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Cement and Concrete Research 34 (2004) 2309–2317

CEMENT AND CONCRETE RESEARCH

# Properties of rubberized concretes containing silica fume

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Received 24 January 2004; accepted 8 April 2004

**Abstract**

A test program was carried out to develop information about the mechanical properties of rubberized concretes with and without silica fume. Two types of tire rubber, crumb rubber and tire chips, were used as fine and coarse aggregate, respectively, in the production of rubberized concrete mixtures which were obtained by partially replacing the aggregate with rubber. Six designated rubber contents varying from 2.5% to 50% by total aggregate volume were used. The concretes with silica fume were produced by partial substitution of cement with silica fume at varying amounts of 5–20%. Totally, 70 concrete mixtures were cast and tested for compressive and splitting tensile strengths, and static modulus of elasticity in accordance to ASTM standards. The design strength level ranging from 54 to 86 MPa was achieved using water–cementitious material (w/cm) ratios of 0.60 and 0.40. Test results indicated that there was a large reduction in the strength and modulus values with the increase in rubber content. However, the addition of silica fume into the matrix improved the mechanical properties of the rubberized concretes and diminished the rate of strength loss. Results also revealed that a rubber content of as high as 25% by total aggregate volume might be practically used to produce rubberized concretes with compressive strength of 16–32 MPa.


*Keywords:* Concrete; Mechanical properties; Rubberized concrete; Silica fume; Waste management

## 1. Introduction

One of the most crucial environmental issues all around the world is the disposal of the waste materials. Accumulations of discarded waste tires have been a major concern because the waste rubber is not easily biodegradable even after a long-period landfill treatment. However, material and energy are alternatives to disposal of the waste rubber [1–6]. Some people propose to use it as fuel material or as raw materials of rubber goods [7]. On the other hand, a wide variety of waste materials has been suggested as additives to cement-based materials [8–14]. Other construction products are also based on rubber powder obtained from the cryogenic milling of tires mixed with asphalt or bituminous materials [15,16]. Unfortunately, not much attention has been paid to use the waste tires in portland cement concrete mixtures, particularly for highway use. Limited work was done by researchers to investigate the potential use of rubber tires in conventional concrete mixtures.

In the study of Eldin and Senouci [7], the strength and toughness properties of the concrete mixtures containing two types of tire rubber were investigated. The aggregate of the control mix was replaced by different amounts of tire rubber particles of several sizes. The control mix had a 28-day compressive strength of 35 MPa. Their results indicated that there was about 85% reduction in the compressive strength when the coarse aggregate was fully replaced by rubber. However, a smaller reduction in the compressive strength (65%) was observed when sand was fully replaced by crumb rubber. Concrete containing rubber did not exhibit brittle failure under compression or tension. It was also concluded that an optimized mix design was needed to provide the optimum tire rubber content in the concrete mixture. Khatip and Bayomy [17] also used recycled tire rubber as aggregate in the concrete mixtures with different rubber content. Similar to the study of Eldin and Senouci [7], the initial 28-day compressive strength of normal portland cement concrete was about 38 MPa. Their results for compressive and flexural strengths indicated that a large reduction was observed with the use of higher rubber content. To estimate the strength loss with the rubber content, they proposed a characteristic function for both compressive and flexural strengths. However, it was ob-

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doi:10.1016/j.cemconres.2004.04.005

served that the function parameters depended on the concrete properties tested and the strength level of the control mixture. Therefore, to utilize this function for the mix design of rubberized concretes, more research is needed to develop a relationship between the concrete properties tested and the amount of rubber used in the mixture. The properties of the rubberized concretes were also studied by Topçu [18]. The physical and mechanical properties of the rubberized concretes with initial compressive strength of 20 MPa was examined. The amounts of the rubber used were 15%, 30%, and 45% by volume of the total aggregate. The study revealed that a general reduction in the compressive strength was observed. Moreover, plastic energy capacity of the normal concrete was increased by adding rubber. Due to their high plastic energy capacities, these concretes showed high strains, especially under impact effects.

The literature [7,17–28] about the use of tire rubber particles in cement-based materials focuses on the use of tire rubber as an aggregate in concrete. Most of the research as mentioned above has shown a remarkable decrease in the mechanical properties of concrete after addition of tire rubber particles as aggregate. The use of only coarse rubber particles affects the properties more negatively than do only fine particles [7,17,18,23]. However, very limited studies have been conducted on the use of coarse and fine rubber particles together in the concrete mixture [17]. Khatip and Bayomy [17] attributed this strength loss to the lack of adhesion between rubber particles and the paste. Therefore, some authors suggested that the loss in the strength might be minimized by prior surface treatment of the tire rubber particles [7,13,26,27]. The surface of the rubber particles was generally modified through immersion in NaOH aqueous solution to increase its adhesion to the surrounding cement paste. However, it is reported that ultrafine mineral admixtures, such as silica fume, increase the homogeneity and decrease the number of the large pores in cement paste [29–31], both of which would lead to a higher strength material. There is also ample evidence that the use of silica fume results in a denser interface between cement paste and coarse aggregates [32–35]. Hence, the use of silica fume might be an alternative way to improve the properties of the rubberized concrete for the structural applications.

In this work, an experimental study was conducted on the development of the rubberized concrete mixtures with and without silica fume and the basic engineering properties were investigated. Two types of rubber, namely, crumb rubber and tire chips, were utilized as fine and coarse aggregates, respectively. A total of six designated rubber contents ranging from 2.5% to 50% by total aggregate volume were used. Silica fume concretes included 5%, 10%, 15%, and 20% silica as equal replacement of portland cement by weight. Totally, 70 concrete mixtures were cast at water–cementitious material (w/cm) ratios of 0.60 and 0.40 and tested for compressive and splitting tensile strengths and modulus of elasticity. The initial compressive strengths of the control mixtures were 54 and 76 MPa for high and low w/cm ratios, respectively.

## 2. Experimental details

### 2.1. Materials

The materials used to develop the concrete mixtures in this study were fine aggregate, coarse aggregate, tire rubber, cement, and silica fume. Natural sand having a maximum particle size of 4 mm and fineness modulus of 1.39 was used as fine aggregate while crushed limestone having 20 mm maximum size and 5.60 fineness modulus was used as coarse aggregate. Two types of scrap tire rubber came from used truck tires castaway after a second recapping. Crumb rubber is a fine material with gradation close to that of the sand and tire chips are produced by mechanical shredding and contain coarser particle sizes. The gradation of crumb rubber was determined based on the ASTM C136 method. It was not possible to determine the gradation curve for the tire chips as for normal aggregates, because they were elongated particles between 10 and 40 mm. Specific gravities for the aggregates and rubber materials are given in Table 1 and their gradation curves are shown in Fig. 1. ASTM Type I portland cement (28-day compressive strength of 50 MPa) and commercial grade silica fume (91.0% $SiO_2$ content) were used as a cementitious material.

### 2.2. Concrete mixtures

Two control mixtures were designed at w/cm ratios of 0.60 and 0.40 with cement contents of 350 and 450 kg/m$^3$, respectively. A partial replacement of cement with silica fume was used to examine the effect of silica fume on the mechanical properties of rubberized concretes. The amount of silica fume varied from 0% to 20% by weight of cement which is the range of silica fume that is most often used [31]. In this study, four values of silica fume content were used: 5%, 10%, 15%, and 20% by weight of cement. The mix proportions of concretes with and without silica fume are given in Table 1. To develop the rubberized concrete mixtures, all mix design parameters were kept constant except for the aggregate constituents. That is, the cementitious material content, w/cm ratio, and aggregate volume were kept constant. Tire rubber was used as a replacement for an equal part of aggregate by volume. The rubberized concretes contained both types of rubbers (crumb and chip) with six designated rubber contents of 2.5%, 5%, 10%, 15%, 25%, and 50% by total aggregate volume. The rubber content was divided equally between the crumb and the chip. That is, for a 50% rubber content, crumb rubber replaced 50% of the sand volume and tire chips replaced 50% of the coarse aggregate volume.

A total of 70 concrete batches was produced. Each batch was mixed according to ASTM C192 standard in a power-

Table 1
Material properties and mix proportioning of control mixtures

| Material | Specific gravity | Water–cementitious materials ratio | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.40 | | | | | 0.60 | | | | |
| Cement (kg/m$^3$) | 3.15 | 450 | 428 | 405 | 383 | 360 | 350 | 333 | 315 | 298 | 280 |
| Silica fume (%) | – | 0 | 5 | 10 | 15 | 20 | 0 | 5 | 10 | 15 | 20 |
| Silica fume (kg/m$^3$) | 2.33 | 0.0 | 22.5 | 45.0 | 67.5 | 90.0 | 0.0 | 17.5 | 35.0 | 52.5 | 70.0 |
| Water (kg/m$^3$) | 1.00 | 180 | 180 | 180 | 180 | 180 | 210 | 210 | 210 | 210 | 210 |
| Superplasticizer (kg/m$^3$) | 1.18 | 13.5 | 13.5 | 13.5 | 13.5 | 13.5 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 |
| Crushed stone (kg/m$^3$) | 2.70 | 1062 | 1058 | 1054 | 1049 | 1045 | 1076 | 1073 | 1070 | 1066 | 1063 |
| Sand (kg/m$^3$) | 2.62 | 688 | 685 | 682 | 680 | 677 | 697 | 695 | 693 | 691 | 688 |
| Crumb rubber (kg/m$^3$) | 0.83 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Tire chips (kg/m$^3$) | 1.02 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

driven revolving pan mixer. The control mixtures given in Table 1 were designed to have slump values of 180 ± 20 and 140 ± 20 mm for w/cm ratios of 0.60 and 0.40, respectively. A high-range water-reducing admixture was used to achieve the specified slump at each w/cm ratio. Three 150-mm cube and three 150 × 300 mm cylinder specimens were cast from each batch and compacted by a vibrating table. A total of 210 cube and 210 cylinder specimens were tested. Test specimens were demoulded 24 h after casting and then water cured for 7 days. Thereafter, the specimens were kept in a curing room at a temperature of 21 ± 1 °C and at a relative humidity of 60 ± 5% until the time of testing. All specimens were tested at the age of 90 days.

### 2.3. Test methods

To evaluate the fresh concrete properties, slump and unit weight were measured according to ASTM C143 and ASTM C138, respectively. For hardened concrete, all mixes were tested for compressive and splitting tensile strengths and static elastic modulus at the age of 90 days. The compression test was carried out on the cube specimens by a 3000-kN capacity testing machine according to ASTM C39. The splitting tensile strength was determined on the cylinder specimens according to ASTM C496. Cylinders were also tested for determining the modulus of elasticity according to ASTM C469 before they were tested for the splitting tensile test. For this purpose, the ends of the cylinders were capped with traditional sulfur mortar conforming the requirements of ASTM C617 prior to testing. Each of the specimens was fitted with a compressometer containing a dial gage capable of measuring deformation to 0.002 mm and then loaded three times to 40% of the ultimate load of companion cube specimen. The first set of readings of each cylinder was discarded and the modulus was reported as the average of the second and third sets of readings. Three specimens were tested for each property.

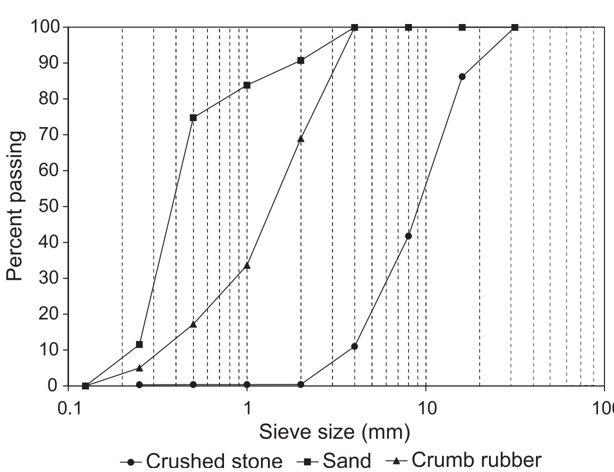


Fig. 1. Sieve analysis of aggregate and crumb rubber.

## 3. Experimental results and discussion

### 3.1. Properties of fresh concrete

Fresh concrete properties (slump and unit weight) are presented in Figs. 2 and 3, respectively. As shown in Fig. 2, the slump of the concretes with and without silica fume gradually decreased for both w/cm ratios with increasing rubber content. At a rubber content of 50% by total aggregate volume, the slump decreased near to zero and the mix was not workable such that an extra effort was required for the compaction of the concretes via tamping with a standard 16-mm-diameter steel rod. Moreover, the decrease in the slump was more remarkable for low w/cm concretes. Fig. 2 also shows that the concretes with silica fume had lower slump than the plain concrete. The reduction in workability as indicated by the reduction in slump values at the higher rubber volumes resulted in a decrease of the unit weight as shown in Fig. 3. The unit weight of the concretes ranged from 2427 to 1805 kg/m$^3$ depending on the silica fume and rubber contents. With the increasing rubber content, the unit weight of the concrete was also reduced resulting in lighter concretes. At 50% rubber content, the unit weight diminished to as low as about 75% of the normal concrete, irrespective of silica fume content.

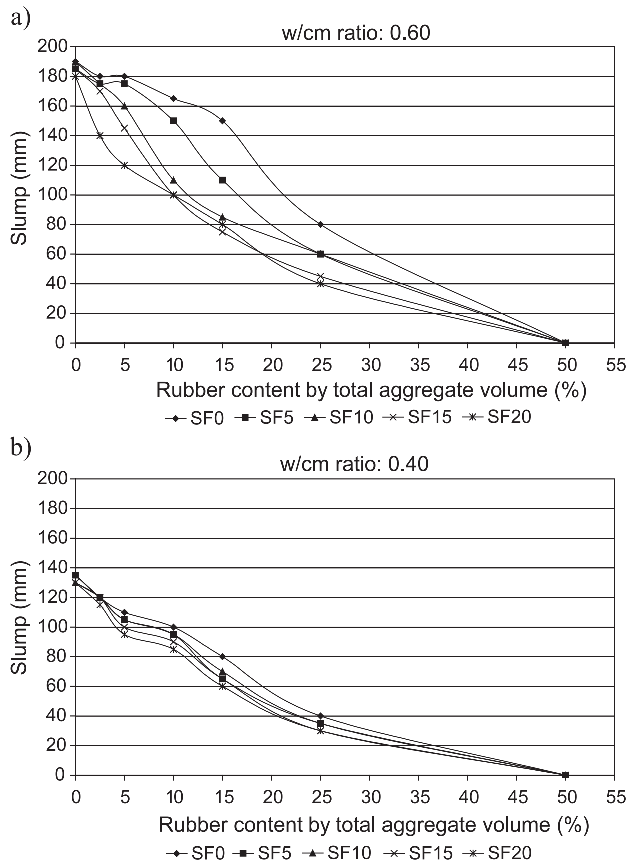


Fig. 2. Variation in the slump of the concretes with rubber and silica fume contents; (a) w/cm ratio: 0.60 and (b) w/cm ratio: 0.40.

### 3.2. Hardened concrete properties

A summary of test results regarding the compressive and splitting tensile strengths, and the static modulus of elasticity of the concretes incorporating rubber and silica fume with varying proportions are given in Table 2 and graphically depicted in Figs. 4, 6, and 8), respectively.

#### 3.2.1. Compressive strength

The results presented in Fig. 4 show a systematic reduction in compressive strength with the increase in rubber content for the concretes with and without silica fume. Two grades of concrete having initial compressive strengths of about 54 and 76 MPa were achieved for 0.60 and 0.40 w/cm ratios, respectively. However, it was observed that these values considerably varied with the amount of silica fume and rubber used. The concretes without silica fume had compressive strength reducing from 47 to 7 MPa and from 70 to 10 MPa at 0.60 and 0.40 w/cm ratios, respectively, with increasing rubber content. On the other hand, with the use of silica fume, the compressive strength reduced from 61 to 7 MPa and from 86 to 11 MPa at high and low w/cm ratios, respectively, as the rubber content increased from 0% to 50% by total aggregate volume. The test results exhibited that rubberized concretes with compressive strength of higher than 40 MPa may be achieved by using a rubber content of as high as 15%, particularly at low w/cm ratio. However, for both w/cm ratios, it was observed that there was about 85% reduction in the compressive strength when 50% of the total aggregate volume was replaced by rubber, irrespective of the silica fume content. The effect of silica fume on the compressive strength of the concretes at varying rubber contents is well observed in Fig. 5. The figure indicated that the beneficial effect of silica fume was more pronounced at high w/cm ratio. The rate of strength increase ranged from 6% to 13% for the plain concretes but from 2% to 43% for the rubberized concrete, depending on the variation in w/cm ratio, silica fume, and rubber contents. For the same w/cm ratio and the rubber content, the compressive strength mostly increased with the silica fume content increasing from 5% to 20%, as seen in Fig. 5. The increase in compressive strength with increasing silica fume content was observed to increase up to 25% rubber content, especially at high w/cm ratio. This was expected because of the filling effect of silica fume due to its finer particle size, thus providing a good adherence between the rubber and the cement matrix. Fig. 5 also indicated that the increase in compressive strength was as high as 40% for the high w/cm

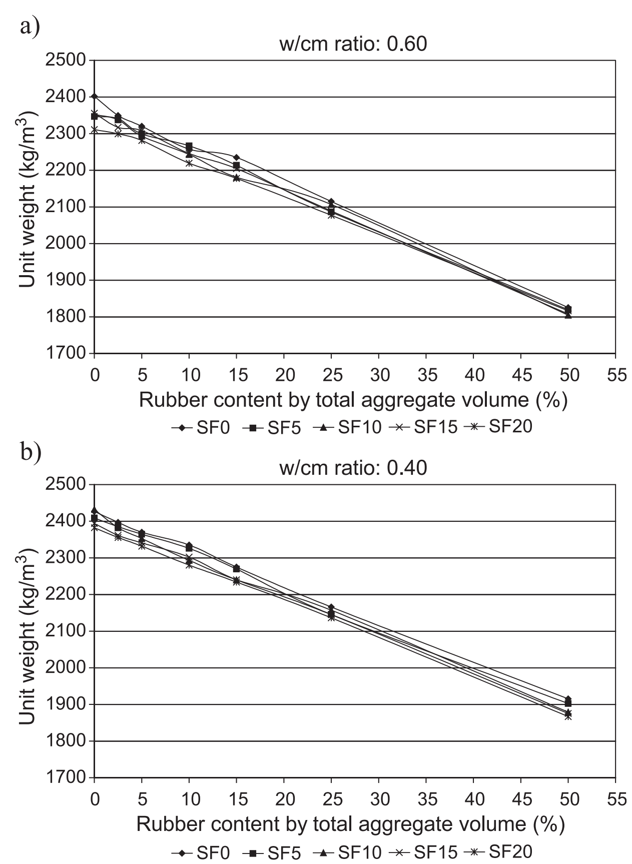


Fig. 3. Variation in the unit weight of the concretes with rubber and silica fume contents; (a) w/cm ratio: 0.60 and (b) w/cm ratio: 0.40.

Table 2
Test results of compressive and splitting tensile strengths, and modulus of elasticity

| Concrete property | w/cm | Rubber content (%) | Silica fume (%) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0 | 5 | 10 | 15 | 20 |
| Compressive strength (MPa) | 0.60 | 0 | 53.8 | 56.8 | 57.7 | 60.3 | 59.7 |
| | | 2.5 | 47.0 | 50.2 | 52.5 | 55.4 | 56.4 |
| | | 5 | 41.5 | 43.1 | 46.1 | 49.3 | 51.3 |
| | | 10 | 31.8 | 35.8 | 37.6 | 41.3 | 41.2 |
| | | 15 | 24.3 | 28.8 | 31.4 | 32.8 | 34.2 |
| | | 25 | 16.2 | 18.2 | 20.1 | 21.2 | 23.1 |
| | | 50 | 7.1 | 7.2 | 8.1 | 8.4 | 8.6 |
| | 0.40 | 0 | 75.8 | 81.0 | 82.7 | 84.0 | 85.7 |
| | | 2.5 | 70.4 | 72.5 | 75.4 | 78.3 | 79.1 |
| | | 5 | 62.8 | 67.8 | 68.2 | 68.0 | 69.4 |
| | | 10 | 50.7 | 55.3 | 56.3 | 55.6 | 61.7 |
| | | 15 | 40.3 | 44.5 | 45.1 | 46.4 | 47.0 |
| | | 25 | 26.4 | 29.6 | 30.5 | 31.8 | 31.8 |
| | | 50 | 10.5 | 11.2 | 11.6 | 11.7 | 11.7 |
| Splitting tensile strength (MPa) | 0.60 | 0 | 3.1 | 3.5 | 3.6 | 3.7 | 3.7 |
| | | 2.5 | 2.8 | 3.2 | 3.3 | 3.5 | 3.7 |
| | | 5 | 2.7 | 3.0 | 3.2 | 3.3 | 3.4 |
| | | 10 | 2.5 | 2.8 | 2.8 | 2.9 | 3.2 |
| | | 15 | 2.1 | 2.2 | 2.5 | 2.6 | 2.7 |
| | | 25 | 1.6 | 1.7 | 2.0 | 2.0 | 2.1 |
| | | 50 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 |
| | 0.40 | 0 | 4.1 | 4.3 | 4.5 | 4.7 | 4.7 |
| | | 2.5 | 4.0 | 4.1 | 4.2 | 4.4 | 4.4 |
| | | 5 | 3.8 | 3.9 | 4.0 | 4.1 | 4.2 |
| | | 10 | 3.2 | 3.4 | 3.5 | 3.6 | 3.6 |
| | | 15 | 2.8 | 2.9 | 3.0 | 3.1 | 3.2 |
| | | 25 | 2.0 | 2.1 | 2.3 | 2.5 | 2.5 |
| | | 50 | 0.9 | 0.9 | 0.9 | 1.0 | 1.0 |
| Modulus of elasticity (GPa) | 0.60 | 0 | 33.1 | 35.0 | 35.3 | 36.0 | 37.0 |
| | | 2.5 | 32.4 | 34.4 | 34.0 | 34.5 | 34.3 |
| | | 5 | 29.0 | 30.0 | 30.5 | 31.0 | 31.4 |
| | | 10 | 26.0 | 27.5 | 28.0 | 27.6 | 27.9 |
| | | 15 | 20.1 | 22.3 | 23.5 | 23.2 | 22.4 |
| | | 25 | 12.8 | 13.0 | 14.3 | 14.0 | 14.7 |
| | | 50 | 6.1 | 6.3 | 6.9 | 6.6 | 6.5 |
| | 0.40 | 0 | 45.9 | 46.0 | 47.5 | 47.0 | 47.5 |
| | | 2.5 | 41.0 | 42.0 | 43.0 | 43.5 | 44.5 |
| | | 5 | 37.6 | 40.0 | 41.0 | 38.5 | 42.3 |
| | | 10 | 29.5 | 30.6 | 31.2 | 32.2 | 31.8 |
| | | 15 | 25.0 | 25.4 | 26.5 | 27.5 | 28.0 |
| | | 25 | 17.5 | 18.5 | 19.0 | 19.3 | 20.0 |
| | | 50 | 7.6 | 8.0 | 8.1 | 8.0 | 8.2 |

concretes containing 15% or 25% rubber by total aggregate volume.

The strength reduction observed in the rubberized concrete with increasing rubber content may be attributed to two reasons as reported by Khatip and Bayomy [17]. First, because the rubber particles are much softer (elastically deformable) than the surrounding cement paste, on loading, cracks are initiated quickly around the rubber particles in the mix, which accelerates the failure of the rubber–cement matrix. Secondly, due to the lack of adhesion between the rubber particles and the paste, soft rubber particles may behave as voids in the concrete matrix. However, the addition of silica fume into the matrix improves the bond between the cement paste and the rubber particles as well as

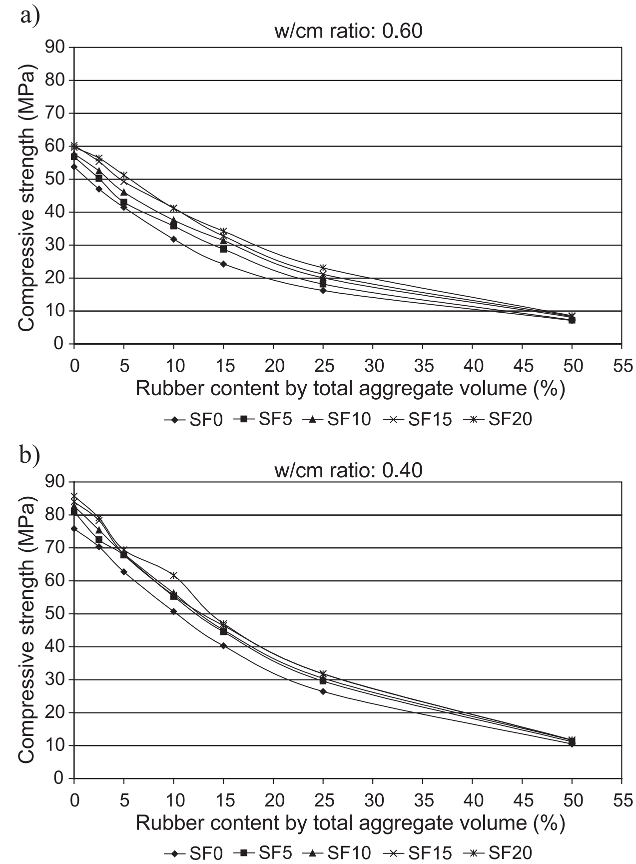


Fig. 4. Variation in the compressive strength of the concretes with rubber and silica fume contents; (a) w/cm ratio: 0.60 and (b) w/cm ratio: 0.40.

increasing the density of the cement paste, which, in turn, significantly enhances the compressive strength of the rubberized concretes [29–35].

### 3.2.2. Splitting tensile strength

The results of splitting tensile strength tests, Brazilian method, were given in Fig. 6. The strength reduction pattern

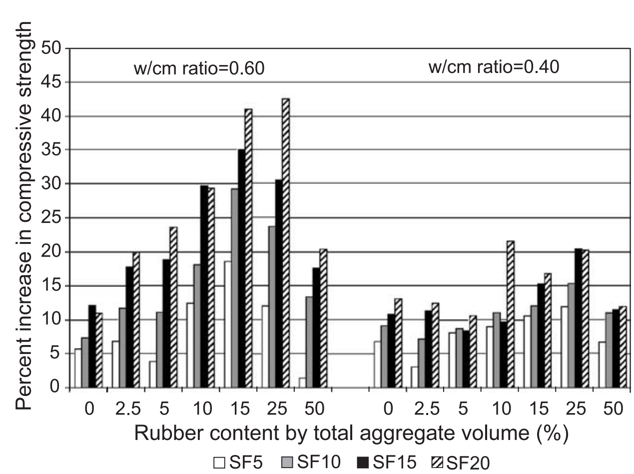


Fig. 5. Average percent increase in the compressive strength of the plain and the rubberized concretes with the use of silica fume.

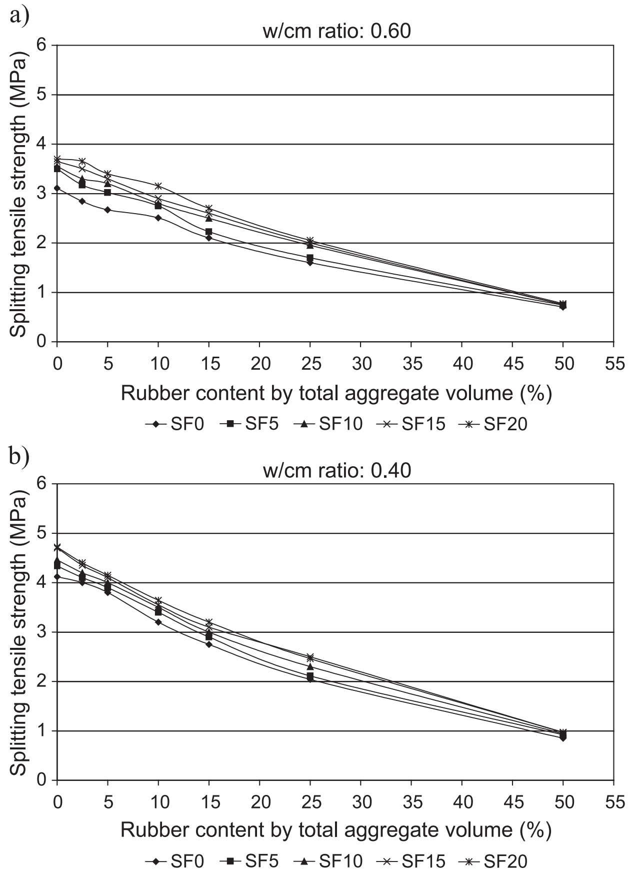


Fig. 6. Variation in the splitting tensile strength of the concretes with rubber and silica fume contents; (a) w/cm ratio: 0.60 and (b) w/cm ratio: 0.40.

for the splitting tensile strength is similar to that of the compressive strength. However, the rate of strength reduction in the former was lower than that in the latter. Plain concretes had initial characteristic strengths of about 3.1 and 4.1 MPa for 0.60 and 0.40 w/cm ratios, respectively. However, the concretes with silica fume acquired indirect tensile strengths varying from 3.5 to 3.7 MPa and from 4.3 to 4.7 MPa for high and low w/cm ratios, respectively, depending mainly on the silica fume content. Interestingly, these initial strength values dropped to about 0.7 and 0.9 MPa when 50% of the total aggregate volume was replaced with the rubber for the concretes with and without silica fume. This represents an 80% reduction in the splitting tensile strength for all concretes. Fig. 7 shows percent increase in the splitting tensile strength of the concretes with the use of silica fume for various rubber contents. Similar to the effect of silica fume on the compressive strength, the splitting tensile strength was greater for the concretes with silica fume, especially at high w/cm ratio. It was noticed that strength increments of as high as 27% and 23% were achieved for the rubberized concretes at high and low w/cm ratios, respectively. This beneficial effect of silica fume on the rubberized concretes was much higher at silica fume contents of 15% and 20% due to the fact that the higher the silica fume content, the higher the filler effect on the bond between the rubber particles and the surrounding cement paste. Furthermore, the ratio of splitting tensile strength to the corresponding compressive strength varied from 5.4% to 6.2% for the concretes with and without silica fume for both w/cm ratios. However, this ratio ranged from 5.6% to 10.3% for the rubberized concretes depending on the rubber content. This implied that the reduction in the splitting tensile strength with the rubber content was much lower than that in the compressive strength.

### 3.2.3. Modulus of elasticity

Static modulus of elasticity test results as a function of rubber and silica fume contents are depicted in Fig. 8. Moduli of elasticity of the plain concretes were about 33 and 46 GPa at 0.60 and 0.40 w/cm ratios, respectively. However, the silica fume concretes had slightly greater elastic modulus values which were about 36 and 47 GPa for high and low w/cm ratios, respectively, irrespective of the amount of silica fume used. Graphs in Fig. 8 showed that the static elastic modulus decreased with increasing rubber content in a fashion similar to that observed in both compressive and splitting tensile strengths. With increasing the rubber content to 50% of the total aggregate volume, the modulus of elasticity reduced to about 6.5 and 8.0 GPa for w/cm ratios of 0.60 and 0.40, respectively. This indicates a general reduction of about 83% in the elastic moduli in all concretes. With the use of silica fume, however, the elastic moduli of the concretes slightly increased and this positive effect is illustrated in Fig. 9. It was clearly observed that the increase in the elastic modulus was smaller as compared to that in the compressive and splitting tensile strengths. Generally, the plain and the rubberized concretes exhibited an increase in the modulus values of up to 15% depending on the amount of silica fume used. However, for the same w/cm ratio and the rubber content, all mixtures attained almost similar results.

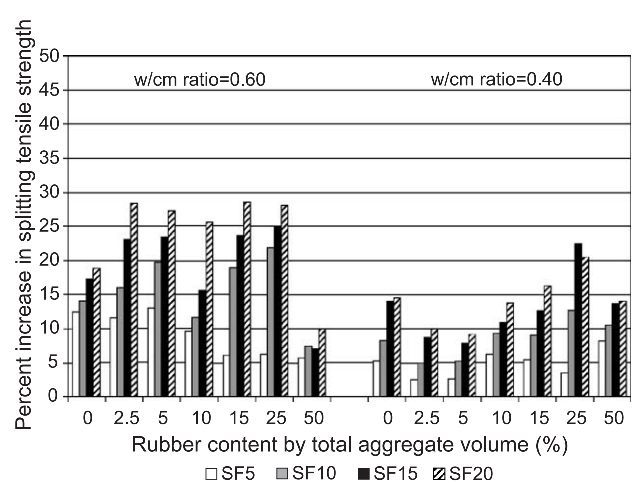


Fig. 7. Average percent increase in the splitting tensile strength of the plain and the rubberized concretes with the use of silica fume.

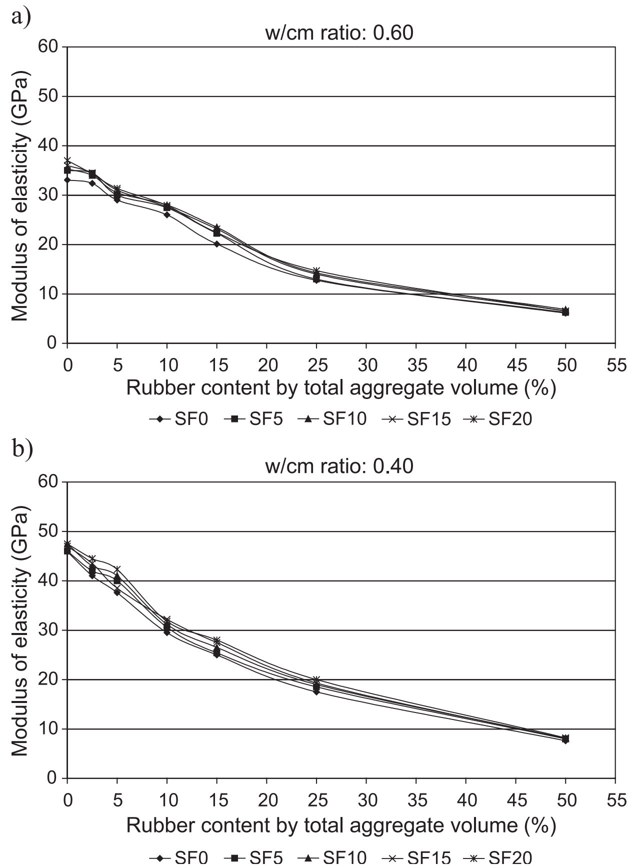


Fig. 8. Variation in the static elastic modulus of the concretes with rubber and silica fume contents; (a) w/cm ratio: 0.60 and (b) w/cm ratio: 0.40.

### 3.2.4. Reduction factors (RF) for the concrete properties

To simulate the reduction with rubber content in the mechanical properties of the rubberized concretes, a relation between an RF and the rubber content was examined and the parameters of this relationship were determined through regression analysis. The RF was defined as the ratio of the concrete property (compressive and splitting tensile strengths, and modulus of elasticity) of the mixture containing a rubber content $R$ to that of the control mixture. The variation of the RF determined for compressive strength, splitting tensile strength, and modulus of elasticity with the corresponding rubber content are presented in Figs. 10–12, respectively. The RF was unity at 0% rubber content, meaning the control mix. However, it gradually reduced with increasing rubber content from 0% to 50% by total aggregate volume. Similar results were reported by Khatip and Bayomy [17]. They studied several mathematical functions, including various degrees of polynomial functions and proposed the Eq. (1) to quantify the reduction in the compressive strength.

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

with the condition that

$$a = 1 - b \tag{2}$$

where, SRF is the strength reduction factor varying from 0 to 1; $R$ is the rubber content in volumetric ratio by total aggregate volume; $a$, $b$, and $m$ are the function parameters. In the study of Khatip and Bayomy [17], the control mixtures had 7- and 28-day compressive strengths of 20 and 38 MPa, respectively, both of which decreased to almost 3.2 MPa when 50% rubber had replaced the total aggregate volume. They found the function parameters ($a$, $b$, and $m$) as 0.18, 0.82, and 10 for the concretes tested at 7 days, and 0.10, 0.90, and 7 for the concretes tested at 28 days, respectively. This indicates that the function parameters significantly change for different strength levels. In this study, the function parameters that appeared in Eq. (1) were recalculated for the high-strength concretes with and without silica fume having an initial 90-day compressive strength ranging from 54 to 86 MPa. For this purpose, the test data obtained for compressive and splitting tensile strengths, and modulus of elasticity were applied to Eq.

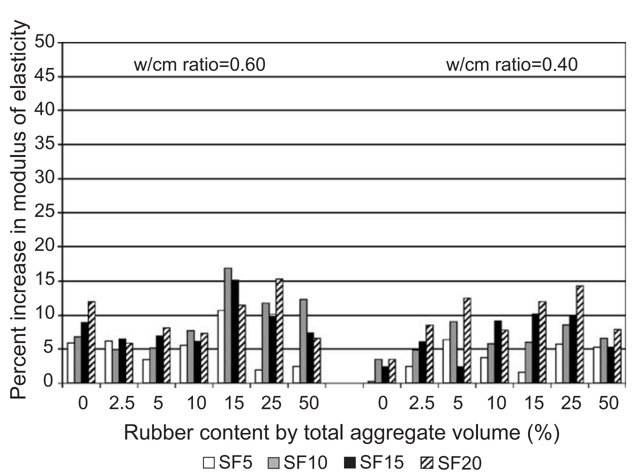


Fig. 9. Average percent increase in the static elastic modulus of the plain and the rubberized concretes with the use of silica fume.

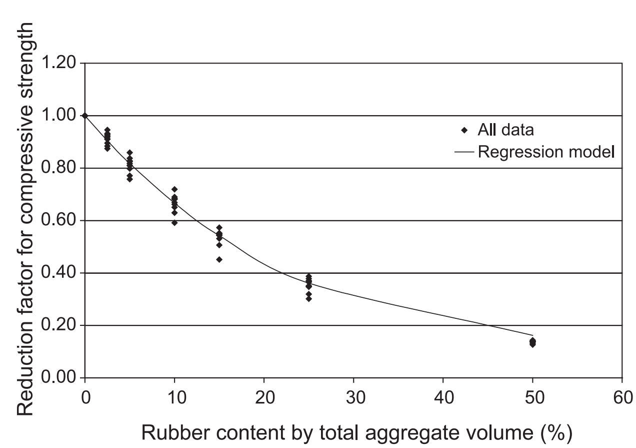


Fig. 10. Relationship between RF for the compressive strength and rubber content.

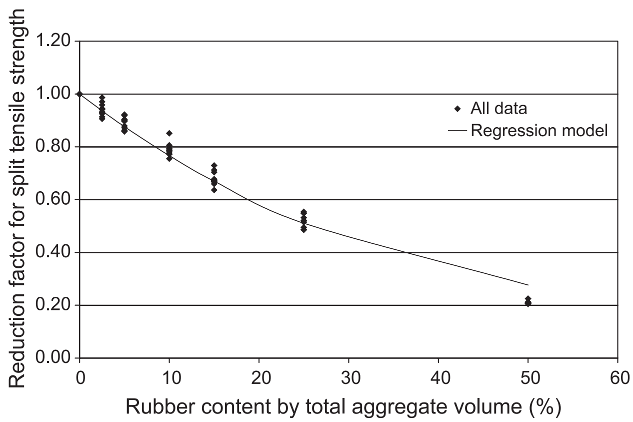


Fig. 11. Relationship between RF for the splitting tensile strength and rubber content.

(1) through regression analysis and presented in Figs. 10–12, respectively. Regression analysis was performed to fit a function for each group and for all groups as one set. It was found that for the mixes tested in this study, one function with the same parameters was sufficient to fit all the data. The proposed regression model for each concrete property is also depicted in Figs. 10–12 for compressive and splitting tensile strengths, and modulus of elasticity, respectively. Moreover, the relevant function parameters (*a*, *b*, and *m*), Pearson correlation coefficient ($r^2$), and the analysis of variance, *F* statistics, are summarized in Table 3. It was clearly observed from the analyses that the function parameters varied for each concrete property. However, all the proposed functions appeared to fit the test data perfectly as observed in the figures, and as seen by their significantly high $r^2$ values. In addition, the analysis of variance, *F* statistics, showed that all the relationships were significant at a 0.01 level. The above analyses indicate that the function parameters strongly depend on the concrete property tested (compressive and splitting tensile strengths, and modulus of elasticity) as well as the initial strength level of the control mixture.

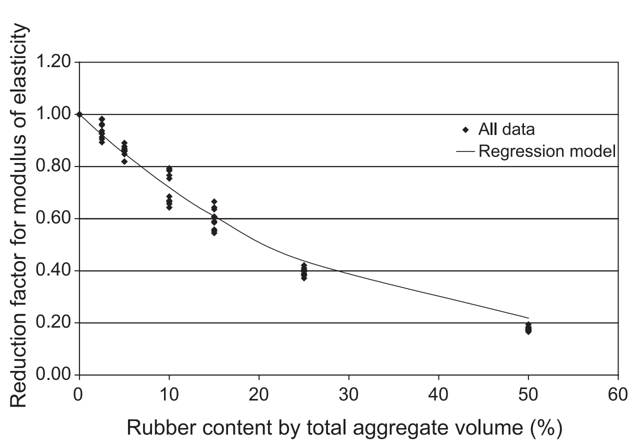


Fig. 12. Relationship between RF for the static elastic modulus and rubber content.

Table 3
Parameters of the proposed models for concrete properties and statistical test results

| Model parameters | Concrete property | | |
|---|---|---|---|
| | Compressive strength | Splitting tensile strength | Modulus of elasticity |
| *a* | 0.125 | 0.190 | 0.160 |
| *b* | 0.875 | 0.810 | 0.840 |
| *m* | 4.55 | 3.22 | 3.85 |
| Number of case, *n* | 70 | 70 | 70 |
| $r^2$ | 0.91 | 0.86 | 0.89 |
| *F* statistics | 658 | 415 | 554 |
| *P* level | 0.000 | 0.000 | 0.000 |
| Significance | Yes | Yes | Yes |

## 4. Conclusions

A series of tests has been carried out to measure the mechanical properties of the rubberized concretes with and without silica fume. Initially, the control concretes with compressive strengths ranging from 54 to 86 MPa were obtained at w/cm ratios of 0.60 and 0.40. The following conclusions may be drawn from the results of this study:

1. Based on the fresh concrete properties, rubberized concrete mixtures with and without silica fume appeared to be workable to a certain degree and they resulted in lighter weight concrete. Unit weight was decreased to as low as 77% of the normal weight concrete when 50% of the total aggregate volume was replaced with rubber.
2. The test results indicated that there was a systematic reduction in the compressive and splitting tensile strengths, and modulus of elasticity with the increase in rubber content from 0% to 50%. However, the use of silica fume considerably enhanced these mechanical features of both plain and especially rubberized concretes and decreased the rate of strength loss accompanied by the addition of rubber. This beneficial effect of silica fume was more pronounced for the compressive and splitting tensile strengths and resulted in a strength increment of as high as 43% and 27%, respectively, depending on the variation in the w/cm ratio and the amounts of silica fume and rubber used. On the other hand, the elastic moduli of the rubberized concretes slightly increased up to 15% with the use of silica fume.
3. From a practical point of view, rubber content should not exceed 25% of the total aggregate volume due to the severe reduction in the strength. When an upper level of 50% rubber was used, general reductions of up to 86%, 80%, and 83% of the compressive strength, splitting tensile strength, and modulus of elasticity were observed, respectively. However, the test results implied that it was

possible to produce a high-strength rubberized concrete with a compressive strength of about 40 MPa with the addition of rubber up to 15% of the total aggregate volume at 0.40 w/cm ratio.

4. The mathematical model proposed in the study well estimates the reduction in the mechanical features for any rubberized concrete with respect to rubber content. It was found that different function parameters were obtained for each concrete property tested and all the relationships were statistically significant at a 0.01 level. The functions presented are helpful in establishing the targeted basic engineering properties of the rubberized concretes for the mix design purposes.

This study has been exclusively focused on the workability, unit weight, and the mechanical properties of the rubberized concrete with and without silica fume and it should be pointed out that further research should be carried out on the durability of the rubberized concretes under adverse weathering conditions, such as wetting–drying cycles, long-term exposure to hot/humid environment, freezing and thawing cycles, etc.

## Acknowledgements

The authors would like to thank Mr. Mehmet Emre Baştopçu for his invaluable assistance during the laboratory phase of the study. The waste tire rubber supplied by Postaş A.Ş. is gratefully acknowledged.

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