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Mechanical behavior of self-compacting concrete pavements incorporating recycled tire rubber crumb and reinforced with polypropylene fiber

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A B S T R A C T

Increasing quantity of scrap tires are potential sources of fire and health hazards. Rubberized pavement is being considered as one of the promising and sustainable solutions to this current environmental and economic crisis in the world. This research focused on finding the best way of producing paving concrete with the use of tire rubber waste as a component material. Therefore, Tire Rubber Crumb (TRC) was used as a partial sand replacement (5%, 10% and 15%) material in the mix design of self-compacting concrete. Self-compacting concrete (SCC) is considered an energy efficient material; because it reduces on-site working and does not need any compacting energy. Fine aggregates with fineness modulus of 2.9, specific gravity of 2.64 (g/cm^3) and water absorption of 1.5% and coarse aggregates with maximum size of 12.7 mm, specific gravity of 2.68 (g/cm^3) and water absorption of 0.8 were used in this research. According to the results of this study, fresh concrete tests showed that both fiber and TRC have negative effects on rheological properties of fresh concrete. Furthermore, the hardened concrete tests showed that TRC decreases compressive strength, tensile strength, flexural strength, abrasive strength and modulus of elasticity while increasing water absorption of SCC. Therefore, polypropylene fibers were added into SCC specimens containing TRC and resulted in significant increases in compressive, tensile, flexural and abrasion strength but had no considerable effect on the modulus of elasticity of these specimens. Moreover, the presence of fiber in rubberized SCC decreased water absorption based on evaluation of ultrasonic waves velocity.

1. Introduction

Rapid growing amounts of rubber tire wastes is a serious consequence of significant increase in the number of vehicles. The high volume storage of scrap tires has deleterious effects on the environment. Waste tires would lead to significant health and environmental concerns if not recycled or discarded properly. One of the recent way of tackling this challenge is to apply this type of wastes into civil engineering infrastructures. Shredded rubber tires have been used as aggregates in concrete and gained popularity over the last years. Many studies have been conducted on using Tire Rubber Crumb (TRC) in different types of concrete in order to study crumb rubber effects on these concrete mechanical behavior (Meddah et al., 2014; Murugan & Natarajan, 2015; Elchalakani, 2015). Investigating mortars containing TRC resulted in the decreases in the flexural strength and the increase in probability of occurrence of accumulative plastic cracks (Meddah et al., 2014). Although the concrete made up of the large amount of TRC, up to 75%, and had the required workability, it was not suitable to be used as common structural concrete. Recently, many studies have been dedicated the use of TRC in self-compacting concrete (SCC) (Mishra and Panda, 2015; Venkatesh and Subramanian, 2015; Jedidia et al., 2014). Self-compacting concretes (SCCs), highly fluid concretes placed without vibration, were introduced into French construction works towards the end of the 1990s. Formulating SCCs is a compromise between sufficiently high fluidity to ensure good casting and an adequate consistency to avoid phase separation problems, segregation or bleeding. SCC is able to flow through even heavy reinforcement and achieve full compaction under its own weight (Khayat and De Schutter, 2014; Nikbin et al., 2014).

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Turatsinze and Garros (2008) observed that utilizing crumb rubber reduced concrete modulus of elasticity and any alternation in rubber content yielded a considerable error in conventional relations between modulus of elasticity and compressive strength. They also reported that strain capacity, ductility and strength against cracks increased by using rubber wastes.

Miller (2014) proved that the rubber replacement values more than 60% can increase the flexural toughness of concrete by enhancing its energy absorbing capacity. Rahman et al. (2012) concluded that although SCCs filled with TRC had lower compressive strength values than the normal SCC, using TRC in SCC improved some of its mechanical properties through decreasing natural frequencies and dynamic modulus or through increasing damping. TRC is commonly used in cement concrete paving and has acceptable serviceability and performance (Sukontasukkul and Chaikaew, 2006; Bignozzi and Sandrolini, 2006).

Sukontasukkul and Chaikaew (2006) studied concrete blocks of pavement containing TRC. Based on the results obtained in their study, blocks containing TRC have a lower compressive strength compared to normal blocks but yet are lighter, more flexible and have more energy absorption and lower abrasive strength.

Micro and macro cracks occur in concrete pavements because of their brittle behavior, low resistance to fatigue phenomenon and small toughness. Therefore, fibers are adopted to improve these detrimental properties of concretes. Many studies proved that fibers can considerably improve durability, tensile strength, impact resistance and toughness of the cement matrix, preventing the crack opening and growth in concrete. Fibers are commonly categorized into three groups, natural, metal and artificial (e.g. glass, nylon, polypropylene and carbon). The utilization of polymeric fibers has gained popularity in the recent years because of their advantages over the metallic ones with special regard to chemical stability, lightness and workability. Nobili et al. (2013) by doing an on-site work showed that the fiber reinforced concrete technology provides an efficient, safe as well as economical design solution for roadways. Moreover, polymeric fibers, particularly the polypropylene-based fibers, were found beneficial in reducing shrinkage cracking and improving abrasion resistance of concrete. Most experimental results indicate that using polypropylene can increase the abrasion resistance by 30–60% (Shuan-fa et al., 2001; Chen, 1995).

In the present study, both polypropylene fiber and TRC were utilized into SCC under laboratory conditions in order to detect their impacts on this concrete. Therefore, the specimens were made base on 16 different mix designs and empirical tests for measuring workability and consistency of fresh concrete such as slump, T50 and L-Box were performed. In the case of hardened concrete, many tests were done to determine the concrete physical and mechanical properties such as compressive and tensile strength, flexural strength, abrasion resistance, modulus of elasticity, water absorption, as well as ultrasonic pulse velocity test which is based on the pulse velocity method to obtain information on the uniformity and homogeneity of concrete and its cavities.

2. Methodology

Self-compacting concrete (SCC) with minimum amount of energy consumption in the placement and compaction process has been gaining popularity in the recent decade. Since the flowability is a key feature of SCC, by adding TRC and polypropylene, the flowability of fresh SCC should be studied. Therefore, slump flow, T 50 and L-Box tests were done for studying rheological property of fresh concrete. Each of these tests is indicative of one or several properties of SCC. Slump flow test is introduced to determine the concrete's ability to deflect under its own weight when there are no restrains except for friction and flow plain. Average diameter of the resulting circles formed after the slump test indicates the yield stress of fresh concrete and is a criterion to measure filling ability of concrete. Another parameter measured in slump flow test is the time within which the concrete reaches the radius of 50 cm and is used to determine plastic viscosity of fresh concrete. L-Box test indicates filling and passing ability of SCC and is designed to study flowability of fresh concrete and blockage phenomenon. Moreover, TRC and polypropylene have significant impacts on mechanical features of hardened concrete and as such, compressive strength, tensile strength, flexural strength, modulus of elasticity and abrasion resistance of SCC were needed to be investigated. Besides, the concrete durability is highly dependent on its permeability. The water absorption test measures the capability of fluid transition within the concrete. In addition, ultrasonic pulse velocity was done for achieving information about the uniformity and pore structures of concrete.

3. Experimental design

3.1. Materials used

Gravels and sands utilized in the tests was crashed and had a continuous gradation. In each mix design, fine aggregate with fineness modulus of 2.9, specific gravity of 2.64 (g/cm^3) and water absorption of 1.5% was used, while the coarse aggregate had a maximum size of 12.7 mm, specific gravity of 2.68 (g/cm^3) and water absorption of 0.8. The cement used in this study is Portland type II made in Neka factory, Iran, with density of 3.15 (g/cm^3) and specific surface area (Blaine surface) of 3050 (cm^2/g) as demonstrated in Table 1. In order to increase plastic viscosity of SCC, superplasticizer Glenium110p, provided by BASF Company, was used. It should be noted that in this research, manipulating the content of superplasticizer, all mixes have made to have the same rheological properties. Thus, the mechanical properties could be studied after reaching full compaction. Table 1 also demonstrates the chemical properties of limestone powder which was consumed as a filler with specific gravity of 2.7 (g/cm^3). The fiber used in this study was polypropylene (Fig. 1) which its physical and mechanical properties are provided in Table 2. TRC, provided by Iranian recycling corporation located in Tehran, are made grinding tires of heavy vehicles and used as aggregates in concrete specimens. Maximum size of TRC is 4.75 mm and the specific gravity is 1.122 (g/cm^3). Weight percentage of sulfur was equal to 0.97%. The shape and grading of TRC used in this study are displayed in Fig. 2 and Table 3. This TRC is gained through collecting tires of trucks, treating them with water then grinding them and finally taking wires and fibers out of them by industrial machines. Cryogenic and mechanical techniques are two highly used production process of

Table 1
Chemical composition of cement and limestone powder.

Chemical analysis	Cement	Limestone powder
SiO_2 (%)	21.90	0.3
Al_2O_3 (%)	4.86	0.1
Fe_2O_3 (%)	3.30	0.02
CaO (%)	63.32	–
MgO (%)	1.15	0.2
SO_3 (%)	2.1	–
K_2O (%)	0.56	–
Na_2O (%)	0.36	–
Free CaO (%)	1.10	–
$CaCO_3$	–	99.3
SG (g/cm^3)	3.15	2.66
Blaine (cm^2/g)	3050	2730

Fig. 1. Type of polypropylene employed in this study.

Table 2
Properties of the reinforcing fiber.

Type	Length (mm)	Diameter (mm)	Tensile strength (kg/cm^2)	Aspect ratio l/d	Elastic modulus (GPa)	Density (g/cm^3)
Polypropylene	6	0.1	4500	120	5	0.9

Fig. 2. Type of crumb rubber employed in this study.

granulated rubbers from spent tires. The cryogenic technique has many advantages-better gradation and size control, better maintenance of chemical components and physical structure and less odor or inhalable dust emission into the air-over the mechanical method (Cadle and Williams, 1980; Barbin and Rodgers, 1994; Gomes et al., 2010).

3.2. Mix designs

Determination of mix design for this research to obtain SCC was performed based on EFNARC (2002). By considering previous studies, it was concluded that additional fiber and TRC reduce the concrete workability. According to EFNARK, after addition of fiber and TRC to the concrete, the mixture still can respond positively to tests controlling concrete workability. The mix designs used for experiments as well as different volumes of polypropylene fiber (VF) and TRC are introduced in Table 4. TRC was used up to 15% volume of fine aggregate and polypropylene was utilized up to 0.15% of concrete volume. The mixing sequence was as follows. First, all materials were weighted based on the mix design and superplasticizer was added into mixing water. Second, the coarse and middle-sized aggregates were poured into rotary electric mixer drum along with a quarter of the mixing water and the drum ran for 2 min. Third, TRC and sand were added into the mixture and the drum rotated for 2 min. In the final stage, cement, limestone powder and the rest of mixing water were gradually added and mixed with the mixture for 6 min. For specimens with polypropylene, mixing fiber with the mixture after final stage lasted 4 min. Fresh concrete tests, slump flow, T 50 and L-Box tests were immediately done after mixing. In order to perform hardened concrete tests, from each mix design, cube specimens ($10 \times 10 \times 10$ cm^3 and $15 \times 15 \times 15$ cm^3), cylindrical specimens with 15 cm diameter and 30 cm height and also beam specimens ($10 \times 10 \times 50$ cm^3) were prepared. As it is shown in Fig. 3, all specimens were cured in the water, according to ASTM C192 standard for 28 days.

Table 3
TRC specification.

Sieve size	Percent remaining on the sieve
4.75 mm	0
2.36 mm	13.95
1.18 mm	74.10
600 µm	10.35
300 µm	1.45
150 µm	0.10
<150 µm	0.05
Specific gravity (g/cm^3)	1.122

Table 4
Concrete mixture proportion.

Series	Mix No.	TRC (%)	Fiber Vf (%)	Gravel (Kg/m^3)	Sand (Kg/m^3)	Crumb rubber (Kg/m^3)	Limestone powder (Kg/m^3)	Cement (Kg/m^3)	Water (Kg/m^3)	SP (Kg/m^3)
A	1	0	0.00	722.00	826.00	0.00	288.90	413.10	162.00	7.00
	2		0.10	722.00	826.00	0.00	288.90	413.10	162.00	7.50
	3		0.12	722.00	826.00	0.00	288.90	413.10	162.00	8.00
	4		0.15	722.00	826.00	0.00	288.90	413.10	162.00	8.50
B	1	5	0.00	722.00	784.70	17.55	288.90	413.10	162.00	7.50
	2		0.10	722.00	784.70	17.55	288.90	413.10	162.00	8.00
	3		0.12	722.00	784.70	17.55	288.90	413.10	162.00	8.50
	4		0.15	722.00	784.70	17.55	288.90	413.10	162.00	9.00
C	1	10	0.00	722.00	743.40	35.10	288.90	413.10	162.00	8.00
	2		0.10	722.00	743.40	35.10	288.90	413.10	162.00	8.50
	3		0.12	722.00	743.40	35.10	288.90	413.10	162.00	9.00
	4		0.15	722.00	743.40	35.10	288.90	413.10	162.00	9.50
D	1	15	0.00	722.00	702.10	52.65	288.90	413.10	162.00	8.50
	2		0.10	722.00	702.10	52.65	288.90	413.10	162.00	9.00
	3		0.12	722.00	702.10	52.65	288.90	413.10	162.00	9.50
	4		0.15	722.00	702.10	52.65	288.90	413.10	162.00	10.00

4. Results and discussion

4.1. Fresh concrete properties

High workability is a distinguished advantage of SCC over other kinds of concrete. Utilizing new materials such as TRC and polypropylene in SCC can directly influence the workability of SCC and as such, this crucial feature of the concrete must be characterized. Fresh concrete properties were studied through slump flow, T 50 and L-Box tests. The results obtained from fresh concrete tests are displayed in Table 5. According to Table 5, fiber and TRC have negative effects on rheological properties of fresh SCC. This is due to the reduction of water to cement ratio and the shape of TRC which partly have jagged edges while some do not have a regular shape. TRC absorbs the water of the mixture and reduces the necessary water needed for cement hydration and aggregate lubrication. Aggregate shape is a distributing factor which affects the concrete consistency. The coarser aggregates are needed more energy to overcome their internal friction and to flow with more ease. Moreover, fibers, spreading through the concrete, form a three-dimensional web preventing concrete flowability and aggregate segregation. This leads to the increase of internal friction and as such have negative effects on rheological properties of SCC. Furthermore, as can be observed, due to high deviation of rheological properties from an allowable range, the properties of hardened SCC containing TRC are not studied when over 0.15% fiber is applied.

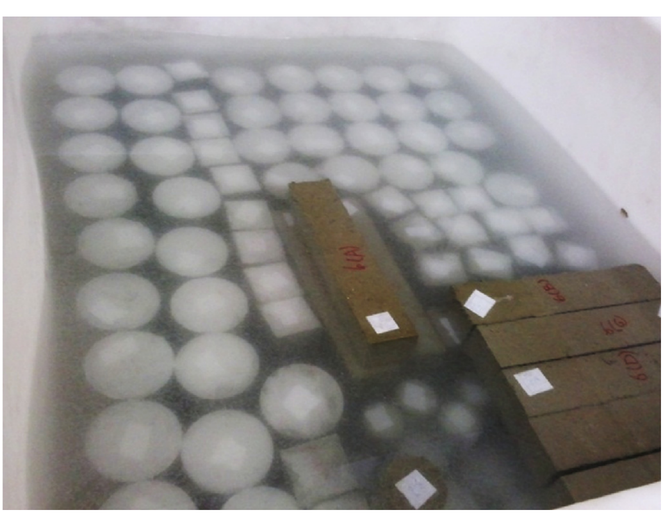

Fig. 3. Curing of specimens.

4.2. Properties of hardened concrete

4.2.1. Compressive strength tests

Compressive strength as an important property governing other mechanical properties corresponding to load-bearing capacity and is a defining index of concrete classification in international codes. The 10 × 10 × 10 cm^3 cube concrete specimens containing polypropylene fiber and TRC as aggregate replacement were prepared and compressive strength of these specimens at the age of 28 days, according to BS EN, 12390, were measured. All specimens were cured in water one day after they had been cast and demolded. Three specimens were made based on each mix design and the average values are displayed in Table 6. As it can be seen in Table 6, generally the compressive strength decreases with the increase of TRC as sand replacement.

Adding 15% rubber as aggregate replacement, without the inclusion of fibers, reduces the compressive strength by 29% while for 5% replacement there is roughly a 13% reduction of compressive strength as compared to the original mix design. This decrease is because of the fact that rubber has lower strength than the aggregate. This strength reduction, due to the addition of rubber, is also attributed to physical properties of TRC. Strength reduction can also be due to behavior of rubber as a soft material which

Table 5
Result of fresh concrete test.

Series	Mix No.	Slump flow D_{ave} (mm)	Flow time T_{50} (sec)	L-Box (h_2/h_1)
A	1	74.50	2.21	0.88
	2	72.00	2.75	0.83
	3	70.00	3.51	0.82
	4	67.00	4.43	0.76
B	1	74.00	2.52	0.84
	2	70.30	3.13	0.81
	3	68.30	3.84	0.76
	4	65.00	4.85	0.69
C	1	72.50	2.89	0.81
	2	68.70	3.64	0.77
	3	64.50	4.56	0.73
	4	62.50	5.65	0.68
D	1	70.00	3.51	0.76
	2	66.50	4.12	0.72
	3	64.70	5.03	0.68
	4	60.30	6.07	0.65

Table 6
Result of hardened concrete test.

Series	Mix No.	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Flexural strength (MPa)
A	1	78.05	4.90	42.53	8.45
	2	79.65	5.85	44.65	10.66
	3	74.53	6.27	46.39	11.24
	4	–	–	–	–
B	1	68.12	4.82	40.21	8.03
	2	73.21	5.70	43.74	9.94
	3	70.07	6.08	44.09	10.74
	4	–	–	–	–
C	1	59.94	4.63	38.56	7.48
	2	68.55	5.54	41.26	9.49
	3	66.10	5.90	42.76	10.02
	4	–	–	–	–
D	1	55.15	4.20	35.03	6.98
	2	67.21	5.09	36.45	8.45
	3	54.01	5.33	37.59	9.14
	4	–	–	–	–

contributes to stress concentration. Stress concentration can cause the rubber to detach from the cement matrix forming micro cracks in the concrete. Moreover, the bond between rubber and paste is weak which causes segregation (Ismail and Al-Hashmi, 2008). In the case of reinforcement, adding polypropylene to the reference specimens caused an increase in the compressive strength. This strength growth is because of the bridging role of fibers preventing full segregation of the composite by the time fracture occurred. Through decreasing the rate of crack formation and development, changing the direction of the crack and improving strength of concrete matrix, fibers resist against the degradation which is induced by the high-range loads. Decrease of the compressive strength in concrete, due to increase of volumetric content of fiber, can be attributed to fiber balling which happens when fiber content percentage exceeded the optimum value and fibers are evenly scattered and thus improper bond is formed between fiber and cement matrix. This significantly reduces the fiber function in improving the concrete structure. It can be generally concluded that fiber percentages in fiber concrete does not have considerable effect on the compressive strength.

4.2.2. Splitting tensile strength

Splitting Tensile strength test, according to ASTM C496, was carried out on cylindrical specimens (15×30 cm^3) in 28 days of curing. From each mix design, three specimens were made and the average of measured valued are provided in Table 6. From Table 6, it can be concluded the declining trend of tensile strength with the increase of rubber content. As it can be observed, 15% replacement of sand volume with rubber, when no fiber is added, causes the tensile strength to decrease by 14.29%.

The more similar moderate trend was observed for compressive strength. Strength reduction can be due to reduction of load bearing capacity of material as well as stress concentration (tensile and compressive) in the paste of the transition zone between aggregate and rubber (Ismail and Al-Hashmi, 2008). The curve provided in Table 6 shows the positive effect of increasing fiber content of tensile strength. This is due to the fact that the tensile fracture mode in concrete containing fiber does not follow the tensile fracture mode of normal concrete. Thus, unlike fiber-less concrete where the fracture is immediate and roughly brittle, in fiber concrete, fracture is gradual and less brittle and the two parts are not completely separated. Fracture of the fiber concrete can be divided into two stages. First, tensile strength is provided only by concrete and fiber is not involved yet. Second, after the concrete yields and fracture occurs, fiber launches into resisting against the tensile stress and transferring them to the two adjacently separated part which results in increase of energy absorption of concrete. As can be detected, fiber has been more significant on tensile strength than the compressive strength.

4.2.3. Modulus of elasticity

Modulus of elasticity is an important mechanical property used to determine the behavior of concrete. Modulus of elasticity is determined according to ASTM C469 standard through averaging the test results of three cylindrical specimens (15×30 cm^3) as shown in Table 6. As can be seen in Table 6, modulus of elasticity is more sensitive to change of rubber contents than fiber content. Since concrete's deflection is partly dependent to deflection of the aggregate (Duarte et al., 2015; Rahmani et al., 2013), so the type of aggregate used affect the modulus of elasticity. Thus decrease of modulus of elasticity can be due to a low modulus of elasticity of TRC. Moreover, as can be observed from Table 6, the presence of fiber has no considerable effect on the modulus of elasticity and only an imperceptible increase is detected (Tassew and Lubell, 2014; Yang et al., 2012; Karahan and Atiş, 2011; Zhang et al., 2014).

4.2.4. Flexural strength

Since bending loads cause the most critical stresses on pavement structures, the flexural strength (also known fracture modulus) is used as a decisive assessment factor of pavement strength. The flexural strength of concrete is determined according to ASTM C78 or AASHTO T97 standards. While some research institutes use the results of center-point flexural strength included in ASTM C293 or AASHTO T97 to assess the traffic serviceability of pavements. In this study, in order to investigate the effect of varying percentages of TRC as sand replacement and varying contents of polypropylene, the beam specimens ($10 \times 10 \times 50$ cm^3) have been prepared based on the ASTM C293 standard. All specimens have been demolded after being cured one day in 20 °C water. The three specimens were made from each mix design and all specimens were tested by Universal Machine (Fig. 4). The average values are displayed in Table 6. As it shown in Table 6, the use of rubber in concrete leads to a decline in the flexural strength of the samples. For instance, 15% rubber content addition caused a 17% decrease in flexural strength. The same trend, more moderate though, happens for flexural strength. This strength reduction is due to the fact that the strength of TRC is lower than the natural aggregate. Also, as can be seen in Table 6, reinforcing the concrete in three dimensions, fiber can increase durability and resistance against all types of cracks. After a crack is formed, fiber can function as a bridge holding the initially formed cracks together and resist the load until fiber is pulled out of the cement matrix or yields.

Fig. 4. Flexural strength test using "Universal Machine".

4.2.5. Water absorption

Permeability, in concrete, is defined as the ability of concrete to transmit fluid. Almost all pavement damages, are attributed to durability, can be reduced or even stopped through decreasing permeability. This is because of most durability dependent failure mechanisms originate from harmful substances penetrating the concrete. Water absorption rate in specimens was measured according to ASTM C642 after 28 days of curing. Thus, three cube specimens (10 × 10 × 10 cm^3) were used and the average values have been presented. The results of water absorption test for various amount of rubber contents and different percentages of polypropylene fiber are provided in Table 7. As can be observed in Table 7, increasing TRC as sand replacement increases water absorption. 15% sand replacement with TRC, in fiber concrete, leads to 26.47% increase of water absorption. This increase is due to the fact that sand is substituted by TRC which have different shapes and structures, some porosity is formed increasing water absorption. On the other hand, increasing of fiber content in concrete decreases water absorption.

4.2.6. Ultrasonic pulse velocity

Ultrasonic pulse velocity provides information on the uniformity and homogeneity of concrete and its cavities. The amount of cavities in the pavement influences the amount of noise generated by vehicles. In order to measure the velocity of ultrasonic waves, according to the ASTM C597, nondestructive electrical device (PUNDIT 7 MODEL PC 1012) with accuracy of 0.1 micro second is used. A transducer with a vibration frequency of 52 kHz, accuracy of ±1% for travel time and ±2% for distance were also utilized. Nine measurements were made for three cube specimens (10 × 10 × 10 cm^3) from each mix design. The average time has been recorded and the results are provided in Table 7. According to Table 7, since adding rubber makes the pore structure in the concrete, the increase of TRC in concrete mixes decreases the velocity of ultrasonic waves. The cavities formed by TRC develops resistance against the transmission of ultrasonic waves and thus passing of waves is attenuated. When wave emissions reach different materials, some are reflected while some pass through and thus the velocity is decreased. Decreased velocity is also detected when polypropylene fiber content is increased because this type of fiber is insulated against ultrasonic waves (Nik and Omran, 2013).

4.2.7. Abrasion resistance

Abrasion resistance of concrete is defined as concrete's capability to resist surface abrasion and is dependent on the compressive strength of concrete and the type of aggregate used. Harder aggregates have higher abrasion resistance as compared to softer aggregates. In order to investigate the effect of varying percentages of sand replacement with TRC on abrasion resistance of the concrete, according to GB/T 16925-1997, specimens with dimensions of 15 × 15 × 15 cm^3 were prepared. Table 7 shows the results of abrasion resistance for all specimens at the age of 28 days. As it can be seen, the index of abrasion resistance of SCC has a declining trend with the increase of rubber content. Since cement paste does not display considerable abrasion resistance, the abrasion resistance is dependent on aggregate stiffness and thus substitution of aggregate by TRC reduces the aggregate volume and thus abrasion resistance is decreased. Moreover, Table 7 shows that index of abrasion resistance of concrete containing polypropylene fiber increases with the fiber content growth. The amount of this growth is roughly the same as those reported in previous studies indicating that use of fiber improves the abrasion resistance of concrete. Most experimental results maintain that use of polypropylene fiber can increase the abrasion resistance by 20–60% (Shuan-fa et al., 2001; Chen, 1995). Thus, the declining trend of abrasion resistance, due to addition of TRC, is compensated and the index of abrasion resistance increases.

5. Conclusion

Rubberized pavement is being taken into account as a sustainable approach to deal with the environmental and economic crisis

Table 7
Results of water absorption test, ultrasonic wave test and abrasion resistance.

Series	Mix No.	Water absorption (%)	Ultrasonic pulse velocity (m/s)	Index of abrasion resistance
A	1	1.36	5128.00	1.31
	2	1.18	4615.70	1.58
	3	1.15	4531.50	1.78
	4	–	–	–
B	1	1.49	4871.50	1.28
	2	1.27	4579.50	1.43
	3	1.19	4420.20	1.61
	4	–	–	–
C	1	1.60	4728.20	1.15
	2	1.40	4533.90	1.30
	3	1.26	4387.50	1.55
	4	–	–	–
D	1	1.72	4539.00	1.03
	2	1.50	4449.10	1.22
	3	1.38	4322.90	1.50
	4	–	–	–

of large amount of waste tire in the world. In addition, since self-compacting concrete (SCC) reduces the amount of energy needed for filed working, it is considered as an energy efficient material which is sustainably suitable for pavement construction. In the present study, physical properties of SCC containing TRC as partial sand replacement and also the effect of addition of polypropylene fiber to this type of concrete have been investigated and the following results have been obtained.

1. The results of tests carried out on fresh concrete signifies the negative effects of increasing fiber content and TRC in concrete on rheological properties of fresh SCC.
2. With the increase of rubber content, the compressive strength of concrete at the age of 28 days decreases because aggregates are expected to bear the higher level of loads than rubbers and also, the adhesion between TRC and paste is weaker than that between aggregate and paste. However, addition of fiber up to the optimum content of 0.1% increases the compressive strength.
3. The results of the tensile strength test indicated that the tensile strength decreases by increasing the sand replacement with rubber. For instance, 15% sand replacement with rubber resulted in a 14.29% decrease in the compressive strength. This is due to the fact that the tensile fracture mode in concrete containing fiber is different from tensile fracture mode of normal concrete.
4. Replacing the aggregate with TRC decreases the modulus of elasticity. Moreover, the results showed that presence of fiber does not have considerable effect on modulus of the elasticity of concrete and only an imperceptible increase is detected.
5. Increasing the share of rubber as a sand replacement leads to a reduction in the flexural strength. For instance, 15% sand replacement with TRC, when no finer is used, leads to a 17% decrease in flexural strength. However, addition of fiber can improve the flexural strength after the formation of cracks.
6. Increasing the rubber content from 0 to 15%, when no fiber is used, increases the water absorption by 26.47% while addition of fiber decreases water absorption.
7. By increasing the rubber content in SCC, the velocity of ultrasonic wave is reduced. This is due to the shape of TRC which contributes to the pore structure. Also, the increase of polypropylene fiber causes a reduction in the velocity of the ultrasonic waves.
8. Abrasion resistance index of has a declining trend by the growth of rubber content or the reduction in the content of fiber. Finally, considering the results obtained, it can be stated that increase of TRC in SCC up to 15% has no considerable negative effect on some of the properties studies in this research. However, this effect can be compensated through adding a certain percentage of fiber to the mix. Since enormous volume of concrete is used in different industries every year, considerable quantities of waste rubber can be used in concrete and thus a huge step is taken toward the elimination of such durable pollutants in the environment.

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