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Initial Assessment of Liquefied Scrap Tire Concrete

Abdulkareem Kuaryouti[1] and Christopher D. Eamon[2]

Abstract

A new approach to incorporate scrap tire material into concrete was investigated, where two reclaimed waste tire components, carbon black and fuel oil, were used to replace a portion of water. The effect of "liquid tire" content to water ratios from 5-40% on an otherwise typical concrete mix were assessed, where compressive and flexural strength, flexural toughness, modulus of elasticity, and several fresh concrete properties were determined. Results were compared to typically expected results of traditional shredded tire mixes with equivalent tire content. It was found that the liquid tire mixes experienced significantly less losses of compressive strength and workability than associated with shredded rubber mixes; an increase in flexural strength over a traditional concrete mix; and a significant decrease in stiffness over traditional as well as shredded tire mixes.

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Introduction

Of the approximately one billion scrap tires produced throughout the world, fewer than half are recycled, leaving the majority to be disposed of in landfills (Mouri 2016; Thomas and Gupta 2016). To encourage the use of recycled tire material in civil engineering applications, various agencies have attempted to provide incentives. For example, the State of Michigan has provided a 50% price reimbursement for purchasing scrap tires to advance their recycling and reuse (MDEG 2011), while the Intermodal Surface Transportation Efficiency Act of 1991 encourages the use of waste tire rubber in federally funded projects. As a result, highway construction provides a significant market for waste tire recycling, and various states, such as California, Florida, and Arizona, among others, routinely use a significant amount of recovered tire material in road construction (NSF 2014).

A typical vehicle tire is comprised of about 28% carbon black, 27% synthetic rubber, 16% fabrics, 15% natural rubber, and 14% steel (Brentin and Sarnacke 2011). In the shredding and grinding process, the fabric and steel components are removed while the remaining rubber materials are reduced in size to pass a No. 4 (4.75 mm) sieve to produce crumb rubber, or a No. 100 (0.152 mm) sieve to produce rubber powder. This material has been incorporated into hot-mix asphalt and in Portland cement concrete pavements for more than several decades. Although tire shred has been more commonly used in asphalt because of the closer relationship between the organic bitumen binder and hydrocarbons in tires, its use in Portland cement has also been well studied (Thomas and Gupta 2016).

One of the earlier research efforts on this approach was what was reported by Eldin and Senouci (1993), who found that replacing a portion of concrete aggregate with scrap tire chips provided significant improvement in toughness and ability to absorb fracture energy. Since then, a large body of knowledge concerning the performance of rubberized concrete has been generated. To synthesize these results, Roychand et al. (2020) recently reviewed over one hundred studies spanning the last three decades. Their summary concluded that increasing rubber content generally decreases workability, compressive, flexural, and split tensile strengths, as well as stiffness, but increases fatigue life and fracture toughness. It was also noted that the typical losses in mechanical properties can be reduced to some extent with treatments such as NaOH and other solvents, as well as simply soaking or washing rubber aggregates with water. Similar results were found in an earlier literature review by Thomas and Gupta (2016). However, Li et al. (2016a) surveyed various studies as well and found that high strength rubberized concrete is possible in some cases with the use of treatments, additives, and careful mix design.

Various other avenues of research in this area have been recently conducted, including the use of crumb rubber in engineered cementitious composites (ECC), where increases in tension strength and resistance to cracking have been found, but with significant loss of stiffness (Zhang et al. 2015; Alaloul et al. 2020). Other recent topics include the bearing strength of crumb rubber concrete, where up to a 30% strength loss was found (Xu et al. 2020); the potential use of rubberized concrete to resist dynamic loads due to its increased damping and ductility (Habib et al. 2020); and adding rubber to recycled aggregate concrete (Tamanna et al. 2020), among many others.

The purpose of this study was to explore the effect of incorporating tire waste into an otherwise common concrete mix design in a way that might minimize the strength loss associated with typical rubberized mixes. The method examined was the addition of "liquid" tire waste, which was taken as a mixture of carbon black and waste (unprocessed) tire fuel oil. These additives are products of shredded tires when processed in a liquefaction reactor (Moulin et al. 2017; Piskorz et al. 1999), though various other processes can be used to extract these components as well (Zhang et al. 2018; Gomez-Hernandez 2019). Different types of carbon black are available, which can be classified as a function of particle size, tensile strength, and abrasion resistance.

Materials

The concrete mix used in this study was composed of Type I Portland cement, 9.5 mm (3/8 in) P-stone, 2-NS sand, and potable water, with one part cement, two parts sand, and two parts aggregate by weight. For the control (i.e. no liquid tire content) specimens, a water/cement ratio of 0.42 was used. Specimens with different amounts of liquid tire content were also prepared, with liquid tire/water (LT/W) ratios of 5%, 10%, 20%, 30% and 40% by weight, where the LT/W ratio refers to the percentage of water replaced with liquid tire. Initial test results indicated LT/W ratios less than about 5% produced only minor changes in mix properties, and thus lower ratios were not further explored. ASTM N110 (ASTM 2019) carbon black was used for the mixes, which has a nominal particle size from 20-25 mm (Figure 1). The carbon black was then ground and mixed with tire fuel oil in a 1:1 ratio by weight to form a liquid tire solution. The resulting mixture had a specific gravity of 0.83.

Test Specimens

Test specimens consisted of a set of 64 mm deep x 32 mm wide x 305 mm long (2.5 x 1.25 x 12 in) concrete beams and 102 mm x 203 mm (4 x 8 in) cylinders. The casting and curing of the specimens was in compliance with ASTM C31 (ASTM 2011b). Liquid tire concrete (LTC) specimens were prepared as follows:

1. Cement, sand, and aggregates were thoroughly mixed using a small concrete mixer for 3-5 minutes.
2. Water and liquid tire solution were mixed for approximately 2 minutes.
3. The water/liquid tire solution was added to the dry mixture and mixed for approximately 2 minutes.
4. The mix was poured into the specimen molds in two equal layers, and each layer was compacted and vibrated using a vibratory table.
5. The mold was covered with a plastic sheet for an initial 24 hour curing period.
6. Specimens were removed from the molds and placed in a water bath for further curing until testing (at 7 and 28 days).

Three replicates of each concrete specimen were subjected to mechanical tests. It should be noted that the authors found that, although suppliers are willing to sell carbon black in large quantities (tons), the much smaller quantity needed for experimental work was difficult to obtain. For this study, sufficient material could be acquired for about 60 specimens. Fortunately, results from multiple specimens were relatively consistent, as shown below.

Fresh Concrete Properties

Workability of the mixtures was estimated using a slump test complying with ASTM C143 (2010), while air content was determined using standard equipment in compliance with ASTM C231 (2011). Slump, air content, density, as well as temperature for each batch were found to be close in value, regardless of LT/W ratio. Ambient temperature at the time of testing was approximately 21 ºC. Results are given in Table 1. As shown in the table, slump increased with increasing LT/W ratio until 20-30%, then abruptly decreased from its peak value at 40% LT/W. The overall slump ranges from 90 – 130 mm (3.5 – 5 in), was not too large. Air content was inconsistent, and appears to be a function of the natural variation of batch properties and the test procedure rather than due to liquid tire content. Density slightly decreases as LT/W increases, as expected given the lower density of tire content compared to water.

Mechanical Testing Procedures

Specimens were tested for compressive strength, flexural strength, Young's modulus, and assessed for flexural toughness. The cylinder specimens were tested for compressive strength after 28 days of wet curing according to ASTM C39 (2011) using a calibrated MTS 810 test machine, operated by a closed loop, servo-hydraulic system. Force was monitored with a load cell at the test machine crosshead while displacement was recorded with an LVDT integral to the load cylinder. Load and displacement data were recorded electronically with a PC-driven data acquisition system, then converted to corresponding (engineering) stress and strain. As specified in ASTM C39, the load rate was applied to correspond to a stress rate on the specimen of approximately 0.25 MPa/s (35 psi/s). To estimate flexural strength, the beam specimens were placed on two simple supports and loaded at mid-span with the same system described above to produce a three point bending test similar to the descriptions in ASTM D790 (ASTM 2014) and C293 (2016), where a typical test is shown in Figure 3 for a 20% LT/W specimen.

Specimen Test Results

Mean compressive stress-strain curves are given in Figure 2, while numerical results are given in Table 2. As shown in Figure 2, a loss of initial stiffness as well as ultimate capacity is evident as the LT/W ratio was increased. In accordance with this loss of stiffness, a higher strain value is associated with peak capacity, which was approximately 0.0025 for the mean control specimen result, but approximately 0.004 for most of the mean LTC specimen results. Also of interest is that the LTC specimens retained more of their post-peak strength at higher strains, as seen by the lower negative LTC post-peak slopes as compared to that of the more sharply-declining control specimen. Interestingly, the post-peak slope remained constant, regardless of the LT/W ratio. Strength and stiffness results are quantified in Table 2, where the mean peak strength (f'_c), Young's modulus (E), ratio of specimen compressive strength to that of the control specimen (f'_c/f'_{c0}), ratio of specimen E to that of the control specimen (E/E_0), and coefficient of variation (COV) of the specimen results are given. As shown in the Table, there was an initial steep drop in f'_c of 9% from the control mix when 5% LT/W was added. Thereafter, there was an approximately linear reduction of compressive strength as a function of LT/W ratio, where 10% LT/W resulted in 89% of the compressive strength of the control mix while 40% LT/W resulted in 84% strength. A similar pattern was seen with Young's modulus, where a large loss of stiffness of approximately 57% occurs at the initial LT/W ratio of 5%, then a more gradual, approximately linear decrease thereafter, with an E/E_0 ratio of 0.45 at 10% LT/W to 0.34 at 30-40% LT/W. Also notice in the Table that relatively low COVs for specimen strength were realized, below 5% (except for the

40% LT/W specimens), though higher COVs for modulus were obtained. For comparison, the COV of self-weight of a typical cast-in-place structural concrete member is approximately 0.05 (Eamon and Nowak 2005). Note that Young's modulus was computed based on the secant modulus, taken at a compressive strength of $0.5f'_c$ (ACI 318-2014).

When tested in flexure, regardless of LT/W ratio, the failure of the beams were similar, with predominant cracks near midspan. However, beams with liquid tire content displayed a larger number of significant flexural cracks along the beam length when compared to the control specimens. No meaningful difference in crack pattern or other crack characteristics were observed among specimens with different LT/W content. Mean flexural stress vs deflection curves are given in Figure 4. The 10, 30, and 40% LT/W specimens maintained flexural stiffness at higher strains as compared to the 5 and 20% LT/W cases as well as the control specimens. In particular, the 10, 30 and 40% cases demonstrated a significant flexural-crack induced change in stiffness at a flexural stress from about 3.5-5.2 MPa (500-750 psi), whereas the 5%, 20%, and control cases lost stiffness near 1.4 MPa (200 psi). Moreover, these latter cases demonstrated a subsequent hardening behavior around 2 MPa (300 psi), whereas the 10, 30 and 40% cases showed little changes in flexural stiffness prior to peak capacity.

It can be observed that the three cases with lowest LT/W ratio (5, 10, and 20%) reached peak strength at a larger deflection level than the control, as well as held a relatively high level of post-peak load at levels of strain greater than the control specimen. However, the highest LT/W cases of 30 and 40% reached peak capacity at a lower deflection value than the control specimen, as well as lost post-peak capacity at a faster rate than the control.

Note that this behavior was not simply due to natural variations in specimen behavior, as differences in performance among specimens of the same type was relatively low, and thus the mean curves given in the Figure are representative of actual differences in response. For example, individual test specimen curves are given for the control specimens and for 30% LT/W in Figures 5 and 6, respectively, where it can be seen that the same trend in slopes and overall behavior exist for the duplicate specimens. A similar degree of similarity exists for the remaining LTC specimens as well. Table 3 provides the mean 7 and 28-day modulus of rupture (MOR) for the specimens, where the ratio of specimen strength to the control (MOR/MOR_0) and COV is given. As shown, all LTC specimens had greater flexural strength than the control, while specimens from 5-30% LT/W experienced nothing less than an approximately 20% flexural strength increase. The MOR/MOR_0 ratio was greatest for the 20% LT/W case, where a 36% increase in strength was realized. Larger LT/W ratios lost effectiveness, where the largest LT/W ratio of 40% resulted in only a minor increase in strength of 4%.

One potential advantage of rubberized concrete is an increased resistance to fracture, the toughness of the liquid tire mixes were also evaluated. Although various definitions of toughness exist, it may be broadly defined as the amount of energy absorbed prior to failure. As there are no existing standards to measure toughness for the relatively flexible LTC material, absolute flexural toughness (*T*) is defined in this study as the total measurable work done; i.e. the integration of the complete load-displacement curve of the test specimen. These results are presented in Table 4, were the load-displacement data used to generate the mean stress-displacement curves in Figure 4 were evaluated. As shown in the Table, the ratio of toughness of a LTC specimen to that of the control (T/T_0) peaked with a modest value of 1.2 at 20% LT/W. Interestingly, the 5% LT/C specimens showed a slight drop of approximately 2% of T on average from the non-LTC mix.

Comparison to Shredded Tire Results

To evaluate the effectiveness of LTC relative to the traditional shredded rubber approach for introducing recycled tire content into concrete, the effect of adding rubber to concrete on the compressive strength, MOR, and Young's modulus are shown in Figures 7-9.

A large variety of experimental results exist for rubberized concrete. To provide typically expected comparison properties for this material, the expressions developed by Aslani (2016) are used, where best-fit empirical curves were fit to approximately 90 (for flexural strength) to 300 (compressive strength) 28-day results reported in the literature, and are in the form of: $R = ae^{bV}$. The expressions provided the reduction factor R to the property in question, relative to traditional concrete, as a function of the percentage of aggregate volume V replaced by tire material, while factors a and b vary as a function of the property considered (i.e. compressive strength, flexural strength, modulus) and the type of rubber aggregate used (chipped rubber, crumb rubber, or both), and are given by Aslani (2016). For consistent comparison to the LTC specimens considered here, the hypothetical shredded rubber cases that were evaluated were taken to have a rubber aggregate volume that produces the same rubber/water ratio (by weight) as the LT/W ratios tested in this study (which varied from 1.6 – 25.7% of rubber to aggregate volume V), while using the same mix proportions of the LTC specimens.

As shown in Figure 7, the compressive strength differences between the LTC and shredded rubber mixes increase with increasing rubber content, where typical shredded rubber mixes have significantly higher strength reductions. In particular, the LTC mixes result in strength reduction factors from 0.91-0.84, whereas the corresponding shredded mixes range from 0.84-0.48. For the largest tire/water ratio considered of 40% (or, a corresponding rubber-to-aggregate percentage of approximately 26% of either fine or coarse aggregates), the shredded mixes result in close to twice the strength reduction as the comparative LTC mix. In Figure 8, reduction factors for flexural strength from typical shredded mixes range from 0.97-0.68 across the tire/water ratios considered, whereas the LTC mixes provide a significantly different trend, resulting in strength increases by factors of 1.04-1.36, peaking at a LT/C ratio of 20%. In contrast to compressive and flexural strength, however, Figure 9 reveals a significant performance drop in LTC relative to shredded rubber mixes, where the compressive stiffness of the LTC mix is significantly reduced from 0.45-0.32 to that of a traditional non-rubberized mix. In contrast, typical corresponding reduction factors for shredded mixes range from approximately 0.9-0.56. This is somewhat interesting, considering the strength increases of LTC compared to shredded.

Although various other concrete properties may be of interest depending on the application, an additional characteristic of general concern is workability. Using slump as a metric, for the range of tire content considered in this study (LT/W weight ratios from 5-40%, or mixes with approximately 1.6-13% of total aggregate volume), Khatib & Bayomy (1999) reported reductions in slump of approximately 12-62% when sand was replaced with crumb rubber; no significant changes in slump when coarse aggregate was replaced with chipped rubber, and reductions from approximately 2-15% when both crumb and chipped rubber were used. Danko et al. (2006)

reported larger proportional reductions in slump, from 69-94%, when 5-10% of chipped rubber was used. For the case of Danko et al., however, it should be noted that the slump of the control mix was reported as 50 mm (2 in), so relatively smaller absolute variations in slump result in large percent changes. In contrast, the use of LTC at the same replacement content resulted in increases in slump from approximately 12-25% from 5-30% LT/W, and a maximum reduction of 12% at 40% LT/W (13% total aggregate volume).

Discussion

The loss of compressive strength and Young's modulus in LTC demonstrate trends similar to those in traditional rubberized concrete, where a general reduction in f'_c and E occur as rubber content is increased. A difference shown with LTC is the degree of change, where f'_c is reduced less whereas E is reduced more, as compared to the traditional rubberized approach. However, a large variation in results is given in the literature for rubberized mixes, and the LTC results fall within the range of existing observations synthesized from literature surveys (Li et al. 2016a; Roychand et al. 2020). The general reasons for this performance loss reported in the literature are weakened bonds between the cement and rubber particles; the low stiffness of the particles, which encourages crack development at the particle-cement interface; and general reductions in concrete density. The authors suggest that similar mechanisms exist for LTC as well. The authors would further suggest that the reason LTC experienced a significantly less reduction in compressive strength (for the same rubber content) as compared to the traditional approach is primarily due to tire particle size. This follows the general trend found in the literature where as particle size is reduced (from shredded to crumb), less reduction in f'_c is experienced (Li et al. 2016a; Roychand et al. 2020). It is thus not unexpected that the very fine particles used in LTC similarly produced less of a strength loss than found from crumb or ground rubber. Although the reason for this size effect does not appear to be well described in the literature, the authors suggest that smaller, more evenly distributed imperfections, or points of weakness, more effectively limit the formation of large cracks that readily propagate through fewer but more significantly sized flaws.

Somewhat unusual is the increase in flexural strength found in LTC beyond the control mix. However, this is not unheard of for traditional rubberized concrete, where as summarized by Li et al. (2016a) and Roychand et al. (2020), a number of studies have shown that adding rubber particles can increase the flexural strength beyond that of the non-rubberized mix. This increase is generally believed to be due to the ability of the rubber particles to limit crack growth and correspondingly delay failure by allowing flexural strains to increase without material fracture. This suggestion is supported in part by the observed increase in flexural deflection at failure of the rubberized mixes. The increase in LTC flexural strength is further aligned with the explanation of smaller particle size, where the majority of studies have shown losses of flexural strength as particle size increased (Roychand 2020).

Currently, is not clear why flexural strength and toughness peak at 20% LT/W content. The authors suggest that this trend may in fact occur in some traditional rubberized mixes as well but is typically unobserved. Of the studies that have shown an increase in flexural strength in traditional rubberized mixes over the control mix (e.g. Segre and Joekes 2000; Chou et al. 2010; Najim and Hall 2013; Li et al. 2016b; Munoz-Sanchez et al. 2017) only Li et al. considered different amounts of rubber content, a procedure that could potentially allow detection of this phenomenon. In that study, rubber content was varied from 5 – 30%, and indeed it was found that flexural strength peaked as well (at about 10% rubber content by aggregate volume). It was proposed that the cause of this peak was due to several factors, including lowering the degree of bond-enhancing chemical treatment on the rubberized particles; decreasing mix density; and potential particle clumping as rubber content increased, all negative factors which eventually outweighed the positive crack arresting effect that the particles provided with increased rubber content. Similarly, the authors of this study suggest that two opposing phenomenon are occurring as LTC content is increased: increases in strength due to the mitigation of large catastrophic flexural crack growth, and decreases in strength due to the typical reasons given for general compressive strength loss (loss of aggregate bond, low particle stiffness, loss of concrete density). An optimal amount of rubber content exists that balances these conflicting trends and maximize flexural strength.

Conclusions

Several key mechanical properties of a typical concrete mix with the addition of two reclaimed scrap tire components, carbon black and fuel oil, were examined. Considering LT/W ratios from 5- 40%, it was found that 28-day compressive strength decreased from approximately 10-15%; flexural strength increased from 5-35%, flexural toughness increased up to 0-20%, Young's modulus decreased from 55-65%, and air content and unit weight exhibited only minor changes.

In comparison, typical mixes with equivalent volume of shredded tire or crumb rubber generally experience significantly greater reductions in compressive and flexural strengths, as well as workability. However, the LTC mixes suffered a significant compressive stiffness loss compared to the traditional scrap tire approach. Such a trade-off may be acceptable for a variety of concrete elements including non-loadbearing walls and facades, as well as potential uses in some pavement applications, where durability concerns rather than stiffness may be critical. Of particular interest is the increase in flexural strength of the LTC mixes over traditional concrete. As such, the mechanical advantages of LTC may be worthy of additional investigation.

As the current study represents a preliminary assessment of the LTC approach, a variety of additional avenues of investigation may be useful, including the use of different grades of carbon black, fuel oil, and mix proportions; freeze-thaw durability; and alternative measures of toughness considering impact resistance and crack opening energy. Although no significant differences could be seen between the failed LTC and control specimen cross-sections by visual inspection, of particular interest is developing an understanding of the morphology and microstructure of the LTC specimens via use of scanning electron microscopy or a similar procedure. An in-depth analysis of this nature may reveal meaningful evidence to provide further insight to the behavior of this material.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

References

ACI. 2014. *318-14: Building Code Requirements for Structural Concrete and Commentary*. Farmington Hills, MI: American Concrete Institute.

Alaloul, W., Musarat, M., Tayeh, B., Sivalingam, S., Faridzuan, M., Rosli, B., Sani Haruna, S., and Khan, M. 2020. "Mechanical and Deformation Properties of Rubberized Engineered Cementitious Composite (ECC)." Case Studies in Construction Materials 13, e00385.

Aslani, F. 2016. "Mechanical Properties of Waste Tire Rubber Concrete." Journal of Materials in Civil Engineering 28(3), 04015152.

ASTM 2010. *C143: Standard Test Method for Slump of Hydraulic-Cement Concrete.* West Conshohocken, PA: American Society for Testing and Materials.

ASTM 2011. *C231: Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.* West Conshohocken, PA: American Society for Testing and Materials.

ASTM 2011b. *C31: Standard Practice for Making and Curing Concrete Test Specimens in the Field.* West Conshohocken, PA: American Society for Testing and Materials.

ASTM 2014. D790: *Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*. West Conshohocken, PA: American Society for Testing and Materials.

ASTM 2016. C293: *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading).* West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 2011. *C39: Standard Test Method for Compressive Strength of Cylinder Concrete Specimens.* West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 2019. *D1765: Standard Classification System for Carbon Blacks Used in Rubber Products.* West Conshohocken, PA: American Society for Testing and Materials.

Brentin, R. and Sarnacke, P. 2011. "Rubber Compounds: A Market Opportunity Study." Omni Tech International.

Chou, L, Yang, C., Lee, M., and Shu, C. 2010. "Effects of Partial Oxidation of Crumb Rubber on Properties of Rubberized Mortar." Compos. B Eng. 41(8), 613–616.

Danko, M., Cano, E., and Pena, J. 2006. "Use of Recycled Tires as Partial replacement of Coarse Aggregate in the Production of Concrete", Purdue University Calumet.

Eamon, C., and Nowak, A. 2005. "Effect of Edge-Stiffening and Diaphragms on the Reliability of Bridge Girders," Journal of Bridge Engineering, 10(2), 206-214.

Eldin, N., and Senouci, A. 1993. "Rubber-tire particles as concrete aggregates." ASCE Journal of Materials in Civil Engineering 5(4), 478–496.

Gomez-Hernandez, R., Panecatl-Bernal, Y., and Mendez-Rojas, M. "High yield and simple one-step production of carbon black nanoparticles from waste tires." Heliyon 5(7), e02139.

Habib, A., Yildirim, U., and Eren, O. 2020. "Mechanical and Dynamic Properties of High Strength Concrete with Well Graded Coarse and Fine Tire Rubber." Construction and Building Materials 246, 118502.

Khatib, Z. and Bayomy, F. 1999. "Rubberized Portland Cement Concrete." Journal of Materials in Civil Engineering 11(3), 206-213.

Li, D., Mills, J., Benn, T., Ma, X., Gravina, R., and Zhuge, Y. 2016a. "Review of the Performance of High-Strength Rubberized Concrete and Its Potential Structural Applications." Advances in Civil Engineering Materials 5(1), 149–166.

Li, G., Wang, Z., Leung, C., Tang, S., Pan, J., Huang, W. and Chen, E. 2016b. “Properties of Rubberized Concrete Modified by using Silane Coupling Agent and Carboxylated SBR.” Journal of Cleaner Production 112, 797–807.

MDEQ. 2011. *Scrap Tire Regulatory Program – Scrap Tire Market Development Grant*. Lansing, MI: Michigan Department of Environmental Equality.

Moulin, L., Da Silva, S., Bounaceur, A., Herblot, M., and Soudais, Y. 2017. “Assessment of Recovered Carbon Black Obtained by Waste Tires Steam Water Thermolysis: An Industrial Application.” Waste and Biomass Valorization 8(8), 2757–2770.

Mouri, H. 2016. “Bridgestone’s View on Circular Economy, in Towards a Circular Economy: Corporate Management and Policy Pathways.” ERIA Research Project Report 2014-44, Jakarta: ERIA, V. Anbumozhi, Ed., 31–42.

Munoz-Sanchez, B., Arevalo-Caballero, M., and Pacheco-Menor, M. 2017. “Influence of Acetic Acid and Calcium Hydroxide Treatments of Rubber Waste on the Properties of Rubberized Mortars.” Mater. Struct. 50(1), 75.

Najim, K., and Hall, M. 2013. “Crumb Rubber Aggregate Coatings/Pre-treatments and Their Effects on Interfacial Bonding, Air Entrapment and Fracture Toughness in Self-Compacting Rubberised Concrete (SCRC).” Mater. Struct. 46(12), 2029–2043.

National Science Foundation. 2014. “Old tired become material for new and improved roads.” Research News.

Piskorz, J., Majerski, P., Radlein, D., Wik, T., and Scott, D. 1999. “Recovery of Carbon Black from Scrap Rubber.” Energy Fuels 13(3), 544-551.

Roychand, R., Gravina, R., Zhuge, Y., Ma, X., Youssf, O., and Mills, J. 2020. "A Comprehensive Review on the Mechanical Properties of Waste Tire Rubber Concrete." Construction and Building Materials 237, 117651.

Serge N and Joekes I. 2000. "Use of Tire Rubber Particles as Addition to Cement Paste." Cement and Concrete Research 30(9), 1421-1425.

Tamanna, K., Tiznobaik, M., Banthia, N., and Shahria Alam, M. 2020. "Mechanical Properties of Rubberized Concrete Containing Recycled Concrete Aggregate" ACI Materials Journal 117(3).

Thomas, B. and Gupta, R. 2016. "A Comprehensive Review on the Applications of Waste Tire Rubber in Cement Concrete." Renewable and Sustainable Energy Reviews 54, 1323-1333.

Way, G., Kaloush, K, and Biligiri, K. 2011. "Asphalt-Rubber Standard Practice Guide," Final Report, Rubber Pavements Association (RPA), Tempe, AZ.

Xu, X., Zhang, Z., Hu, Y., and Wang, X. 2020. "Bearing Strength of Crumb Rubber Concrete under Partial Area Loading." Materials 13, 2446.

Zhang, X., Li, H., Cao, Q., Jin, L., and Wang, F. 2018. "Upgrading Pyrolytic Residue From Waste Tires to Commercial Carbon Black." Waste Management and Research 36(5), 436-444.

Zhang, Z., Ma, H., and Qian, S. 2015. "Investigation on Properties of ECC Incorporating Crumb Rubber of Different Sizes." Journal of Advanced Concrete Technology. 13(5), 241–251.

Table 1. Batch Properties

LT/W (%)	Slump (cm)*	Air (%)	Specific Gravity
0	10	1.33	2.28
5	11.5	1.5	2.27
10	10	2.5	2.25
20	13	1.8	2.26
30	13	2.3	2.24
40	9	1.9	2.24

*reported to the nearest ½ cm.

Table 2. Mean Compressive Strength and Young's Modulus

	Compressive strength			Young's Modulus		
LT/W (%)	f'_c (MPa)	f'_c/f'_{c0}	COV	E (GPa)	E/E_0	COV
0	24.9	1.00	0.046	18.0	1.00	0.077
5	22.8	0.91	0.047	7.66	0.43	0.161
10	22.2	0.89	0.016	8.03	0.45	0.129
20	21.9	0.88	0.010	5.77	0.32	0.253
30	21.1	0.85	0.034	6.16	0.34	0.132
40	20.9	0.84	0.088	6.16	0.34	0.144

Table 3. Mean Flexural Strength

	7-day Strength			28-day Strength		
LT/W (%)	MOR (MPa)	MOR/MOR_0	COV	MOR (MPa)	MOR/MOR_0	COV
0	3.90	1.00	0.075	4.33	1.00	0.050
5	4.84	1.24	0.042	5.15	1.19	0.027
10	5.16	1.32	0.024	5.51	1.27	0.063
20	5.60	1.44	0.011	5.91	1.36	0.025
30	4.98	1.28	0.027	5.29	1.22	0.024
40	4.15	1.07	0.146	4.49	1.04	0.106

Table 4. Flexural Toughness.

LT/W (%)	T (N-m)	T/T_0	COV
0	7.65	1.00	0.067
5	7.54	0.98	0.058
10	8.74	1.14	0.092
20	9.18	1.20	0.065
30	8.42	1.10	0.080
40	8.12	1.06	0.099

Figure Captions

Figure 1. Carbon Black Additive.

Figure 2. Mean 28-Day Compressive Stress-Strain Relationship.

Figure 3. Typical LTC Flexural Test.

Figure 4. Mean 28-Day Flexural Stress-Deflection Curves.

Figure 5. Individual 28-Day Flexural Stress-Deflection Curves, Control Specimens.

Figure 6. Individual 28-Day Flexural Stress-Deflection Curves (LT/W = 30%).

Figure 7. Comparison of LTC to Solid Rubber Specimens, Typical f’c Reduction.

Figure 8. Comparison of LTC to Solid Rubber Specimens, Typical MOR Reduction.

Figure 9. Comparison of LTC to Shredded Rubber Specimens, Typical E Reduction.

Figure 1. Carbon Black Additive.

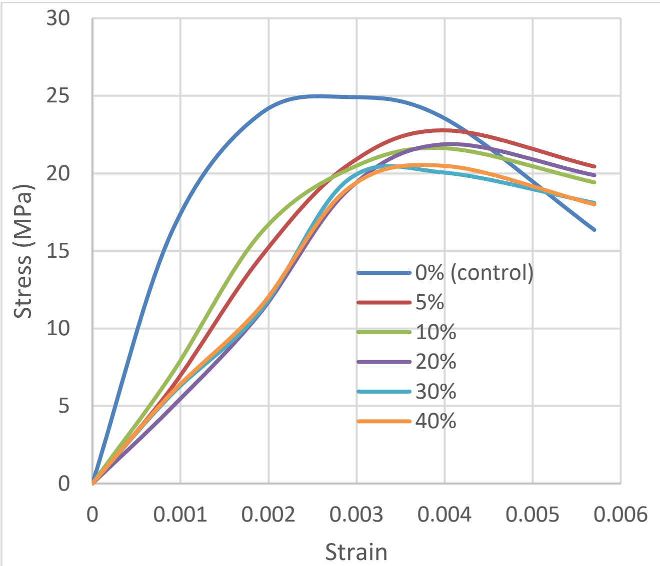

Figure 2. Mean 28-Day Compressive Stress-Strain Relationship.

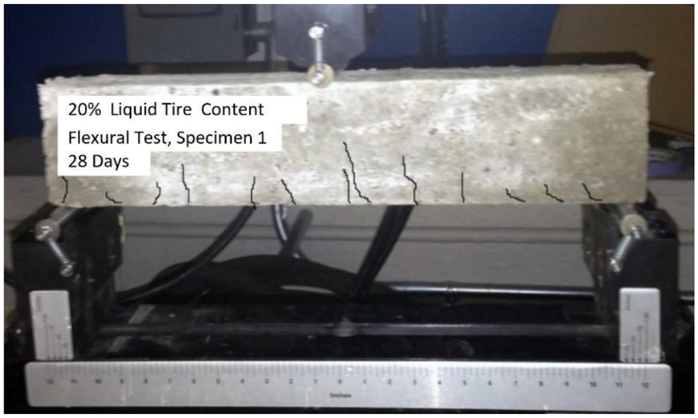

Figure 3. Typical LTC Flexural Test.

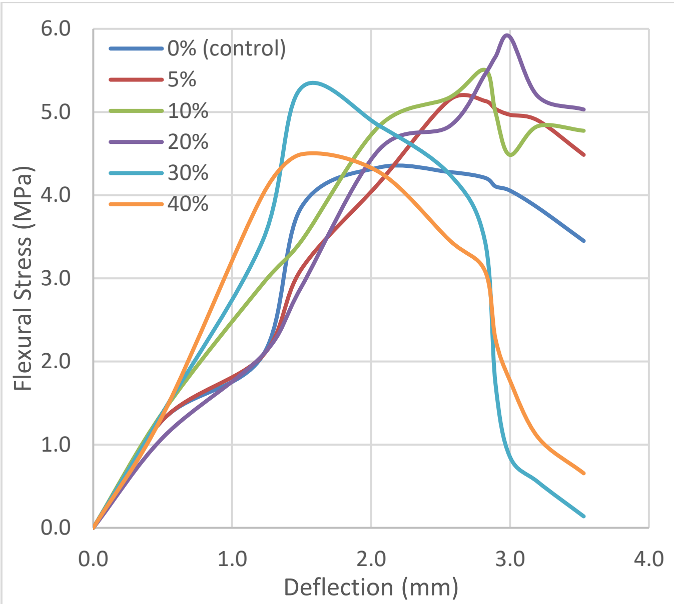

Figure 4. Mean 28-Day Flexural Stress-Deflection Curves.

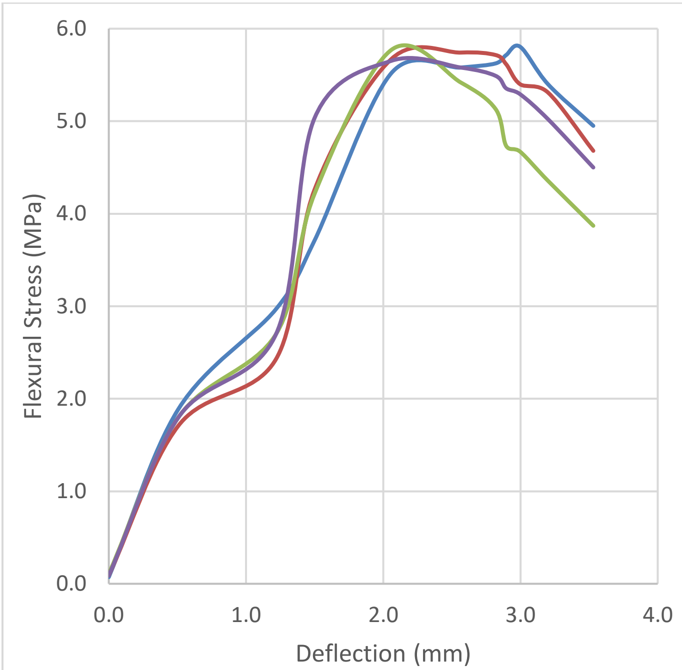

Figure 5. Individual 28-Day Flexural Stress-Deflection Curves, Control Specimens.

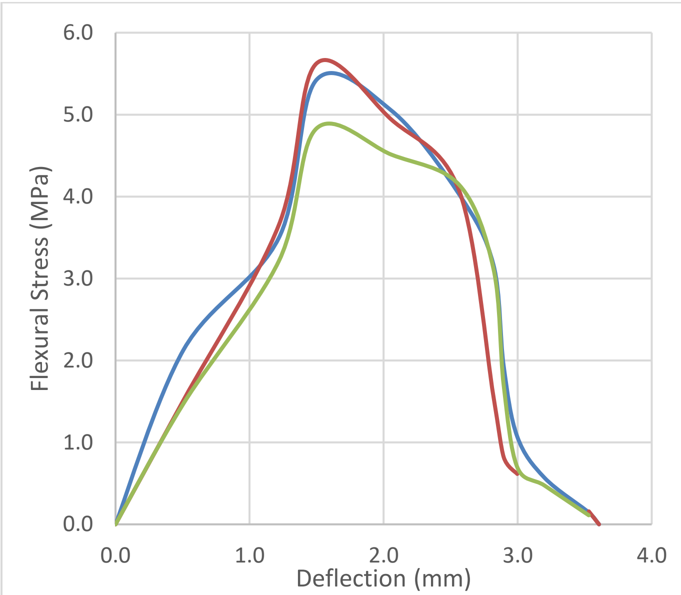

Figure 6. Individual 28-Day Flexural Stress-Deflection Curves (LT/W = 30%).

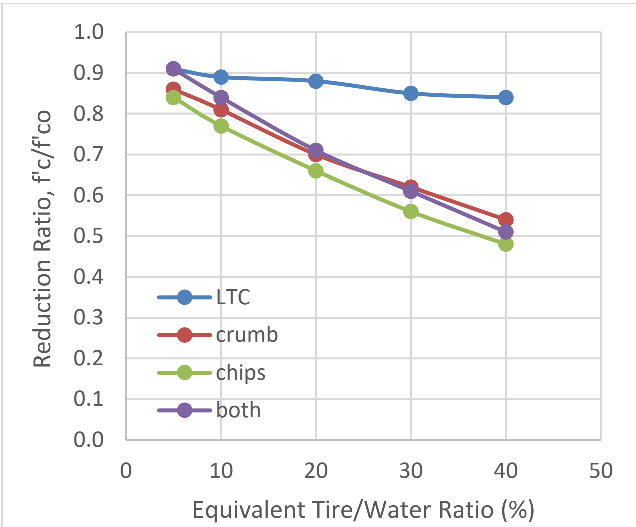

Figure 7. Comparison of LTC to Solid Rubber Specimens, Typical f’c Reduction.

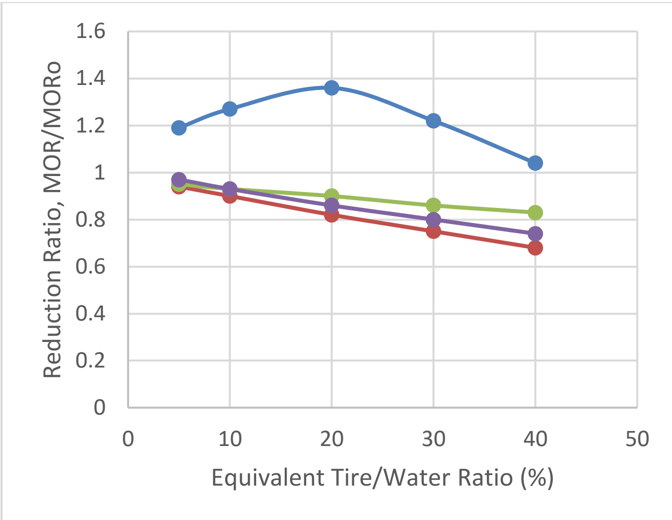

Figure 8. Comparison of LTC to Solid Rubber Specimens, Typical MOR Reduction.

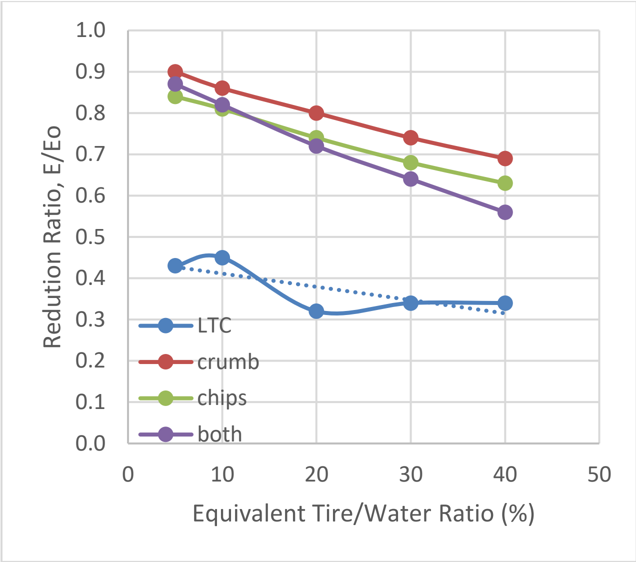

Figure 9. Comparison of LTC to Shredded Rubber Specimens, Typical E Reduction.