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Effect of waste tyre rubber on mechanical and durability properties of concrete – A review

A. Sofi

Department of Structural and Geotechnical Engineering, School of Civil and Chemical Engineering, VIT University, Vellore 632014, India

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ABSTRACT

Disposal of waste tyre rubber has become a major environmental issue in all parts of the world representing a very serious threat to the ecology. One of the possible solutions for the use of scrap tyre rubber is to incorporate it into concrete, to replace some of the natural aggregate. An estimated 1000 million tyres reach the end of their useful lives every year and 5000 millions more are expected to be discarded in a regular basis by the year 2030. Up to now a small part is recycled and millions of tyres are just stockpiled, landfilled or buried. The volume of polymeric wastes like tyre rubber and polyethylene terephthalate bottles (PET) is increasing at a fast rate. This paper reviews the tests performed to determine the compressive strength, flexural tensile strength, water absorption and water penetration of using rubber tyre waste concrete samples. Scanning Electron Microscopy (SEM) images were also presented in this paper. It was observed that the compressive strength, flexural tensile strength and depth of water penetration of the rubberized concrete were less than that of the control mix, while the abrasion resistance and water absorption (up to 10% substitution) exhibited better results than that of the control mix concrete. This paper also reviews the performance of concrete mixtures incorporating 5%, 7.5% and 10% of discarded tyre rubber as aggregate and cement replacements. Numerous projects have been conducted on replacement of aggregates by crumb rubbers but scarce data are found on cementitious filler addition. 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.

1. Introduction

The vehicle tyres which are disposed to landfills constitute one important part of solid waste. Stockpiled tyres also present many types of, health, environmental and economic risks through air, water and soil pollution. The tyres store water for a long period because of its particular shape and impermeable nature providing a breeding habitat for mosquitoes and various pests [1–3]. Tyre burning, which was the easiest and cheapest method of disposal, causes serious fire hazards [4]. Once ignited, it is very difficult to extinguish as the 75% free space can store lot of free oxygen. In addition, the residue powder left after burning pollutes the soil. The oil that is generated from the melting of tyres can also pollute soil and water. An estimated 1000 million tyres reach the end of their useful lives every year [1]. At present enormous quantities of tyres are already stockpiled (whole tyre) or landfilled (shredded tyre), 3000 millions inside EU and 1000 millions in the US [2]. By the year 2030 the number of tyres from motor vehicles is expect to reach 1200 million representing almost 5000 millions tyres to be discarded in a regular basis. Tyre landfilling is responsible for a serious ecological threat. Mainly waste tyres disposal areas contribute to the reduction of biodiversity also the tyres hold toxic and soluble components [3]. Secondly although waste tyres are difficult to ignite this risk is always present. Once tyres start to burn down due to accidental cause's high temperature take place and toxic fumes are generated [4] besides the high temperature causes tyres to melt, thus producing oil that will contaminate soil and water. Classification of scrap rubber tyre 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

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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 [5]. Investigations carried out so far reveal that tyre waste concrete is specially recommended for concrete structures located in areas of severe earthquake risk and also for applications submitted to severe dynamic actions like railway sleepers. This material can also be used for non-load-bearing purposes such as noise reduction barriers. Investigations about rubber waste concrete show that concrete performance is very dependent on the waste aggregates [6]. Even though the compressive strength is reduced when using the crumb tyres, it can meet the strength requirements of light weight concrete. The addition of crumb rubber to the mix has a limited effect toward reducing the workability of the mixtures [7]. The rubberized concrete mixtures showed lower unit weight compared to plain concrete and good workability. The results of compressive and flexural tests indicated a larger reduction of mechanical properties of rubcrete when replacing coarse aggregate rather than fine aggregate. The post-cracking behaviour of rubberized concrete was positively affected by the substitution of coarse aggregate with rubber shreds, showing a good energy absorption and ductility indexes in the range observed for fibrous concrete [8]. Replacement of rubber for aggregate or cement in concrete caused a reduction in its flexural strength. The reduction was about 37% for coarse aggregates replacement and 29% for cement replacement. 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 [9]. The surface treatments tested to enhance the hydrophilicity of the rubber surface, a sodium hydroxide (NaOH) solution gave the best result [10]. Rubberised bituminous layers had better skid resistance, reduced fatigue cracking and longer design life than conventional bituminous mixtures [11]. The particles were surface-treated with NaOH saturated aqueous solutions for 20 min before using them in concrete. Accumulation of discarded tyres is a major problem as degradation of these tyres is very difficult because of the highly complex configuration of the ingredient materials [12–14]. The available studies regarding utilization of waste rubber tyres in concrete provide a strong recommendation for the use of this waste as a partial replacement of fine aggregate in concrete production [15–17]. This would facilitate the effective use of the solid waste, minimize the accumulation of the tyres and reduce the consumption of natural resources [18]. Some studies are available on chloride-ion penetration resistance of mortar and rubberized concrete with waste rubber aggregates. A higher resistance to chloride ion penetration was reported by [19] for rubberized mortar, containing 5% and 10% rubber particles (tyre rubber ash) for a single w/c ratio (0.65). The higher resistance of chloride-ion penetration was attributed to the effect of rubber ash filler packing, which reduces the air content of mortar and consequently increases the resistance of mortar to chloride-ion penetration. A reduction of 14–35% in chloride ion penetration for 2.5–15% granulated rubber content in cement mortar as partial replacement of sand for a single water cement ratio for each replacement level [20]. However, [21] reported a progressive increase in the chloride-ion penetration on partial replacement of coarse aggregate and fine aggregate by crumb rubber and rubber chipsrespectively. The penetration was found to decrease on addition of silica fume to the concrete mixture. The filling of voids in the cement paste and aggregate-paste transition zones by the silica fume was cited as the reason for the improved resistance. A reduction in chloride ion permeability on addition of silica fume. The reduction in the calcium hydroxide in the mortar was attributed as the reason [22].

2. Material properties

Ordinary Portland cement of grade 43, conforming to Indian Standards (IS): 8112-1989 was used. Specific gravity of cement was found to be 3.15, Normal consistency was 34%, Initial setting time was 99 min, final setting time was 176 min. Natural river sand confirming to zone II as per IS: 383-1970. Specific gravity of fine aggregate was found to be 2.63, free surface moisture 1%, water absorption 1.5%, fineness modulus 2.83). Coarse aggregate of 10 mm and 20 mm sizes of 40% and 60% were used, fineness modulus of 10 mm size aggregates was found to be 5.573 and its water absorption was 0.3%, fineness modulus of 20 mm size aggregates was found to be 7.312 and water absorption was 0.25%. Fig. 1 shows the various stages of rubber tyre. Crumb rubber was supplied by a local industry. Tyre rubber was ground into three sizes after removing the steel and textile fibres (powder form of 30 mesh, 0.8–2 mm, 2–4 mm) [1]. The difference in specific gravity of river sand and crumb rubber was taken into consideration while replacing. The ratio of specific gravity of rubber to the specific gravity of sand was taken and that was multiplied to the mass of fine aggregate to be replaced. The specific gravity of rubber powder was 1.05 and that of the other two sizes were 1.13. The three sizes of crumb rubber were mixed in definite percentages (25% of 2–4 mm size, 35% of 0.8–2 mm size and 40% rubber powder) to bring it to zone II. When the surface of the crumb rubber 'and river sand is observed, the former seems to have a smooth, hard surface while the latter has a rough, irregular one. To investigate the suitability of discarded tyre rubber as a substitute for fine aggregate in concrete, M60 grade concrete was designed (as per IS:10262-2010). The ratio of cement, fine aggregate and coarse aggregate are 1: 1.48: 2.67 by weight (1 part of cement, 1.48 parts of fine aggregate and 2.67 parts of coarse aggregate). Crumb rubber replaced natural sand by weight from 0% to 20% in multiple of 2.5%. Only the fine aggregate was replaced with crumb rubber, while all the other parameters were kept constant. To enhance the interfacial transition zone bonding, 6% silica fumes by weight of cement were added to the concrete [3] Silica fume can contribute to the increment in strength of concrete by creating dense packing and as a pore filler of cement paste. At ordinary temperatures and in the presence of moisture, silica fume is more reactive than fly ash. A super plasticizer based second generation poly carboxylic ether-polymer was used to improve the workability of concrete mixes (above 0.91). The mixtures were prepared and casted at an indoor temperature range of 25–30 °C. Figs. 2–4 shows the SEM image of rubber tyre. Tables 1 and 2 shows the slump performance of crumb rubber content.

The relative density of chipped rubber was 1.3. Ground rubber of particles of size between 45 μm and 1.2 mm diameter are used and mostly pass 600 μm. The relative density (specific gravity) of ground tyre powder was 0.8. Mixture preparation in the first mixture, 5%, 7.5%, and 10% by weight of coarse aggregates were

Fig. 1. Crushed rubber from waste tyre.

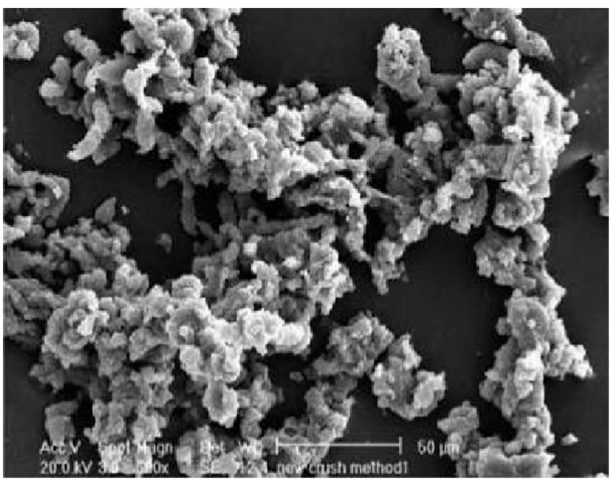

Fig. 2. SEM micrograph of waste rubber powder.

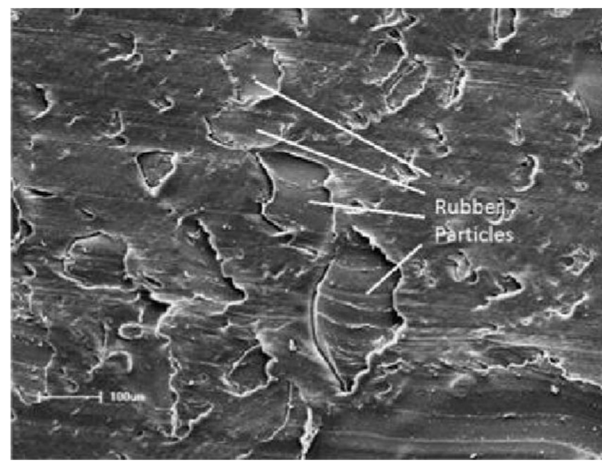

Fig. 3. SEM micrograph of the HDPE/C2C8/RTP 60/30/10.

replaced by chipped tyre rubber. Mixture proportioning specifications are detailed in Table 3.

3. Mechanical properties

3.1. Compressive strength

Fig. 5 shows the variations in compressive strength obtained at 7, 28 and 90 days with respect to the percentage of crumb rubber [23]. Gradual decrease in compressive strength was noticed as the percentage of crumb rubber increased. The reduction in compressive strength of the mix with 20% crumb rubber was more than 50% than the value of the control mix. At 7 days, the maximum compressive strength (65.5 MPa) was obtained for the control mix with 0% crumb rubber and the minimum value (27 MPa) for the mix with 20% crumb rubber. Same trend was observed for the compressive strength at 28 and 90 days. At 28 days, a strength above 60 MPa was obtained for all the mixes in which the amount of rubber was from 0% to 10% and at 90 days, all the mixes in which the crumb rubber was substituted from 0% to 12.5% crossed the 60 MPa threshold.

The control specimens exhibited brittle failure while the rubberized concrete did not show brittle failure under compression loading. Horizontal cracks were observed for the specimens with rubber and inclined cracks were observed in the control specimens. The loss in mechanical properties of rubberized concrete was supported by the results obtained by various researchers [16]. The reasons for the decrease in compressive and flexural strength of the rubberized concrete [28]. (a) The aggregate would be surrounded by the cement paste containing rubber particles. This cement paste would be much softer than that without rubber. This results in rapid development of cracks around the rubber particles while loading and this leads to quick failure of specimens. (b) There would be lack of proper bonding between rubber particles and cement paste, as compared to cement paste and natural aggregate. This can lead to cracks due to non-uniform distribution of applied stresses. (c) The compressive strength depends on the physical and mechanical properties of the constituent materials. If part of the materials is replaced by rubber, reduction in strength will occur. (d) Due to low specific gravity of rubber and lack of bonding of rubber with other concrete ingredients, there is a tendency for rubber to move upwards during vibration leading to higher rubber concentration at the top layer. Such a non-homogeneous concrete sample leads to reduced strengths.

The compressive strength of the waste rubber tyre fiber concrete for w/c ratios 0.35, 0.45 and 0.55 at 7 days and 28 days is shown in Figs. 6 and 7 where the error bars show the standard deviation. It can be seen from that the compressive strength decreases with an increase in the replacement level of rubber fibres for all three w/c ratios. The compressive strength of the control concrete (without rubber fiber and silica fume) decreases by 51.8%, 53.2% and 54.6% for w/c ratios 0.35, 0.45 and 0.55 respectively on 25% replacement of sand by rubber fiber.

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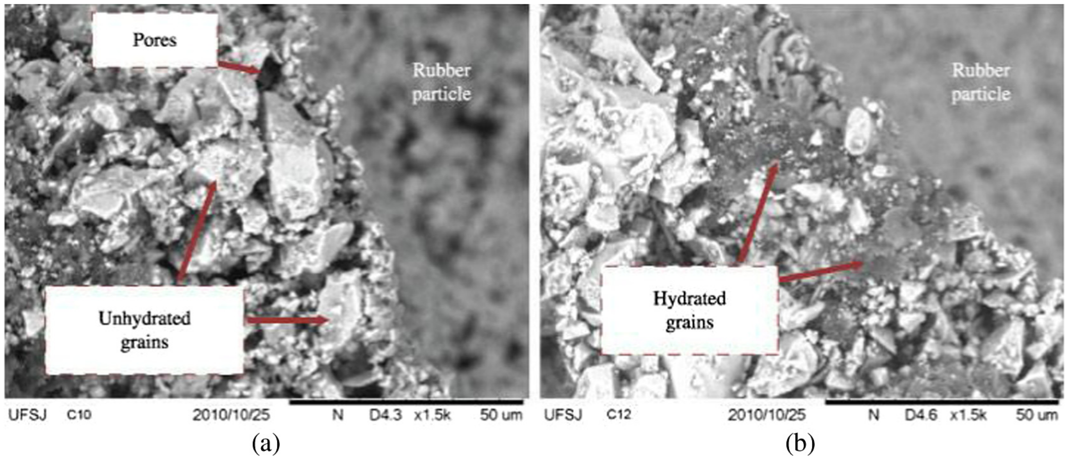

Fig. 4. Backscatter Electron imaging @1500× of magnification composites, (a) 15% rubber @ w/c ratio = 0.5, (b) 30% rubber @ w/c ratio = 0.5.

Table 1
Slump performance according to crumb rubber content.

Rubber content (%)	Slump (mm)
0	75
20	61
40	36
60	18
80	10
100	5

Reduction in compressive strength in the present study may be due to (i) replacement of hard, dense aggregate by a less dense rubber aggregate, (ii) lesser stiffness of the substitute material.

The results of 7-days and 28-days compressive strength tests for concrete mixtures are shown in Figs. 7 and 8. 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 the compressive strength was reduced by only about 5% when compared to control mixture despite 5% reduction in cement content by weight. Replacements of 7.5 and 10 of powder rubber reduced the strength by 10–23%, 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. Table 4 shows the compressive strength of concrete with aggregate replaced by rubber.

Table 2
Slump tests of fresh concrete with aggregates replaced by rubber particles.

Mixture	Slump (mm)
Reference concrete with rubber waste replacing coarse aggregate (W/B = 0.52)	180
25% rubber volume	220
50% rubber volume	215
75% rubber volume	215
Reference content with rubber waste replacing fine aggregate (W/B = 0.60)	180
15% rubber volume	220
30% rubber volume	220
50% rubber volume	215
75% rubber volume	225

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.

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

Table 3
Concrete mix proportions.

Description	Cement (kg/m^3)	Weight of material (kg/m^3)		Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
		Chipped	Powder		
Control	380	0	0	858	927
Replacing 5% by weight rubber particles for aggregates	380	46.40	0	858	884
Replacing 7.5% by weight rubber particles for aggregates	380	69.50	0	858	861
Replacing 10% by weight rubber particles for aggregates	380	93	0	858	839
Replacing 5% by weight rubber particles for cement	361	0	19	858	927
Replacing 7.5% by weight rubber particles for cement	352	0	28	858	927
Replacing 10% by weight rubber particles for cement	342	0	38	858	927

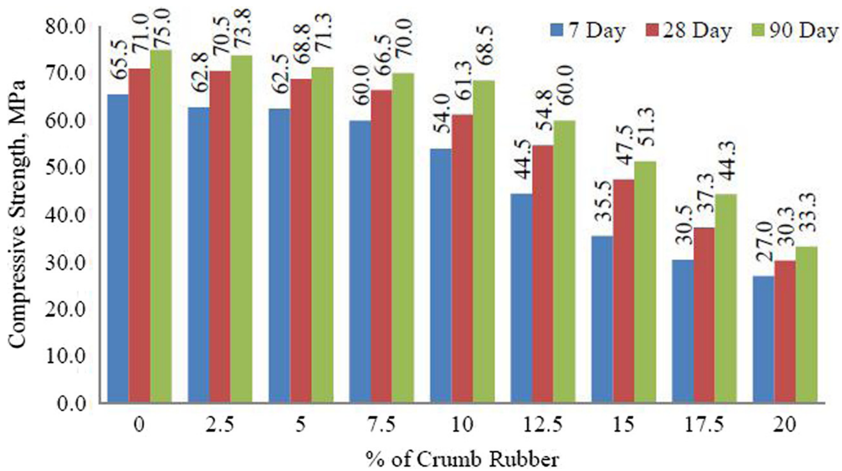

Fig. 5. Compressive strength of varying crumb rubber (%).

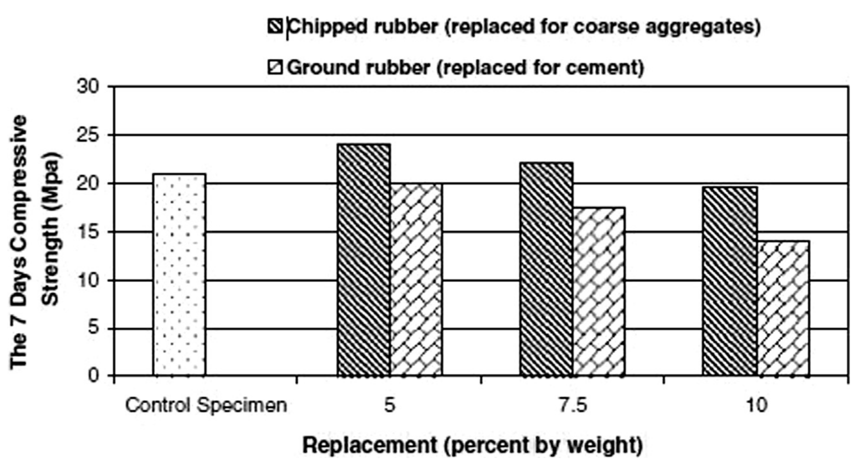

Fig. 6. Compressive strength @ a curing period of 7 days.

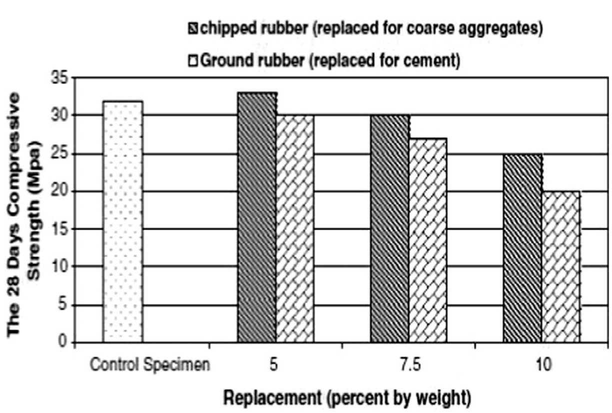

Fig. 7. Compressive strength @ a curing period of 28 days.

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% chipped rubber can be due to improvement of the coarse and fine aggregates grading. The findings of this research in line with others [4,9,13] reveal that addition of 5% by weight of tyre rubber would not have noticeable negative impact on concrete strength.

3.2. Flexural strength

The variations in flexural tensile strength obtained at 7, 28 and 90 days with respect to the percentage of crumb rubber shown in Fig. 8 [24]. At 7, 28 and 90 days, gradual reduction in the flexural strength was noticed as the percentage of crumb rubber increased. At 7 days, the maximum value (6.2 MPa) was observed for the mixes with 0% and 2.5% crumb rubber and minimum value (4.6 MPa) observed for the mixes with 17.5% and 20% crumb rubber. At 28 days, the maximum value (7.3 MPa) was obtained in the mix with 2.5% crumb rubber and minimum value (5.5 MPa) was obtained for the mix with 20% crumb rubber. Same trend as 28 days has been observed at 90 days, where the maximum and minimum values were 7.9 MPa and 5.7 MPa respectively. When the 90 days strength was considered, there was 28% reduction in the flexural tensile strength of the rubberized specimen (20% crumb rubber) when compared to the control mix specimen.

Also it was observed that the control specimens exhibited brittle failure and was broken to two pieces under loading while the

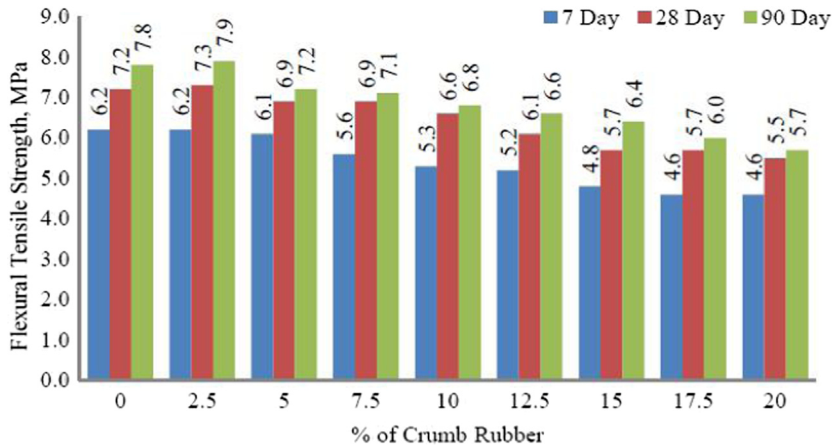

Fig. 8. Flexural tensile strength for varying curing period 7 days, 28 days and 90 days.

Table 4
Compressive strength of concrete with aggregate replaced by rubber.

Mixture	Compressive strength (N/mm^2)	Compressive strength decrease (%)
Reference concrete with Rubber waste replacing coarse aggregate (W/B = 0.52)	45.80	–
25% rubber volume	23.90	47.80
50% rubber volume	20.90	54.40
75% rubber volume	17.40	61.90
Reference content with Rubber waste replacing fine aggregate (W/B = 0.60)	27.10	–
15% rubber volume	24.00	11.60
30% rubber volume	20.40	24.70
50% rubber volume	19.50	28.30
75% rubber volume	17.10	37.10

rubberized concrete did not show brittle failure under flexural tensile loading [1]. The specimens containing tyre rubber (in the form of fibres) up to 20% exhibited higher flexural strength than the control specimens [27]. The flexural strength decreases when the amount of rubber was increased from 20 to 30%. The control specimens exhibited brittle failure and split into two pieces immediately after cracking, while the specimens containing rubber fibres showed deformation without complete disintegration. Su et al. [30] observed a reduction of 12.8% in the flexural strength when 20% fine aggregate was substituted with rubber aggregate. Less loss in strength was obtained when the size of rubber particles were smaller. This would be due to the filler effect of small rubber particles that increase the compactness of concrete, reduce the stress singularity at internal voids and hence reduce the likelihood of fracture. The addition of silica fume and reduction in water-cement ratio has enhanced the flexural strength of rubberized concrete [31]. As the effect of silica fume enhanced the interfacial transition zone bonding, the reduction in strength of high strength rubberized concrete was lower than that of the normal strength concrete. The highest strength (3.18 MPa) was obtained for the control mix specimens and lowest value (2.15 MPa) was observed for the specimens with 20% crumb rubber. Gradual decrease in the pull-off strength was observed as the percentage of crumb rubber substitution was increased. It was clear from the results that the variation in pull-off strength closely follows the trends of the corresponding compressive strength results of the mixes as reported by [29].

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% with respect to the control sample was observed in the first mixture. This value reached to 29% for the second mixture. 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.

3.3. Modulus of elasticity

The results of modulus of elasticity tests are given in Fig. 10. 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, 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.

3.4. Tensile strength

The results of tensile strength test are given in Fig. 11. Tensile strength of concrete was reduced with replacement of rubber in both mixtures. The percentage 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% replacement was 44% for the first mixture and 24% 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. 11). The reason for this behaviour is that during crack expansion and when it comes into contact with rubber particle, the

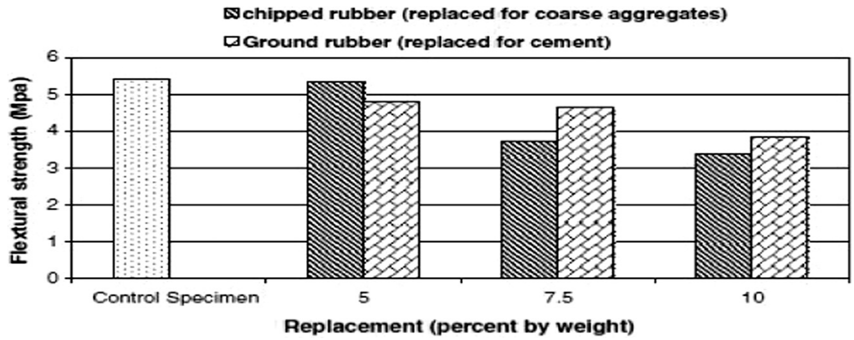

Fig. 9. Flexural strength test for varying (%) of crumb rubber.

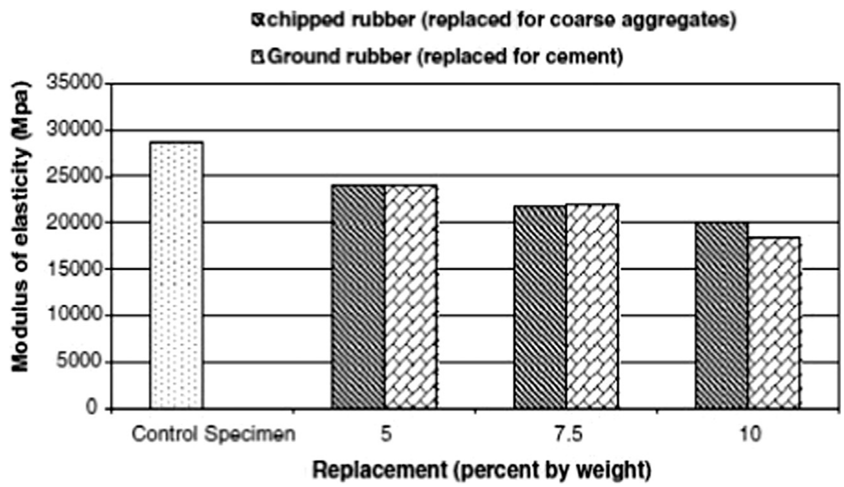

Fig. 10. Modulus of elasticity for varying crumb rubber (%).

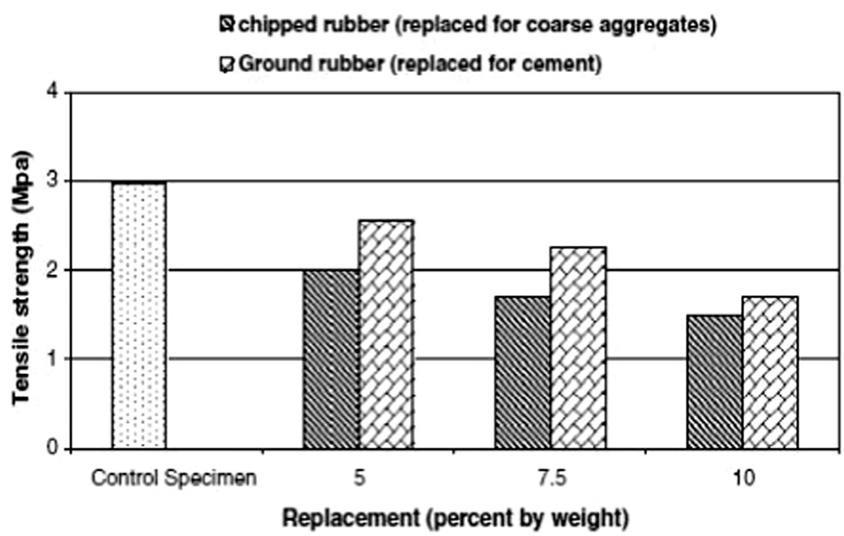

Fig. 11. Tensile strength for varying crumb rubber (%).

exerted stress causes a surface segregation between rubber and the cement paste.

4. Durability studies

An experimental investigation to comparatively study the depth of chloride penetration, resistance to acid attack and macro-cell corrosion of rubberized concrete and control mix concrete was performed. It is assumed that the procedures will have no significantly damaging effects on frost-resistant concrete which may be defined as any concrete not critically saturated with water (that is, not sufficiently saturated to be damaged by freezing) and concrete made with frost-resistant aggregates and having an adequate air-void system that has achieved appropriate maturity and thus will prevent critical saturation by water under common conditions [26].

Hence freezing and thawing test not focussed in this paper. Waste tyre rubber in the form of crumb rubber was replaced for natural fine aggregates from 0% to 20% in multiples of 2.5%. It was observed that the depth of chloride penetration of the concrete with 2.5–7.5% crumb rubber was lower than or equal to the control mix concrete. In the water absorption test of acid attacked specimens, gradual increase was observed as the percentage of crumb rubber was increased. After acid attack, more losses in the weight and compressive strength were observed in the control mix concrete than the rubberized concrete. There was no presence of sufficient corrosion in the specimens from the macro-cell corrosion test. The analytical results have shown the same trend for compressive strength and flexural tensile strength as obtained in the laboratory. It can be concluded that the rubberized concrete is highly resistant to the aggressive environments and can be implemented in the areas where there are chances of acid attack. Yilmaz and Degirmenci [27] have observed decrease in the water absorption upon increase in size of the rubber particles in the concrete. Bravo and Brito [17] have reported that the water absorption (by the process of immersion) of rubberized concrete increases as the percentage of rubber and the particle size of rubber increases. The results were not conclusive when the capillary water absorption test was done. It is possible to maintain a low capillary action even at the rubber content of 15% in concrete. Li et al. [32] observed higher strength and stiffness in the waste tyre fiber modified concrete when compared to the tyre chip modified concrete. Both the specimens had higher post crack toughness when compared to the control specimens (without rubber). Increasing the stiffness of the tyre fibres and the use of thin fibres can help to increase the strength and stiffness of rubberized concrete.

4.1. Chloride ion penetration

The results for the chloride penetration for the mixes with w/c 0.4 and 0.45 are reported in Figs. 12 and 13. It was observed that there was an increase in the depth of chloride ion penetration for higher water/cement ratios and with respect to age. When we consider the concrete mixes with water/cement ratio 0.4, the chloride penetrations of all the mixes in which crumb rubber was replaced up to 7.5% of fine aggregates were lesser than or equal when compared with the value of the control mix specimens. Similar trend was observed for the mixes with water/cement ratios 0.45. In the case of the series with w/c 0.5, the depth of chloride penetration of the concrete mixes with crumb rubber above 5% were higher than that of the control mix. A decreasing trend was observed in the depth of chloride penetration for the concrete mixes in which crumb rubber was substituted from 0% to 5% of fine aggregates. In the mixes where crumb rubber was above 5%, there was gradual increase in the depth of chloride ion penetration. At 91 days, the depth of penetration was 21 mm for the control mix (0% crumb rubber), 22 mm for the mix with 10% crumb rubber and 25 mm for the mix with 20% crumb rubber.

4.2. Water absorption of acid attacked specimens

The comparison of the water absorption values of acid attacked specimens at 28, 56 and 84 days shown in Fig. 14 [25]. In the case of concrete mixes with water/cement ratio 0.4; gradual increase in the amount of water absorption was noticed at 28 days in the mixes where the crumb rubber was replaced from 0% to 20% for fine aggregates. Same trend was noticed at 56 days and 84 days. At 84 days, the amount of water absorption for control mix was 2.89%, for the mix with 10% crumb rubber it was 3.15% and for the mix with 20% crumb rubber it was 3.32%. Similar pattern was observed for the series with water/cement ratios 0.45 and 0.50. The amount of water absorbed by the specimens had increased in all the concrete mixes when compared to the control mix with respect to the amount of crumb rubber and with respect to age. At the end of 28, 56 and 84 days, more destruction of the specimen took place with respect to the increase in the amount of crumb rubber. This may cause the occurrence of micro voids around the surface of the specimen and have enabled more water absorption. When we compare the water absorption of the control mix and that at 28, 56 and 84 days of acid attack, we can observe that the water absorption of specimens increases with time. As the water cement ratio increases, the internal voids increase resulting in the increase in amount of water absorption for the increase in the rubber content. When we observe, the top layer of the concrete specimens with 0% crumb rubber was completely removed (100%) by the action of sulphuric acid. In the case of the mix with 20% crumb rubber, less than 100% top surface were attacked by acid.

Concrete mixes when compared to the control mix with respect to the amount of crumb rubber and with respect to age. At the end of 28, 56 and 84 days, more destruction of the specimen took place with respect to the increase in the amount of crumb rubber. This may cause the occurrence of micro voids around the surface of the specimen and have enabled more water absorption. When we compare the water absorption of the control mix and that at 28, 56 and 84 days of acid attack, we can observe that the water absorption of specimens increases with time. As the water cement

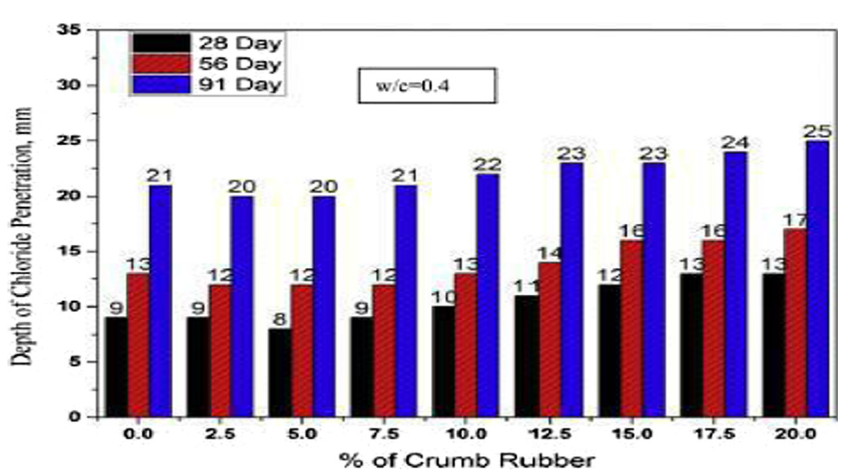

Fig. 12. Depth of chloride penetration of specimen with w/c ratio 0.4.

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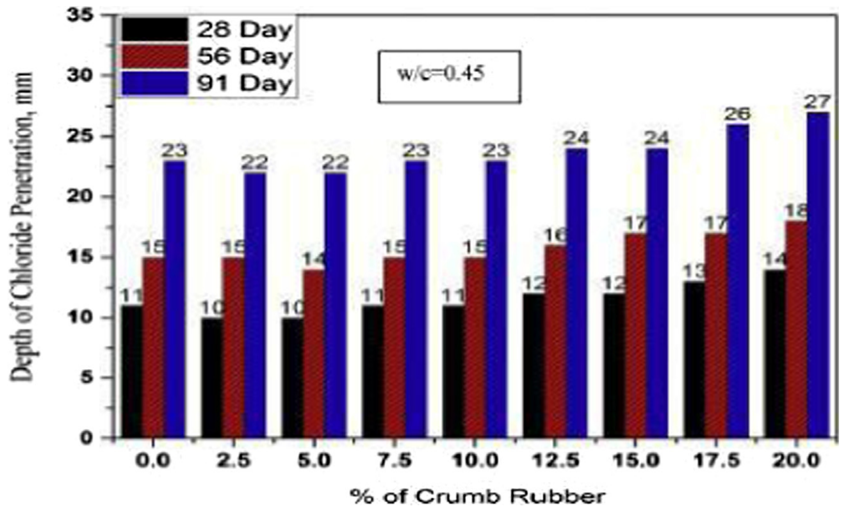

Fig. 13. Depth of chloride penetration of specimen with w/c 0.45.

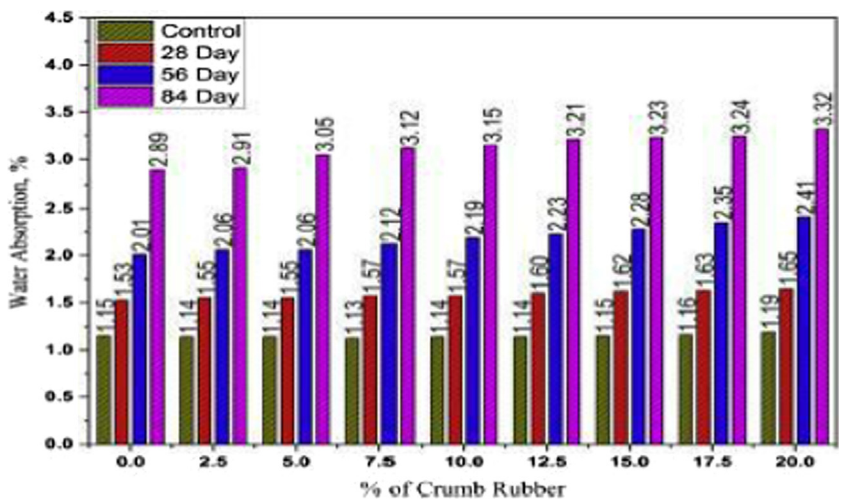

Fig. 14. Water absorption of acid attacked specimens, w/c 0.4.

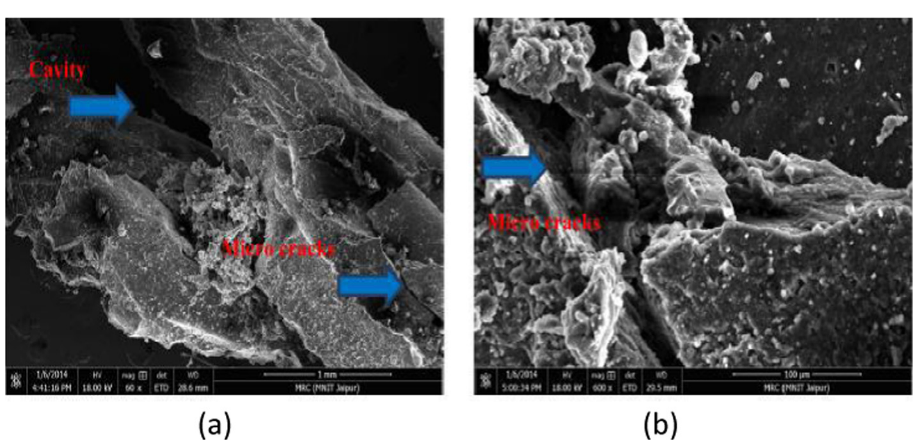

Fig. 15. (a) SEM image of rubber fiber @ 60× magnification, (b) SEM image of rubber fiber @600× magnification.

ratio increases, the internal voids increase resulting in the increase in amount of water absorption for the increase in the rubber content. When we observe, the top layer of the concrete specimens with 0% crumb rubber was completely removed (100%) by the action of sulphuric acid. In the case of the mix with 20% crumb rubber, less than 100% top surface were attacked by acid.

4.3. Weight loss of acid attacked specimen

At water/cement ratio 0.4, 0.45 and 0.5; more amount of weight loss was observed in the control mix specimens and it was found decreasing as the amount of crumb rubber was increased in the concrete. It means that the control mix specimens have recorded maximum loss in weight and the specimens with 20% crumb rubber have recorded the least loss in weight. In the case of w/c 0.4 and at 84 days, maximum weight loss (8.5%) was recorded for the control mix and minimum weight loss was for the mix with 20% crumb rubber (7.24%). The percentage loss in weight was 7.61 for the mix with 10% crumb rubber. Similar trend has been observed for the series with water cement ratios 0.45 and 0.50. The crumb rubber particles present in the rubberized concrete were holding the constituent particles of the concrete from breaking away by preventing the formation of cracks and material separation. Fig. 15 shows the SEM image of acid attacked specimens.

5. Conclusions

The compressive and flexural values were gradually decreasing with increase in the amount of crumb rubber in concrete. In the compressive strength test, all the concrete mixes with 0–12.5% crumb rubber, crossed the limit of 60 MPa. The rubberized concrete exhibited better resistance to abrasion than the control mix. The water penetration of rubberized concrete was higher than control mix concrete and all the mixes with up to 12.5% crumb rubber had exhibited lesser or similar water absorption value when compared with the control mix. It is possible to design high strength concrete in which waste tyre rubber may be utilized as a partial substitute for fine aggregate up to 12.5% by weight. It can be applicable in structures where there are chances of brittle failure. The high strength concrete with crumb rubber shows better resistance to abrasion than the control mix. So it can be applied in pavements, floors and concrete highways, hydraulic structures such as tunnels and dam spillways, or for other surfaces upon which the abrasive forces are applied by moving objects during service.

The highest reduction was related to 7.5% and 10% replacement for both grades of rubber used. The reduction in compressive strength at 28 days of age was about 10–23% for aggregates and 20–40% for cement replacement. Modulus of elasticity of concrete was reduced with the replacement of rubber for aggregate or cement. Reduction in modulus of elasticity was 17–25% in the case of 5–10% aggregate replacement by chipped rubber and the corresponding reduction for powdered rubber was 18–36%. Tensile strength of concrete was reduced with increased percentage of rubber replacement in concrete. Tensile strength of concrete containing chipped rubber (replacement for aggregates) is lower than that of concrete containing powdered rubber (for cement replacement). 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 depth of chloride penetration of the mixes with crumb rubber up to 7.5% was lower than that of the control mix in case of w/c 0.4. In the water absorption test of acid attacked specimens, gradual increase in the percentage of water absorption was observed as the percentage of crumb rubber was increased.

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