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A Review on the Enhancement of Asphalt Cement using Different Additives

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Abstract. Asphalt cement, commonly known as asphalt or bituminous, is one of the basic materials used to produce hot mix asphalt (HMA) for road pavements. In the past, asphalt was mixed directly with other materials to produce a conventional HMA without any modification. However, the asphalt binder has failed in many places worldwide due to climate change and various issues such as cracking, bleeding, shoving, etc. Therefore, they modify asphalt cement by using many types of additives to overcome these problems. This work aims to review these studies that have been concerned with improving asphalt cement as a pre-action before mixing it with other materials to make modified hot mix asphalt (HMA) for road pavements. The present paper reviews published studies (1978–2019). It is evident from literature survey studies that modification of asphalt cement gives more efficient, economic, and eco-friendly results.

INTRODUCTION

Nowadays, asphalt cement results from the fractional distillation of petroleum [1, 3, 5, 6] as a residuum from the vacuum distillation tower. In the United States, more than 35 million tons of asphalt cement produces annually. They use seventy percent of this quantity for paving roads [4] due to its low cost, weather resistance properties, and ease of processing in the molten state [7]. the american society for testing and materials astm-d8 defines asphalt cement as "a class of black or dark-colored cementitious substances, natural or manufactured, composed primarily of high molecular weight hydrocarbons, completely insoluble in carbon disulfide (cs_2), and includes of both tar and asphalt" [8, 9]. generally, the structural formula is $c_nh_{2n+b}x_d$, where *n* ranges from 25-150, *x* may be s, n, or o trace metals, *d* is usually small, and *b* may be negative [4]. the chemical composition of asphalt cement varies according to its source, but approximately it is shown in table 1 as follows:

TABLE 1. Chemical composition of asphalt cement [4].

Item	Range
Molecular Weight (g/mol)	300-2000
Carbone (%)	80-87
Hydrogen (%)	9-11
Oxygen (%)	2-8
Nitrogen (%)	0-1
Sulfur (%)	0.5-7
Trace Metals (%)	0-0.5

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Sometimes, asphalt cement does not characterize by its chemical composition due to different molecules possessing. Therefore, the total mix of its components defines its properties. In general, asphalt cement is a mixture of large, complex, and often poly-functional molecules, as explained below:

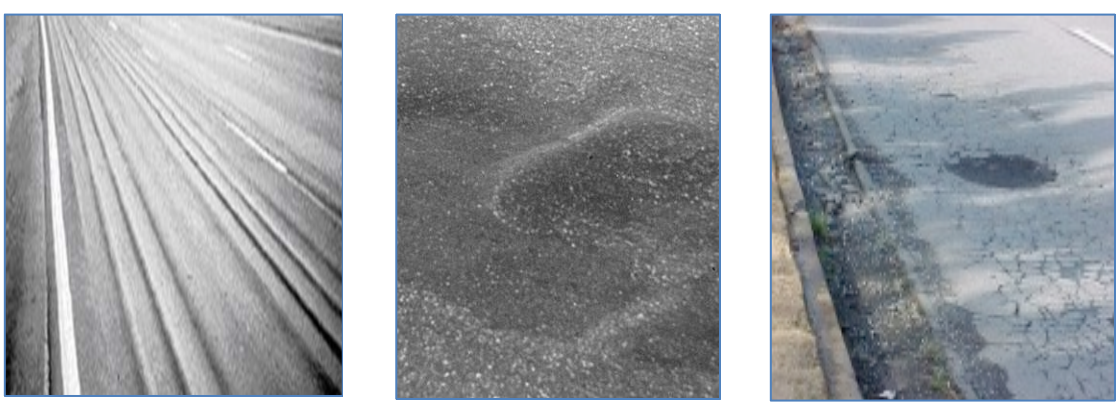
a) Asphaltene: It is a black or brown solid material precipitated from asphalt with normal pentane. It is significant discrete solid inclusions with high viscosity. The typical asphalt cement generally contains between 5% and 25% by weight of asphaltenes [10], which is responsible for the strength and the stiffness of asphalt cement [11].
b) Resins: A solid or semisolid material at room temperature transforms into a liquid phase when heated and brittle when cold. These materials disperse the asphaltenes in oils, resulting in a semi-colloidal structure in asphalt cement [5, 12]. They also contribute to adhesion, that describes as the amount of tensile stress required to break the bond between asphalt cement molecules [13].
c) Oils: Either aromatic and saturated are colorless liquids. The low viscosity component is responsible for the viscosity and liquidity of asphalt cement. The amount of heavy gasoil controls the grade of asphalt cement. [1].

The physical properties of the unmodified asphalt cement are shown in the following explanation [7]:

- It is presented as a viscous fluid at 50ºC and more and becomes brittle at 30ºC and less, which means that A.C is a very temperature sensitive material [14, 15] . Its behavior differs between an elastic solid and viscous liquid, i.e., viscoelastic materials [2]. There are five grades of asphalt cement according to the classification of ASTM- D3381 [4, 8] depended on the proportions of the constitutes of A.C. [12]; AC-2.5, AC-5, AC-10, A.C- 20, AC-30, and AC-40.
- Low creep resistance decreases at high temperatures and when exposed to long-term loads [14].
- It deforms significantly over time due to the applied load, which limits its use for long periods.

MODIFICATION OF ASPHALT CEMENT

In the 19th century, asphalt cement began to use for road construction, then the demand for using asphalt cement is increased due to the fast-growing car industries, which required more and more paved roads. Several problems show when using conventional Hot-mix asphalt (HMA) for road pavements, such as rutting, shoving, and fatigue cracking as shown in Fig. 1. Many studies are concerned with enhancing asphalt cement by using different materials as modifiers for the pure asphalt cement to control these problems and obtain a highly efficient pavement. Pavlovich and Morris, 1978, employed ambient crumb rubber (25wt%) to modify asphalt cement (AC-10) at 200ºC for a restricted period of mixing time. Using Marshall's properties, they demonstrated that the modified rubber asphalt binder performs better than the standard mix [16]. Fayadh, 1987, studied the impact of using hydrated lime (1-1.5wt%) and waste tires rubber (20wt%) on the asphalt cement produced from various refineries located in different places. These additives decreased the susceptibility of temperature and oxidative hardening for asphalt cement [17]. Heitzman, 1992, found that the mixing temperature, mixing time, and the mechanical energy required was affected by the asphalt binder's performance produced by wet or dry mixtures.



(a) Rutting (b) Shoving (c) Fatigue cracking

FIGURE 1. The main problems with roads [7].

The study proved that any increment of crumb rubber powder employed (0 to 21wt%) had increased the viscosity of asphalt cement when the blending temperature was 135ºC, which may reach 100-fold when 21wt% of crumb rubber powder was added [18]. Moreover, Zaman and Frickem, 1995, proved that the excellent addition of crumb rubber powder to asphalt cement (AC-30) enhanced the asphalt binder's fatigue cracking resistance, particularly in a cold climate. The variables studied were the amount of crumb rubber powder (2.5 to 10wt%) and mixing temperature (175-200ºC) for 30min of each period of the mixing process [14]. Coomarasamy and Hesp, 1997, investigated the impact of crumb rubber powder size on modifying two grades of asphalt cement (85/100 and 150/200) penetration using three grades of crumb size. They proved that the excellent service of crumb rubber powder had increased the high-temperature performance and the thermal cracking resistance of the modified mixture compared to that contained the coarse size of crumb rubber [19]. Carlson and Zhu, 1999, tested the possibility of using waste rubber as a modifier for the hot mix binder under the effect of temperature and time of mixing. Several methods produced the crumb rubber powder, but they had concluded that the ambient crumb rubber was more efficient when (10-20wt%) used at (149-204ºC) and (45-60min). This study proved that crumb rubber could not consider as a waste material [20].

Muhammed Ali and Al-Mansoori, 2021 found that mixing the control asphalt binder with three percentages of ceramic waste powder (3 %, 6 %, and 9 %by weight of the binder) improved the physical properties of viscosity, storage stability, and softening point. Thus, decreasing penetration. Furthermore, high percentages of ceramic waste powder increased $G^*/\sin\delta$ and decreased $G^*\sin\delta$, resulting in binders being more resistant to permanent deformation (rutting and fatigue) [21]. Other research studies have enhanced the asphalt cement with external rejuvenators to trigger and accelerate the self-healing phenomenon of the asphalt materials by increasing the aromatic fraction by either adding cooking oil or increasing the temperature to reduce the asphalt viscosity [22-25].

At 150 ºC of mixing temperature, Schulz et al. 1999 invented the possibility of modifying asphalt cement using different types of polymers (1 to 10% wt%) such as conjugated di-olefin monomer, vinyl aromatic monomer, and N-isobutoxymethyl acrylamide (IBMA). The problems of rutting, shoving, and fatigue cracking had been significantly minimized [3]. Lu and Isacsson, 2000, tried to modify asphalt cement using different thermoplastic polymers, such as SBS, EVA, SEBS, and EBA. The study employed several tests and then proved that the morphology properties of the additives were affected positively on the modified asphalt binder. Nevertheless, there was a significant difference in rheological behavior when the modified binder containing SEBS and SBS compared to that included EBA and EVA [26]. Sousa et al. 2000, found that the employment of a proper amount of crumb rubber powder (18wt%) as a modifier for asphalt mixture, gap-graded type, affected the properties of resilience and the formation of the fatigue cracking compared to that of the conventional dense-graded mix [27]. Airey, 2002, used fluorescent microscopy, differential scanning calorimetry, and a dynamic shear rheometer test to investigate and analyze asphalt binder's thermal properties. The study proved that modification of the asphalt was because of the increment of stiffness and elasticity of this binder at a high temperature [28].

Engle and Mujeeb, 2002, used several tests to compare the performance of HMA modified with crumb rubber powder in various projects to that of conventional pavement. They concluded that the modified pavements have higher performance than the unmodified hot mix asphalt, especially fatigue cracking formation [29]. Battey, 2004, investigated the effect of using several types of additives individually and compared the modified hot mix binder with the conventional one. Styrene-butadiene-styrene (SBS), styrene-butadiene-rubber (SBR), ambient crumb rubber (ACRM), polyethylene (P.E.), and gelled asphalt (G.A.) were the modifiers used. The addition of these polymers improved the performance of the hot mix binder by four times over that of the conventional HMA [30]. Daranga, 2005, investigated the advantages of adding polymers to the wearing course pavement layer, such as tri-block SBS. The study employed several devices and tests to prove that the addition of SBS copolymer helped increase the aging resistance of the hot mix binder according to the theory of increasing the critical temperature of the pavement aging [5]. Aisien and Hymore, 2006, used Marshall methods to compare between the modified and unmodified hot mix asphalt. The modifier was a mixture of different crumb rubber particle sizes (0.1 to 0.5wt%) added to the preheated aggregate for a limited period and then mixed with asphalt cement for 2.5 minutes. They concluded that the modified binder had the same mechanical properties when cured in air or water. In contrast, the unmodified hot mix binder specimens soaked in the water had inferior mechanical properties [31].

Brule and Gazeau, 2006, used the Differential Scanning Calorimeter (DSC) to study the rheological properties and thermal behavior of asphalt cement modified by different ethylene copolymers (10wt%). They found that the characteristics of each additive affect the behaviors of rheological and thermal objects depending on the cases of elastic solid and a viscous liquid of the modified asphalt cement [15]. Williamson, 2006, investigated the impact of using crumb rubber (10wt%) as an asphalt cement modifier on the performance of wet and dry mixtures under the effects of the operational variables such as mixing temperature (176 to 226ºC) and mixing time (45-60min). These variables had affected the reaction rate between asphalt cement and the additives, as the study proved [32]. Ahmed, 2007, used Maleic Anhydrite Grafted Polyethylene (MAH-g-PE) as an additive for penetration grade (40/50) asphalt cement to improve Marshall properties, such as stability and flow. The weight of the modifier used was (2, 4, 6, 10, and 12wt%). The obtained results coincided with ASTM and AASHTO requirements, with the maximum value of Marshall properties obtained when the additive content is equal to 10%. Still, as the percentage increases, Marshall stability decreases, and the modified asphalt mixture fails [33]. Fernandes and Forte, 2008, investigated the effects of adding SBS copolymers (3wt%) to the conventional mix and the compatibilizer agent, aromatic oil, or shale oil (4wt%) to the modified asphalt cement. The results showed an increment of the performance of the modified asphalt cement and then the modified HMA consequently [34].

Furthermore, Fonts and Triches, 2008, compared modified and unmodified hot mix binders under the influence of operational variables such as dense and gap graded aggregate, 21wt% of cryogenic crumb rubber, 90 minutes of mixing time, 180°C mixing temperature, and 50/70 grade of penetration asphalt cement. The study proved that the modified mix was more effective than the unmodified one due to viscosity and softening point increment. Moreover, the modified binder can carry loads approximately ten-fold more traffic than the other type [35]. Ghaly, 2008, studied the ability to add additives such as crumb rubber, SBS, and elemental sulfur to enhance the Marshall stability of the hot mix asphalt. The operational parameters were 160°C, (2 to 5wt%), (2 to 5wt%), and 1wt% for crumb rubber, SBS, and sulfur, respectively. The study results showed that the modified mix's temperature susceptibility reduced, and the stability increased when crumb rubber, SBS, and sulfur values were 4wt%, 4wt%, and 1wt%, respectively [36]. Shuart et al. 2008, discovered the effect of using plaster and an elastomer (0.1 to 5wt% for both) on the enhancement process of asphalt cement (AC-20). They proved that the modified asphalt cement had higher storage stability and best workability due to these additives, i.e., oxidized polyethylene and SBS block copolymer [37]. Abbass F. and Abass, M., 2009, investigated the possibility of using coarse scrap tires rubber to enhance asphalt binders' performance and wet and dry mix techniques. The particle size of wasted rubber was (1-5cm), and (10-30wt%) was employed. The percentage of asphalt cement used was (3-6.5%wt. of total mix). The most efficient performance was achieved when the operational parameters were set to 20 wt% CRM, 3cm particle size, and 6.482 wt% asphalt cement, which resulted in high crack resistance, less rutting, long life, deceased life-cycle cost, reduced traffic noise, improved resistance to permanent deformation at high temperatures, decreased pollution, and increased environmental quality [38]. Fonts and Triches, 2009, developed two models: a stiffness model that relates the stiffness of the binder to the amount of asphalt cement in the mix and a fatigue model that describes the fatigue resistance to the number of voids filled with asphalt cement. They used ambient crumb rubber (15-20wt%) as a modifier for asphalt cement with a penetration grade of 50/70 [39].

Kumar and Mehndirtta, 2009, studied the effect of using crumb rubber (3 to 9wt%) as a modifier on the rheological properties by using the Dynamic Shear Rheometer (DSR) test. They demonstrated that increasing the mixing temperature gradually improves rheological properties [40]. Mohammed and Omar, 2009, demonstrated that using crumb rubber (1-5wt%) to improve asphalt cement (80/100) penetration grade at 180°C with a blending velocity of 2200rpm for an hour could result in a continuous elastic network. They used the Dynamic Shear Rheometer (DSR) to test their experiments [41]. Neto and Farias, 2009, found that the mixing time (60-300min) of producing asphalt cement modified by crumb rubber (21wt%) at (210ºC) affects the properties of the modified hot binder such as the tensile strength, fatigue life, aging resistance, and G* modules [42]. Sabina et al. 2009, used plastic/polymer (P.P.) (8% and 15wt%) as an additive to asphalt cement (60/70 penetration grade) to improve it. The results proved an enhancement of Marshall stability and following compared to that obtained in the conventional mix [43]. AL Salami, 2011, studied the enhancement of asphalt cement via the use of two additives, waste polystyrene (WPS) (0.2, 0.4, 0.6, and 0.8 wt %) and polyvinyl acetate (PVA) (0.5, 1.5, 2, and 2.5 wt %). High values of Marshall properties were obtained when the values of modifiers were 0.6 wt% and 1.5 wt% of WPS and PVA, respectively [10].

Bahia and Davies, 2011, used crumb rubber produced by different processes, i.e., ambient, cryogenic, and other types produced by a special process, to study their effects on the properties of asphalt cement according to the specifications of the Strategic Highway Research Program (SHRP). They found that the viscosity of asphalt increases when crumb rubber for different types was employed. The modified asphalt cement minimizes the rutting and thermal cracking resistance of hot mix bonders [44]. Jabari 2014, studied the effect of classification of the crumb rubber according to the size of scrap tire particles, either wasted car tire rubber or wasted truck tire rubber. The studied operational variables were mixing temperature (150-180ºC), mixing time (20-60min), wasted car tire rubber WCTR (10-20g), and wasted truck tire rubber WTTR (0-4g). The effectiveness of this classification was demonstrated in a novel study that produced high values of Marshall stability. It flowed, 13.5 kN and 3.5mm, respectively, at the optimum values of the operational variables of 176 ºC, 21min., 18g, and 3.5g [7]. Zhu et al. 2014, focused on the advantages and disadvantages of using various types of additives and how to overcome these disadvantages by using saturation, sulfur vulcanization, and reactive polymers to increase aggregate adhesion recyclability and efficient performance [45].

Karim et al. 2015, investigated the effect of the operational parameters such as mixing time, temperature, and the amount of crumb rubber, on the performance properties of the asphalt binder. Brookfield viscosity and dynamic shear rheometer (DSR) tests were performed that showed the significant effects of crumb rubber and mixing temperature on the performance in comparison to the time of blending [46]. Al-Jumaili 2016 investigated the rheological properties of asphalt binder when polypropylene and cellulose materials were modified. The research included several tests, such as ductility, penetration, softening point, rotational viscosity, and a dynamic shear rheometer (DSR). The study revealed that the physical properties of the modified binder had enhanced at low and high temperatures, such as the deformation resistance [47]. Mubarak et al. 2016, employed an asphalt cement modifier containing acrylate styrene acrylonhrtilrei (ASA) polymer and (Al_2O_3) nanoparticles (3 to 7wt%). This modifier had influenced the rheological properties of the asphalt cement at high temperatures and better storage stability and rutting resistance at 75ºC [48]. Taherkhani et al. 2016, proved that the stiffness of asphalt binder increased when it was modified by nano-silica (i.e., 1, 3, and 5 wt%).

In contrast, the temperature sensitivity decreases along with the increment of this modifier [49]. Oruç et al. 2016, invented four new additives containing boron to modify asphalt at limited amounts and constant values of the temperature and mixing. This process was characterized by Fourier transform infrared spectrometer (FTIR) and scanning electron microscopy (SEM). The tests required to investigate the performance were the softening point, penetration, rotational viscosity, and dynamic shear rheometer. They concluded that the use of these additives had increased the rutting resistance and elastic properties [50].

Badejo et al. 2017, investigated the possibility of polyethylene terephthalate (PET) (1 to 5wt%) as a modifier to asphalt binder. Tests of Marshall stability and flow were performed to compare the performance between the modified and unmodified asphalt binders. The optimum value of PET was 1wt% that had given 17.01kN and 4mm of Marshall stability and flowed, respectively [51]. Ferretti et al. 2017, focused on the impact of using additives as modifiers on the performance properties of asphalt binders for warm mix pavement through the employment of a neat bitumen and two different additives. Several tests showed that these additives had minimized the viscosity-temperature susceptibility of the modified asphalt when the temperature ranged (80 to 140ºC), as well as the increase of rutting resistance and elastic behavior at high temperatures [52]. Jan et al. 2017, evaluated the effect of using waste polyethylene modifiers on the performance of the hot mix binder by several tests such as penetration and softening point. They proved that waste plastic materials could modify asphalt binder but in the condition of employing the exact proportions of these additives [53]. Keymanesh et al. 2017, used a modifier contained crumb rubber (2 to 6wt%) and ethylene-vinyl acetate (EVA) (3 to 7wt%) to improve the performance of asphalt binder. The bending beam rheometer test was employed to evaluate creep properties of stiffness indexes and the rate at a low temperature according to SHRP specifications. The best performance was obtained when the optimum values of crumb rubber and EVA were 4wt% and 3wt%, respectively [54].

Al Qudah et al. 2018, evaluated the impact of crumb rubber (5 to 15wt%) as a modifier to asphalt binder (dense-graded type). Marshall stability and flow, stiffness, and indirect strength tests were employed to investigate that impact. The results showed that the modified binder was better than the unmodified binder when the optimum value of crumb rubber was (5-10wt%) [55]. Farahani et al. 2018, utilized crumb rubber and low-density polyethylene (LDPE) to enhance asphalt binders' performance properties and overcome the problem of massive waste materials. The best performance results were obtained when the LDPE and crumb rubber values were 3wt% for each one via the bending beam rheometer test [56]. Kasanagh et al. 2018, used waste polyethylene and waste tire rubber to obtain the thermoplastic dynamic vulcanizate (TDV) then use it as an asphalt cement modifier (3 to 7wt%) to overcome the problems of production cost and ecology. Several tests were performed to accomplish the study, such as penetration, softening point, rolling thin film oven, Superpave, and multiple stress creep. The study concluded that the use of TDV as a modifier had improved the rheological properties of asphalt binders [57]. Mohanta et al. 2018, invented a new modifier that contained crumb rubber (1 to 30wt%), polyethylene terephthalate (PET) (0.01 to 20wt%), and bi-functional reactive compounds that were selected from different sources such as aliphatic or aromatic compounds. They proved that the new modifier possesses good applicability to enhance the asphalt binder [58].

Liang et al. 2017, found that polymerized sulfur and storage stability affect viscosity function, complex dynamic, and steady flow of asphalt cement modified by SBS additive. Several devices were employed to test the behavior of modified binders that had revealed in their results the decrease of vulcanization rate along with the increment of polymerized sulfur. The study proved that modified asphalt, which possesses a higher level of polymerized sulfur, improved storage stability [59]. Wulandari et al. 2017, used two different sizes of crumb rubber (#40 and #80) and two different amounts of it (1wt% and 2wt%) to investigate its effect on the binder performance according to the

Marshall method. The results proved the positive effect of this additive thanks to the increasing quality and the modified binder resistance [60]. Sheng et al. 2017, tested the swelling issue of desulfurized rubber asphalt (DRA) fabricated with various rubber powder contents under different shear conditions and mixing times. The optimum values of the operational variables were 20wt% of crumb rubber, 7000 rpm/min of blending velocity, 170°C of mixing temperature, 60min of shear time, and 45min of mixing time which proved a notable enhancement of the modified asphalt binder that could use for flexible pavements [61]. Nguyen et al. 2018, studied the effect of using crumb rubber as a modifier on the mechanical properties of asphalt cement by varying the content of additive (0 to 3wt%) and the mixing time. The study revealed that the optimum value of crumb rubber was (1.5-2wt%), whereas the mixing time ranged (0-5h). They proved that the performance of the modified binder was not influenced by aging compared to the conventional asphalt binder [62].

Table 2 lists some common asphalt cement modifiers and additives used in HMA and the general purpose of their use:

TABLE 2. Common asphalt cement modifiers that used in HMA [63].

Type	General Purpose	Examples
Filler	• Fills voids to decrease asphalt cement content. • Performed to satisfy the grading requirement. • Enhances stability. • Enhances asphalt cement aggregate interaction.	• Mineral filler • Crushed fines • Portland cement • Lime • Fly ash • Carbon black
Extender	• Substitutes a limited amount of asphalt cement to minimize the ratio of AC required. • Enhances the storage stability of SBS modified mixtures.	• Sulfur
Rubber (elastomer)	• Raises HMA stiffness at the higher temperatures. • Produces a higher elastic HMA to overcome fatigue cracking at intermediary temperatures. • Lower stiffness at low service temperatures to overcome thermal cracking.	• SBR • Synthetic rubber • SBS • Crumb rubber and AC-rubber
Plastic (plastomer)	• Enhances resistance to permanent deformation and improve workability.	• EVA

According to the previous review, crumb rubber is significantly employed as an additive to modify the HMA for road pavements. Waste rubber takes from different types of tires, either passenger cars or trucks, which are produced in massive amounts annually around the world due to the continuous demand for these tires due to the rapidly growing number of vehicles, as shown in Fig. 2 based on tire revenue in billion U.S. dollars.

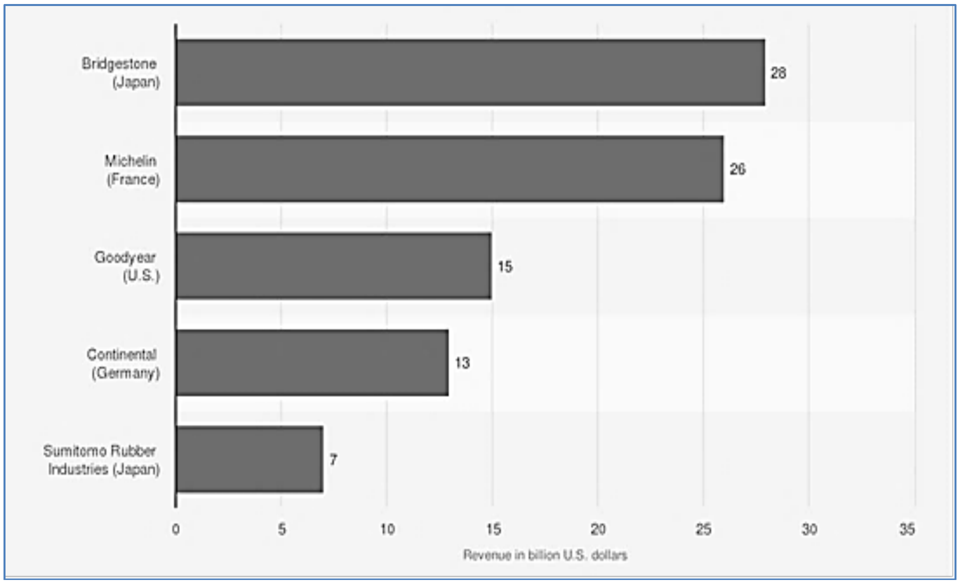


FIGURE 2. Production of tires based on tire revenue in 2018 [59].

In 1839, Charles Goodyear invented the first rubber tire by employing the natural rubber that was initially derived from trees [1] and adding some of the sulfur to increase the hardness of rubber. The first production of synthetic rubber was during World War II in the United States. Nowadays, there are numerous kinds of synthetic rubber with various physical and chemical characteristics that could remain flexible down to about (-50ºC) [64] in comparison to the status of the natural rubber.

Numerous additives are added to the tire rubber, such as accelerators and activators, to be vulcanized (tensile, elongation, and elastic properties) [1]. The proportion of natural to synthetic rubber [18, 65] varies according to passenger cars or trucks' size and tire use [63]. In practice, the truck tire contains a higher percentage of natural rubber than that in-car tire [36]. To enhance rigidity in the tire tread, 28% of carbon black is added to the rubber to reduce the buildup of heat in the sidewalls of different tires [10, 42].

PRODUCTION OF CRUMB RUBBER

To produce crumb rubber from scrap tires rubber that contains about 5 to 6 kg in car tires and 60-70% in truck tires of crumb rubber, these tires supplied to rubber processing plants as a whole, cut, or shredded tires than one of the following grinding [1, 32, 65, 66] processes are employed to obtain crumb rubber:

Ambient Tire Grinding

The consecutive cracker mills method is employed to minimize the size of rubber particles to finer mesh with a highly rough surface texture [18, 63]. In this method, no cooling is performed to make the rubber brittle. The ambient crumb rubber reveals better performance due to the large surface area than dynamic bonding properties. Figure 3 shows a schematic of a typical ambient scrap tire processing plant.

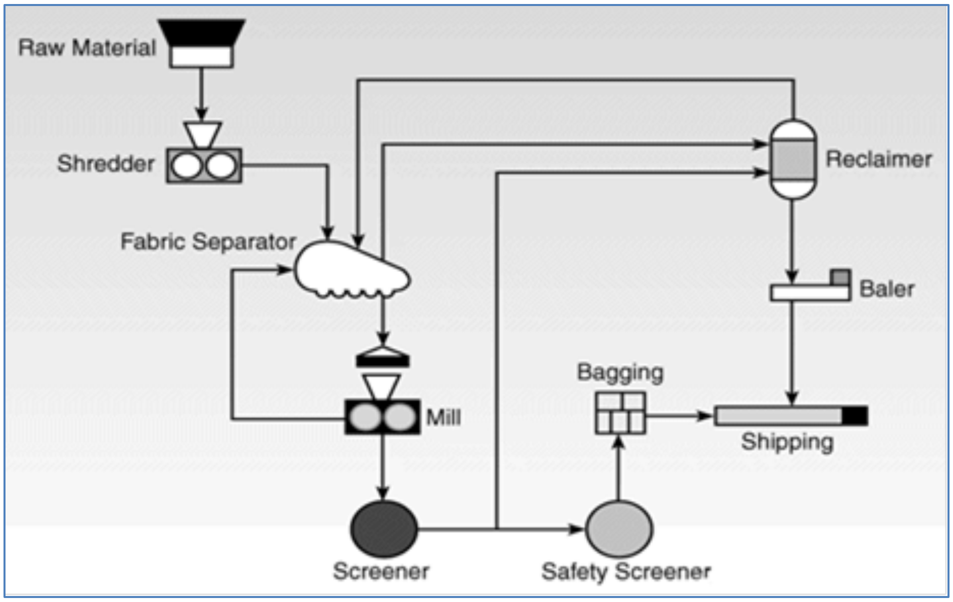


FIGURE 3. Schematic of an ambient scrap tire processing plant [59].

Cryogenic Tire Grinding

In contrast to the ambient grinding method, whole tires or tire chips are performed to be cooled nearly as brittle as glass matter by employing liquid nitrogen at a temperature of (-80oC) where the processes of crushing and breaking are used for size reduction. Figure 4 explains a continuous, fully automatic controlled, and cryogenic process under an inert nitrogen atmosphere.

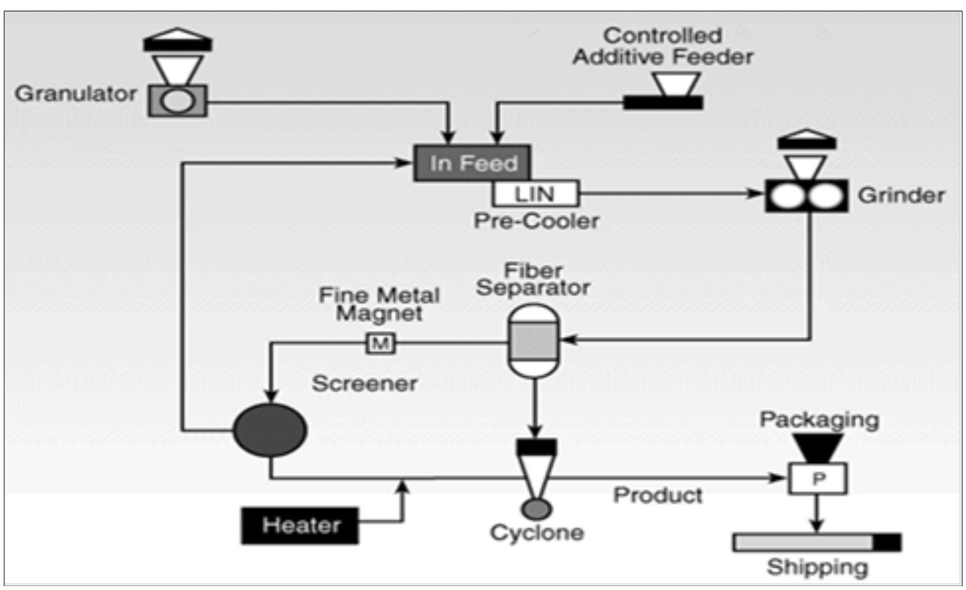


FIGURE 4. Schematic of a cryogenic scrap tire processing plant [59].

Comparing the previous grinding methods, the latter method produces crumb rubber with a lower surface area, which is a critical factor in modification requirements [66]. Therefore, it classifies as a less effective modifier, but it requires less energy and fewer pieces of equipment. Moreover, the steel and fiber liberation from tires is much more comfortable, but the disadvantage is the cost of liquid nitrogen required [63]. Crumb rubber derived from waste tires cannot be considered a waste material because it classifies as an efficient modifier in road paving, which improves the HMA performance [14, 20, 41]. The interaction between the CRM and asphalt cement containing aromatic oils is a diffusion process including physical adsorption between asphalt cement and CRM surface according to the forces of Van der Waals followed by the absorption process of the aromatic oils into the internal matrix of the rubber [2, 66, 67] as shown in Fig. 5.

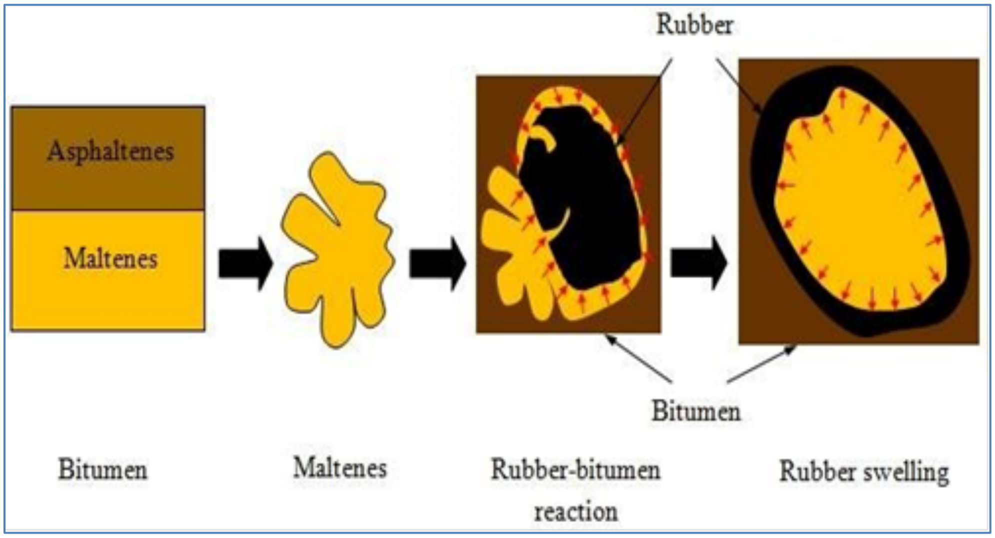


FIGURE 5. Asphalt-rubber interaction /blending process [63].

The depletion of aromatic oils in the asphalt cement, except minimal left to allow flow, causes the viscosity increment phenomenon [68]. This mechanism makes the rubber particles swell [69] approximately to double the size of the elementary particles [16] and still suspended in the blend under high agitation [1]. The interaction rate can increase by enlarging the CRM surface area [66], which makes the ambient crumb rubber preferred, as mentioned before.

METHODS OF PRODUCING ASPHALT RUBBER

Corresponding to an appropriate grade for a climatic region, such as hot, mild, and cold, as well as traffic conditions [1,65], the design of the asphalt rubber incorporation must be developed to evaluate the compatibility between materials used and the required stability of blend over time. Besides, asphalt cement content must be enough for coating the aggregates to provide excellent adhesion between the aggregates and to prevent the excess amount that acts as lubricants, which will reduce particle-to-particle contact between the aggregates [4].

There are two main methods [44,70] of incorporating rubber into asphalt cement, Wet and Dry processes.

- Wet process or HMA- McDonald's technique was discovered in early 1960 in the U.S. In this method, the blending of the CRM with the asphalt cement [18,44] is achieved through hot mix asphalt (HMA) mixtures. HMA method is used in areas characterized by seasonal temperature fluctuations, areas under high ambient temperatures for long periods, in areas of high stress such as heavy traffic, or subjected to high loading under slow-moving traffic [13]. The wet process blending consists of 3 minutes: Preheated A.C. and CRM storage tanks, Blender vessel, and interaction vessel, as shown schematically in Fig. 6 [30]. In this process, the interaction is occurred between the two materials at a specific temperature in a continuous agitation-mixing vessel to prevent the suspension of CRM and, the resultant mixture is gel-like. The modified binder product is then transferred to the required project application [18]. Oil coils heat the vessels instead of direct flame heating to minimize the degradation of CRM. The CRM should be dry for free-flowing and not produce foaming when blended with the hot asphalt cement [13, 29].
- The dry process developed in late 1960 in Sweden [18]. The method used made the CRM blended with the aggregate for approximately 15 seconds before adding asphalt cement to the batch.

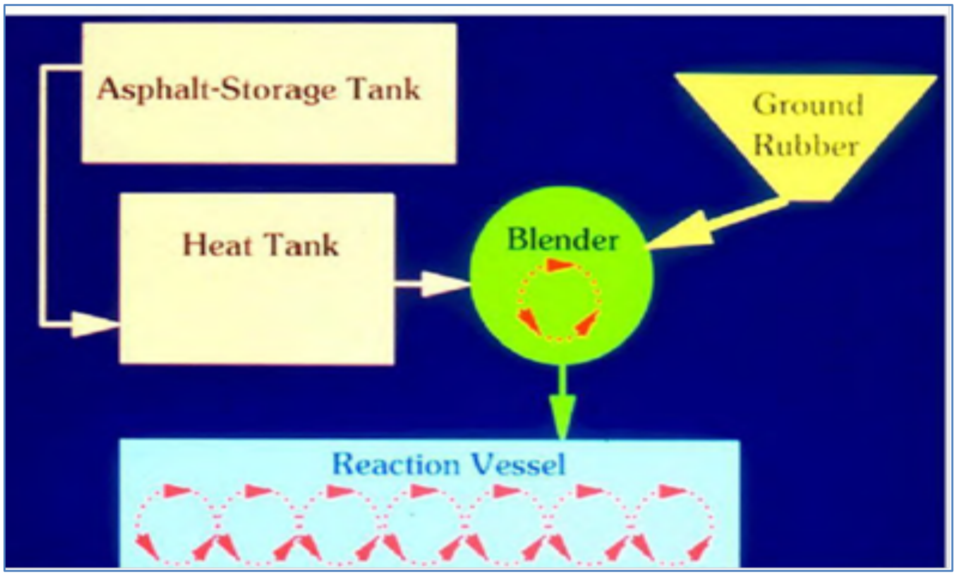


FIGURE 6. Schematic of the wet process [63]

The properties of the modified asphalt cement depend on CRM characteristics, asphalt cement characteristics, mixing conditions, and compatibility of CRM with asphalt cement [13], i.e., the ability of the CRM to remain distributed in the asphalt cement without phase separation.

ADVANTAGES OF ASPHALT RUBBER

There are several advantages of using CRM in asphalt paving application [63,68], as shown below:

1) Increased recycling of wasted tires is the primary source of CRM. The most common specifications for asphalt rubber hot mix recommend using approximately 13.608 kg of CRM per ton of hot mix [20].
2) Scrap tire rubber affects resilience [1,42] to the asphalt rubber binder, where resilience measures the elastic properties of the asphalt rubber binder. Resilience is an essential indicator of performance.
3) Increases the viscosity [33,40,65] of the mix due to the depletion of aromatic oils and leads to a reduction in the reflective cracking and penetration [27].
4) Reduces temperature susceptibility of the mix [14,40,69], which improves rutting resistance, shoving resistance in the high temperatures range, and thermal cracking resistance in the low temperatures range [30,35,71]. Thermal cracks result from internal stresses induces by temperature change and stresses exceeding the strength of the pavement. Fatigue cracking occurs over periods and then can lead to potholes [37]. Rutting is channelized deformation under traffic loading [4], which can result from pavement compaction within wheel paths or occurs with a sub-grade failure [29], and shoving is the pushing of the mixture under loading and stopping. Figure (1.10) shows the main problems with roads.
5) Increases ductility at lower climatic temperatures and the ability of the binder to withstand shear stresses imparted by heavy traffic. This test will not proceed in modified asphalt cement in high climatic temperatures because increasing the softening point to the highest temperature and minimizing the penetration value will affect the modification process more than the ductility value will be neglected [17].
6) Improves adhesion characteristics [63], where the adhesion [13] measures the stresses required for breaking the bonds between the asphalt cement and the mineral aggregate. The breaking of the adhesive bond is called stripping [3] and can reduce by increasing the viscosity of asphalt cement.
7) Increases the resistance of aging and oxidation [42] by increasing the film thickness around aggregates [1,65,66]. Aging [13] is a measure of the change in properties of asphalt binder over time as the hardening (increase in stiffness [34] and reduction of elastic properties) of a binder during its life on the road when exposed to constant traffic and ultra-violet radiation [2].
8) The presence of carbon black in CRM is improving the binder durability [2,4,20,65].
9) Reduces maintenance [34], provides smooth riding [1] and increases skid resistance [4].

10) Reduces pavement tire noise [1,39,70] and makes it more than 50 percent quieter surface.
11) High-temperature softening point [14,34,72], which means the rate of increase in the softening point is dependent mainly on the asphaltenes content of the asphalt cement, the type, and the percentage of the additive [69].
12) Reduces traffic accidents by more than 51 percent [1,39] and shows high performance at critical locations such as intersections of busy streets, airports, and vehicle weight stations [71].
13) Asphalt rubber mix specimens have better mechanical properties [31], confirmed by the Marshall test for stability and flow. The Marshall stability for modified mixes is knowing to be higher than conventional mixes [33].

Compared with the advantages, the disadvantages of using CRM will be less critical than the additional cost, but the cost-effective alternative addresses a significant environmental concern.

CONCLUSIONS

As previously mentioned, traditional hot-mix asphalt (HMA) for road pavements suffers from several problems, such as rutting, shoving, fatigue cracking, and other issues. Since asphalt cement is the most critical component of binders, researchers and scientists must give their full attention to it. Various types of materials are used as additives to modify asphalt cement. So, they improve the hot mix binder performance positively. The types, amounts, and properties of additives differ depending on the weather, for example, using these additives in hot climates can minimize asphalt cement bleeding and overcome shoving and fatigue cracking in cold temperatures. Recovering waste materials, such as crumb rubber, and using them to modify asphalt cement has more successive results economically and environmentally.

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