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S.A. Kosparmakova[1], M.J. Konkanov[1], Zh.A. Nurakhmetova[2], R.M. Dyusova[3], G.Zh. Seytenova[2]
[1]Research and Production Center "ENU-Lab", Astana, Kazakhstan
*E-mail: smartsam0509@gmail.com**
E-mail: marcon@metrology.kz
[2]L.N. Gumilyov Eurasian National University, Astana, Kazakhstan
E-mail: zhanaranurakhmet@gmail.com
E-mail: gainiseitenova@gmail.com
[3]NAO "Toraigyrov University", Pavlodar, Kazakhstan
E-mail: riza92@bk.ru

REVIEW OF RUBBER RECYCLING PRACTICAL STUDIES AND TECHNOLOGICAL DEVELOPMENTS IN USING ASPHALTCONCRETE PAVEMENTS

АСФАЛЬТТЫ ЖОЛ ЖҮЙЕЛЕРІНДЕГІ РЕЗЕҢКЕНІҢ ҚАЙТА ӨҢДЕЛУІ: ҚОЛДАНБАЛЫ ЗЕРТТЕУЛЕР МЕН ТЕХНОЛОГИЯДАҒЫ ЖЕТІСТІКТЕРГЕ ШОЛУ

ОБЗОР ПРАКТИЧЕСКИХ ИССЛЕДОВАНИЙ ПО ПЕРЕРАБОТКЕ РЕЗИНЫ И ТЕХНОЛОГИЧЕСКИХ РАЗРАБОТОК ПРИ ИСПОЛЬЗОВАНИИ АСФАЛЬТОБЕТОННЫХ ПОКРЫТИЙ

Abstract. *This review paper examines the global situation of modifying asphalt binder using crumb rubber, offering a thorough summary of the progress achieved in this area till now. Utilizing a broad range of international experiences, the study explores the various procedures, strategies, and formulations used by researchers and practitioners throughout the globe. The examination covers significant advancements in the manufacture of crumb rubber, the modification procedures of binders, and the subsequent improvements in the performance of asphalt.*

The article analyzes case studies and research results from different nations, highlighting the intricate strategies used to enhance the integration of crumb rubber into asphalt binders. Moreover, the study examines the economic, environmental, and performance-related consequences linked to these alterations, emphasizing the sustainable and cost-efficient elements that have gained growing recognition within the global asphalt community.

This paper seeks to provide significant insights into the current practices, problems, and possible future prospects in the field of modifying asphalt binder using crumb rubber by synthesizing and comparing data from various locations. This resource is very beneficial for academics, engineers, and politicians who want to use worldwide experiences to improve sustainable and resilient asphalt infrastructure.

Keywords: *asphalt modification, bitumen, pavement, crumb rubber, asphalt concrete.*

Аңдатпа. *Бұл жетістіктерге шолу мақалада резеңке ұнтақтарды қолдана отырып, асфальтбетон тұтқыр модификациясының жаһандық жағдайы қарастырылады, осы салада бүгінгі күнге дейін қол жеткізілген прогреске егжей-тегжейлі шолу жасалады. Халықаралық тәжірибенің кең ауқымын пайдалана отырып, зерттеу бүкіл әлем бойынша зерттеушілер мен тәжірибешілер қолданатын әртүрлі технологияларды, әдістер және тұжырымдамаларды* *зерттейді. Сараптама резеңке ұнтақтарын өндірудегі елеулі жетістіктерді, тұтқыр заттарды өзгерту процедураларын және асфальтбетонның пайдалану сипаттамаларын одан әрі жақсартуды қамтиды.*

Мақалада әртүрлі елдердегі жағдайлық зерттеулер мен зерттеу нәтижелері талданады, резеңке ұнтақтардың асфальтбетон тұтқырларына интеграциясын жақсарту үшін қолданылатын күрделі стратегиялар қарастырылады. Сонымен қатар, зерттеу асфальт өндірушілердің әлемдік қауымдастығында барған сайын танымал болып келе жатқан тұрақты және үнемді элементтерге назар аудара отырып, осы өзгерістерге байланысты экономикалық, экологиялық және өнімділікке байланысты салдарды қарастырады.

Бұл мақаланың мақсаты – әртүрлі көздерден алынған деректерді жалпылау және салыстыру арқылы резеңке ұнтақтарды қолдана отырып, асфальтбетон тұтқыр затын өзгерту саласындағы қазіргі тәжірибе, проблемалар және мүмкін перспективалар туралы маңызды түсінік беру. Бұл ресурс тұрақты асфальтбетон инфрақұрылымын жақсарту үшін әлемдік тәжірибені пайдаланғысы келетін ғалымдар, инженерлер және саясаткерлер үшін өте пайдалы.

Түйін сөздер: *асфальт модификациясы, битум, жол жамылғысы, резеңке ұнтақтары, асфальтбетон.*

Аннотация. *В данной обзорной статье рассматривается глобальная ситуация с модификацией асфальтового вяжущего с использованием резиновой крошки, а также дается подробный обзор прогресса, достигнутого в этой области к настоящему времени. Используя широкий международный опыт, в исследовании рассматриваются различные процедуры, стратегии и формулы, используемые исследователями и практиками по всему миру. Рассматриваются значительные достижения в производстве резиновой крошки, процедуры модификации вяжущих веществ и последующее улучшение характеристик асфальта.*

В статье анализируются тематические исследования и результаты исследований, проведенных в разных странах, подчеркиваются сложные стратегии, используемые для улучшения интеграции каучуковой крошки в асфальтовые вяжущие. Кроме того, в исследовании рассматриваются экономические, экологические и эксплуатационные последствия, связанные с этими изменениями, подчеркиваются устойчивые и экономически эффективные элементы, которые получили растущее признание в мировом асфальтовом сообществе.

Данная работа призвана обеспечить значительное понимание текущей практики, проблем и возможных будущих перспектив в области модификации асфальтового вяжущего с использованием резиновой крошки путем синтеза и сравнения данных из различных мест. Этот ресурс очень полезен для ученых, инженеров и политиков, которые хотят использовать мировой опыт для улучшения устойчивой и жизнеспособной асфальтовой инфраструктуры.

Ключевые слова: *модификация асфальта, битум, дорожное покрытие, резиновая крошка, асфальтобетон.*

Introduction. Over the past few years, the traffic intensity on the roads of Kazakhstan and the world as a whole has increased significantly. In addition, the number of vehicles and the traffic load on the road have increased, but with such a load, the road construction technologies themselves are developing much more slowly than necessary. To solve this problem, the government decided to put new roads into operation and repair the old ones. In accordance with the road projects implemented under the Nurly Zhol state program, taking into account that almost all constructed roads are covered with both asphaltconcrete and cement, and the importance of comprehensive research on their development [1].

The asphalt concrete road construction industry most often uses asphalt or bitumen as a binder in the design of asphalt concrete pavement and modifies its composition and properties with various additives in order to improve the quality of the pavement. Based on international research, an in-depth study of the use of natural waste and local materials in the country, their reuse is of the most important task [2]. According to various sources, the viscosity of asphalt used in flexible hot-added asphalt coatings (HMA) is a hydrocarbon containing saturated substances, aromatic compounds, resins and asphaltenes (according to the analysis of the Sara test) [3]. There are various methods and sources of its production. Currently, the production of 1 ton of bitumen (asphalt binder) requires 22.5 kg of natural gas, 50.5 kg of crude oil, 10.9 kg of coal, 0.003 kg of uranium and 1239 liters of water. In addition, the extraction process generates

300 g of greenhouse gas (GHG) emissions, 1800 g of compounds are used in the production of asphalt in the sea or on land, and 155 g of hydrocarbons are washed out into the soil [4]. In terms of the life cycle of the European Bitumen Association's flexible asphalt pavers, the production and design of these materials have a major impact on the environment. At the beginning of the nineteenth century, a number of scientists documented the factors affecting the chemical composition, physical characteristics, origin and properties of asphalt concrete binders [5]. The materials production stage includes processing of raw materials/secondary raw materials/secondary raw materials in one plant, transportation of processed materials to the production site and production of finished asphalt concrete mix, and the construction stage includes roadbed mixes and final size composition [6].

In order to solve the oxidation process, its causes, and ways to change the rheological and mechanical properties associated with the construction, operation, and maintenance of flexible sidewalk systems, sidewalk manufacturers mainly focus on obtaining modified binders with improved rheological properties [7].

With reduced crude oil reserves, reduced quarry volumes, and increased environmental restrictions, opportunities have opened up for processing asphalt by-products. The foreground includes recycling waste tires or rubber. Tires are disposed of at the end of their service life [7]. Geographically, the lack of dedicated recycling lines is the biggest challenge for the tire or rubber industry. This leads to the fact that used tires and used tires are freely released into external spaces, which leads to serious environmental consequences [4].

As the main activity of many countries to limit the accumulation of discarded tires in warehouses, the main goal is to process tires into pellets or rubber powders (CR) through various mechanical processes, including puncturing, separating, shredding and disassembly. One of the advantages of tire recycling is the separation of iron steel and textiles from rubber parts [6]. This regenerative material can significantly reduce the load on the tire's environment. According to a study by Dauer et al. (1985), asphalt has found that there are different sizes of rubber powder mixtures for viscosity, which can give significantly different results and may be the most economical technological solution [8].

There is still a very high interest in creating asphalt concrete with environmentally friendly CR powders, which contribute to the closed-loop economy by recycling materials obtained from used tires. Therefore, the main purpose of this research review is to collect and present up-to-date information on rubberized asphalt concrete material. Special attention is paid to rubber processing technologies, methods of production of rubberized asphalt, interaction of rubber with asphalt, and innovative products of the road surface made of rubber [9].

Materials and methods of research. Production and composition of rubber powders. The term "rubber powder modifier" (CRM) is a general term referring to the process of adding tire rubber to an asphalt binder that has been used to improve the quality of asphalt concrete. In general (West et al., 1998) there were the methods and equipment used to process or recycle tire scrap in full using cracker mills, granulators, micromachines, and cryogenic machines [10]. Each operation creates different CR sizes, textures, and gradations. These classifications are determined by the type of equipment used, the size of fractions, and the scope of application. The scientist (Presti, 2013) described several solutions that can reduce the number of tires that are recycled today [11]. Among the procedures currently used waterproofing grinding, cryogenic grinding, wet grinding, and natural grinding. All of these processes involve different operating modes, each characterized by a unique combination of temperature, pressure, and crushing equipment. In contrast to cryogenic grinding, grinding in the environment leads to the formation of rubber chips with such properties as a large surface area of rubber, low density, rough texture, irregular shape and porosity (Memon, 1998a; West et al., 1998; Presti, 2013) [12]. Compared to the cryogenic procedure, the method in the medium has become more economical due to the use of a simpler processing technique. Recently, a thermomechanical extrusion method using a twin screw extruder has been invented (Rasool et al., 2017). This process is also known as the tire recycling method. This twin-screw extrusion technology requires high operating speed, high operating temperature, constant CR regeneration, and high productivity [13]. In 1998, it was discovered that viscous AR developed using CRM at various CRM processing facilities has significant differences in storage quality and characteristics. The ability of a modified CR asphalt product to succeed depends not only on the choice of a suitable CRM method, but also on the type of road surface used [14]. The CR results obtained by various CRM methods, in contrast to the 1998 studies by West et al., showed that the results of rubberized asphalt or bitumen differed in their storage properties and characteristics [15]. Taking into account the amount of energy resources consumed for the production of 1 ton of CR rubber powder, according to the work of Farina et al. [16] (2017), 1.45 tons of discarded tires are obtained and 384 kWh of electricity, 2.99 liters of diesel fuel, 0.22 m3 of water, 0.04 kg of lubricating oil and various auxiliary materials are required. When assessing environmental impacts, CR production accounts for 10% of global warming potential (GWP), freshwater toxicity, and average terrestrial toxicity (Bartolozzi et al., 2012) [17]. In addition, if secondary products (steel and textiles) are not taken into account in CR production, greenhouse gas emissions and energy losses amount to about 307 kg of CO2. Although Steel is an expensive recyclable commodity, if textiles are used as a fuel resource in the production of refractories, the overall environmental load of CR production will have a negative value, as well as the fact that electricity used in grinding is the main source (72-73%). Farina et al. (2014) note that the presence of both reserves is not known [18].

As noted above, changes in the performance characteristics of asphalt pavements are affected by the viscoelastic properties of the binder asphalt under various environmental conditions. To develop an effective AR binder based on the CR mixture, it is necessary to describe the rheological properties of modified CR binders, since binders are significantly affected by CR processing technology, fraction size, gradation, CR dosage, mixing methods, asphalt treatment time, and the origin of vulcanized rubber, according to Navarro et al., 2006, which is also found in Chetin's 2013 paper [19]. The CR ranges in size from 4.75 to 0.075 mm and is made up of smaller remanufactured rubber parts. The ASTM D 6114 standard (ASTM, 2009) recommends that the size of rubber parts in any case should not exceed 2.36 mm of the screen for use on AR road surfaces. In many countries, CR grading for the production of AR binders that meet local and regional conditions has its own characteristics (Austroads, 2000; California Department of Transportation, 2006; SABITA, 2015).

Many specifications do not mention the number of CRS passing through the 0.075 mm Screen, which can play an important role in creating the AR binding matrix. Various CR gradations with fine CR particles less than 0.150 mm in size (No. 100 sieves) have been found to result in AR binders, resulting in higher gauge tolerances and lower viscosity and temperature sensitivity (Venudharan and Biligiri, 2017) [20]. The concentration of CR added to asphalt depends on the type of road surface. According to ASTM (2009), the minimum amount of CR for the classification of rubberized bitumen AR should be 15% of the total weight of the main binder. Percentage ranges of CR for different organizations/guidelines were shown in Table 1, depending on the type of total gradation [21]. With an increase in the CR content by 5-40% of the total mass of the main binder, the results of the study led to an improvement in the rheological characteristics and storage stability of the AR binder (Navarro et al., 2005) [22]. However, in the case of an unconventional porous asphalt mix, Cetin (2013) notes that as a result of the dry process, the CR particle size was higher (more than 10%) with a fraction from 4.75 to 0.9 mm (from No. 4 to No. 20 sieves), which led to a decrease in productivity [19].

Table 1. Guidelines of various organizations for the approved CR size

Organizations / Guides	Arizona DOT	Florida DOT	Caltrans,	2006Sabita, 2015	Austroads, 2000
CR size, %	≥20	5-12	18-22	18-24	15-18

Many researchers have identified the concept of exceeding the maximum size of CRM supplements over the average as the best way to assess the impact of the amount of CR (Shen et al., 2009a, b) [21]. The scope of this study included two types of CRM mixtures with three-dimensional (14, 30 and 40 sieves) obtained as a result of environmental and cryogenic methods. The average amount of cryogenic CRM mixtures was approximately 15% higher compared to the ambient method. In addition, the surface area of environmental and cryogenic CRM (SA) mixtures was, Emmett and quantified with the help of Brunauer, Emmett and Teller (BET) experts, and it was found that CRM impurities in the environment twice as large as cryogenic SA [23]. In the environment, grinding results in granular CR with a large SA and spongy surface structure, while cryogenic grinding results in CR with a clean, smooth smooth surface (Roberts et al., 1989) [24]. A larger volume of CRM impurities results in a higher reaction rate with asphalt viscosity.

Siddiq and Nike (2004) identified typical materials used in tire manufacturing. The CR product obtained from tire waste comes from two sources: (1) passenger cars and (2) trucks. Figure 1 shows the percentage of the main components of automobile tires used in several regions of the world [25].

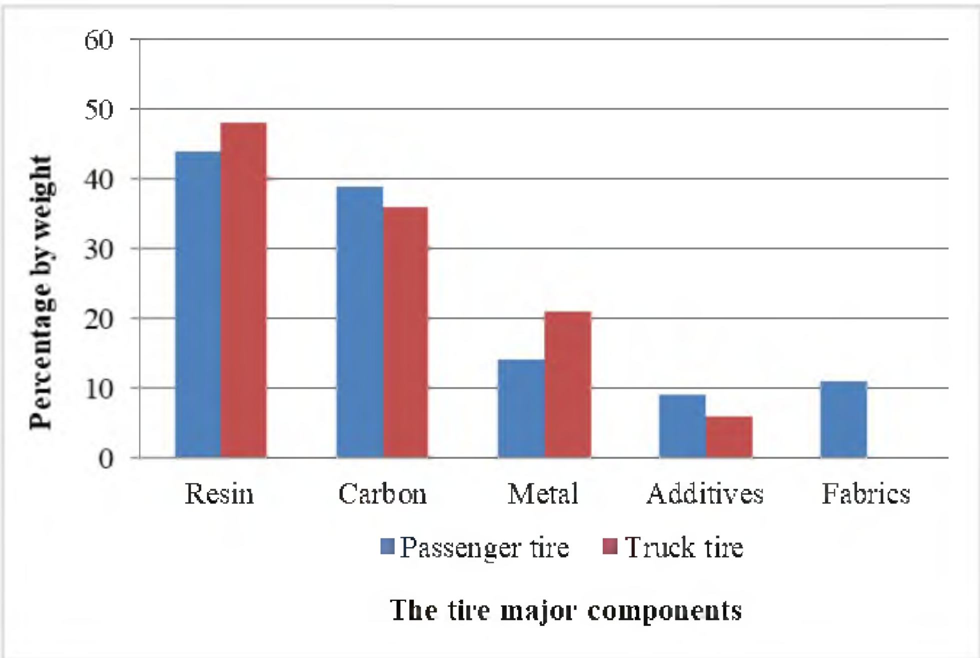

Figure 1. Percentage of the main components of automobile tires used in several regions of the world

The elastomeric component of two types of tires (passenger and cargo vehicles) weighs about 40-45%. The second important component is coal-black in the range of 22-28% by weight [26]. Black carbon протекторларыgives stiffness and flexibility to tire treads and sidewalls

(Way et al., 2012). The following calculation of steel is about 12-18% by weight, which gives strength and hardness. Other components may include mixtures and fabrics in the range of 5-10% by weight [27]. Typically, CR is a mixture of natural rubber (NR) or polyisoprene, synthetic rubber (SR), such as styrene-butadiene-rubber. In addition, (Dower et al., 1985; Roberts et al., 1989; Mikinis and Michon, 1998; Navarro et al., 2005, 2006; Siddiq and Naik, 2004; Miskolci et al., 2008; Way et al., 2012; Cetin, 2013; Gawibazou and Abdelrahman, 2013; Presti, 2013), according to (SBR), cross-binding agent (e.g., sulfur), metal oxides (e.g., zinc carbon monoxide), accelerator (e.g., fatty acids, amines), anti-oxidation substances (e.g., metal oxides), antioxidants, antiozonants, enhancers such as stearic acid, carbon black, process oils, plasticizer, fillers, fibers, steel, metal, textiles (for example, nylon, polyester) and powders depending on the area are available [28].

Technology for obtaining a rubber powder modifier. Anymethod of mixing CRM with hot asphalt viscosity using special equipment is a wet process. In accordance with the ASTM D8 standard (ASTM, 2018), viscous substances modified only with CR are designated as "AR" if the rubber content is at least 15% of the total mass of the asphalt binder, and they are created by a wet process [29]. Various problems were solved with a coating in the form of viscous asphalt AR obtained by the wet method, cracked seals absorbing the stress of membrane layers (SAMI), and an AR-HMA mixture (Heitzman, 1993; Presti, 2013). One of the objectives of the review of this document was to cover the limitations and application areas of the augmented reality creation process. For example, Memon (1998a) notes that after adding CR to the binder, new molecular-sized particles are formed in the matrix during wet mixing, and it tends to settle on the bottom of the tank before mixing with fillers. Due to the heterogeneity of the AR binder, a modified AR mixture was implemented for smoothing at the earliest stages (Memon, 1998a, b). The reason for CR precipitation was its limited solubility in various pure binders (Shatanavi et al., 2013). AR binders have been found to have poor storage stability at high temperatures due to segregation (Navarro et al., 2006).

In addition, it is recommended to use an AR binder produced using existing technologies for a short time, since the AR interaction гельсan quickly reach the gel point, and when the binder has a very high viscosity, the system loses its fluidity (Zanzotto and Kennepol, 1996). The reason for this was due to the small amount of CR depolymerization and poor dispersion. From a practical point of view, AR production requires the use of ground-based mobile mixing units and a modified binder within six hours of its production (Takallow and Senton, 1992). The most important problems associated with the stability of storage of modified asphalt in the field include: (1) phase separation at high storage temperatures and (2) decomposition of the grated asphalt mixture (Bahia et al., 1998; Bahia and Zhai, 2011). The results of the laboratory test method for asphalt stability (the latter), introduced by Bahia and his colleagues, showed that the storage stability of the modified binder depends on the storage time, the type of converter, the source of pure asphalt, the storage temperature and the speed of mechanical mixing. (Bahia and Simply, 2011) [30]. The Asphalt-Rubber standard practice Manual (Way et al., 2012) indicates the need for special pumping and flow-measuring equipment required for the production of AR binder. Regardless of the specific equipment; pumping and measuring the required proportion of a unique AR binder with the appropriate consistency is a difficult task. Several agencies and researchers (Tacallow and Senton, 1992; Heitzman, 1993; Hicks, 2002; California Department of Transportation, 2006; Way et al., 2012; Presti, 2013) approved various stages of AR production, storage, advantages and limitations as a document. In fact, the requirements for specialized mixing plants, storage tanks, and high initial costs have limited the increased use of AR-based laying procedures in major sidewalk construction work in some regions [31]. In this review, various factors were grouped into two main parameters: (1) internal and (2) external. Internal parameters include the materials involved in the production of the CRM binder, while external parameters include processing conditions such as mixing speed, mixing time, and processing/curing temperature [32].

Results and their discussion. The effective performance of the AR binder depends on the molecular interactions between CR and asphalt cement. The fact that the two main interaction mechanisms that affect the binding properties of CRM using the wet method are rubber swelling and rubber depolymerization can be found in the work of Abdelrahman and Carpenter (1999). According to many researchers (Gael et al., 2006; Putman and Amirhanian, 2006), CR particle swelling in an asphalt medium is a physical type [33]. It was found that lower molecular weight fractions in fats and primary binders contained in bitumen interact with crushed CR, which leads to swelling of CRM controlled by the diffusion rate. (Stroup-Gardiner et al., 1993) in their work proved that swelling is associated with diffusion resulting from the movement of liquid into the inner matrix of the polymer, and not with a chemical process. (Billiter et al., 1997a) are aromatic oils that help achieve a homogeneous AR binder by digesting / dissolving CR particles [34].

Since the interaction between asphalt and CR is physical, the fact that their compatibility depends on the proximity of their solubility parameterscan be found in Stroop-Gardiner and Havel (1993, 2006). Gawel et al. (2006) found that light asphalt fractions easily penetrate the internal CR matrix as a result of gel liquidity chromatography. According to Ibrahim et al. (2013), rubber saw dust swells up to 3-5 times its original size due to the absorption of maltenes in the main binder, leaving a relatively high proportion of asphaltenes and subsequently increasing the viscosity of the modified binder [35]. According to the work of Bahia and Jay in 2011, it was found that the chemical components of the main binder also affect the storage resistance, where it was found that bituminous asphalt with a high asphalt content has a higher degree of decomposition than bituminous asphalt with a low content [36].

Billiter et al. studied five types of asphalt cement classified by SARA composition and their effect on rubber dissolution. The saturation content in binders below asphalt also led to faster and higher dissolution of rubber. Abdelrahman and Carpenter concluded that the modification of the main binder is based on the exchange of components, since rubber particles absorb light fractions during swelling and release fat components during digestion. According to a study conducted by Ayeri et al., bitumen and CR mixed in a 2:1 ratio showed a decrease in the amount of saturating substances and aromatics at three different processing times (1, 6 and 24 hours) and one test temperature (155 °C), but showed an increase in the amount of asphalt and rubber. Green and Tolonen (1997) identified the following factors that potentially affect the rate of swelling: (1) the balance of interaction between the maltene fractions of asphalt and rubber, (2) the activity of maltenes, and (3) the absorption of fats by rubber particles.

The fact that the amount of rubber chips in AR is regulated by the pumping and mixing capabilities in the production of HMA asphalt concrete for road surfaces is stated in the work of Chekhov [37]. Increasing the rubber concentration resulted in increased elasticity at low temperatures, better wear resistance, high fatigue resistance, and a lower oxidation index. It was shown that the viscosity of AR mixtures increases proportionally, starting from 15%, while a small increase in the CR content above 15% quickly increases the viscosity of AR mixtures [38]. An increase in the rubber content reduced the leakage index, and the binder began to exhibit non-Newtonian behavior (Stroup-Gardiner et al., 1993). Studies of air-blown bitumen (Billiter et al., 1997a; Divya et al., 2013) showed a change in strain values and an increase in elastic strain recovery with increasing rubber size. Increasing the rubber concentration above 20%, according to Novarro et al., led to the creation of a two-phase system with a non-uniform temperature dependence (2005). The introduction of CR into the asphalt binder in various doses, up to a maximum of 40%, reduces the storage modulus (G) and loss modulus (G) at lower temperatures (-10 °C), demonstrating significantly greater flexibility [39]. On the contrary, at high temperatures (70 °C), it was found that the value of both module parameters was relatively higher than the loss modulus of the storage module, which indicates the potential for resistance to the formation of a circular footprint [40]. Various percentages of CR mixed with asphalt binder are collected in Table 2 to describe its effect on various rheological parameters.

In addition, to obtain a uniform AR viscosity, asphalt binder and rubber crumbs are mixed and mixed in a bowl with rotating blades (Way et al., 2012). The complexity of the AR binder increases when both materials move against gravity and centrifugal force when mixed, Green and Tolonen published in the paper. According to experts, excessive shear force should not be used, as it has been found to accelerate the vulcanization process of rubber.

Table 2. Set of conclusions for different CR percentages

Works of the author	Rubber content	Conclusions
Thodesen et. al.	5,10,15 20%	particle effect (PE) and interaction effect (IE) increases with increasing CR concentration
Takallou, Sainton	8,9, 10%	optimal thermorheological properties can be obtained in 10%.
Shen et. al.	10 15%	a high percentage of CRM leads
Stroup-Gardiner et. al.	10, 15, 20%	viscosity increases with an increase in the percentage of CR regardless of the type of rubber
Billiter et. al.	10, 20%	an increase in the amount of rubber increased complex viscosity |G* / and a reduced phase transition angle (δ)
Putman and Amirkhan	10, 15%	particle effect (PE) significantly affects the composition of CRM, while the interaction effect (IE) increases with increasing CR concentration.
Cetin	The permeability of porous asphalt mixtures Cetin 10, 15, 20%	The permeability of porous asphalt mixtures decreased with increasing amount of rubber

In the work of Ibrahim et al. mixing at a high shear rate is considered to reduce the size of large rubber particles, which reduces the mixing time. AR mixtures prepared at 4000 rpm (rpm) and mixtures prepared at 8000 rpm using a high-speed mixer had a similar viscosity at high temperatures (Billiter et al., 1997a). Abdelrahman and Carpenter (1999) used three-bladed propellers without a shear mechanism at two rotational speeds. The 200 rpm speed was initially maintained for three minutes, and then reduced to 80 rpm over a three-hour interaction period. However, no conclusions were drawn about the variable shear rate, since it was assumed that the interaction begins in three minutes. Gavibazou and Abdelrahman (2013) noted that the dissolution of bulk CR fractions at the initial mixing stage (10 min) depends on the shear rate during mixing. Table 3 summarizes various studies that study the effect of the mixing rate on the mechanism of interaction of CR with asphalt.

Study by Mikinis and Michon also states that mixing time can lead to loss of volatiles from CR when heated at high temperature with increasing mixing time, or to rubber dissolving in asphalt. At the total temperature (177 °C) used to produce AR, mixing time intervals of 15, 30 and 45 minutes did not significantly affect the viscosity and phase angle of the modified binders. At different processing times (0.5, 1 and 2 hours) at temperatures below 200 °C, the deformable part of natural and synthetic rubber increases with increasing reaction time.

However, at temperatures above 220 °C, with a mixing time of 2 hours, the elastic recovery for both types of rubber did not significantly improve, while natural rubber, on the contrary, showed a decrease in deformation recovery.

Green and Tolonen, found that the mixing temperature had two different effects on the CR swelling mechanism: (1) the rate of swelling increased significantly with increasing temperature, and (2) the degree of swelling decreased with increasing temperature. Billiter and others have reported that CR devulcanization increases at 232°C, and devulcanization and depolymerization increase at 260°C, which is worrisome. Leite and Soares noted that AR obtained at 190 °C for the same type of asphalt and recovery conditions showed higher compatibility than at 150°C. Increasing the mixing time led to an increase in interaction, and increasing the mixing temperature led to faster interaction. The experimental research program of these scientists used an operating temperature of 177 °C, since it was taken into account as similar to that used for the production of CRM binders in the field in general. Experiments with formulas close to 177± 10°C at the production temperature made it possible to obtain a homogeneous and stable AR matrix.

Table 3. Collection of various studies that study the effect of the mixing rate on the mechanism of interaction of CR with asphalt

The authors	State that mixing speed, rpm	Mixing temperature, °C	Conclusions
Billiter et.al	4000 and 8000	232-260 °C increasing	mixing rate reduced the deposition rate of the rubber fraction in the binder
Billiter et. al.	500	177 °C	the degree of rubber dissolution may not be optimal at low shear rates
Leite and Soarses	4000	180-200 °C	Increasing the mixing speed leads well to homogeneous mixtures with sealing properties and storage
Novarro et. al.	1200	180 °C	it is recommended to increase the mixing speed
Novarro et. al.	8200, 1200 and 100 (with two different devices)	90, 120, 180, 210 to 250 °C	the geometry of the mixing device and impeller has little effect on the rheology of the CRMB.
Li and Liao	7000	180 °C	asphalt is absorbed by CR, forming a homogeneous mixture with better penetration and softening values.
Aflaki and Memarzadeh	5500 and 600	170 ° C	shear rates had a significant impact on low temperature performance, and mixing at low shear improved intermediate and high temperature performance.

Conclusion. The possibility of recycling tire scrap re-introduces the boundaries of the life cycle of transport tires. Thus, asphalt concrete with rubber chips (gravel) is one of these reclaimed materials that are widely used in the road system. It can reduce energy consumption and greenhouse gas emissions if considered over its entire life cycle. In addition, as a CR modifier, AR improves the rheological and mechanical properties of mixtures, extending the service life of special coating systems or delaying maintenance and restoration strategies compared to conventional unmodified asphalt coatings. The main purpose of this review was to provide information on various aspects related to CR modified materials, such as raw material extraction, rubberized asphalt production methods, and improved rubber products, with a particular focus on their effectiveness in overcoming the challenge of storage sustainability, energy use during production, and resource savings as well as mechanical characteristics.

In general, the origin and attributes of CR related to production methods, source, physical nature, physiognomy, chemical composition, and environmental impact have been documented abroad. The technology for processing the addition of CR to an asphalt binder was also considered, paying particular attention to their limitations from an engineering and environmental point of view. The review also showed that the curing parameters had a significant impact on the rheology of the AR binder, including: mixing temperature, mixing speed, and mixing time were considered, as well as the lack of consensus on a uniform working/processing state that can provide the best AR mixture with a wet process.

According to the authors cited earlier, the best temperature range for making polymer-modified bitumen with rubber granules is between 177 and 232 degrees Celsius. The temperature range depends on the size of the rubber powder particles used in the combination. Furthermore, it is advisable to maintain a period of two hours for both the swelling and mixing procedures in order to guarantee the precision and effectiveness of the experimental results.

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