

A Review on Application of Waste Tire in Concrete

M. A. Yazdi, J. Yang, L. Yihui, H. Su

Abstract—The application of recycle waste tires into civil engineering practices, namely asphalt paving mixtures and cement-based materials has been gaining ground across the world. This review summarizes and compares the recent achievements in the area of plain rubberized concrete (PRC), in details. Different treatment methods have been discussed to improve the performance of rubberized Portland cement concrete. The review also includes the effects of size and amount of tire rubbers on mechanical and durability properties of PRC. The microstructure behaviour of the rubberized concrete was detailed.

Keywords—Waste rubber aggregates, Microstructure, Treatment methods, Size and content effects.

I. INTRODUCTION

RECENTLY researchers has focused on seeking alternate ways to use wastes emerging in the world [1]. The management of end-of-life tires is a great environmental challenge. In 2004, 120 million of scrap tires were generated in china and this number is increasing 12% each year [2]. Moreover, the United States alone generates about 300 million scrap tires across the country, with an increase of 290 million tires generated per year [3]-[8].

Since waste rubbers are likely to generate toxic fumes, the storage of this type of wastes in landfills could be a serious issue [5]. Nowadays, there are different approaches to get rid of the waste tires: reuse, rethreading, recycling/ mechanical recycling, landfill engineering and energy recovery[9].

Recycling of waste rubber tires in civil engineering is considered as ecological and economical solutions due to the advantages it can offer [6]. It preserves natural resources and produces an eco-friendly material. In addition to great environmental benefits such as reducing harmful environmental pollution of disposing tires to landfill sites, the most significant advantage of PRC is its excellent energy absorbing characteristics. Researchers have found that PRC can effectively improve the ductility, reduce weight, and prevent brittle failures [6], [7], [10]-[13]. However, the strength reduction is one of the most significant disadvantages of PRC, which prohibits its applications to structural components subjected to impact and dynamic load [10], [14].

Many research efforts have been conducted in order to improve the performance of PRC through surface treatment, reducing the size of rubber particles or using supplementary cementitious materials [4], [10], [14]. Onuaguluchi and Panesar [14] examined an approach to pretreat crumb rubber

in conjunction with the addition of supplementary cementitious materials in order to mitigate the loss of mechanical properties in rubberized concrete. Huang et al. [10] used two staged surface methods to treat rubber particles. In the first stage, they used silane coupling agent to modify rubber particle surface and develop chemical bonds between rubber particles and cement paste. In the second stage, cement was used to coat the silane-treated particles. Segre and Joeke [15] used NaOH to treat the waste tire chips before incorporating into PCC. Lee et al. [16] applied HNO₃ and a METHOCEL cellulose ethers solution. Li et al. [17] employed cement paste pre-coating of rubber particles. Rostami et al. [18] simply washed rubber chips with water before applying them to the cement concrete. Tantala et al. [19] applied acidic and plasma etching to enhance the surface area of the rubber particles.

The object of this review is to investigate different treatment methods for improving the performance of plain rubberized concrete (PRC), and its microstructure behaviour.

II. SCRAP TIRE

Discarded end-of-life tires are the main source of rubber aggregates. Waste rubber tires are known as black pollution since they do not decompose and disintegrate in the nature and pose a potential fire hazards to the environment at their storage locations [19]-[22].

Many efforts have been proposed to eliminate these problems. To this end, different methods have been proposed in order to dispose the scrap tires. Including use of rubber particles in petroleum industry as a last circulating material, use of tires as fuel, ground rubber applications for play-ground or sports surfacing or use in new rubber products, also in asphaltic pavement and recently in Portland cement concrete [21], [22].

Concrete is the second most widely used material in the world, which can consume large amount of waste rubber tires by replacing them with natural aggregate of concrete [22]. In addition, waste tires can be used in cement kilns as feedstock for energetic purposes and to produce carbon black by tire pyrolysis [23]. They are usually used to substitute part of natural aggregates or as additive of concrete mixture. Thermal decomposition of these waste rubbers in the absence of oxygen can also produce by-products that have low economic viability. Thus, reusing waste rubber tires as replacement in concrete could be a potential solution [24].

The size of waste rubber tires to be used in the construction industry is as follows: Chipped tire aggregate with the size of 25 mm to 50 mm is generated by mechanical grinding at ambient temperature and considered as coarse aggregate. Crumb rubber aggregates (4.75 mm to 0.425 mm), are

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produced by cryogenic grinding at a temperature below the glass transition temperature, and replaced fine aggregates. Ground tire rubber aggregates, which are passed through sieve No. 40 (0.425 mm), and also short fibre rubber aggregates, typically between 8.5 and 21.5 mm in length with an average of 12.5 mm. Tire chips and fibers can be produced by shredding.

III. MICROSTRUCTURE BEHAVIOUR OF RUBBERIZED CONCRETE

The microstructure of the concrete matrix is one of the crucial factors in controlling the development of strength characteristics [35].

Increasing energy absorption is one of the benefits of using waste rubbers in concrete. Tire rubber particle pullout and internal tire rubber microcracking are two toughening mechanisms for energy consumption in the rubber-concrete matrix that cannot be observed in ordinary concrete.

Some researchers related the strength reduction of the rubberized concrete with increasing rubber content to two reasons: First, initiated cracks around of the rubber particles due to the softy of rubber particles can accelerate the failure of the rubber-cement matrix. Secondly, because of the lack of bond strength and adhesion between the rubber particles and cement paste, soft rubber particles may behave as voids in the concrete matrix [36].

Pelisser et al. [27] determined the morphology and porosity of the interface between the rubber and the cement matrix by scanning electron microscopy (SEM). The addition of rubber to concrete led to the presence of large gaps in the interface rubber/cement matrix (as shown in Fig. 1). However, a porosity reduction was observed in the transition zone when the rubber treatment by sodium hydroxide and 15% silica fume was added. They claim that this is attributed to the high concentration of sodium hydroxide in the area, which is probably due to the hydrophilic effect of the treatment with sodium hydroxide. Moreover, the presence of silica fume can contribute to better adherence and reduction of the weakness points.

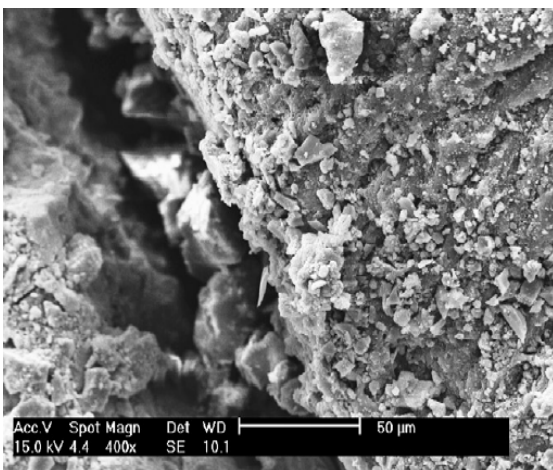


Fig. 1 Rubber/concrete interface (SEM)[27]

One of the reasons why rubber particles decrease the mechanical properties of PRC was proposed by [37]. They claim that rubber particles easily rise to the surface of concrete, which lead to the internal stress concentration due to their uneven distribution. Arisen weak interfaces and defects, and extend Arisen weak interfaces and defects, and extended internal cracks in concrete were mentioned as another side effect of rubber particles, see Fig. 2.

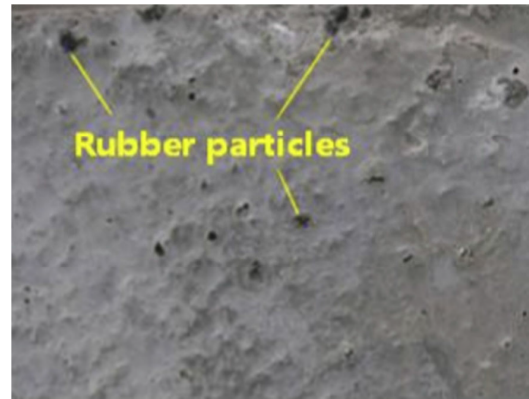


Fig. 2 Rubber particles rising to the RC surface [37]

Reda Taha et al. [38] observed the extensive microcracking in the tire rubber particle vicinity, which weakens the bond between tire rubber particles and the cement paste matrix. This confirms the fact that the soft behavior of the tire particles produces tensile strains at the tire rubber particle surface, which causes microcracking in the cement paste vicinity.

The results of surface contact angle for rubber particles treated with analytically pure anhydrous ethanol (AE) solvent, acrylic acid (ACA) and polyethylene glycol (PEG) indicates that the unmodified rubber surface is hydrophobic with a surface contact angle of 105.13° . However, the modified rubber surface was developed into the hydrophilic one with a contact angle of 68.00° [39].

The reduction of the contact angle and weakness of the repellent action of capillary force by rubber particle modification leads to an increase in the air-entrainment agent. The repellent action of capillary force lets water only enter into the larger pits on rubber particle surface during concrete mixing, but not into the smaller pits or the smaller parts of larger pits. As a result, the air in smaller pits, which is proportional to rubber substitution ratio, cannot be displaced by water and is left between the interface of cement matrix and rubber particles. Therefore, the entrained air by rubber particles consists of two parts: the air between cement matrix and rubber particles, and the air bubbles in the concrete. In fact, the weakness of the repellent action of capillary force associated with the modified rubber surface contributes to a reduction in the air content between cement matrix and rubber particles [39].

IV. EFFECT OF RUBBER SIZE AND CONTENT ON PROPERTIES OF RUBBERIZED CONCRETE

The shape and texture of the rubber particles, the quantity of steel and textile fibre reinforcement present, and the content of rubber particles can affect the properties of the PRC [28], [40], [41].

One approach is to minimize the strength loss in rubberized concretes is reducing the size of rubber particles. The reduction of rubber size to about 20 μm comparable to cement particles effectively reduces the strength loss of rubberized concretes. However, producing very fine rubber powder is more expensive than rubber chips [4]. Yang et al. [42] reported the increased manufacturing cost of producing rubber particles finer than 1.5 mm. This is in agreement with [43]. Therefore, it should be considered along with the benefits that rubber powders offer.

The use of coarse rubber particles exhibited more negative effects on the properties of mixtures compared to fine particles [18], [44]-[46].

Huang et al. [43] reported that the rubber chip size has an important effect on the strength of rubberized concrete. With the same amount of rubber chips used, reducing rubber chip size significantly increases the strength of rubberized concrete. In fact, reducing the rubber chip size significantly decreases the stress and strain concentrations. The previous experimental studies by other researchers also support this statement. Crumb rubbers-filled concrete has a larger strength than rubber chip-filled concrete [44], [45].

Lijuan et al. [37] investigated the influence of rubber content and particle size on the mechanical properties of concrete. They revealed that higher rubber content and smaller particle size decreased the compressive strength and elastic modulus of rubber concrete, while the ultimate strain of PRC increased as rubber content increased and particle size dwindled. Moreover, the width, length, and number of cracks reduced with increased rubber content and decreased particle size. This result, the reduction of compressive strength and modulus of elasticity when the rubber content increased, is in agreement with [13], [32], [47].

This finding has also been confirmed by a separate study, rubber with large particle sizes (diameter of 2–16 mm) significantly decreased the mechanical properties of concrete [15], whereas the brittleness of concrete improved with the addition of smaller rubber particles [48]. The experimental results achieved by [49] demonstrated that the rubber particle size affects the workability and water permeability of concrete to a greater extent than the fresh density and strength.

Even the type of rubber can influence the quality of treatment methods. In [11], it was found that NaOH surface treatment is not suitable for larger sized tire chips and is more effective on powdered rubber. They also reported the better performance of truck tires compared to car tires.

In terms of the optimum content of rubber particles, several researchers have recommended the maximum rubber content should not exceed between 20-30% [50] total aggregate volume in order to mitigate the loss of significant reductions in mechanical properties. In fact, the higher rubber content,

the greater toughness and lower strength will be. A concrete with high rubber content is mainly utilized in roads and bridges at present [11], [17]. Test results obtained by [36] also indicated that the increase in rubber content reduced the strength and modulus values largely.

V. TREATMENT METHODS

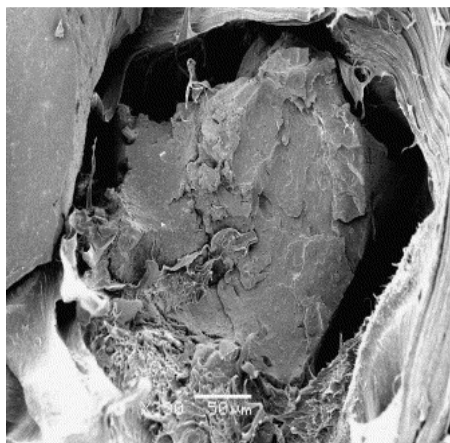
Previous studies indicated that the replacement ratio of rubbers should not exceed 30% of the total aggregate volume, in order to maintain the strength and stiffness of the rubberized concrete. In fact, one of the most common deficiencies of the use of waste tires in cement-based materials is the significant reduction of strength. In this case, research studies have been conducted on the physical properties of concrete to determine concrete degradation with the inclusion of rubber particles [22]. Summarizing the literatures shows that the reduction of mechanical properties of concrete with rubber addition can be attributed to two factors: 1) the reduced adhesion between the interface of cement and rubber grains, which is resulted from the hydrophobic nature of untreated rubber, and 2) the presence of rubber particles disturbs water flow in the rubberized concrete, which is due to the variation of intermolecular interaction forces. This phenomenon leads to insufficient and imperfect hydration in some parts of concrete. As a result, the strength of rubberized concrete is decreased [51]. In fact, modulus (stiffness) of rubber is low and also it is softer than mortar and aggregates, leading to its particles act like ‘‘holes’’ inside the concrete. These ‘‘holes’’ create stress concentrations during loading conditions and thus decrease the strength of the overall concrete samples [43]. Turatsinze and Garros reported substantial reduction in the compressive strength and modulus of elasticity of concrete containing scrap tire rubber when used as natural aggregate replacement material [52]. Similar reductions in the compressive strength, splitting tensile strength and flexural strength of concrete mixtures containing crumb rubber were also reported by [3].

In order to solve the above-mentioned problems, researchers have proposed the pre-treatment of tire rubber aggregates to improve the aggregate/cement paste adhesion [11], [15], [22], [53], [54]. They tried to modify the surface properties of the rubber particles to enhance its adhesion to C–S–H. Chou et al. [51] tried to develop the bonding between rubber particles and cement hydration products (C–S–H) by modifying the surface properties of rubbers. To this end, the crumb tires were treated with waste organic sulfur compounds from a petroleum refining factory. Experimental results revealed that the compressive, tensile, and flexural strengths of concrete samples containing treated rubber particles increased significantly.

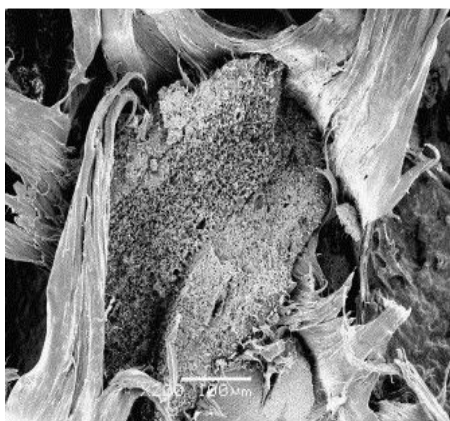
Two important factors influenced the mechanical strength of rubberized concrete treated with organic compounds. On one hand, organic sulfur compounds with amphiphilic properties can enhance the intermolecular interaction forces between rubber and C–S–H, and on the other hand, they improve the hydrophilic properties of the rubber [43], [46].

Segre and Joeke [15] utilized sodium hydroxide (NaOH) as a treatment for rubber tire particles (35 mesh maximum size).

The rubber particles were submerged in NaOH solution for 20 min at room temperature before incorporating them into cement. According to the results, the abrasion resistance, water absorption, flexural strength, and fracture energy all improved, except compressive strength that is usually observed. Other researchers used carboxylic acids to improve the adhesive properties of SBR admixtures, which strengthens the bonding characteristics between hardened cement paste and the surface of rubber aggregates by 'bridging the gaps' [50].



(a)



(b)

Fig. 3 SEM Microphotographs of fracture surface of composite (a) untreated (b) pretreated with H_2SO_4 [55]

Several pre-treatments were performed over the rubber tires by [55]: sulphuric acid etching, use of a silane coupling agent and chlorination with trichloroisocyanuric acid (TCI). Reused tire rubber added to the HDPE acts as a filler, improving the stiffness and providing a more brittle behaviour. Pre-treatment with TCI obtaining lower mechanical properties than neat HDPE in some cases and always worst properties than sulphuric or silane coupling agent. Treatments with H_2SO_4 increased the material's stiffness and its tensile strength. Sulphuric acid improved mainly mechanical adhesion by

modifying the chemical and physically the particles' surface (Fig. 3), but silane developed chemical matrix-reinforcement interactions.

Figs. 3 (a) and (b) show a microphotograph of the untreated and treated composite materials with H_2SO_4 . Untreated particles show a smooth surface, which is not suitable for mechanical adhesion. As Fig. 3 (a) shows, the surface of the reinforcement appears completely flat and free of any adherences of matrix segments. That indicates a poor adhesion, because the fracture was appeared through the interface.

Colom et al. treated reused tires using various chemical acids, such as H_2SO_4 , HNO_3 and $HClO_4$, as reinforcement material in HDPE-reused tire composites. Results revealed that, the treatment with H_2SO_4 was the most effective approach, while $HClO_4$ did not affect material's properties [9]. Aziz and Salwa revealed that CH_3COOH gave a better improvement compared with H_2SO_4 . The treatment of rubber by HCl showed negative effects on all cement mortar properties [56].

Huang et al. [10] used two staged surface methods to treat rubber particles. In the first stage, they used silane coupling agent to modify rubber particle surface and develop chemical bonds between rubber particles and cement paste. In the second stage, cement was used to coat the silane-treated particles.

According to some previously published literatures, pre-coating the rubber aggregate with cement paste and allowing it to harden, before adding the rubber to the concrete mix, not only led to an increase in the compressive strength by between 30% [17] and 50% [25], but also improved slightly the flexural strength.

Haibo et al. [57] improved the compressive and flexural strengths of the PRC (10% rubber particle content) by 25.9% and 26.4%, respectively. To improve the combination of cement matrix and waste tire rubber particles in concrete, the rubber particles were treated with analytically pure anhydrous ethanol (AE) solvent, acrylic acid (ACA) and polyethylene glycol (PEG) for grafting hydrophilic groups on their surfaces. Eldinand Senouci [44] soaked and washed off the surface of the rubber powder with water. Rostami [18] used water and carbon tetrachloride to wash the surface of the rubber powder.

Albano et al. found an insignificant improvement in the compressive and splitting tensile strengths of rubberized concrete containing NaOH and silane pre-treated scrap tire waste as a fine aggregate replacement material [58]. Balaha et al. reported that the use of polyvinyl alcohol (PVA) and sodium hydroxide (NaOH) treated crumb rubber reduced the compressive and tensile strength loss observed in these concrete mixtures compared to mixtures containing untreated crumb rubber [59].

Li et al. [11] drilled a 5-mm-diameter hole for each chip for some batches to form physical anchorage. It was found that the small cement paste column only was observed in a small number of chips and a majority of chips failed to form the anchorage. In fact, the drilled holes in most of chips have already been closed before mixing through the rebound of the

rubber. As a result, it was impossible to make the physical anchorage. This might be the reason why an insignificant improvement was seen in strength and stiffness.

Some studies have also investigated the application of supplementary cementitious materials (SCMs) such as fly ash, silica fume, and metakaolin as an approach to minimizing the mechanical strength loss in PRC.

The positive effect of using silica fume in concrete was reported by [36], the addition of silica fume and rubber up to 20% wt powder and 50%, respectively, had a beneficial effect in terms of mechanical properties and diminished the rate of strength loss.

Pelisser et al. [27] reported a synergy between the combinations of sodium hydroxide followed and 15% silica fume. They concluded that the addition of 15% silica fume in addition to washing the rubber with NaOH solution led to the improvement of concrete strength and lower permeability. Azevedo et al. [60] reported that the synergetic effect between fly ash and metakaolin mitigate the strength loss attributed to the presence of waste rubbers. Results also implied the possibility of using waste rubbers up to 15% to maintain a high resistance to acid attack. Gesogulu and Güneyisi [61] reported that chloride penetration decreased remarkably with the use of silica fume, especially for PRC.

Güneyisi et al. [36] implied that the use of silica fume dramatically improved the compressive and splitting tensile strengths, and modulus of elasticity of mixtures. The effective role of silica fume was more pronounced at high w/c ratio. This finding is in agreement with several other studies [61]. In fact, for the high w/c concretes containing 15% or 25% rubber, the increase in compressive strength was as high as 40%. For the same w/c ratio and the rubber content, the compressive strength mostly increased with the silica fume content increasing from 5% to 20%. Surface modified rubber pre-treated with silane coupling agent was more effective for the concrete properties than that treated with saturated sodium hydroxide solution, was also reported by [22]. The pre-treatment effect of saturated sodium hydroxide solution for less than 24 hours was not that pronounced in the properties of concrete in comparison with the concrete containing as-received rubber.

VI. CONCLUSION

It can be concluded that untreated rubber concrete should be only used for applications in which the strengths are not critical. The optimized replacement ratio of rubber aggregates was varied between 20-30% by volume. Source type of waste tire from which the rubber aggregates have been obtained is effective for the performance of the concretes. It seems that there is still a need for future studies to optimize the size, shape, grading, density, amount, and methods of pre-treatment of rubber particles on the properties of rubber concrete.

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