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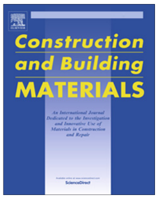

Recycling of waste tire rubber in asphalt and portland cement concrete: An overview

Xiang Shu, Baoshan Huang [*]

Dept. of Civil and Environmental Engineering, Univ. of Tennessee, Knoxville, TN 37996-2313, USA

HIGHLIGHTS

- More than 80 references are cited.
- The latest advances and studies in recycling of waste rubber are summarized.
- Recycling of rubber in both asphalt and Portland cement concrete were included.
- Reasons for the success or technical barriers of waste rubber recycling are explored.

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ABSTRACT

Waste tires pose significant health and environmental concerns if not recycled and/or discarded properly. Over the years, recycling waste tires into civil engineering applications, especially into asphalt paving mixtures and portland cement concrete, has been gaining more and more interests. This review summarizes the recent advances in the use of waste tire rubber in asphalt and portland cement concrete. The use of crumb rubber in asphalt paving mixture has long been proven successful due to good compatibility and interaction between rubber particles and asphalt binder, leading to various improved properties and performance of asphalt mixtures. The rubberized asphalt mixtures also have shown good compatibility with two widely used sustainability technologies in asphalt paving industry – reclaimed asphalt pavement (RAP) and warm-mix asphalt (WMA). In comparison with its use in asphalt paving mixtures, recycling of waste rubber in Portland cement concrete has not been so successful due to two factors: (1) incompatibility in chemical property between rubber and cement paste and (2) the significant difference in stiffness resulting in stress concentrations. Various methods have been proposed to overcome the barriers to improve the performance of rubberized portland cement concrete, some of which have shown to be promising.

1. Introduction

The United States generates approximately 300 million scrap tires annually, about 40% of which are used as fuel for generating energy, 26% ground into crumb rubber, 13% discarded in landfills, 5.5% used in civil engineering applications [1]. More and more environmental awareness has led people to seek alternative usage of scrap tires.

The use of waste automobile tires in civil engineering applications dates back to the very early ages when automobiles were first invented. Waste tires became natural candidates for construction materials, such as landfills and cushion materials. However, large scale recycling of waste tires in civil engineering applications did not happen until the 1960s, which was stimulated by both an ever-increasing number of scrap tires and a stronger environmental awareness movement.

The current applications of recycling waste tires in civil engineering practices mainly are as follows:

(1) used as modifiers to asphalt paving mixtures;
(2) used as an additive to portland cement concrete;
(3) used as light weight fillers; and
(4) used in whole tires as crash barriers, bumpers, and artificial reefs, etc.

During the late 1980s and early 1990s, the US Department of Transportation (USDOT) and Federal Highway Administration (FHWA) launched several major studies related to utilizing recycled tire products in highway constructions [2–4]. Recycling scrap tires was even mandated by the US Congress and was written into both the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 and the Resource Conservation Recovery Act, which states

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[*] Corresponding author. Tel.: +1 865 9747713; fax: +1 865 9742608.
E-mail address: bhuang@utk.edu (B. Huang).

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that any highway project funded by the federal government has to use certain percentages of recycled tire project, otherwise the funds will be withheld [5]. Section 1038 of the ISTEA (Use of Recycled Paving Material) addresses the use of scrap tires in asphalt concrete mixtures and contains three primary requirements including: (a) the federal regulations regarding the use of scrap tires should be relaxed; (b) the performance, recycling and environmental impact related to the use of scrap tire must be studied; and (c) each state must satisfy a minimum waste tire utilization requirement. However, Section 1038(d) was repealed by the US Senate in 1995.

Nevertheless, the major research efforts during the 1980s and 1990s have brought significant technology development and stimulated greater applications of waste tire products in civil engineering, especially in highway constructions.

2. Recycled tires in asphalt paving mixtures

2.1. Production of crumb rubber

Perhaps the largest quantity of recycled waste tires in civil engineering applications has been put to use in asphalt paving mixtures. Recycled waste tires are used in asphalt paving mixtures in the form of crumb rubber with sizes ranging from 4.75 mm to 0.075 mm. Crumb rubber is produced by mechanically grinding shredded tire pieces to desired sizes under different conditions: ambient temperature, ambient temperature and wet condition, high temperature, or cryogenic temperature [6]. Ambient grinding is a process in which waste tire chips are crushed in fast running granulators or mills at ambient temperature. The wet grinding process at ambient temperature is introduced to spray water to crumb rubber to eliminate the temperature rise due to milling. High-temperature grinding takes place at about 130 °C, resulting in granules of 1–6 mm [6]. In the cryogenic grinding process, tire pieces are frozen below its glass transition temperature and thus embrittled, and then shattered with an impact-type mill. Since high-temperature grinding is seldom used, ambient grinding and cryogenic grinding are the two major categories [6,7].

Due to the differences in grinding process, the crumb rubber particles from these two major processes show different surface characteristics. The particles from ambient grinding have irregular shape and rough surface, whereas those from cryogenic grinding have regular shape and smooth surface, resembling shattered glass. The ambient grinding also gives crumb rubber a much higher specific surface area, twice that of cryogenic crumb rubber [6,7]. These differences in surface characteristic have significant effects on the adhesion between rubber particles and the matrix in which they are embedded (such as asphalt binder), leading to different properties and performance of the rubber-modified materials [8–10].

2.2. Processes of recycling crumb rubber into asphalt

The processes of applying crumb-rubber modifier (CRM) in asphalt mixtures can be divided into two broad categories—dry process and wet process. In the dry process, crumb rubber is added to the aggregate before the asphalt binder is charged into the mixture. In the wet process, asphalt cement is pre-blended with the rubber at a high temperature (177–210 °C) and specific blending conditions. Crumb rubber particles in the dry process are normally coarser than those in the wet process and are considered as part of the aggregate gradations (called "rubber–filler") whereas, in the wet process, fine crumb rubber powders fully react with asphalt binders (called "asphalt–rubber") and improve the binder properties. Common dry process methods include the PlusRide™, chunk rubber, and generic dry. Common wet process methods include the Arizona (ISI), McDonald, Ecoflex, and Rouse continuous blending method [11].

The Federal Highway Administration (FHWA) and many state agencies have conducted numerous field studies for the feasibility of using recycled rubber tire products in asphalt pavements. The National Cooperative Highway Research Programs (NCHRP) "Synthesis of Highway Practice 198 – Uses of Recycled Rubber Tires in Highways" provides a comprehensive review of the use of recycled rubber tires in highways based on a review of nearly 500 references and information recorded from state highway agencies' responses to a 1991 survey of practices [4]. Florida DOT began constructing demonstration projects of asphalt pavement with CRM wet processes in 1989 and has reported satisfactory pavement performance [12]. It concluded that the addition of CRM would increase the asphalt film thickness, binder resiliency, viscosity, and shear strength. Virginia DOT constructed pavements containing CRM asphalt mixtures produced by two wet processes, McDonald and Rouse, and compared the pavement performance to that of conventional asphalt mixtures. Maupin [13] reported that the mixes containing asphalt rubber performed at least as well as conventional mixes. In Virginia mixes, the inclusion of asphalt rubber in hot-mix asphalt (HMA) pavements increased construction cost by 50–100 percent as compared to the cost of conventional mixes [13]. Troy et al. [14] conducted a research on CRM pavements in the state of Nevada. In their study, they evaluated a CRM binder using the Superpave binder testing protocols and conducted the mix design using the Hveem procedure. They concluded that the conventional sample geometry in Superpave binder test protocols cannot be used to test the CRM binders and that the Hveem compaction is inadequate for mixtures containing CRM binders.

According to Tahmoressi [15], crumb rubber has usually been applied in asphalt paving mixtures in the following forms:

1. Chip Seal Coat: In this application asphalt rubber is used as the binder for the seal coat, which is the finished pavement layer. This application is also known as SAM (Stress Absorbing Membrane).
2. Underseal: In this application asphalt rubber is used as the binder for chip seal application. After construction of chip seal layer an asphalt overlay is applied on the chip seal layer. The function of this underseal is to waterproof the existing pavement and retard reflective cracking. This application is also known as SAMI (Stress Absorbing Membrane Interlayer).
3. Hot Mix: Asphalt rubber is used as the binder for hot mix.
4. Porous Friction Course (PFC): Asphalt rubber is used as the binder for open graded porous friction course.

2.3. Asphalt–rubber interaction

The interaction of crumb rubber and asphalt binder plays an important role not only in the performance of crumb rubber modified asphalt mixtures, but also in the processing and storage of crumb rubber modified asphalt binder. The asphalt–rubber interaction involves two opposite mechanisms that occur simultaneously: particle swelling and dissolution [16–18]. Rubber particle swelling takes place when asphalt is absorbed into the particles. Due to the same organic hydrophobic nature, when rubber particles are added into heated asphalt binder, the light fractions (aromatic oils) of the binder are absorbed into the polymer chains of crumb rubber. The absorption is not a chemical reaction. Rather, it is a physical reaction, resulting in rubber particles swelling to two to three times their original volume and forming a gel-like material [2,16]. The change in rubber particle shape and size shortens the distances between particles, causing an increase in binder viscosity up to a factor of 10 [16,18–20].

Rubber particle dissolution happens only if mixing time is unnecessarily long and mixing temperature is excessively high. It includes two chemical reactions – depolymerization and devulcanization [17]. Depolymerization refers to the chemical breakdown of polymer chains of rubber into small molecules such as monomers. Devulcanization is a process of cleaving the crosslink bonds developed via sulfur atoms in the vulcanized rubber. Both processes break down part of rubber particles and dissolve them into the liquid phase of asphalt binder, causing a reduction in binder viscosity. Fig. 1 graphically explains the particle swelling and dissolution as well as the associated change in binder viscosity. The asphalt–rubber interaction is influenced by many factors, such as rubber type, rubber size, rubber composition, source and type of asphalt binder, compatibility between rubber and binder, mixing temperature and duration, shear rate [16–20].

2.4. Performance of crumb rubber modified asphalt pavements

Numerous studies carried out by the state DOTs have indicated that wet-processed CRM asphalt pavement has increased pavement performance [15,22–24]. Both SAM and SAMI have been proven to be very effective in reducing cracking in asphalt pavements [11,23]. In a study carried out by the Louisiana Transportation Research Center (LTRC), the asphalt pavement with CRM SAMI pavement has no visible cracks after seven years of heavy traffic [11]. It is notable that SAMI has been widely accepted as a treatment for reflective cracking in asphalt pavement.

When used in normal HMA mixtures, CRM has significantly improved the performance of asphalt binder. The effect of CRM has been roughly equivalent to the addition of polymer to conventional asphalt cement [25–27]. The increased binder stiffness effectively reduces rutting; whereas the much increased film thickness and improved ductility generally mitigates the fatigue cracking in asphalt pavement [11,23].

Nowadays, CRM has been more and more routinely used in open-graded friction course (OGFC) in some states (such as Arizona, Utah, and Texas). OGFC are gap-graded mixtures with very high interconnected air voids (between 15 and 22 percent) that provide excellent skid resistance and low splashing during rainy conditions. In addition, OGFC also reduces the noise level (about 3–5 dB) on highways. The advantages of applying CRM to OGFC are the stiffened asphalt binder and increased film thickness, which effectively eliminates the drain-down segregation during the construction. In the state of Arizona, all interstate and high volume highways, regardless of being asphalt or concrete pavement, have been surfaced with crumb rubber modified OGFC.

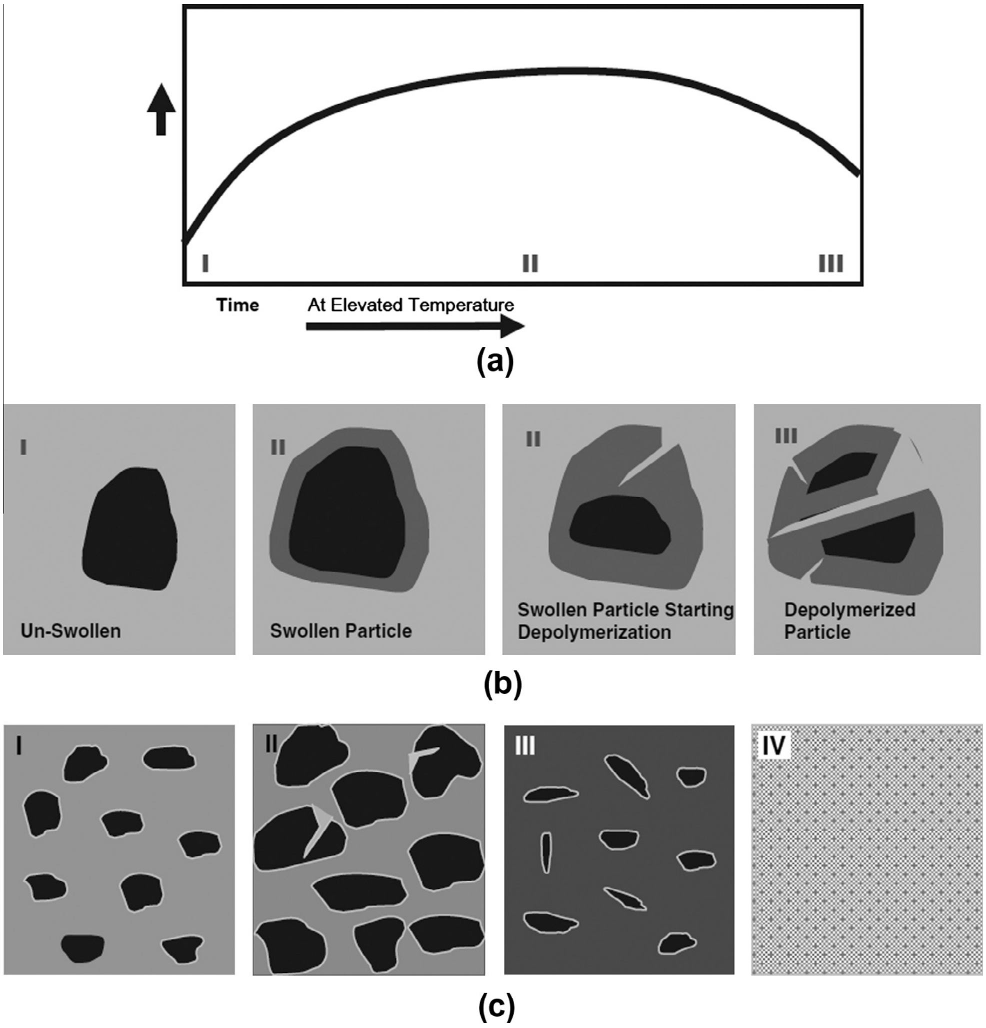


Fig. 1. Progression of asphalt–rubber interaction at elevated temperature: (a) change in binder viscosity over time at elevated temperature, (b) change in particle size over time at elevated temperature, and (c) change in binder matrix over time at elevated temperature [21].

2.5. Storage instability issue of crumb rubber modified asphalt

In practice, crumb rubber modified asphalt is stored at high temperatures after its production for easy handling and operation. However, due to the differences in specific gravity (specific gravity of rubber is approximately 1.15 while asphalt's about 1.03), crumb rubber particles dispersed in asphalt matrix tend to settle down to the bottom, resulting in the separation of crumb rubber and asphalt phases. Therefore storage instability poses a big problem in application of crumb rubber modified asphalt [16,28–30].

The phase separation phenomenon of two-phase system such as crumb rubber modified rubber is governed by Stoke's law. The terminal velocity of rubber particles settling down can be expressed as follows [31]:

$$v_t = \frac{2a^2 \Delta\rho g}{9\eta} \tag{1}$$

where v_t is the settling velocity of dispersed particles, a is the radius of dispersed particles, $\Delta\rho$ is the density difference between two different phases, g is the gravitational acceleration, and η is dynamic viscosity of liquid medium.

It is evident from Eq. (1) that the settling velocity of crumb rubber particles increases as [30]

- The rubber particle size increases.
- The density difference between rubber and asphalt phases increases, and
- The dynamic viscosity of asphalt matrix decreases.

Therefore, stable crumb rubber modified asphalt can be achieved by (1) decreasing the rubber particle sizes, (2) decreasing the density difference, and (3) increasing asphalt viscosity.

In addition to the above-mentioned factors, storage stability of crumb rubber modified asphalt is also related to compatibility and interaction between rubber and asphalt [18,31]. Abdelrahman and his research team reported that adding polymer modifier and regulating the interaction between rubber and asphalt through control of interaction temperature, interaction mixing speed and time can improve the storage stability of crumb rubber modified asphalt [21,31,32].

2.6. Integration of crumb rubber with RAP and WMA technologies

In addition to crumb rubber from waste tires, use of reclaimed asphalt pavement (RAP) and warm mix asphalt (WMA) are two other sustainability technologies that have been widely used in the infrastructure industry [33–38]. RAP has been applied in asphalt paving mixtures for several decades. Use of RAP can conserve natural resources (virgin asphalt and aggregate), reduce energy consumption and negative impact to environments. With WMA technology, asphalt mixtures can be produced, constructed, and compacted at temperatures lower than for HMA, resulting energy saving and environmental friendliness. Today, more and more interests have been shown in combining crumb rubber with RAP and/or WMA technologies in asphalt paving industry.

The asphalt rubber technology service (ARTS) at Clemson University conducted comprehensive laboratory studies on combining crumb rubber with RAP or WMA technologies. They investigated into the possibility of using Superpave mix design for asphalt mixtures containing both crumb rubber and RAP [39]. They found that the Superpave mix design method and the volumetric analysis can both be used for rubberized asphalt mixtures with RAP [39]. In the mix design, they found that crumb rubber increases the optimum asphalt content and the voids in mineral aggregate (VMA) [39,9]. Xiao et al. [40] found that use of both RAP and crumb rubber in HMA can effectively improve the rut resistance of HMA mixes. In another study on moisture susceptibility, Xiao and Amirkhanian [41] reported that although RAP could increase the resistance to moisture damage, addition of crumb rubber seems to have a slightly negative impact on moisture resistance. As for the fatigue life of asphalt mixtures, Xiao and Amirkhanian [42] found that crumb rubber can improve the aging resistance of asphalt binder and thus prolong the fatigue life of mixtures without RAP. However, for mixtures containing 30% RAP, addition of crumb rubber did not show a clear effect on the fatigue life of mixtures.

Due to the increased viscosity caused by the addition of crumb rubber, crumb rubber modified asphalt mixtures generally require higher mixing and compaction temperatures than conventional HMA. The WMA technology has the potential to lower the production and compaction temperatures of CRM mixtures as it does with conventional HMA mixtures while maintaining the good properties and performance of CRM mixtures. Many researchers have investigated the effects of WMA additives on the properties of CRM binders. They found that addition of WMA additives can improve the high-temperature properties of CRM binders, resulting in a possibly higher rut-resistance of mixtures [43–46]. However, researchers at ARTS found that addition of WMA additives may compromise the resistance of conventional rubberized binders to fatigue and low-temperature cracking, making CRM mixtures containing WMA additives vulnerable to these two pavement distress [46,47]. Yu et al. [48] investigated the effects of two WMA additives, Sasobit and Evotherm, on the high-temperature behavior, low-temperature behavior, temperature susceptibility, and fatigue cracking of crumb rubber modified asphalt. They found that the type and content of WMA additives have a significant effect on these properties and recommended that optimal type and content of WMA additives be determined based on specific conditions [48]. Yu et al. [49] also investigated the interaction mechanism between the WMA additive Evotherm-DAT with crumb rubber using multiple techniques including environmental scanning electron microscope (ESEM), chemical composition, differential scanning calorimeter, Fourier transform infrared spectroscopy (FTIR), and nuclear magnetic resonance. They found that Evotherm-DAT affects the state of aggregation of crumb rubber and the intermolecular forces between rubber particles. However, they did not find any complex chemical reaction between Evotherm-DAT and crumb rubber modified asphalt.

Studies on asphalt mixtures containing both crumb rubber and WMA additives indicated that WMA additives could reduce the mixing and compaction temperatures of CRM mixtures by up to 20–30 °C, making them comparable to those for conventional HMA [46] [50,51]. Use of both crumb rubber and WMA additive in HMA can effectively improve the engineering properties of asphalt mixtures [46,50].

2.7. Concerns of using CRM in asphalt pavements

The biggest concern of using CRM in asphalt pavements is the higher cost. Other concerns include the recyclability, negative environmental impacts, and equipment modifications.

2.7.1. Higher cost

Nearly all literature reported higher construction cost of crumb rubber modified asphalt pavements when compared to conventional ones. The unit cost of CRM asphalt mixtures has been ranging between 1 and 3.6 times of conventional asphalt mixtures [11,23,52]. However, it should be pointed out that most literature report projects that only use small amount of CRM asphalt pavement test sections. The smaller experimental scale partially contributed to the higher unit cost. When a decent scale is in place, the unit cost gradually decreases [23,53].

When considering the cost, the real cost to be concerned should be the life cycle cost (LCC) of the pavements, instead of the initial construction cost. Hicks and Epps [24] conducted a comprehensive study on a statistically based life cycle cost analysis (LCCA) for CRM asphalt paving materials. After comparing different pavements from Arizona, California, and Texas, they concluded that when appropriately designed, asphalt rubber pavement could be more cost effective than conventional pavement [24].

2.7.2. Recyclability

There have been some concerns regarding the recyclability of CRM asphalt pavements. However, studies and experiences indicate that recycled asphalt pavement (RAP) containing CRM asphalt cement is fully recyclable into new HMA mixtures [53,54].

2.7.3. Negative environmental impact

Crumb rubber modified asphalt mixtures require a higher temperature to blend, thus potentially increasing the hazardous emission in hot-mix plants. A study conducted by the Michigan Department of Transportation indicated that the inclusion of CRM will not produce additional hazardous emissions [55].

In a comprehensive research (NCHRP 25-9), Azizian et al. [56] examined the environmental impact of crumb rubber asphalt concrete to the ground water near the highways. They found that crumb rubber asphalt concrete leachates contain a mixture of organic and metallic contaminants, which are moderately toxic for algae and water fleas. However, the influence of the contamination is limited since the contaminants from leachates are degraded or retarded in their transport through nearby soils and ground waters [56].

2.7.4. Equipment modification

One big hurdle of promoting crumb rubber modified asphalt mixture has been the reluctance of contractors to modify their existing equipment. Studies have shown that little modification is needed to most hot-mix asphalt plants in order to accommodate the use of crumb rubber. None of the paving equipment needs any modifications for paving crumb rubber modified asphalt [53]. The contractors, however, do need to make some changes during operation to handle the crumb rubber modified asphalt mixtures more efficiently.

3. Recycled waste tires in portland cement concrete (PCC)

Compared to their applications in asphalt paving mixtures, the use of recycled tires in portland cement concrete (PCC) has been limited [57]. The size of waste tires used in PCC ranges from rubber chips (25 mm to 50 mm) to crumb rubber powders (4.75 mm to 0.075 mm). When used in PCC, waste tire materials replace part of coarse or fine aggregates. The addition of waste tire rubber into PCC significantly alters the properties of the concrete. Due to the hydrophobic nature of rubber, the bond between the untreated rubber and hydrated cement is weak, which results in the significant reduction of both compressive and tensile strength of rubber modified PCC [57,58]. On the other hand, concrete becomes more ductile, as illustrated by the limited viscoelasticity and higher post failure toughness [59].

Eldin and Senouci [60] investigated the strength and toughness of concrete with a portion of coarse aggregates replaced by waste tire chips. They observed that the compressive strength and split tensile strength were reduced, while its toughness and ability to absorb fracture energy were enhanced significantly. They also provided an explanation of the fracture mechanisms of rubber-filled concrete based on the theory of strength of materials. Topcu [58] investigated the size and amount of tire rubbers on the mechanical properties of concrete. He found that although the strength was reduced, the plastic capacity was enhanced. Lee et al. [61] investigated the flexure and impact strength of crumb rubber-filled concrete. They found that crumb rubber-filled concrete had higher flexure and impact strength than conventional Portland cement concrete and latex-modified concrete. They attributed the increased strength to an improved interfacial bonding between crumb rubber particles and cement paste due to the existence of styrene-butadiene rubber (SBR) latex. Goulias and Ali [62] used nondestructive testing (NDT) to evaluate crumb rubber-filled concrete. They attempted to establish a relation correlating the strength and elastic modulus with parameters from NDT results. Khatib and Bayomy [63] used fine crumb rubber and tire chips to replace a portion of fine or coarse aggregates. They found that the rubber-filled concrete showed a systematic reduction in strength, while its toughness was enhanced. They also proposed a regression equation to estimate the strength of rubber-filled concrete.

3.1. Concerns of using waste tires in PCC

Throughout the literature, the most common negative comment of the use of waste tires in PCC has been the significant reduction of strength. Generally, the addition of 15% rubber chips to replace coarse aggregate results in a 45% reduction of compressive strength and 25% reduction in split tensile strength [57,60,63]. The significant loss of strength can be attributed to two factors: (a) the hydrophobic nature of untreated rubber, which creates a weak interfacial bond between the rubber chips (particles) and cement mortar; and (b) the significantly low modulus (stiffness) of rubber. The fact that rubber is significantly softer than its surrounding media (mortar and aggregates) makes rubber particles act like “holes” inside the concrete. Theses “holes” inside the PCC generate stress concentrations during loading conditions and thus the strength of the overall concrete samples (or structures) is significantly reduced. Because of the “holes” effect, given the same condition (such as waste tire proportions), the bigger the particle (chip) size, the lower the concrete strength [57].

3.2. Applications of PCC with waste tires

Most applications of PCC with waste tires have been on secondary or non-critical structures. Zhu et al. [64] reported the use of adding crumb rubber into exterior wall materials. Sukontasukkul and Chaikaew [65] reported the successful application of crumb rubber modified PCC on pedestrian blocks in Thailand. Pierce and Blackwell [66] studied the potential of using crumb rubber as lightweight aggregate in flowable fill for both PCC and trench bedding materials. Potential uses of rubber modified PCC have also been reported for highway sound walls, residential drive ways, and garage floors, etc.

3.3. Advantages of rubber modified PCC

In addition to environmental benefits, the most significant advantages of rubber modified PCC have been their excellent energy absorbing characteristics. Researchers have found that rubber modified PCC can effectively increase the ductility and prevent brittle failures [59,67,68]. Potential applications of the ductile rubber modified PCC could be structural components subjected to impact and dynamic load (such as bridge approach slabs and airport runways). However, the significant reduction of strength has prohibited these applications.

Another benefit of rubber modified PCC is the light weight. Rubber has much lower specific gravity than aggregates, so the replacement of aggregates with rubber consequently reduces the overall specific gravity of the rubber modified PCC [69].

Most researchers reported the improved freeze and thaw resistance of rubber modified PCC [70,71]. However, some researchers [72] indicated that a higher percentage of rubber content compromises the freeze-thaw durability of rubber modified PCC.

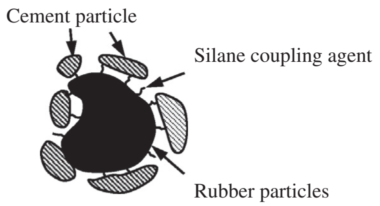
3.4. Latest research of PCC with rubber

Researchers have been working to improve the properties of rubber modified PCC so that it could be suitable for more applications. Two approaches have been adopted by researchers to prevent the significant loss of strength of rubber modified concrete. The first approach is to reduce the size of rubber particles. Since rubber chips produce flaws in concrete mass and generate stress concentrations, the reduction in size of "holes" would effectively reduce the stress concentration. However, only if the rubber particles can be reduced to the dimension that is comparable to cement particles (around 20 μm) can a significant increase of both compressive and tensile strength be expected. The processing of extremely fine rubber powder will inevitably increase the cost, which should be considered along with the benefit of improved performance of the modified concrete.

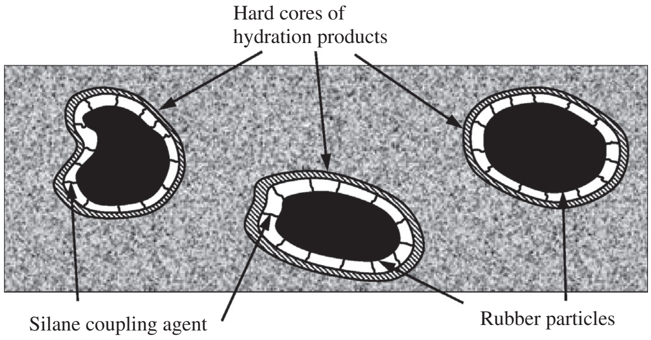
Another school of thought to improve the performance of rubber modified concrete is to treat the surface of rubber particles. Natural rubber does not form a strong bond with cement mortar. Chemical treatment of the rubber particles alters the surface properties of rubber particles and will potentially improve the bond between the rubber and cement mortar. Segre and Joekes [73] used NaOH to treat the waste tires before incorporating them into PCC. Lee et al. [74] applied HNO_3 and a METHOCEL cellulose ethers solution. Li et al. [75] employed cement paste pre-coating of rubber particles. Rostami et al. [76] simply washed rubber chips with water before applying them to the cement concrete. All of the surface treatments have reported varying degrees of success. Li et al. [59,77] used multiple techniques (chips vs. fibers, fibers with various aspect ratios, surface treatment by saturated NaOH solution, physical anchorage by drilling a hole at the center of the chips, and hybrid reinforcement of waste tire fiber and polypropylene fiber) to improve the properties of waste tire rubber modified concrete.

However, none of the surface treatments so far have shown significant effect in preventing the huge strength loss due to the incorporation of rubber particles/chips. While surface treatment does have the potential to help improve the bond, it will not change the fundamental fact of stiffness incompatibility between the rubber and other constituents of PCC. Reducing the size of rubber particles (down to the same order of magnitude of cement powders) will both reduce the "flaw" induced by the rubber and increase the stiffness of the particles. Combining the surface treatment and reducing the particle size might produce PCC that can be used in varieties of applications. Reduction of processing cost will be a key issue.

Recently, Chou et al. [78] performed a theoretical analysis to explain the effect of rubber additives on the properties of rubber modified concrete. They found that rubber particles block water diffusion in rubberized concrete, leading to insufficient and imperfect cement hydration in some regions and thus the reduced properties of concrete. In order to improve the mechanical properties of rubber modified concrete, they proposed to modify the surface properties of rubber particles and change them to hydrophilic [78]. Two ways they used to enhance the hydrophilic characteristics are partial oxidation at elevated temperatures and treating crumb rubber with waste organic sulfur. Both have shown to be successful in improving the mechanical properties of rubber modified cement mortar and concrete [79–81]. Huang and his research team developed a two-staged surface treatment to improve the properties of rubber modified cement composites and concrete (Fig. 2) [82–84]. The first treatment is to develop chemical bonds between rubber particles and cement paste by using silane coupling agent and the second step to increase the stiffness of rubber particles by developing a "hard shell" around the rubber particles with cementitious materials [82]. The results from their studies show that the compressive strength of rubber-modified cement mortar could be increased by up to 110% and the method was also effective in improving performance of rubber modified concrete [82,84].



(a) Before hydration



(b) After hydration

Fig. 2. Illustration of effects of two-staged surface treatment [82].

4. Conclusions

Use of waste tire rubber in asphalt paving mixtures and portland cement concrete has been gaining more and more attention in civil engineering area due to the associated economic, technical, and environmental benefits. Recycling of crumb rubber into asphalt paving mixtures, especially the asphalt rubber technology has been proven successful for decades. The addition of crumb rubber into asphalt binder can lead to the increased resistance to the three major modes of asphalt pavement distress, rutting, fatigue cracking, and low-temperature cracking. Once properly constructed, rubberized asphalt pavements can perform much better than conventional asphalt roads. One technical problem that still needs to be addressed is storage stability – how to store crumb rubber modified asphalt at high temperatures for as long as possible without phase separation.

Compared to its use in asphalt mixtures, use of recycled rubber in portland cement concrete is not so technically successful due to the two inherent factors – the incompatibility issues caused by chemical composition and stiffness. Researchers have proposed various methods to reduce or eliminate the negative effects while keeping the beneficial effects of waste rubber in portland cement concrete. Still more research efforts have to be made to significantly improve the properties and performance of rubber modified concrete and to increase its use in structural engineering.

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