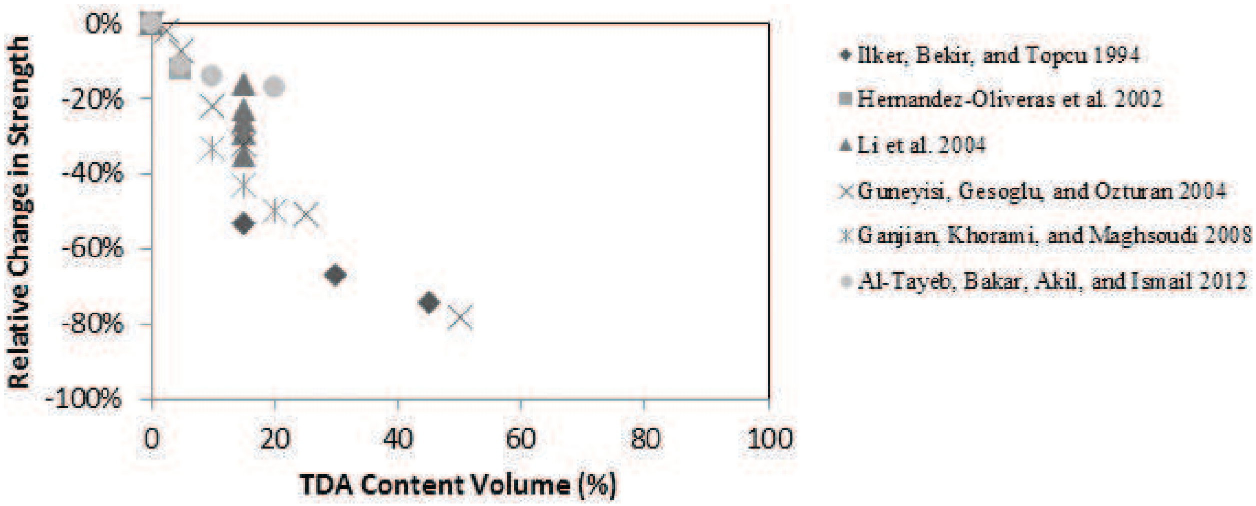

Figure 4. Selected reported relative changes in the split-tensile strength of rubberized concrete.

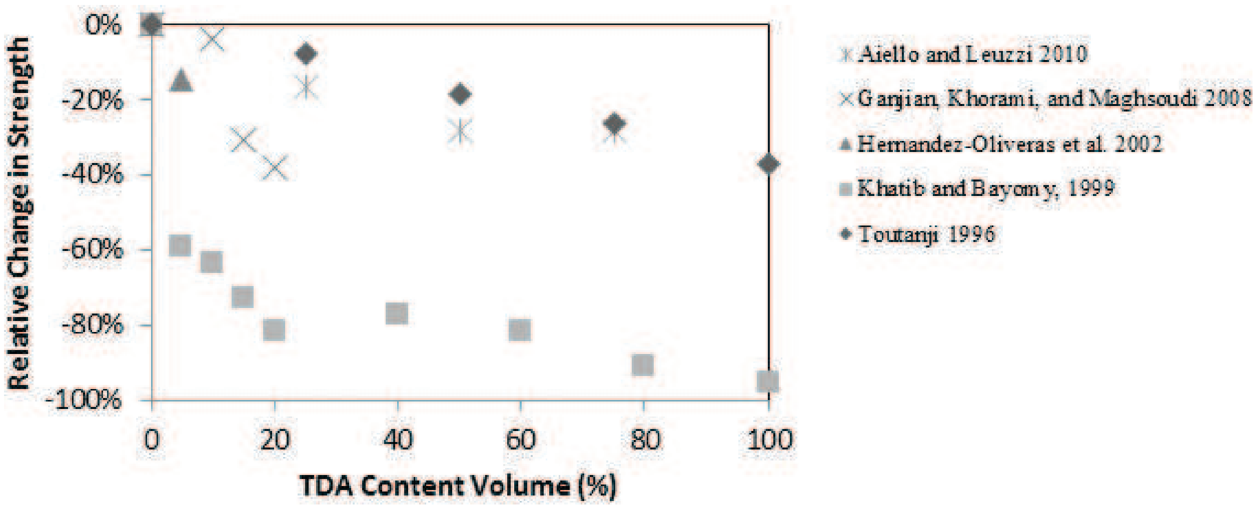

Figure 5. Selected reported relative changes in the flexural strength of rubberized concrete.

Rubberized concrete has also applications in composite floors. Research shows that floors with 10% rubber content have smaller failure load due to flexure in large spans, but nearly the same failure load caused by shear in short spans. The capability of TDA composite floors in withstanding larger deformations has a significant impact on the ductility of the system [26].

3.5. Toughness

Figure 6 contains selected reported data on the relationship between toughness and rubber content in TDA concrete. Toughness is generally a measure based on the area covered by the load-deflection diagrams, thus, it relates to both ductility and strength. As a result, reported data points on toughness are scattered, as rubber contents increases the ductility,

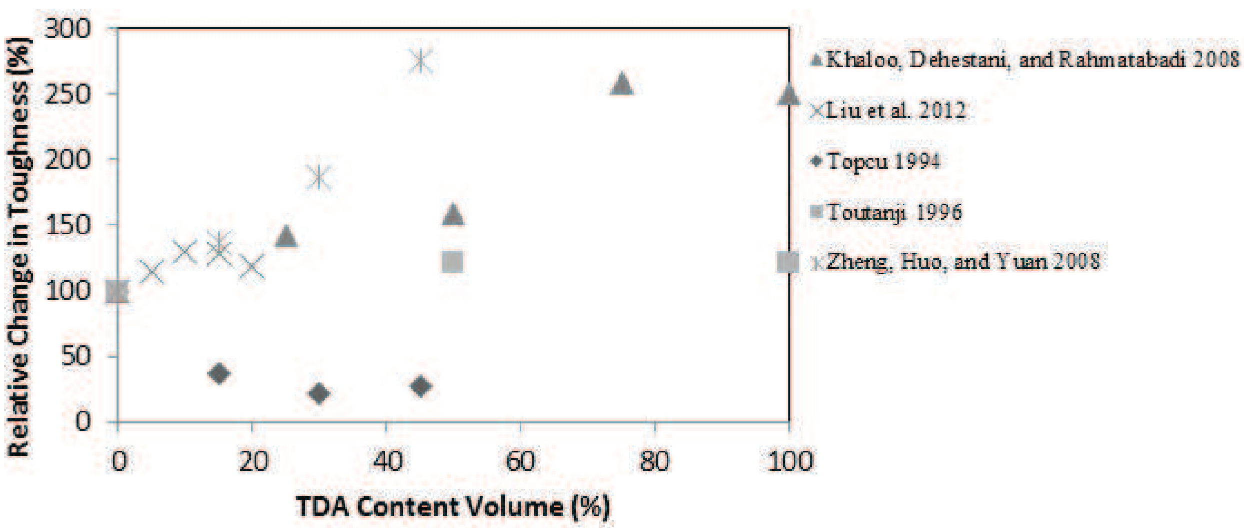

Figure 6. Selected reported relative changes in the toughness of rubberized concrete.

but reduces the strength. This explains how some studies have shown a reduction of toughness because of increasing the rubber content, even though subjected specimens have shown significant increase in ductility [20]. Nevertheless, most reported data show a general increase in toughness with the increase in rubber content [5, 22]. Some research studies have also suggested that a maximum toughness value exist for the optimum rubber content and proper TDA gradation [14]. Measuring toughness from the brittleness index using the stress-strain hysteresis loops also confirms the positive effect of rubber on the toughness [25]. In addition, the toughness of TDA concrete subject to impact load also increases with the increase in strain rate [17]. Furthermore, application of fibers, particularly in tensile specimens, significantly enhances the toughness [16].

3.6. Dynamic properties

Some of the most beneficial properties of rubberized concrete include its behavior under dynamic loading, making the enhancement of these properties desirable in comparison with the brittle and rigid behavior of plain concrete. Research suggests that rubberized concrete may have practical applications as traffic barriers, vibration mitigation, and seismic force mitigation among others. There are various techniques for investigation of these behaviors. **Figures 7** and **8** show two significant parameters, energy absorption and damping, respectively, measured for TDA concrete at different rubber contents. As shown in these figures, there are limited studies as the basis for each of these relationships.

The full-scale New Jersey-shaped safety barriers subject to non-severe impact loads indicate a gradual increase in the energy absorption when rubber content changes from 0 to 100% by volume [7]. These results are qualitatively comparable with similar collision testing studies [21]. However, impact testing on hybrid beams, containing a layer of TDA concrete on top of plain concrete has resulted in significant increase in energy absorption for only 20% rubber content [6]. Similar tests using falling weights confirms the effectiveness of TDA concrete in reducing the severity of the impact at only 20–40% rubber contents, even though, the pest performance is achieved at rubber contents larger than 60–80% [8].

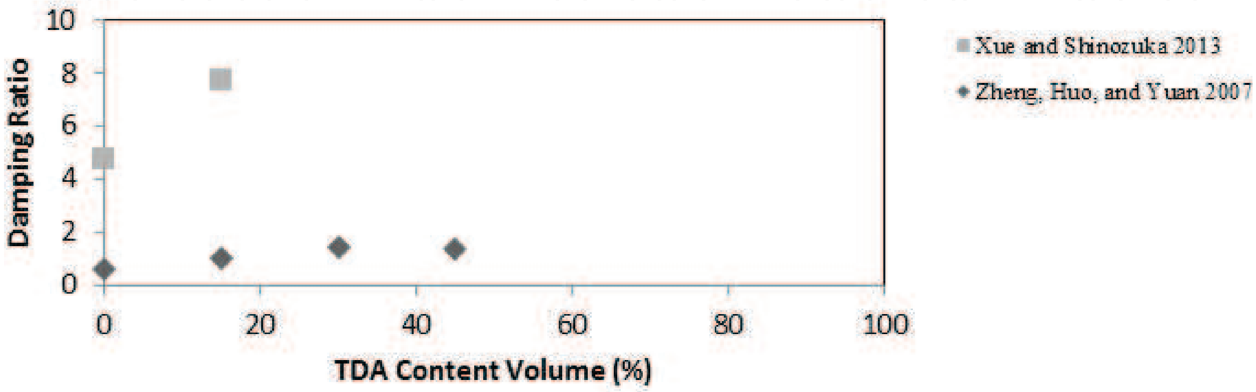

Figure 7. Selected reported relative changes in the damping ratio of rubberized concrete.

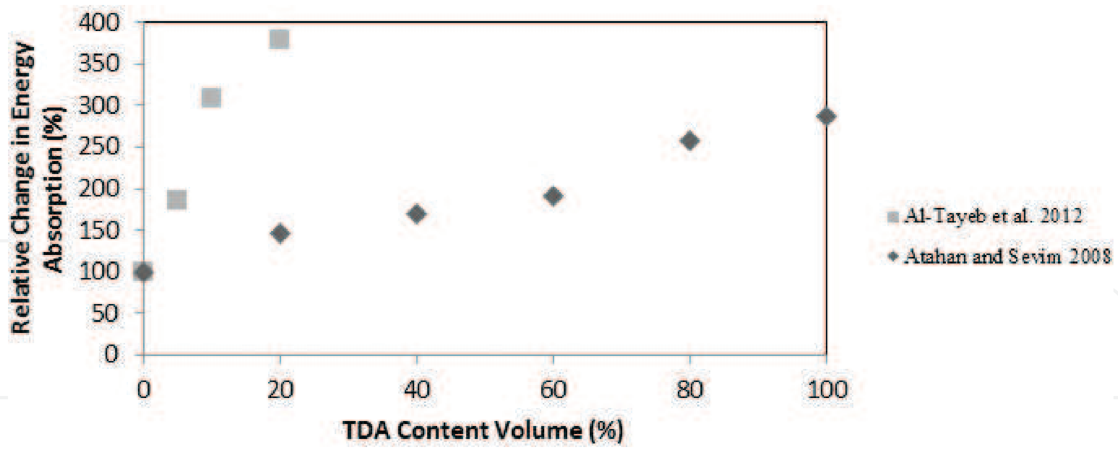

Figure 8. Selected reported relative changes in the absorbed energy of rubberized concrete.

Similarly, the damping ratio of TDA concrete measured by elastic wave method showed a moderate increase because of the increase in the rubber content in concrete [24]. However, the shake-table studies on TDA concrete columns indicated much higher damping ratios [23]. These comparisons indicate how TDA becomes more effective in post-peak performance of concrete specimens. Further, same shake table studies have shown that increasing rubber content in the TDA concrete reduces the natural frequencies and the response acceleration by 28 and 27%, respectively [23].

Non-destructive tests using ultrasonic pulses confirm that rubber reduces the velocity of waves, which is in correlation with lower dynamic modulus of elasticity [14]. Dynamic compression tests confirm the capability of TDA concrete in dissipating energy and show that increasing the load frequency or strain rate increases the dynamic modulus of elasticity [12, 17]. However, the age of the specimens has an adverse impact on the energy dissipation [12].

3.7. Thermal conductivity, electrical conductivity and sound absorption

Nonstructural mechanical properties of TDA concrete have been subject to studies for specific applications. Non-loadbearing wall elements often require proper thermal and electrical insulation as well as sound absorption. Studies indicate that TDA improves the sound absorption of concrete, reduces the thermal conductivity coefficient, and increases the electrical resistivity [13, 18, 27].

4. Design guidelines

4.1. Theoretical modeling and numerical simulation of rubberized concrete

A typical model for the behavior of TDA concrete is a modification of Holmquist-Johnson-Cook (H-J-C) constitutive model. The original H-J-C model contains 21 modifiable parameters to present characteristics of TDA concrete, which was simplified to ten parameters in the modified form [17].

Numerical simulations using finite element analysis are also available to model mechanical properties of TDA concrete. The basis for these simulations is generally an elastoplastic model for the behavior of materials. Successful modeling of beam specimens has been reported using hexahedron elements with standard shape functions [6]. Using a two-phase composite material helps to define the dispersion of TDA in the cementitious matrix. This model utilized three-node triangular elements to simulate split-tensile tests [16].

4.2. Suggested strength reduction factors

Figure 9 shows a comparative view of the relationships between mechanical properties of TDA concrete and the TDA content volume. This figure suggests that developing a simple model for practical design of TDA concrete elements may be possible, as various strengths follow similar trends in respect to TDA content.

Eq. (1) presents a proposed model to find the strength reduction factor [15]:

$$SRF = a + b(1 - R)^m \tag{1}$$

In this model, SRF is the "strength reduction factor"; R is the rubber content as a volumetric ratio by the total volume of aggregates; and a, b, and m are modeling parameters. This equation is equal to unity at a rubber content of 0% and reaches an asymptote at higher rubber content values. The m parameter indicates the degree of curvature of the reduction and is a function of the particle size. In addition, parameters a and b must satisfy the relationship $a + b = 1$. **Table 2** contains suggested modeling parameters from past studies.

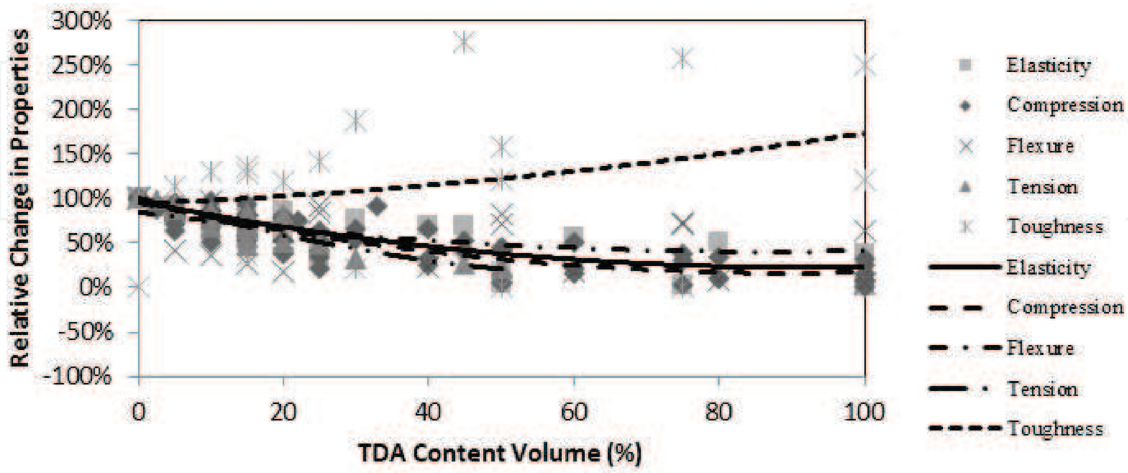

Figure 9. Selected reported relative changes in the dynamic properties of rubberized concrete (marked data) and their general trends (trend-lines).

Reference	a	b	m	Mechanical properties
Khatib and Bayomy [15]	0.1	0.9	3	Compression
	0.1	0.9	2	Split-tension
Khaloo et al. [14]	0.02	0.98	12	Compression
	0.01	0.99	11	Modulus of elasticity

Table 2. Summary of selected modeling parameters.

4.3. Handling procedures

Another important aspect of concrete design is the handling procedures used when placing the concrete while in the workable state. Care needs to be taken to ensure that segregation of materials does not occur and the mix remains as homogenous as possible while being placed and cured. An uneven distribution of rubber particles has been observed in concrete mixes, particularly when specimens are vibrated during placement causing light TDA to surface [10, 23].

5. Conclusions and recommendations

The state of the research on TDA concrete warrants further studies on analytical, experimental, and practical areas. On material properties, the environmental impacts on durability of rubber and long-term properties of TDA concrete is an area of interest for future research. Further, investigating the micromechanical characteristics of the bond between rubber particles and the cement paste is essential to understand the mechanical properties of TDA concrete, including toughness and tensile strength, better. Constitutive modeling and numerical simulation of the behavior of rubberized concrete are other areas of interest that can benefit from recent advancements in computational engineering and mechanics.

Application of TDA concrete requires development of design guidelines and specifications. Defining strength reduction factors is an area that requires further development. Current research studies are scattered in respect to parametric modeling and can benefit from additional experimental results. Further, these parametric analyses are essential for optimization of TDA concrete mix design to obtain proper rubber content for specific objectives. In addition, practical issues in mixing and placing concrete require development of proper specifications for handling TDA materials in concrete.

Mechanical properties of TDA concrete have shown to be desirable for many applications, such as traffic and sound barriers. Toughness and ductility of TDA concrete can be also effective in concrete elements subject to dynamic loads caused by earthquake and wind. Large-scale experimental studies are required for investigating these applications.

There has been limited studies on alternative TDA concrete products with application of fiber reinforcement, lightweight aggregate, fiber-reinforced polymers, admixtures, and supplementary cementitious materials. Enhancing the properties of TDA concrete using these methods require further research.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this work.

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