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Scrap-tyre rubber replacement for aggregate and filler in concrete

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Abstract

In this research the performance of concrete mixtures incorporating 5, 7.5 and 10 percent of discarded tyre rubber as aggregate and cement replacements was investigated. Numerous projects have been conducted on replacement of aggregates by crumb rubbers but scarce data are found on cementitious filler addition in the literature. Hence to examine characteristics of tyre crumb-containing concrete, two sets of concrete specimens were made. In the first set, different percentages by weight of chipped rubber were replaced for coarse aggregates and in the second set scrap tyre powder was replaced for cement. Selected standard durability and mechanical test were performed and the results were analysed. The mechanical tests included compressive strength, tensile strength, flexural strength and modulus of elasticity. The durability tests included permeability and water absorption. The results showed that with up to 5 percent replacement, in each set, no major changes on concrete characteristics would occur however with further increase in replacement ratios considerable changes were observed.

Keywords: tyre rubber; crumb rubber; shredded rubber; rubber aggregates; tyre rubber powder; rubber-containing concrete; rubber concrete; concrete durability.

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1. Introduction

In recent decades, worldwide growth of automobile industry and increasing use of car as the main means of transport have tremendously boosted tyre production. This has generated massive stockpiles of used tyres. In the early 1990s, extensive research projects were carried out on how to use used tyres in different applications. Scrap tyre is composed of ingredients that are non-degradable in nature at ambient conditions. They usually produce environmental mal-effects. One of the methods for utilisation of these materials is their use in concrete and other building products. From the macro-economic perspective, the following issues should be compared and evaluated when considering the application of such materials in the concrete:

1. Collection, processing and transport costs of scrap tyres
2. Reduction in the environmental costs of landfilling and increase in landfill voids; and,
3. Saving in the virgin materials used to make concrete, by substituting tyre rubber.

In this respect, many authorities in European Union and North America have forbidden the landfilling of scrap tyres in the recent years. Hence their reuse in the fabrication of other products has been growing immensely.

Rubber Manufacturer's Association [1] estimates that about 300 million tyres were generated in the USA in 2005 and the total number of scrap tyres consumed in end-use markets reached approximately 260 million tyres. It also estimates that about 190 million scrap tyres remained in stockpile at the end of 2005 in the USA [1].

Official Iranian statistics estimated that about 20 million tyres were produced in the country in 2005 [2] and estimated that about 10 million scrap tyres were added to the existing stockpile annually in Iran. To this effect in the last decade considerable research and development has been carried out for the use of tyre crumbs in asphaltic pavement layers in Iran [3]. Their results showed that rubberised bituminous layers had better skid resistance, reduced fatigue cracking and longer design life than conventional bituminous mixtures [4 and 5]. In order to expand the current research knowledge-base on the use of this crumbs an extensive research programme was set up to find first, the feasibility of cement replacement by scrap tyre powder in concrete and second to compare and contrast the aggregate replacement by tyre crumbs in concrete.

In this research work the effect of replacing 5, 7.5, and 10 percent by weight of coarse aggregates by chipped tyres and the same replacement ratios for cement by powder tyre crumbs, were investigated.

2. Classification of the scrap tyres

Tyres may be divided into two types: car and truck tyres. Car tyres are different from truck tyres with regard to constituent materials, especially natural and synthetic rubber contents (Table 1). Considering the high production volume of car tyres as compared to truck tyres, the former is usually of more interest to researchers.

In most of the researches performed, usually three broad categories of discarded tyre rubber have been considered such as chipped, crumb and ground rubber:

1) Shredded or chipped rubber to replace the gravel. To produce this rubber, it is needed to shred the tyre in two stages. By the end of stage one, the rubber has length of 300 - 430 mm long and width of 100 - 230 mm wide. In the second stage its dimension changes to 100 - 150 mm by cutting. If shredding is further continued, particles of about with 13 - 76 mm in dimensions are produced and are called “shredded particles”.
2) Crumb rubber that replaces for sand, is manufactured by special mills in which big rubbers change into smaller torn particles. In this procedure, different sizes of rubber

particles may be produced depending on the kind of mills used and the temperature generated. In a simple method, particles are made with a high irregularity in the range of 0.425 - 4.75 mm.

3) Ground rubber that may replace cement is dependent upon the equipment for size reduction. The processed used tyres are typically subjected to two stages of magnetic separation and screening. Various size fractions of rubber are recovered in more complex procedures. In micro–milling process, the particles made are in the range of 0.075 - 0.475 mm.

3. Research on application of tyre rubbers in concrete

Many authors have reported the properties of concrete with used tyre rubbers. Their results indicate that the size, proportion, and surface texture of rubber particles affect the strength of used tyre rubber contained in concrete [4-12]. Eldin and Senouci [6] conducted experiments to examine the strength and toughness properties of rubberised concrete mixtures. They used two types of tyre-rubber, with different tyre-rubber content. Their results indicated approximately 85% reduction in compressive strength, whereas the splitting tensile strength reduced by about 50% when the coarse aggregate was fully replaced by chipped tyre-rubber. A smaller reduction in compressive strength (65%) was observed when sand was fully replaced by fine crumb rubber. Concrete containing rubber did not exhibit brittle failure under compression or splitting tension and had the ability to absorb a large amount of energy under compressive and tensile loads. A more in-depth analysis of their results indicates an optimised mixture proportion is needed to optimise the tyre rubber content in the mixture. Biel and Lee [13] had used recycled tyre in concrete mixtures made with magnesium oxychloride cement, where aggregate was replaced by fine crumb rubber up to 25% by volume.

Their results of compressive and tensile strength indicated that there is better bonding when magnesium oxychloride cement is used. They discovered that structural applications could be possible if the rubber content is limited to 17% by volume of the aggregate. Schimizze et al. [14] developed two rubberised concrete mixtures using fine rubber crumbs in one mixture and coarse chipped rubber in the second. While these two mixtures were not optimised and their mixture proportioning parameters were selected arbitrarily, their results indicated a reduction in compressive strength of about 50% with respect to the control mixture. The elastic modulus of the mixture containing coarse chipped rubber was reduced by about 72% of that of the control mixture, whereas the mixture containing the fine rubber crumbs showed a reduction in the elastic modulus by about 47% of that of the control mixture. The reduction in elastic modulus indicates higher flexibility, which may be viewed as a positive gain in mixtures used in stabilized base layers in flexible pavements. In recent years, used tyre chipped rubber containing Portland cement concrete for uses in sound/crash barriers, retaining structures, and pavement structures has been extensively studied [4, 6, 9, 15, 16, 17]. Test results showed that the introduction of used tyre chipped rubber considerably increases toughness, impact resistance, and plastic deformation but in almost all cases a considerable decrease in strength was observed.

Khatib and Bayomy[4] studied the influence of adding two kinds of rubber, crumb (very fine to be replaced for sand) and chipped (at the size of 10 – 50 mm to be replaced for gravel). They made three groups of concrete mixtures. In group A, crumb rubber to replace fines, in group B, chipped rubber to replace coarse aggregate, and in group C both types of rubber were used in equal volumes. In all, the three groups had eight different rubber contents in the range of 5 – 100 % were used. They found that the compressive strength of concrete would decrease with increasing rubber content. For example, replacing 100% gravels by chipped rubber would decrease the compressive strength of concrete up to 90%. Meanwhile, they showed that the rubberised concrete made with chipped rubber has less strength than concrete made with crumb rubber.

Topcu [9] investigated the particle size and content of tyre rubbers on the mechanical properties of concrete. He found that, although the strength was reduced, the plastic capacity was enhanced significantly.

Serge and Joekes [18], in their study, added rubber particles in cement paste (rubber particles had a size with maximum 500 μm). In order to decrease hydrophobic nature of rubber surface, NaOH was chosen. At first, the surface of rubber particles were modified by saturated NaOH for 20 minutes. They concluded that the rubber particles treated by NaOH show better cohesion with cement paste. Their results indicated that there was an improvement in flexural strength by this procedure, but a 33% decrease occurred in compressive strength.

Naik et al [11, 19] studies concluded that among the surface treatments tested to enhance the hydrophilicity of the rubber surface, a sodium hydroxide (NaOH) solution gave the best result. The particles were surface-treated with NaOH saturated aqueous solutions for 20 minutes before using them in concrete. Then, scanning electron microscopy (SEM) and measurements of water absorption, density, flexural strength, compressive strength, abrasion resistance, modulus of elasticity, and fracture energy tests were performed, using test specimens (water-to-cementitious materials ratio of 0.36) containing 10% of powdered rubber or rubber treated with 10% NaOH. The test results showed that the NaOH treatment enhances the adhesion of tyre rubber particles to cement paste, and mechanical properties such as flexural strength and fracture energy were improved with the use of tyre rubber particles as addition instead of substitution for aggregate. Some reduction in the compressive strength (33%) was observed, which was lower than that reported in the literature.

Li et al [20] tried to improve the strength and stiffness of used tyre modified concrete by using larger sized (approximately 25, 50, and 75 mm long and 5 mm thick) chipped rubber fibres and NaOH-treating. They concluded that such fibre-rubbers perform better than chipped rubbers (approximately 25 × 25 mm square shaped with 5 mm thickness) do but the NaOH surface treatment does not work for larger sized chipped tyres.

Researchers [4, 6, 9, 14, 16, 21] found that the dynamic modulus of elasticity and rigidity decreased with an increase in the rubber content, indicating a less stiff and less brittle material. Also the impact resistance of concrete increased when rubber aggregate were incorporated into the concrete mixtures. The increase in resistance was derived from the enhanced ability of the material to absorb energy.

From the above literature survey, it is seen that used tyre rubber concrete is characterised as having high toughness but low strength and stiffness. By comparing and contrasting these studies, it is clear that these differences in their results are due to the quality of gravel materials and cement, as well as various procedures used for attaining to concrete mixture proportions. Meanwhile, in all of these studies, replacing gravel had been done by volume percentage. In the research programme reported in this paper, to review the influence of using used rubber, the percent replacement by weight was considered for replacing the standard Iranian coarse aggregate. Various mixtures were proportioned and mechanical tests were performed.

4. Experimental programme

4.1. Materials used

Commercially available crushed siliceous aggregates complying with ASTM C33-78 were employed for both coarse and fine fractions to make concrete specimens. Coarse aggregates used to make concrete test samples were angular type with maximum 25 mm in size. Fine aggregates, were also selected from the washed crushed stone. Grain size distributions for coarse and fine aggregate used are shown in Figs. 1 and 2. The Iranian Standard boundaries are also shown in Figs. 1 and 2 in dotted lines. The relative density (specific gravity), saturated surface-dry absorption, and fineness modulus of the fine aggregate were 2.65, 4.2%, and 3.7, respectively. The specific gravity and absorption for coarse aggregate were 2.64 and 1.8%, respectively.

Tyre rubber used in the experiments was applied in the following two size grading:

1. Chipped rubber for replacement with coarse aggregates in normal concrete was to prepare in the laboratory by scissor into smaller chips, from big pieces of tyre rubber. The specified size was that grading is similar to that of coarse aggregates. The grading chart for chipped rubber to be replaced for coarse aggregates is shown in Fig. 2. The relative density of chipped rubber was 1.3.
2. Ground rubber (tyre powder) in 200 to 850 micrometre size for replacement of cement in concrete was prepared from crumb rubber by grinding to powder in special grinders (i.e. micro–mills). Particle size analysis of the tyre rubber powder used in making concrete mixtures was carried out using Malvern laser analyser. Results are shown in Fig. 3. Water and 5ml Nonidet P40 as the dispersant was used for the particle size analysis. The Nonidet breaks the surface of the water to stop the sample floating. As it can be seen from this figure, the particles are generally between 45 μm to 1.2 mm diameter and mostly pass 600 μm. The relative density (specific gravity) of ground tyre powder was 0.8.

Concrete specimens were made using locally available Type II Portland cement (ASTM C 150, Type II) complying with Iranian specification 389. Drinking water was used for mixtures and curing.

4.2. Mixture proportions

There were two basic mixtures. The water/cement ratio was taken as 0.5 and super plasticiser, 0.4 percent by weight of cement, was used for both mixtures.

In the first mixture, 5, 7.5, and 10 percent by weigh of coarse aggregates were replaced by chipped tyre rubber. The mixtures were designated as RA x, which stands for 'Replaced Aggregate' by 'x' percent.

In the second mixture, 5, 7.5 and 10 percent by weigh of cement were replaced by ground tyre rubber. The mixtures were designated as RC x, representing 'x' percent replacement for cement.

The control mixture in this research is designated as 'C'. Mixture proportioning specifications are detailed in Table 2.

4.3. Mixing, casting, and testing

The interior of the mixing drum was initially wetted with water to minimise absorption of water added as a part of the concrete mixture. The coarse aggregate fractions were mixed first, followed by the cement, part of the required amount of tyre rubber, sand, and water containing three quarters of the required amount of super plasticiser. One quarter of the super plasticiser was always retained to be added during the last three minutes of the mixing period.

150 mm cube and 100 × 100× 500 mm prism moulds were used for casting test specimens. A vibrating table was used to achieve proper and consistent compaction.

After casting, all concrete specimens were covered with wet burlap in the laboratory at 20±1 °C and 65 % relative humidity for 24 hours.

24 hours after placing concrete in moulds, samples were de-moulded and were kept in a completely humid environment (95 +/- 5 % RH and temperature of 20° C) for 28 days.

The compressive strength of specimens was determined according to the British Standard BS 1881: part 116: 1993. Also the tensile strength and modulus of elasticity were determined according to BS 1881: part 117: 1983 and BS 1881: part 121: 1983.

Flexural strength test was also carried out according to BS 188: part 118: 1983, using prism specimens of 100 × 100× 500 mm dimensions.

Water permeability tests were carried out according to the BS EN 12390-8:2000 [22] (based on the depth of penetration of water under pressure). To determine diffusion depth into samples after water penetration, the samples were crushed and water diffusion depth was measured.

To determine water absorption, samples were tested according to BS 1881-122:1983, i.e., the water absorption of concrete specimens was determined from the mass difference of the sample between dry and wet states divided by its mass in dry condition.

5. Experimental results and discussion

The results of tests and measurement values taken in the laboratory, and their analysis are given below.

5.1. Compressive strength test

The results of 7-days and 28-days compressive strength tests for concrete mixtures are shown in Figs. 4 and 5. As expected, in line with the findings of other researchers, in general, the strength of concrete mixtures containing chipped rubber was reduced. As it can be seen in Figs. 4 and 5, with 5 percent powder rubber replacement, the compressive strength was reduced by only about 5 percent when compared to control mixture despite 5 percent reduction in cement content by weight. Replacements of 7.5 and 10 of powder rubber reduced the strength by 10 to 23 percent, respectively. These were mainly due to reduction in the cement content in these mixtures.

The reasons for reduction in the compressive strength of concrete when rubber was used were more related to differing properties of rubber particles and aggregates. These factors include:

1- As cement paste containing rubber particles surrounding the aggregates is much softer than hardened cement paste without rubber, the cracks would rapidly develop around the rubber particles during loading, and expand quickly throughout the matrix, and eventually causing accelerated rupture in the concrete.

2- Due to a lack of proper bonding between rubber particles and the cement paste (as compared to cement paste and aggregates), a continuous and integrated matrix against exerted loads is not available. Hence, applied stresses are not uniformly distributed in the paste. This is causing cracks at the boundary between aggregates and cement.

3- Since part of the cement and/or aggregates is replaced by rubber particles, their volumes will reduce accordingly. On the other hand, compressive strength of concrete depends on physical and mechanical properties of these materials (which have some superiority over rubber). A reduction in compressive strength of concrete can, therefore, be expected.

4- During casting and vibrating test specimens, rubber particles tend to move toward the top surface of the mould, resulting in high concentration of rubber particles at the top layer of the specimens. This is because of the lower specific gravity of the rubber particles and also due to lack of bonding between rubber particles and the concrete mass. This problem is manifested more clearly in the second mixture. Non-uniform distribution of rubber particles at the top surface tends to produce non-homogeneous samples and leads to a reduction in concrete strength at those parts, resulting to failure at lower stresses.

5- Lower strength of the second mixture, when compared to the first mixture, is due to reduction in the quantity of cement used as adhesive (i.e. cementing) materials.

6- As rubber has lower stiffness compared to aggregates, presence of rubber particles in concrete reduces concrete mass stiffness and lowers its load bearing capacity. The slight increase in compressive strength of sample containing 5 percent chipped rubber can be due to improvement of the coarse and fine aggregates grading.

The findings of this research in line with others [4, 9, and 13] reveal that addition of 5 percent by weight of tyre rubber would not have noticeable negative impact on concrete strength.

5.2. Modulus of elasticity test

The results of modulus of elasticity tests are given in Fig. 6. In general, replacing rubber particles for aggregates and cement will reduce modulus of elasticity of concrete. The behaviour in both mixtures is the same. Better performance of the first mixture compared to that of the second is not considerable. Aggregates characteristics affect modulus of elasticity. Considering concrete as a base model of a composite compound consisting of two phases (aggregate and cement), it is realised that the impact on aggregates is due to modulus of elasticity and to the volumetric ratio of these particles in concrete. Therefore the greater the modulus of elasticity for aggregates, the greater the modulus of elasticity of the resulting concrete. For aggregates with higher modulus of elasticity than cement paste, the higher volume of aggregates in the concrete mixture the greater the modulus of elasticity. Hence, an increase in rubber replacement for coarse aggregates in concrete will cause the equivalent modulus of elasticity and consequently modulus of elasticity of concrete to be reduced. This is directly related to the volume of rubber added.

5. 3. Tensile strength

The results of tensile strength test are given in Fig 7. Tensile strength of concrete was reduced with replacement of rubber in both mixtures. The percent reduction of tensile strength in the first mixture was about twice that of the second mixture for lower percentage of replacements. The reduction in tensile strength with 7.5 percent replacement was 44 percent for the first mixture and 24 percent for the second mixture as compared to the control mixture.

Tyre rubber as a soft material can act as a barrier against crack growth in concrete. Therefore, tensile strength in concrete containing rubber should be higher than the control mixture. However, the results showed the opposite of this hypothesis. The reason for this behaviour may be due to the following variables:

The interface zone between rubber and cement may act as a micro-crack due to weak bonding between the two materials; the weak interface zone accelerates concrete breakdown.

Inspections of the broken concrete samples proved that the chipped rubbers were observed after breaking the concrete specimens in the first mixture (Fig. 8). The reason for this behaviour is that during crack expansion and when it comes into contact with rubber particle, the exerted stress causes a surface segregation between rubber and the cement paste. Therefore, it can be said that rubber acts just as a cavity and a concentration point leading to quick concrete breakdown.

Another variable which may affect concrete behaviour is actually the main region of segregation when tensile strength is exerted on the boundaries of the large grains and cement paste which in turn weaken the generated interface zone.

5.4. Flexural strength

The results of flexural strength tests are shown in Fig 9. Replacement of rubber reduces flexural strength as expected. The reduction in flexural strength occurred in both mixtures and only the rate was different. A reduction of 37 percent with respect to the control sample was observed in the first mixture. This value reached to 29 percent for the second mixture.

According to a general principle governing flexure, flexural stresses exerted on concrete produce tensile stress on one side of neutral axis and compressive stress on the other, so that with combination of the coupled tensile and compressive forces, they can neutralize the compressive moment.

Due to low (negligible) tensile strength of concrete as compared to its compressive strength, in lower stresses and before concrete reaches its ultimate strength in the compression region, failure will occur. As a result the most important factor in reducing flexural strength, as well as the compressive strength is lack of good bonding between rubber particles and cement paste. This conclusion was reached because after breaking the concrete samples for flexural strength test, it was observed that chipped rubber could be easily removed from concrete. Weak bonding in the first mixture, which contained chipped rubber, was more obvious and weaker than the second mixture, which contained powdered rubber.

5.5. Water permeability depth and water absorption

Permeability is the most effective internal factor in concrete durability. A reduction in permeability of concrete would improve its other characteristics including durability against environmental conditions like freezing and thawing cycles, reduction in corrosion of concrete and steel bars exposed to aggressive minerals and or acids.

BS EN 12390-8 [22] does not include any specifications for concrete quality in respect to measured penetration depth results as the DIN standard does. The DIN 1048 standard [23] gives the three permeability classifications of high, medium and low as detailed in Table 3.

The results of permeability test are given in Fig 10. Replacement of rubber increases water permeability depth in the concrete mixtures. The increase in water permeability depth is higher in the first mixture compared to the second mixture. Mixtures with replacements of 5 and 7.5 percent tyre rubber is classified as low permeability according to DIN standard but the mixture with 10 percent tyre rubber replacement is classified as medium.

Increased permeability of the second mixture is also due to reduction in cement content in the concrete and further reduction in bonding between particles in this concrete mixture.

The results of water absorption test are given in Fig. 11. The specimens of the first mixture tested for water absorption appeared to have cracked up during oven drying and this resulted in significantly higher water absorption results. This cracking may be due to the weak bonding between larger rubber particles (compared to powder rubber in the second mixture) and the cement paste. However despite this we can still conclude that the water absorption in the first mixture is increased compared to the control mixture. This is due to large particles of rubber reducing the bonding with the cement paste. On the other hand the water absorption of the second mixture containing powdered tyre rubber is reduced as the percentage of replacement is increased. It seems that reduction in porosity of concrete due to fillings of the voids with powdered rubber has reduced water absorption in this mixture.

Comparison of the results for water absorption and the depth of water penetration for the second mixture show that water absorption is reduced but depth of water penetration is increased.

It appears that water permeability in concrete containing powdered rubber is non-uniform in such a way that even though water absorption is lower than that of the control mixture, but its water permeability is increased. The reason for this behaviour is believed to be due to the existence of capillaries filled with water in the concrete containing rubber. This is also due to lack of good bonding between rubber particles and cement paste where interface surface between cement paste and rubber grains act as the bedding for pressurised water to flow in the concrete containing rubber. Consequently, with the same or lower water absorption than the control mixture, water permeability of the concrete containing rubber is increased with respect to the control mixture.

6. Conclusions

The following general findings are based on the laboratory study reported in this paper. Any other investigation for scrap-tyre rubber replacement for aggregate and cement in concrete may differ with changes in materials characteristics, mixture proportions of the ingredients, curing procedure, and use of admixtures and additives. The specific conclusions that can be drawn from this study are as follows:

1- Compressive strength of concrete depended on two factors: grain size of the replacing rubber and percentage added. In general, compressive strength was reduced with increased percentage of rubber replacement in concrete, though with 5 percent replacement of aggregate or cement by rubber, decrease in compressive strength was low (less than 5 percent) without noticeable changes in other concrete properties. The highest reduction was related to 7.5 and 10 percent replacement for both grades of rubber used. The reduction in compressive strength at 28 days of age was about 10 to 23 percent for aggregates and 20 to 40 percent for cement replacement.

2- Modulus of elasticity of concrete was reduced with the replacement of rubber for aggregate or cement. Reduction in modulus of elasticity was 17 to 25 percent in the case of 5 to 10 percent aggregate replacement by chipped rubber and the corresponding reduction for powdered rubber was 18 to 36 percent.

3- Tensile strength of concrete was reduced with increased percentage of rubber replacement in concrete. The most important reason being lack of proper bonding between rubber and the paste matrix, as bonding plays the key role in reducing tensile strength. Tensile strength of concrete containing chipped rubber (replacement for aggregates) is lower than that of concrete containing powdered rubber (for cement replacement). In the case of 5 to 10 percent aggregate replacement by chipped tyre rubber, the reduction in tensile strength was about 30 to 60 percent where for 5 to 10 percent cement replacement by powdered rubber the reduction was about 15 to 30 percent.

4- Replacement of rubber for aggregate or cement in concrete caused a reduction in its flexural strength for both grades, but the rate of reduction was different. The reduction was about 37 percent for coarse aggregates replacement and 29 percent for cement replacement.

5- Replacement of rubber increased water permeability depth in the concrete mixtures and increases the water absorption in case of coarse aggregate replacement but reduced the water absorption in case of cement replacement.

Acknowledgments

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Figure Captions:

Fig. 1 - Fine aggregate grading, with the Iranian standard boundaries.

Fig. 2- Coarse aggregate and chipped tyre rubber grading, with the Iranian standard boundaries.

Fig. 3 - Particle size analysis of ground tyre powder.

Fig. 4 - Results of 7-day compressive strength test.

Fig. 5 - Results of 28-day compressive strength test.

Fig. 6 - Results of modulus of elasticity test.

Fig. 7 - Results of tensile strength test.

Fig. 8- Rubber particles distribution in concrete matrix after failure during tensile loading.

Fig. 9- Results of flexural strength test.

Fig. 10 – Water permeability depth results.

Fig. 11 - Results of water absorption test.

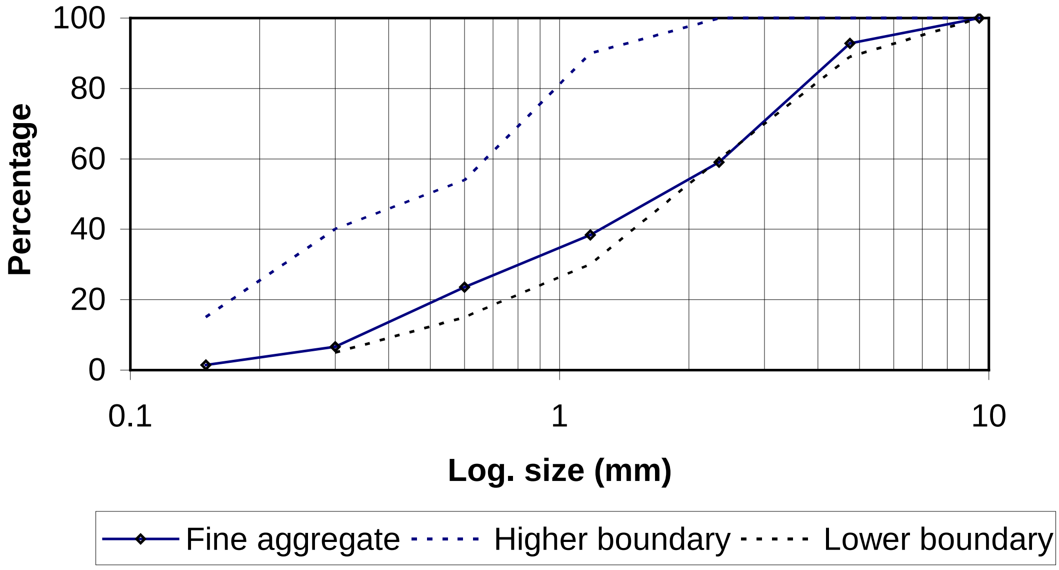

Fig. 1. Fine aggregate grading, with the Iranian standard boundaries.

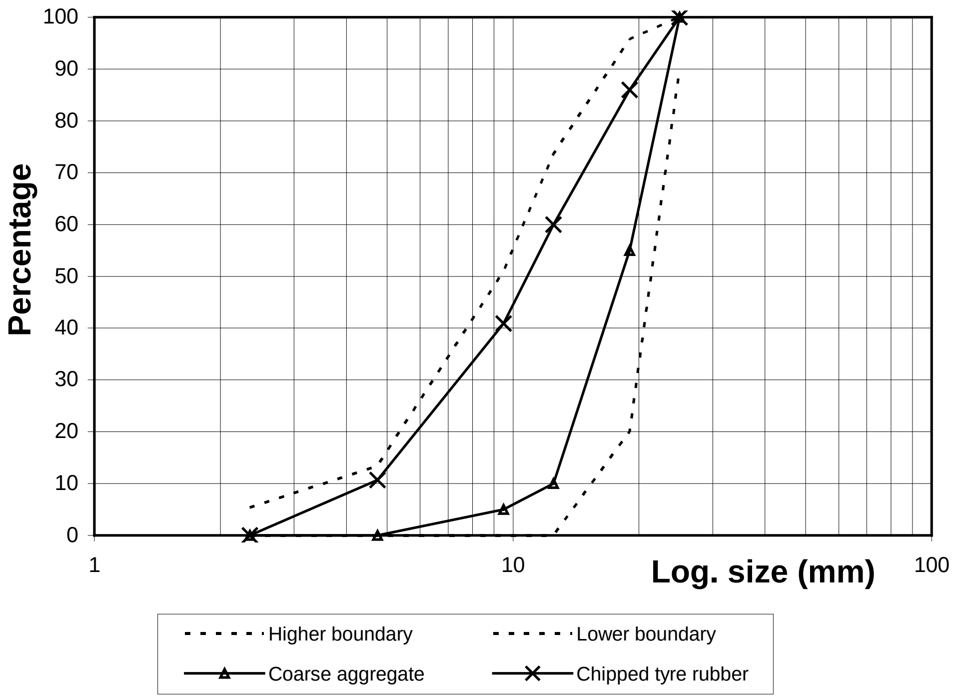

Fig. 2. Coarse aggregate and chipped tyre rubber grading, with the Iranian standard boundaries.

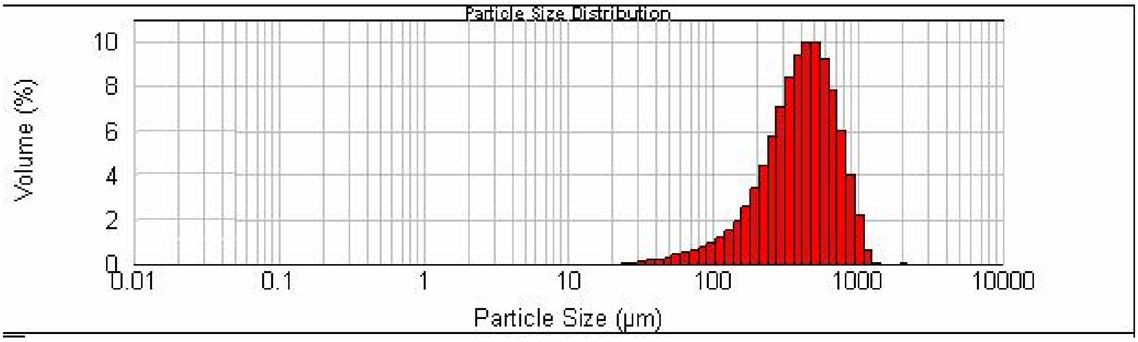

Fig. 3. Particle size analysis of ground tyre powder.

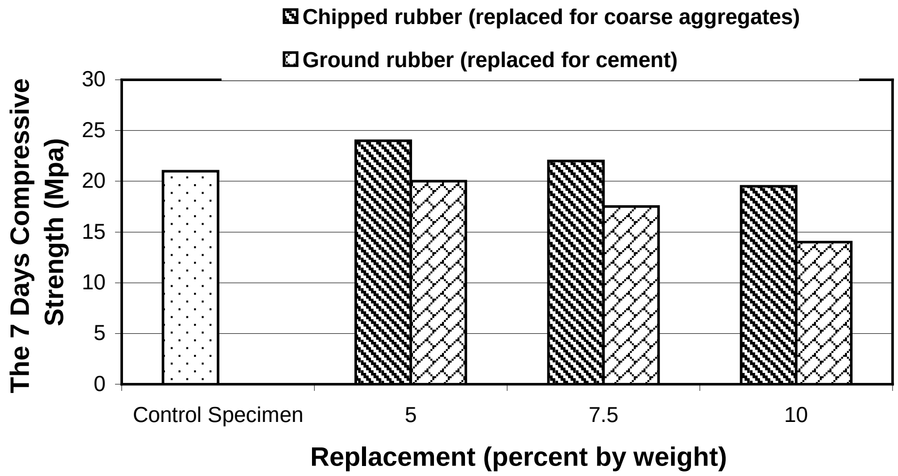

Fig. 4. Results of 7-day compressive strength test.

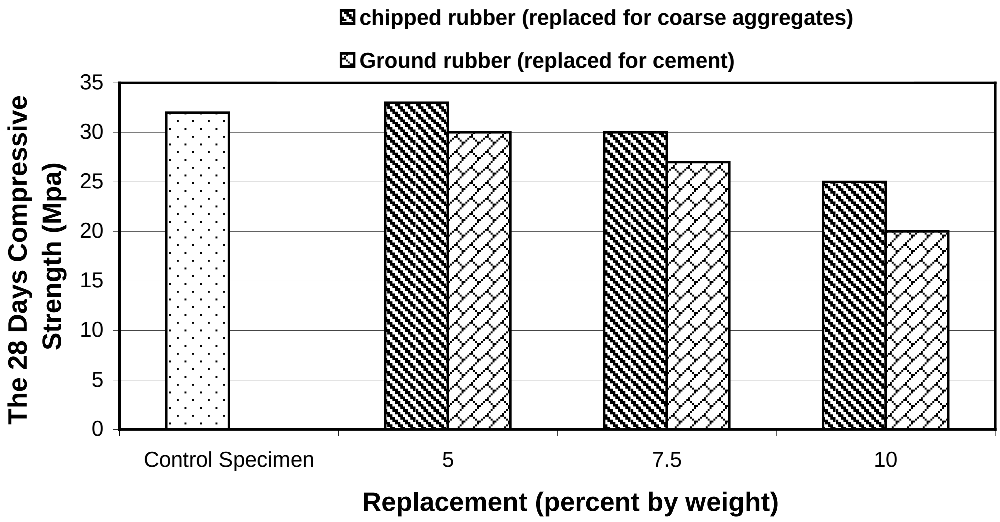

Fig. 5. Results of 28-day compressive strength test.

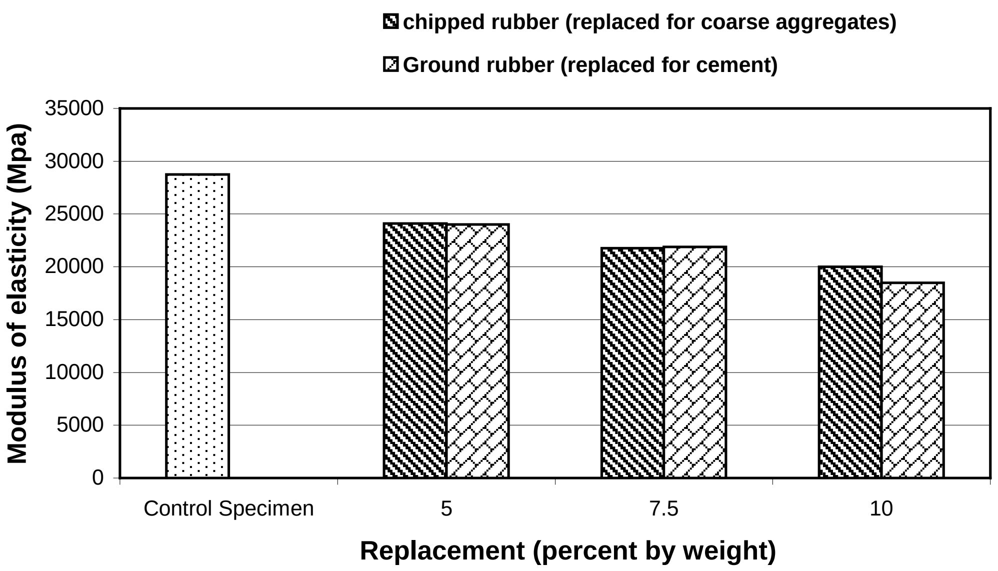

Fig. 6. Results of modulus of elasticity test.

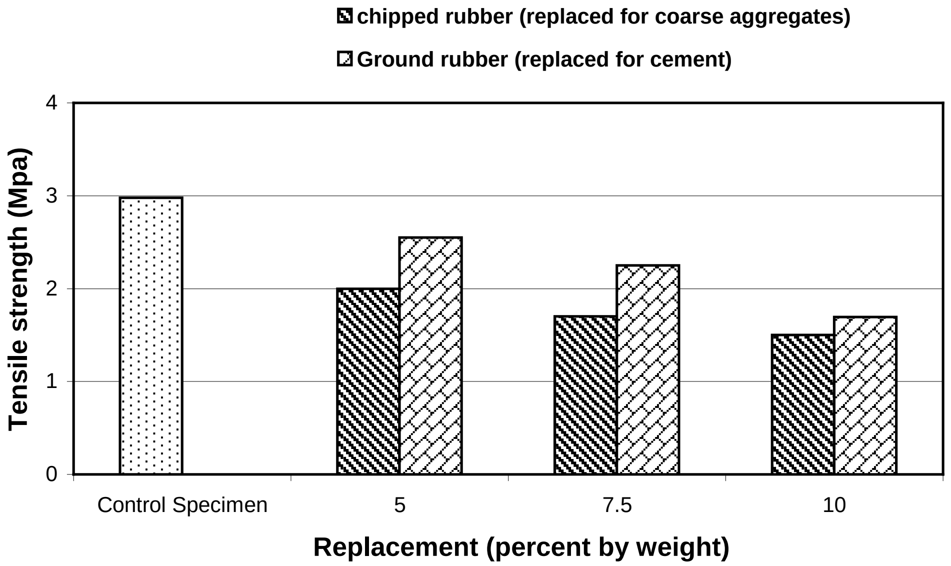

Fig. 7. Results of tensile strength test.

Fig. 8. Rubber particles distribution in concrete matrix after failure during tensile loading.

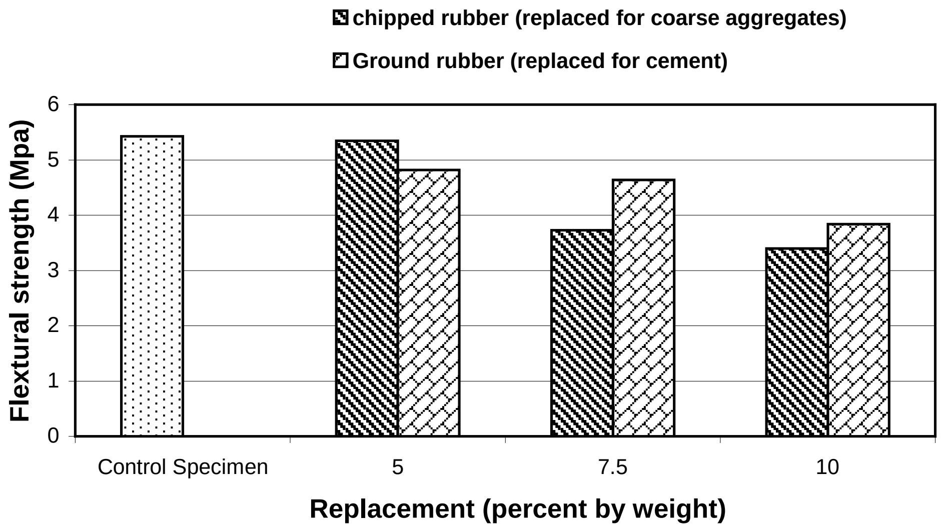

Fig. 9. Results of flexural strength test.

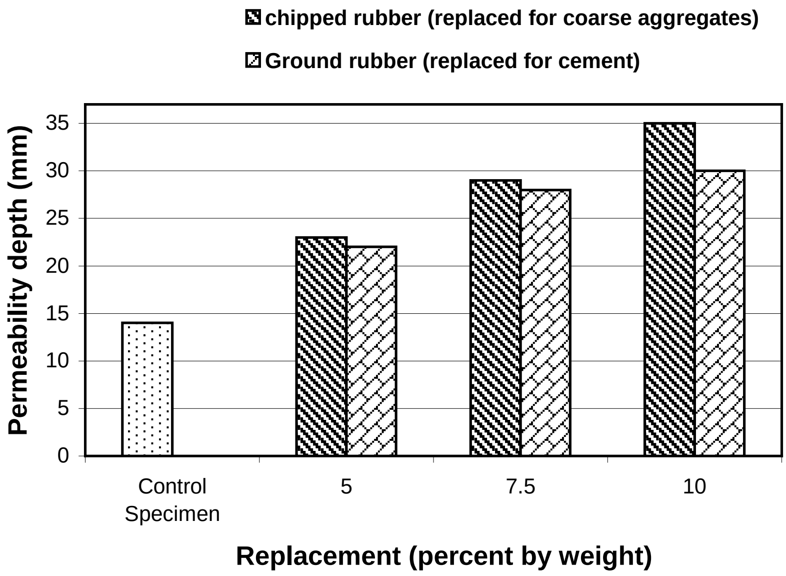

Fig. 10. Water permeability depth results.

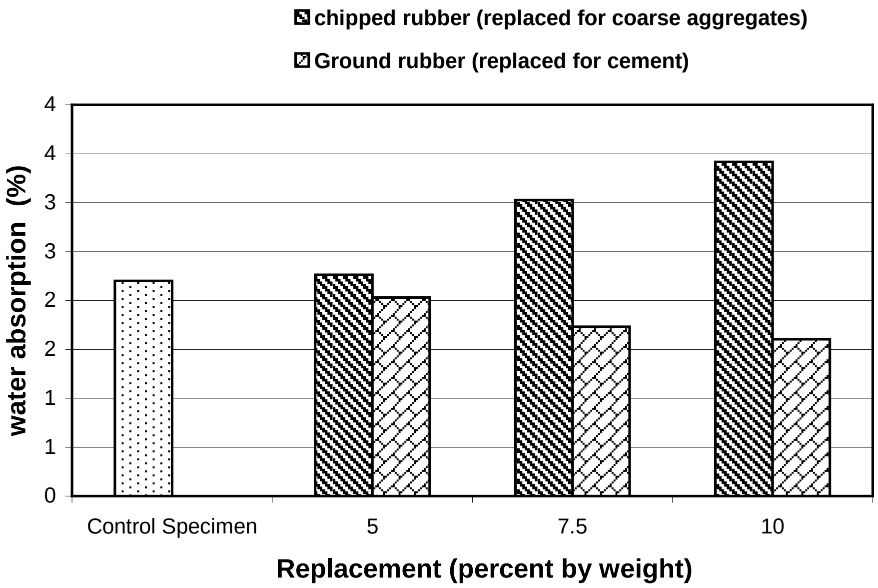

Fig. 11. Results of water absorption test.

Table 1 - Typical constituent materials of tyres [1].

Composition weight (%)	Car Tyre	Truck tyre
Natural rubber	14	27
Synthetic rubber	27	14
Black Carbon	28	28
Fabric , filler accelerators and antiozonants	16-17	16-17
Steel	14-15	14-15

Table 2 – Concrete mixture proportions

Mixture	Description	Cement (kg/m^3)	Weight of the materials used (kg/m^3) Tyre rubber		Fine aggregates (kg/m^3)	Coarse Aggregates (kg/m^3)
			Chipped	Powder		
C	Control	**380**	0.0	0.0	858	927
RA5	Replacing 5 percent by weight rubber particles for aggregates	**380**	46.4	0.0	858	884
RA7.5	Replacing 7.5 percent by weight rubber particles for aggregates	**380**	69.5	0.0	858	861
RA10	Replacing 10 percent by weight rubber particles for aggregates	**380**	93	0.0	858	839
RC5	Replacing 5 percent by weight rubber powder for cement	**361**	0.0	19.0	858	927
RC7.5	Replacing 7.5 percent by weight rubber powder for cement	**352**	0.0	28.0	858	927
RC10	Replacing 10 percent by weight rubber powder for cement	**342**	0.0	38.0	858	927

Table 3 – Water permeability ranges according to standard DIN 1048

Permeability range according to standard DIN 1048	Low	Medium	High
Permeability depth in 4 days (cm)	Less than 3	3-6	Greater than 6