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Use of waste tire steel beads in Portland cement concrete

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Abstract

Large quantities of waste tires are generated every year. The proper disposal of the tires creates an increasing problem that needs to be addressed. Many researchers have investigated the use of recycled tire products in several traditional Civil Engineering materials. The use of crumb rubber and tire chips in Portland cement concrete has been the subject of many research projects over the last years. This study is focusing on the use of steel beads, a by-product of the tire recycling process, in concrete mixtures. Different concrete specimens were fabricated and tested in uniaxial compression and splitting tension. The main variable in the mixtures was the volumetric percentage of the steel beads. The experimental results indicate that although the compressive strength is reduced when steel beads are used, the toughness of the material greatly increases. Moreover, the workability of the mixtures fabricated was not significantly affected.

Keywords: Workability; Compressive strength; Fracture toughness; Tensile properties; Waste tires

1. Introduction

Because of the environmental threat associated with the waste tires, their proper disposal has attracted a lot of attention in the last years. In the United States alone, 290 million tires are generated per year along with an existing 275 million tires currently stockpiled throughout the nation [1]. In order to properly dispose of these millions of tires, the use of innovative techniques to recycle them is important. Without the proper disposal of these waste tires, the resulting stockpiles would cause major health risks for the public and the environment [2–4].

There has been an increased interest in using the recycled waste tire products. This interest is proven by a higher than 80% use of scrap tires produced in the United States for beneficial use, as opposed to only 25% in 1990 [1]. Thanks to Civil Engineering research, numerous uses of scrap tires have been introduced, including use in landfills, septic drain fields, subgrade fill, and chemically modified asphalt binder [1,5]. Of particular interest is the use of waste tires in Portland cement concrete.

The two main products of the tire recycling are: (i) crumb rubber and (ii) tire chips (see Fig. 1a). Crumb rubber consists of ground rubber particles, while tire chips are larger shredded rubber pieces, which contain a relatively small quantity of steel wires. A byproduct of the recycling process is the waste steel bead. The beads in the passenger tires are made of high tensile strength steel wires (1500–1900 MPa) and are used to secure the tire in the rim. The recycled steel beads, being products of the magnetic separation, include short steel wires as well as wires covered by or embedded in rubber pieces (see Fig. 1b). The difference between the tire chips and the steel beads is that the steel beads contain a much smaller quantity and size of rubber pieces and larger quantity of steel wires, as indicated by the rubber and steel volume fractions shown in Table 1. As the steel beads are currently not being reused, it would be environmentally beneficial to study their potential use as a recycled material.

The use of crumb rubber and tire chips in concrete for recycling purposes has attracted a lot of attention [5–17]. It has been reported that the replacement of coarse aggregate with waste tire chips in Portland cement concrete mixtures results in a significant increase of toughness and ductility [5–9,14,15]. On the contrary, losses in compressive strength of up to 85% have been reported when replacing the entire coarse aggregate fraction with tire chips [5–10,14–17]. The type of tire that is

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Fig. 1. Tire chips (a) vs. steel beads (b).

used to replace the coarse aggregate plays a very important role in the performance of the concrete mixture. Tire particles from truck tires are much stiffer than those of car tires, leading to stronger and stiffer concrete mixtures [5,7,17]. Along with the reduction in compressive strength, significant losses in the stiffness of the specimens were reported [5–8,15]. The improved ductility and toughness could be very beneficial in several civil engineering applications. However, the large decrease of compressive strength makes the recycling of waste tire products in concrete unattractive. While the use of both crumb rubber and tire chips has been widely investigated, no study has explored the potential incorporation of waste steel beads. The purpose of the experimental work presented in this study was to investigate the use of waste tire steel beads in Portland cement concrete.

Since the steel beads contain a significant volumetric percentage of steel wires (30–70%), the recycled steel bead concrete (RSBC) could be considered as a relative material to steel fiber reinforced concrete (FRC). However, main differences between the FRC and the RSBC exist: (i) the existence of rubber in RSBC, which is absent in FRC, and (ii) the identical dimensions and properties of the steel fibers used in the FRC, compared to large variations in shape, length, diameter and mechanical properties of the steel bead wires. The addition of steel fibers in FRC results in improvement of most mechanical properties [18–20]. The ductility and toughness is reported to increase, while no reduction in compressive strength is reported. Although previous findings suggest that that the increase in tensile strength provided by steel fibers typically is high, the increase in compressive strength typically does not exceed 25% [18]. Furthermore, the increase in compressive strength can be considered negligible when the volume fraction of the fibers is small.

The authors believe that the RSBC will exhibit better mechanical properties compared to concrete made with the addition of other recycled tire products such as crumb rubber or tire chips. Based on a review of the effects that crumb rubber, tire chips and steel fibers have on the freshly mixed and hardened properties of concrete, the authors believe that the incorporation of steel beads in concrete could lead to a viable, environmentally friendly material with attractive properties.

2. Experimental design

2.1. Mix design and materials

The control mix of concrete was designed with a mix ratio of cement/water/sand/coarse of 1.0:0.45:1.2:2.0 by weight. This mix design yielded an average 28 day compressive strength of 40.92 MPa (5935 psi). In the concrete mix, a Type I/II Portland cement was used. The fine aggregate had a specific gravity of 2.7 and a fineness modulus of 2.8. The coarse aggregate had a specific gravity of 2.65 with a maximum aggregate size of 12.5 mm (1/2 in.).

The waste tire particles used consisted of steel beads, which were generated by the tire shredding process. The recycled tires originate from different vehicles and therefore, there is a high variability in terms of physical and mechanical properties. Their tensile strength also varies from 1500 to 1900 MPa. The steel beads used in this study, consisted of steel wires of varying lengths (20 to 60 mm) and diameters (0.3 to 1.3 mm) as well as rubber particles bonded to the wires. Their cross section was typically circular. The density of the steel beads was found to be approximately 1.6 g/cm^3. The maximum size of the rubber particles was 12.5 mm (0.5 in.), while the volumetric percentage of the steel wires in steel beads was approximately 30%. The steel beads were substituted into the concrete mix in volumetric percentages of 2%, 4%, 6%, and 8%. There were no admixtures used in these mixes.

2.2. Specimen preparation

A total of 84 cylindrical specimens were fabricated and cured according to ASTM C 192-00. For each mix, a minimum of twelve cylindrical specimens were created measuring 100 mm × 200 mm (4 in. × 8 in.). All mixes were tested at 28 days with a minimum of six cylinders for compressive tests and six cylinders for splitting tension tests. For the steel bead percentage of prime concern (2% and 8%) a second batch was made producing another twelve specimens. All of the specimens were moist cured in a humidity controlled curing room.

2.3. Specimen testing

At the time of mixing, the slump and entrained air were recorded for each batch made. After the appropriate curing time, the compressive strength and splitting tension strength were obtained in accordance with procedures based on ASTM C39-03 and ASTM C 496-04, respectively. The compressive and splitting tension strengths were determined using a 1.8 MN (400 kip) Tinius Olsen universal testing machine. The

Table 1
Properties of recycled tire materials

	Tire chips	Crumb rubber	Steel beads
Volume rubber	95–99%	99–100%	30–70%
Volume steel	1–5%	0%	30–70%
Density (g/cm^3)	0.9–1.5	0.8–1.2	1.6–3.8

Table 2
Experimental results

Steel bead content	Slump (cm (in.))	Air content (%)	Density (kg/m^3 (lb/ft^3))	Compressive strength (MPa (psi))	Modulus of elasticity (GPa (ksi))	Splitting tension strength (MPa (psi))
0%	17.8 (7.0)	1.7	2387 (149.0)	40.92 (5935)	29.23 (4240)	2.82 (410)
2%	16.5 (6.5)	1.6	2373 (148.2)	40.13 (5821)	25.86 (3752)	2.75 (398)
4%	15.3 (6.0)	1.6	2355 (147.0)	35.39 (5133)	25.44 (3690)	2.64 (383)
6%	14.0 (5.5)	1.9	2325 (145.1)	33.43 (4848)	25.99 (3770)	2.55 (370)
8%	11.4 (4.5)	2.1	2310 (144.2)	30.07 (4361)	22.06 (3196)	2.47 (358)
P-value	0.00226	0.102	0.000887	0.00256	0.0471	0.000105
Correlation coefficient	−0.98	−0.802	−0.992	−0.983	−0.883	−0.998

compressive specimens were instrumented with a compressometer and LVDT to record deformation and a load cell to record the applied load. The splitting tension data was obtained using an LVDT measuring crosshead movement along with a load cell.

3. Analysis of results

Several properties of the RSBC mixtures were examined in this study. The properties are separated into two main categories: (i) freshly mixed concrete properties and (ii) hardened concrete properties. The effects of the steel beads on the concrete mixture properties are presented below.

3.1. Freshly mixed RSBC properties

The freshly mixed concrete properties under investigation include workability the air content. The workability was measured using the slump test, described in ASTM C143. The findings from this study are similar to the ones reported from other researchers who used FRC [18–20] and tire chips [6,10,13,15]. The effect of the steel bead content on slump is presented in Table 2. The slump decreases at a constant rate as steel bead content increases. In the current study, although the slump decreased, the mix remained workable (slump higher than 100 mm) at all steel bead contents. The steel wires had a tendency to interlock during the mixing process, leaving localized areas of high steel and rubber. This “balling” effect during mixing is also reported by several researchers who incorporated high volume fractions of steel fibers in FRC concrete mixtures [18–20]. The interlocking action of the wires was apparent before the mixing process and was more noticeable at higher volume fractions. In order to avoid this “balling” effect the steel beads were separated by hand before being placed in the mixer.

The air content of the RSBC mixtures was measured using standard ASTM approved testing equipment. The experimental results indicate that the air content for the control mix was 1.7%. It decreased to 1.6% when 2% and 4% steel beads were used. Past 6% the air content began to slightly increase with an increase in steel bead content. The air content results with respect to the steel content are presented in Table 2. In all cases, the air content was kept less than 2.1%. It can be concluded that the variations in air content are not significant ($R = -0.8$ and p-value = 10.2%). This finding is not consistent with findings from studies that reported that the addition of high volumes of rubber particles in concrete increases the air content [6,3,9,10,12]. It was suggested that the non-polarity of rubber causes water to be repelled from the surface of the rubber particles and air to consequently be trapped on the surface [3,12]. Furthermore, the addition of steel fibers in FRC is reported to result in very small increases of air content as well [20,21]. We believe that this phenomenon is not evident here mainly because relatively small volume fractions of steel beads (and therefore rubber) were used. Moreover, the relatively small number of tests, only one per mixing batch, reduces the confidence and could result in experimental error.

3.2. Hardened RSBC properties

The properties of hardened RSBC investigated in this study include the density, compressive strength, splitting tensile strength, and toughness. As mentioned before, the RSBC is a common Portland cement concrete mixture that contains rubber particles as well as steel wires. The rubber particles were expected to be the weak links in the mixture while the high strength steel fibers were expected to provide strength and ductility. Similarities with properties of waste tire modified concrete and steel fiber reinforced concrete were anticipated.

The steel beads are less dense than natural coarse aggregate used in this study. Therefore, it was expected that the addition of steel beads would result in a small reduction of RSBC density. The findings presented in Table 2. suggest that the steel bead content has a very small effect on the density of the concrete mixture. The density for the control mix was 2387 kg/m^3 while

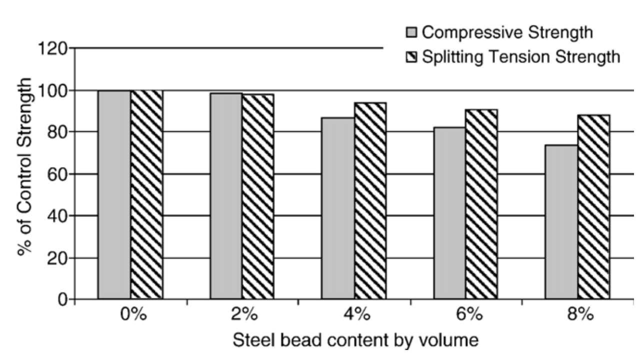

Fig. 2. Variation of 28 day compressive strength and splitting tension strength.

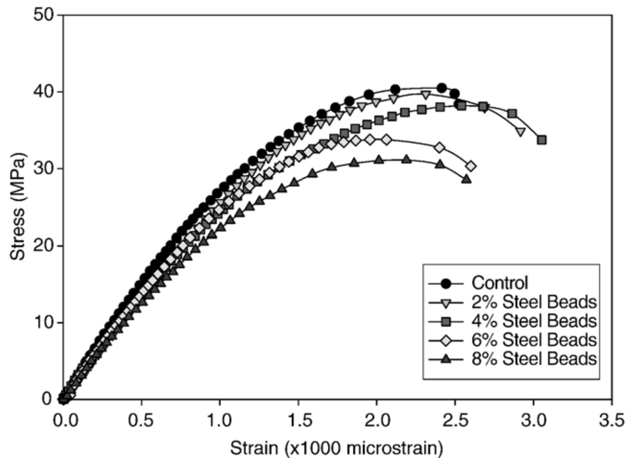

Fig. 3. 28 day compressive stress–strain curves.

the mix containing 4% steel beads had a density of 2310 kg/m^3. A regression analysis indicated that the density decreases with an increasing steel content at a linear rate ($R=-0.99$ and p-value = 0.0887%).

The uniaxial compression tests prove that the addition of steel beads does not enhance the compressive strength of the RSBC. On the contrary, the larger the amount of steel beads in the mix, the higher the losses in compressive strength. The experimental results are shown in Fig. 2, where the percent of the retained compressive strength is presented versus the steel bead content. The reduction in compressive strength can be explained by the following arguments:

- The rubber particles, which are much softer than the surrounding cement matrix, cause cracking at the rubber–cement interface upon loading. These cracks then propagate through the specimen and lead to failure [10]. This elastic imbalance may cause the rubber particles to act as voids in the specimens, and thus supply no major resistance to loading [6].
- The replacement of hard, dense aggregate with a less dense rubber will cause loss in strength because the strength of concrete is highly dependent on these aggregate properties [10,11,16].
- Since the steel beads contain both steel wires and rubber particles, a possible interlocking will lead not only to an area with increased steel content but also to possibly increased rubber content. A higher reduction of strength at higher percentages of steel beads can be explained by the fact that there is a higher possibility of “balling” at higher steel bead volume fractions.

Based on the mechanical properties and geometry of the constituent materials it was expected that the steel beads will have not as strong effect on the compressive strength and stiffness of the concrete mixture as the tire chips and the crumb rubber. Li et al. reported that an addition of 8% tire chips in concrete results in a decrease of approximately 40% in compressive strength and 20% in Young’s modulus [5–7]. From Table 2, we can see that the 8% RSBC exhibits 25% lower compressive strength and Young’s modulus than the control mix.

In order to examine the effects of the steel bead content on the compressive strength and the modulus of elasticity a statistical analysis was performed. The coefficients of correlation were calculated as −0.983 and −0.883 while the p-values were 0.00256 and 0.0471, respectively (see Table 2). Therefore, we can conclude that there is a very strong correlation between the steel bead content and the compressive strength.

Although a reduction in the compressive strength was noticeable, an increase in ductility can be seen for the 2% and 4% steel bead contents (see Fig. 3). The increase was approximately 20%. On the contrary, no increase in ductility was recorded for the higher than 6% RSBC. The steel wires contained in the steel beads act as reinforcement, since they help resist crack growth, and allow for an increased ductility. The increase in rubber content and “balling” effect could have counteracted the gains because of the steel fibers in the cases of 6% and 8% RSBC. The large difference in elastic stiffness between the rubber and cement introduces stress concentrations at the interface region, which then lead to cracking and failure. It should be noted, that the 2% RSBC exhibits only minor losses (2%) in compressive strength with substantial gains in ductility (20%).

From the splitting tension testing it was observed that there is a linear decrease in the splitting tension strength when increasing

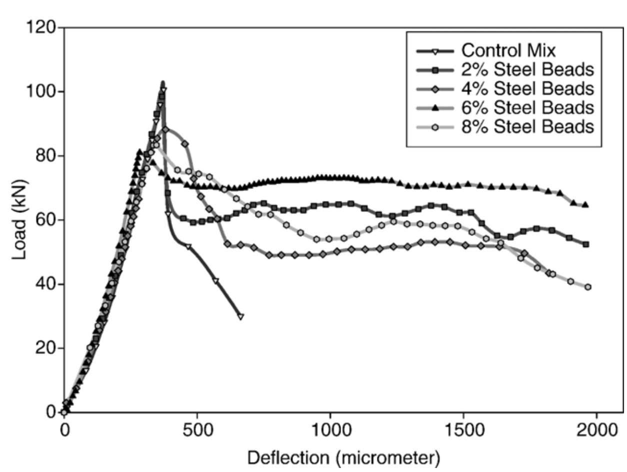

Fig. 4. 28 day splitting tension load–deflection curves.

Fig. 5. Splitting tension failure interface (6% steel bead content).

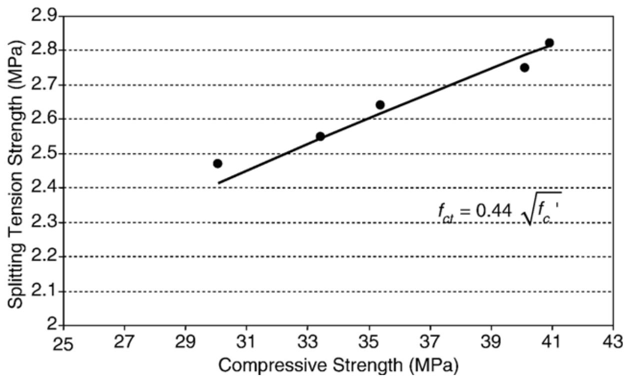

Fig. 6. Relationship between compressive strength and tension strength.

quantities of steel beads are used in the mixture ($R=-0.998$). A bar chart presenting the splitting tension strength versus the steel bead content of the specimens can be seen in Fig. 2. It is clear that the compressive strength reduces at higher rate than the splitting tension strength with increasing steel bead content. The reduction in splitting tension strength can be attributed to the existence of rubber particles. The non-polarity of the rubber as mentioned previously attracts air to its surface and therefore reduces the bond with the cementitious matrix.

The examination of the load deflection curves, shown in Fig. 4, leads to the conclusion that the specimens containing steel beads exhibit much higher toughness. Although the control specimen split in two pieces immediately after the cracking, the RSBC specimens underwent a significant deformation without disintegration (see Fig. 4). Similar behavior is reported for rubber fiber and steel fiber reinforced concrete [5,7,18–20]. The steel wires, (Fig. 5) acting similarly to the fibers in FRC, permit the concrete specimens to exhibit large deformations while resisting significant post-cracking load. Regardless of the steel bead percentage used in the RSBC the experiments had to be stopped because the specimens did not separate (the recorded deformations exceeded 3 mm). The maximum allowed deformation presented in Fig. 4 was limited to 2 mm. From a close examination of the load–deflection curves we can see that the initial slopes of the RSBC are slightly steeper than the slope of the control mix. This phenomenon can be explained by the "tension stiffening" which is very common in steel FRC [22,23]. After the initial cracking of the matrix, the steel fibers hold the microcracking mechanism and limit crack propagation. Due to the "tension stiffening", the toughness and ductility are said to be significantly improved [22]. The increase in stiffness is not as high in RSBC as is in steel FRC but it still is noteworthy.

During the splitting tension testing, the effect of the steel beads was apparent. After the initial cracking, the steel wires appear to control the cracking of RSBC and alter the post-cracking behavior. It was apparent that after the initial major cracking, the recorded load would briefly decrease, followed by an increase as other wires took the load. The steel beads in the specimens seem to provide a load redistribution mechanism after the initial cracking. It was impossible to separate the failed specimens because the steel wires were bridging the gap and keeping the two concrete parts together. Similar behavior has been reported for concrete with tire chips [5,7] as well as steel FRC tested in splitting tension [24]. Although the addition of 2% waste steel beads significantly increased the toughness, there was no difference in toughness among the RSBCs when the steel bead content increased. The high toughness of the steel bead mixes indicates that steel bead concrete mixtures have excellent potential in structures that are required to absorb large amounts of energy (such as blast resistant structures).

The relationship between the tensile strength and the compressive strength is very important. More specifically, the ratio of the compressive to tensile strength is being used in several theoretical models [25,26]. A comparison of the compressive strengths of the specimens with the splitting tension strength has indicated that there is a significant relationship. A regression analysis of the experimental data resulted in the following equation:

$$f_{ct} = 0.44\sqrt{f_c'}, \tag{1}$$

where f_{ct} is the splitting tension strength, and f_c' the compressive strength of the concrete mixtures. The values obtained from the equation were plotted versus the experimental data and are shown in Fig. 6. The coefficient of correlation was calculated as $R=0.97$ while the p value was found to be less than 0.1%. Our results are consistent with previous studies [27,28]. In all cases, the splitting tensile strength increases as the compressive strength increases, but the ratio of splitting tension strength to compressive strength decreases with an increasing compressive strength. Arioglu et al. [28] evaluated the relationship between compressive and splitting tensile strength for a wide range of Portland cement concrete mixtures. One of the three equations they suggest, shown below, is very similar to Eq. (1):

$$f_{ct} = 0.39\sqrt{f_c'} + 0.037. \tag{2}$$

Hence, it can be concluded that the ratio of splitting tension to compressive strength of RSBC is similar to the reported ratios of most common concretes.

4. Conclusions

Based on the results obtained and the observations made during testing of the specimens, the following conclusions can be made:

- Concrete mixtures can be made containing small volume fractions of waste tire steel beads. The mixes are workable up to 4% volume fractions although there is a decrease in workability with an increase in steel bead content.
- The inclusion of waste tire steel beads slightly reduces the density of a concrete specimen when compared to the control mix.
- The addition of steel beads in the concrete mixture results in a reduction of the compressive strength.
- When 2% steel beads are used in the mixtures the compressive strength reduction is minimal (2%) while there is a 20% increase in ductility.
- The control mix exhibited higher strength in splitting tension than the specimens with steel beads. An increasing amount

of steel beads in the mixture leads to a linear decrease in strength.

- Splitting tension tests indicate that concrete mixtures that contain any percentage of steel beads have much greater toughness than the normal concrete mixture.
- Failed splitting tension specimens did not separate because the steel wires act as reinforcement.
- An empirical equation was determined, that can relate compressive with splitting tension strength of the concrete mixtures containing steel beads.
- More research is needed prior to making solid conclusions on the performance of steel bead concrete mixtures.

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