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REVIEW

Effect of Waste Tire Rubber on Properties of Asphalt Cement and Asphalt Concrete Mixtures: State of the Art

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Abstract

This research paper aims at providing a comprehensive analysis of the effect of the addition of waste tire rubber to asphalt mix and its properties. Having reviewed several published research papers, it is concluded that the addition of waste tire rubber to asphalt mix increases the softening point, viscosity, flow, void mineral aggregate (VMA), and Marshall stability. On the other hand, it reduces the penetration, ductility, specific gravity, flash point, and retained stability. It is stated also that the addition of waste tire rubber to asphalt mix is a safe way of managing huge amounts of waste tires generated around the world in a high-value reuse.

Keywords Asphalt concrete mixture · Waste tire rubber · Rubberized asphalt · Modified asphalt · Marshal stability method

1 Introduction

Bituminous roads can be defined as roads that are built using bitumen as a binder. It consists of aggregate and bitumen in addition to some fillers, where the quantity and quality of the filler is used to improve the durability and quality of the road [1]. Many fillers can be used in the bituminous mixture, such as lime, cement, and granite powder, but the problem is that such materials can be used for other purposes which are more important and of higher added value; in addition to that, they are expensive and are extracted from natural sources, which results in more damage to the environment. On the other hand, many waste materials are available and can be used as fillers, which helps to get rid of them and at the same time preserve the environment. Therefore, many recent conducted studies analyzed the effect of using waste materials as fillers in bituminous mixtures on the quality and durability of bituminous mixtures. There are many wastes that can be used as fillers, such as waste vegetable oil [2], oil shale waste ash [3], olive waste ash [4], medical waste ash [5], and olive husk ash [6].

The use of waste tire rubber in asphalt pavements has attracted the interest of researchers around the world, as an alternative additive of the raw materials extracted from natural resources to be used in asphalt concrete mixtures, and as use is an effective way for waste tires' rubber disposal [7–10]. Using waste tire rubber in the asphalt mixture led to reduce the temperature sensitivity, improve the resistant against permanent deformation and rutting, improve the durability, and reduce fatigue cracking [10–12]. Compared to limestone, waste tire rubber has a higher value of accumulated stress when added to asphalt mixtures [13]. Tire rubber crumb-modified asphalt is a general type of modified asphalt mixture that contains the rubber of waste tires. There are many terms that are used for this mixture, such as asphalt rubber, rubber-modified asphalt concrete, and rubberized asphalt [14]. There are two methods for making the rubber asphalt mixture, the dry process and wet process, and the difference in terms used to describe the mixture is usually related to the use of one of these methods [14, 15]. The rubber crumbs are mixed with the binder at a high temperature in the wet process, while in the dry process, a part of the aggregate, about 1–3% of the total weight, is replaced by the rubber crumbs and then mixed with the binder. It was found that the dry process is more effective as it can recycle larger amounts of tires and be more cost-effective. However, the

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dry process has lost its effectiveness due to many unresolved problems including the difficulty in achieving consistent performance in relation to the swelling effect after compaction.

Gawel et al. [16] found that the reaction of rubber with bitumen can inflate rubber particles from three to five times of their original size and may resist compaction effort. The swelling effect can lead to premature failure, such as raveling and cracking due to non-achievement of target density. The term "interaction" refers to rubber particles' swelling due to the diffusion of the lighter bitumen in the rubber [17]. In addition, the reaction of rubber with bitumen leads to maintaining high stiffness at high temperatures and giving greater flexibility at low temperatures due to the increase in the viscosity of bitumen resulting from the reaction [17, 18]. Several studies reported that the interaction between asphalt and added rubber takes place during the mixing and transportation stages, which needs from 2 to 3 h [19–21]. Also, it has been reported that the long-term performance of the modified asphalt mixture with tire rubber using dry proses needs further study [22].

Due to the growth of the world's population and the increasing demand on vehicles, the amounts of generated waste tires have increased considerably, which imposes an environmental challenge that needs to be addressed. One way of managing this type of waste is to use the waste tire rubber in asphalt mix for road pavement. The proposed solution is well aligned with the transition from linear economy to circular economy where in this case we reuse the waste tire as a secondary raw material for road pavement.

Although several studies were conducted into the use of waste tires' rubber in asphalt mixtures for road construction, many countries, including Jordan, have not adopted this technology, and therefore, this review paper aims at summarizing and collecting the latest findings in this regard to facilitate the decision-making on whether to use the waste tire in road construction or not.

The focus of this paper will be on reviewing the previous studies on the effect of adding waste tire rubber on the development of conventional and rheological properties of asphalt mixtures using wet proses. In addition, it analyses the environmental, engineering, and economic aspects resulting from the use of waste tire rubber in asphalt mixtures.

In this paper, some of the conducted research outcomes will be presented to verify the effectiveness of adding waste tire rubber to bituminous mixtures using wet proses, as it was reported as a promising method of increasing the viscosity of asphalt significantly, reducing penetration, and increases the softening point. In addition to these advantages, it was reported that the carbon in the rubber acts as an antioxidant, preventing the asphalt from oxidizing and aging [23].

2 Waste Tire Rubber Material Characterization

The global population and industrial growth in recent decades have led to a tremendous growth in the automobile industry, which has increased the growth of rubber tire industry; which ended up in generating a huge stockpile of used tires. This created a big challenge to manage this waste and led many researchers to conduct various intensive research to find a proper solution and explore the possibility of using waste rubber tires in various applications to protect the environment of this waste in the best possible effective way.

2.1 Physical Characterization

Bekhiti et al. [24] studied the properties of waste tire rubber powder, where rubber powder was produced from the tires of three different cars in a mechanical way under room temperature. In addition, the steel was removed through magnetic separation, and the textile fibers were densely removed. The steel was removed from the sample permanently, but about 2% of the textile fibers remained. A microscopic examination was conducted to find the dimensions of the rubber powder, where it was found that it ranged between 0.08 and 1.6 mm. The density of the obtained rubber powder was 0.83 using a helium pycnometer. The rubber powder is characterized by its low water absorption rate of 3%; Table 1 surmises the physical properties of the waste tire rubber. Figures 1 and 2 shows scanning electron microscopy (SEM) photo for crumb tire rubber and rubberized asphalt, respectively.

2.2 Chemical Properties

Tires consist mainly of rubber. Its composition differs slightly between car tires and heavy truck tires. Rubber consists of a complex mixture of elastomers, polyisoprene, polybutadiene, and styrene. Citric acid, zinc oxide, extender oil, and carbon black are also important compounds in the formation of tires [24]. Figure 3 shows chemical properties of rubber.

The chemical interaction between aggregate and rubber asphalt was analyzed by Wang et al. [27]. Where the researchers found that the mineral composition of the

Table 1 Physical characteristic of waste tire rubber powder

Water absorption rate (%)	3
Particle size	80 µm–1.6 mm
Elongation (%)	420
density	0.83

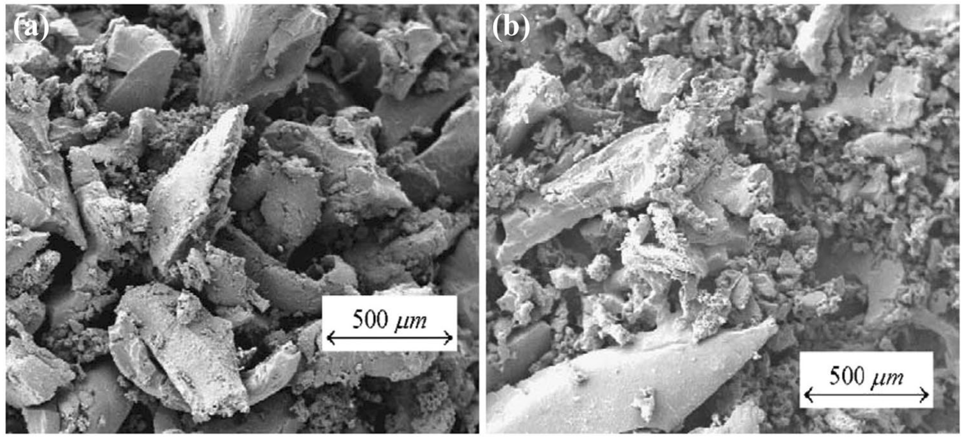

Fig. 1 SEM for different particle size of crumb tire rubber: **a** 0.74 mm and **b** 0.29 mm [25]

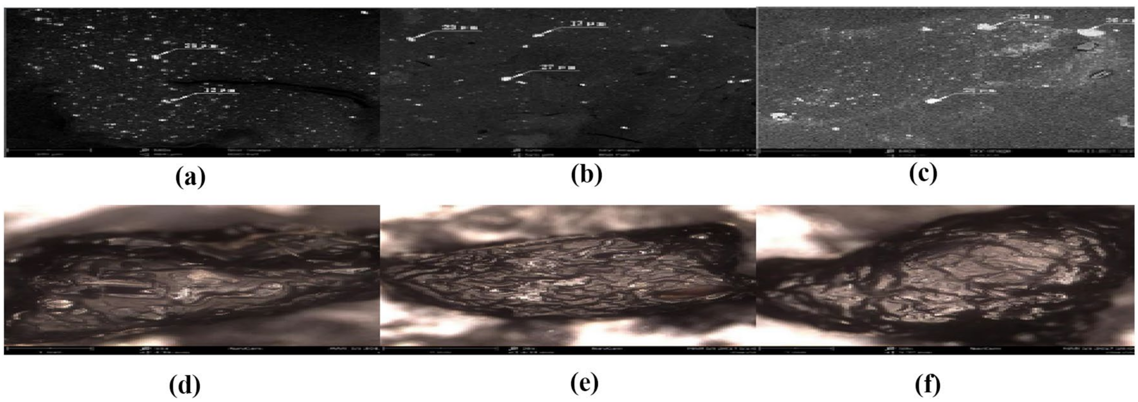

Fig. 2 SEM image for rubberized asphalt: **a** 25% rubber-powder content (560 times); **b** 30% rubber-powder content (520 times); **c** 35% rubber-powder content (640 times); **d** 25% rubber-powder content (55 times); **e** 30% rubber-powder content (39 times); **f** 35% rubber-powder content (50 times) [26]

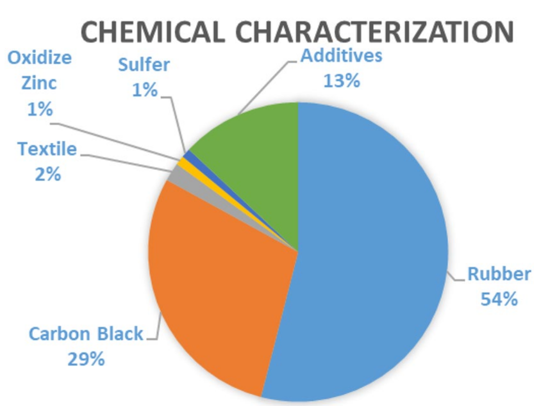

Fig. 3 Rubber powder chemical characterization [24]

aggregates significantly affects the interfacial behavior with rubber asphalt. Also, calcite aggregates have the lowest adhesion energy, followed by dolomites, and the highest adhesion energy with quartz aggregates.

Also, the chemical interaction between asphalt and rubber was analyzed by López-Moro et al. [21] and it was found that crumb rubber particles may efficiently close the spaces between bitumen molecules, producing an asphalt mixture that is denser and more uniform. On the other hand, the researchers shed light on how crumb rubber and bitumen interact at the microscopic level in asphalt mixtures, and this information can be used to develop and improve more durable and reliable roads.

3 Environmental and Economic Aspects of Using Waste Tire Rubber in Road Construction

Wang et al. [28] summarized the environmental impact and energy consumption of using waste tire rubber in asphalt concrete mixtures during the entire service life cycle. It was reported that the use of waste tire rubber helps is an environmentally friendly solution to get rid of waste tires, which leads to energy savings and many other environmental benefits compared to landfilling. Rubber asphalt provides an advantages of saving energy during the life cycle, as it consumes less energy than the traditional asphalt mixture during the construction and maintenance stages. The emissions of carbon dioxide and methane during the mixing process of rubber asphalt are much lower than the emissions during the conventional asphalt mixing by about 39.7% and 61.7%, respectively. The use of rubber asphalt reduces the noise caused by the wheels passing on the pavement with a frequency between 500 and 4000 Hz by 40–88% compared to traditional asphalt. In addition to that, the leaching from rubber asphalt does not pose a threat to the environment.

4 Effect of Waste Tire Rubber Concentrations on Properties of Asphalt Cement

4.1 Effect on Penetration

Some researchers have studied the effect of adding waste tire rubber with different concentrations on asphalt cement penetration. For example, Khedaywi et al. [29] studied the effect of adding tire rubber to the asphalt binder at 0, 5, 10, 15, and 20% by total weight of binders. It was observed that the penetration of the modified asphalt binder decreases with the increase in the percentage of waste tire rubber in the binder. Different sizes of rubber were used (No. 16–20, No. 20–50, and No. 50–200) and it was noted that the highest value of penetration was in a binder with No. 20–50 rubber particle size. However, the penetration value was less when a binder with No. 16–20 rubber particle size was used.

Mbereyaho et al. [30] investigated the effect of adding waste tire rubber with deferent concentration of rubber (0, 5, 10, 15, and 20% of weight) to the binder on penetration. They came to same result that the penetration of the modified asphalt binder gradually decreases with the increase in the percentage of waste tire rubber in the binder.

Moreover, Wulandari and Tjandra [31] investigated the impact of using waste tire rubber as additives to the asphalt binder with different size (#40, and #80) and concentration (1%, and 2%) of rubber particles. Results showed that the increase in the concentration of tire rubber led to the decrease the penetration when using #80 particle size of tire rubber.

After presenting some studies, the researchers unanimously agreed that increasing the percentage of tire rubber reduces the penetration value. The addition of rubber in the asphalt increases the physical particles in the asphalt, which leads to the resistance of the needle implanting in the sample, and this explains the reason for the decrease in penetration when adding rubber to the asphalt. Figure 4 shows the effect of adding rubber into asphalt cement penetration.

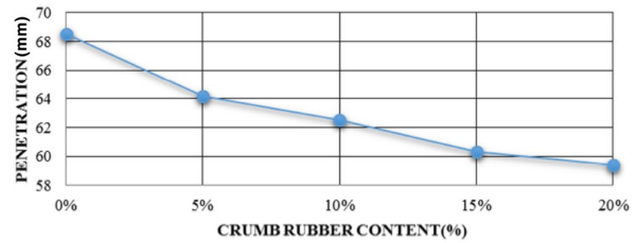

Fig. 4 Penetration test with different concentration of rubber content [32]

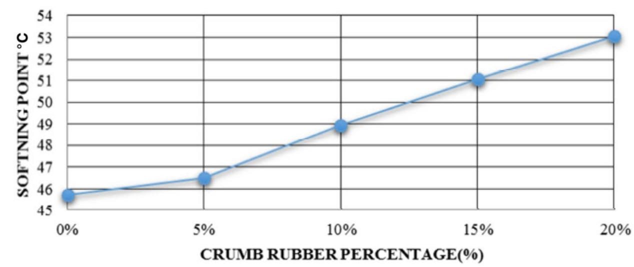

Fig. 5 Softening point test with different concentration of rubber content [32]

4.2 Effect on Softening Point

The effect of waste tire rubber to the binder on softening point was investigated by Khedaywi et al. [29] where the effect of adding tire rubber to the asphalt binder was analyzed at 0, 5, 10, 15, and 20% by total weight of binders. It was observed that the softening point of the modified asphalt binder was directly proportional to the increase in the percentage of waste tire rubber in the binder. Different sizes of rubber were used (No. 16–20, No. 20–50, and No. 50–200) and it was noted that the softening point was the highest possible when using No. 50_200 rubber particle size with a rubber percentage higher than 10%.

In another study by Mbereyaho et al. [30], it was found that the increase in the concentration of the waste tire rubber in the binder led to a gradual increase in the softening point. Also, Mbereyaho et al. [29] and Wulandari et al. [31] found the same result in the experiment.

Results of different laboratory experiments of different researchers showed good agreement that increasing the percentage of rubber increases the softening point. This can be explained, because rubber is an inactive material that needs a high temperature to soften, so adding rubber would increase the resistance to temperature susceptibility. Figure 5 shows the effect of adding rubber into asphalt cement softening point.

4.3 Effect on Ductility

The ductility is one of the vital properties of asphalt, as it enables the asphalt to expand and resist tensile strength without cracking when used in road construction and exposed to traffic volumes. Khedaywi et al. [29] investigated the effect of adding the waste tire rubber to the binder with different percentages by total weight of binder. It was found that the ductility decreases rapidly with the increase in the percentage of rubber when the percentage of rubber is less than 5%, and then increases slightly with the increase in the percentage of rubber.

Askarinejad et al. [33] studded the impact of adding waste tire rubber on asphalt mix design. They found in their experiment adding different concentrations of the waste tire rubber to the binder led to a rapid decrease in the ductility of the binder. Also, the conducted research by [23, 31] confirmed the same result.

The obtained results can be explained by the weakness of the bond between asphalt and rubber, which leads to the loss of the binder's ability to resist tension forces. Figure 6 shows the effect of adding rubber into asphalt cement ductility.

4.4 Effect on Specific Gravity

Khedaywi et al. [29] investigated the effect of adding waste tire rubber to the binder on specific gravity. Results showed that the specific gravity decreases when the rubber concentration increases in the binder. On the other hand, it was found that using rubber as a binder with particle size No. 50–200 has the highest specific gravity, and that the particle size No. 16–20 gives the lowest one. Figure 7 shows the effect of adding rubber into asphalt cement-specific gravity.

Same result was also confirmed by Askarinejad et al. [33] who found that the specific gravity of the modified asphalt binder with waste tire rubber is inversely proportional to the concentration of the waste tire rubber added to the binder.

4.5 Effect on Flash Point

The flash point is the temperature at which the test sample tends to form a flammable mixture when exposed to air under special conditions. Khedaywi et al. [29] investigated the effect of adding waste tire rubber to the binder on flash point. It was found that the flash point decreases when the rubber concentration increases in the binder. On the other hand, it was found that when the rubber particle size No. 20–50 was used, the highest flash point was reached. On the other hand, when the particle size No. 16–20 was used, the lowest flash point was reached. Figure 8 shows the effect of adding rubber to asphalt cement on the flash point.

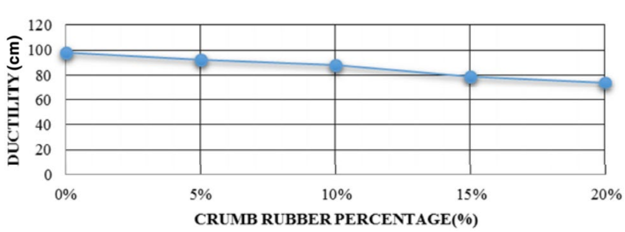

Fig. 6 ductility test with different concentration of rubber content [32]

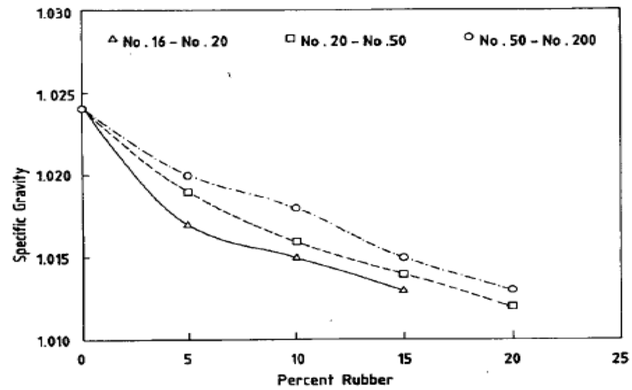

Fig. 7 Specific gravity with different concentration of rubber content and particle size [29]

4.6 Effect on Rheological Properties

Mbereyaho et al. [30] investigated the effect of adding waste tire rubber to the binder on the viscosity. It was found that viscosity is highly affected by the concentration of the tire rubber in the binder. Also, it was found that the viscosity is rapidly increased when the waste tire rubber concentration was more than 15% by the weight of the binder, but

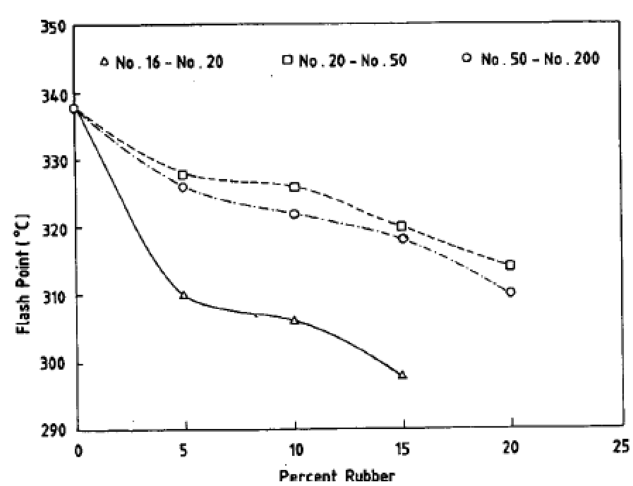

Fig. 8 Flash point with different concentration of rubber content and particle size [29]

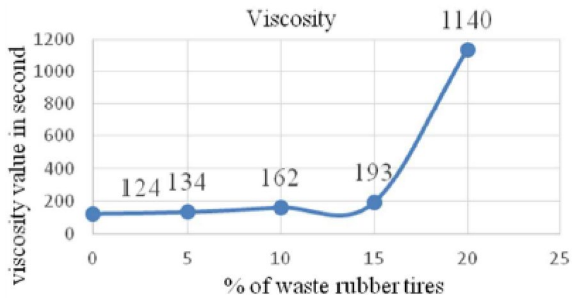

Fig. 9 Viscosity with different concentration of rubber content [30]

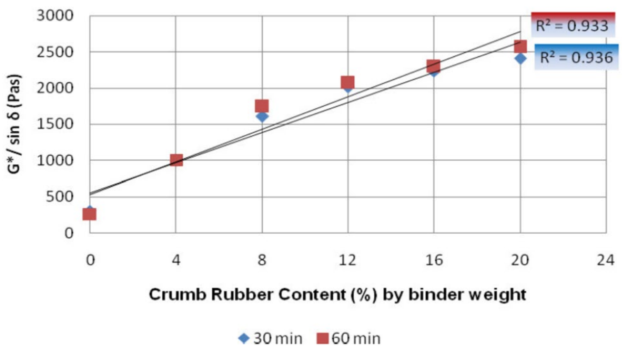

Fig. 10 Rutting factor for the two blending time and various crumb rubber content [36]

it increases gradually when the waste tire rubber concentration less than 15% by weight of binder. Same results were obtained by Stroup-gardiner et al. [34], who found that increasing the rubber content in the asphalt mixture increases the viscosity and passenger tire rubber shows higher of viscosity increase than industrial tire rubber. Figure 9 shows the effect of adding rubber to asphalt cement on the viscosity.

4.7 Effect on Rutting Resistant

Rutting is a longitudinal depression, which occurs in the pavement under the wheel paths due to the continuous intensification by the traffic load [35]. To investigate the effect of adding waste tire rubber on the asphalt binder in the resistance to the rutting, Mashaan et al. [36] conducted the Dynamic Shear Rheometer (DSR) test on samples containing different percentages of added rubber (4, 8, 12, 16, and 20% by weight of asphalt binder), two time periods were used to mix the rubber with asphalt to study the effect of the mixing time as well. It indicates an improvement in the asphalt and an increase in its resistance to rutting. It was also noted that the mixing time had no effect on the asphalt's resistance to rutting, and Fig. 10 shows the effect of adding rubber into asphalt cement on rutting resistant. Studies were also conducted by Bahia et al. [37] which showed that the addition of waste tire rubber to the asphalt binder works to improve the resistance of the pavements to rutting.

Bahia and Davies [38] also worked on conducting laboratory tests on samples of asphalt mixed with varying proportions of added rubber ranging between 0 and 20% to evaluate the rheological and physical properties of the modified asphalt mixture, where the DSR test was used to verify the rheological behavior of the modified asphalt. It was noted that the addition of rubber works to improve the complex modulus and phase angle of the modified asphalt, which indicates that it works to improve the resistance of asphalt pavements to rutting.

Based on the studies presented in this section, adding waste tire rubber to the asphalt binder showed a positive impact on increasing the resistance to the rutting of pavement.

4.8 Effect on Fatigue Resistant

Fatigue is one of the cracks that occur in the structure of asphalt pavements as a result of frequent heavy traffic load that occurs at low and medium temperatures [35]. Due to the importance of this distress, several studies were conducted to verify the effect of adding rubber on the development of fatigue resistance, where Aflaki and Memarzadeh [39] used different shear methods on samples containing different percentages of rubber ranging from 10 to 16% of the asphalt weight at medium and low temperatures to investigate the effect of adding rubber in asphalt mixtures on fatigue resistance. Obtained results showed that the addition of rubber enhanced the fatigue resistance; however, low shear blending showed less effect on the improvement at low temperatures compared to the high shear blending. Many other researchers [40–42] confirmed the same results.

It has been concluded that incorporating waste tire rubber into asphalt cement is a method for utilizing these wastes in the construction of asphalt pavements while also improving the rheological and conventional properties of the asphalt binder and, as a result, the performance of asphalt pavements. Table 2 summarizes the effects of waste tire rubber addition on asphalt cement as described in earlier studies.

5 Effect of Waste Tire Rubber Concentrations on Properties of Asphalt Concrete Mixtures

5.1 Effect on Marshall Stability

The stability of the asphalt mixture is the resistance of the asphalt concrete mixture to deformation under different loading forces.

Table 2 Overview of prior studies on the influence of waste tire rubber on asphalt cement and asphalt concrete mixtures (Researcher's own work)

References	Most appropriate rubber%	Evaluated studies	Findings
Khedaywi et al. [29]	5–15% by weight of binder	Penetration, softening point, flash point, ductility, specific gravity, Marshall stability, flow, VMA, retained stability	The addition of discarded tire rubber improves the characteristics of asphalt concrete mixtures significantly [VMA and air voids, water sensitivity (RS), and creep resistance] and change the properties of binder
Mbereyaho et al. [30]	5% by weight of bitumen	Penetration, softening point, viscosity	The usage of tire rubber waste powder can also help bituminous flexible pavement work better
Wulandari and Tjandra [31]	2% by weight of asphalt mixture	Penetration, softening point, ductility, VMA, air void	Because all of the test results are within the standard requirements, crumb rubber is recommended as an ingredient in asphalt mixture
Askarinejad et al. [33]	5–15% by weight of bitumen	softening point, ductility, specific gravity	With the right ratio, waste tire rubber can be used in asphalt pavements
Stroup-gardiner et al. [34]	–	Viscosity	Viscosities rise as rubber concentrations rise, independent of the type of rubber used
Issa [43]	10% by weight of total aggregate	Marshall stability, flow	Rubber from waste tires can be used in asphalt pavement at a replacement ratio of 10% by weight of total aggregates
Al-Rubaie and Joni [44]	10% by weight of binder	Air void	The addition of soft rubber crumbs that pass through the No. 100 sieve has a clear positive effect on the performance of asphalt mixtures, particularly in terms of boosting rut resistance in hot climates by reducing rut depth when compared to the traditional mixture
Khedaywi and Mashagbeh [46]		Dynamic creep	increase the content of waste tire rubber in the asphalt concrete mixture led to increase the resilience modulus and creep stiffness to an optimum value, and then, decreased and the optimum values were 10% and 15%, respectively

To investigate the effect of adding waste tire rubber to asphalt concrete mixture on Marshall stability, different concentrations of waste tire rubber specimens (5, 10, 15, 15, and 20% by total weight of binder) and different rubber particle size (No. 16–20, No. 20–50, and No. 50–200) at 4% air void were prepared by Khedaywi et al. [29] The results indicated that increasing the percentage of waste tire rubber used to produce asphalt concrete mixtures was of higher Marshall stability when the rubber content was up to 15%, then it decreases at higher percentage using N0 50–200 rubber particle size.

Also, Issa [43] studied the effect of adding waste tire rubber to asphalt concrete mixture on stability using different rubber content. He found that stability increases when the rubber content is up to 10% by weight of binder, and then, it decreases at higher percentage. On the other hand, he found that the stability with rubber 10% content was higher than the stability for asphalt mixture without rubber. Figure 11 shows the effect of adding rubber into asphalt mixture Marshall stability.

5.2 Effect on Flow

In their study, Khedaywi et al. [29] found that the flow increases with increasing the concentration of added waste tire rubber. It was also noted that the highest flow value was when using rubber particles' size No. 20–50 and the lowest flow value was when using rubber particles size No. 16–20. Issa [43] affirmed these findings when he studied the effect of adding waste tire rubber to asphalt mixture; the obtained

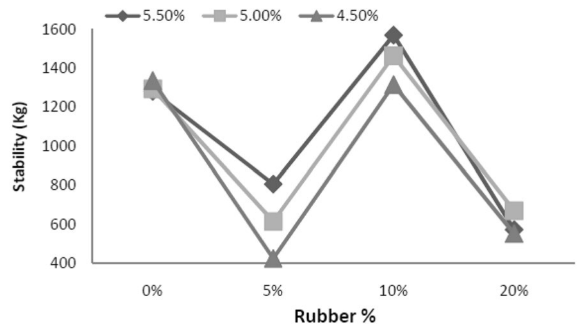

Fig. 11 Stability test with different concentration of rubber and asphalt content [43]

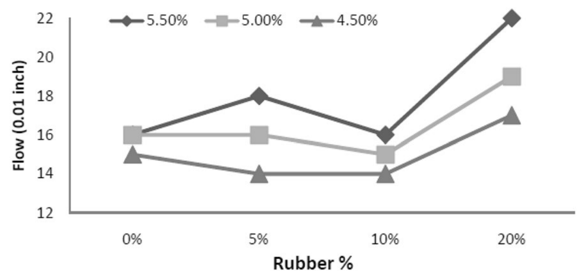

Fig. 12 Flow test with different concentration of rubber and asphalt content [43]

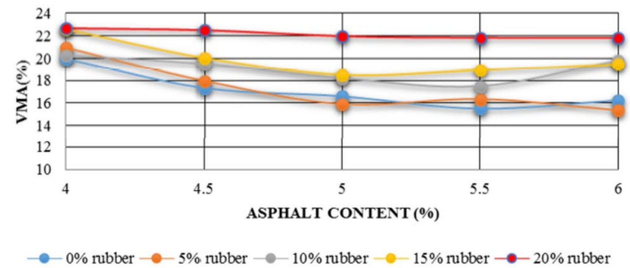

Fig. 13 VMA test with different concentration of rubber and asphalt content [32]

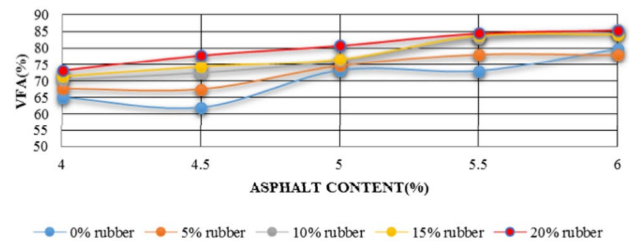

Fig. 14 VFA test with different concentration of rubber and asphalt content [32]

results indicated that the increase in rubber content in the mixture increases the flow of the mixture. Figure 12 shows the effect of adding rubber into asphalt mixture flow.

5.3 Effect on Void in Mineral Aggregate (VMA), Void Filled with Asphalt (VFA), and Air Void

To examine the effect of adding waste tire rubber to asphalt concrete mixtures on VMA with fixing the value of air void at 4%, different samples were prepared with different percentages of the added waste tire rubber by weight of the binder and different rubber particle size by Khedaywi et al. [29]. Obtained results indicated that increasing the amount of tire rubber increases the value of VMA. Also, it was noted that the highest VMA value was when using rubber particles, No. 20–50 and the lowest VMA value was when using rubber particles No. 16–20. Other researchers, Wulandari and Tjandra [31], concluded that the VMA was increasing when the tire rubber content was increasing. Figure 13 shows the effect of adding rubber to asphalt mixture VMA.

Another research conducted by Yigezu Tefera et al. [32] on the performance of asphalt mixtures modified with waste tire rubber using different percentage of tire rubber showed that the VFA increases gradually when the tire rubber content increases in the mixture. This can be explained by the fact that the asphalt film around aggregate particles is thicker than required, resulting in fewer voids. As a result of the increased amount of effective asphalt, the mix will bleed and be less stiff. Figure 14 shows the effect of adding rubber into asphalt mixture VFA.

Al-Rubaie and Joni [44] studied the performance of asphalt mixtures modified with waste tire rubber using different percentage of tire rubber. The results indicate that the air void increases gradually when the tire rubber content is increased in the mixture. In line with that, Wulandari and Tjandra [31] concluded that the air voids increase when the tire rubber content is increased. This significant increase in the percentage of air voids could be due to the excessive hardness of the bitumen because of the higher proportions of rubber in the mixture, which, as previously mentioned, negatively affects the bond between the aggregate and bitumen as a result of rubber crumbs' absorption into light asphalt compounds. Figure 15 shows the effect of adding rubber into asphalt mixture air void.

5.4 Effect on Water Sensitivity

The retained stability RS of the mixture is mainly used to assess the sensitivity of water in asphalt concrete mixtures, which is the ratio between wet and dry stabilities. Most researchers indicated that this percentage should not be less than 75, so it was adopted as a measure of rejection or acceptance criteria [45]. Khedaywi et al**.** [29] investigated the effect of adding waste tire rubber to the asphalt concrete

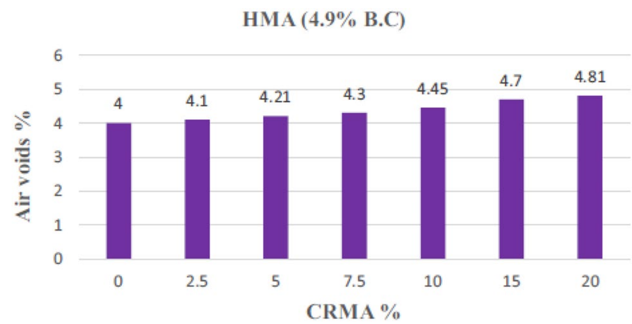

Fig. 15 Air void test with different concentration of rubber and asphalt content [44]

mixture on water sensitivity by preparing different specimens with different content and particle size of rubber. It was found that the RS was inversely correlated with the increase in the amount of rubber in the mixture; in addition to the fact that RS was acceptable except for the mixture with 20% of the rubber content and with the sizes of rubber particles No. 50–200.545. Figure 16 shows the effect of adding rubber into asphalt mixture retained stability.

5.5 Effect on Dynamic Creep

The effect of adding tire rubber to asphalt concrete mixtures on dynamic creep was studied by Khedaywi & Mashagbeh [46] who conducted laboratory experiments on a number of samples containing rubber with five different contents (0, 5, 10, 15, and 20%) of the volume of the binder, as they studied the simulation of dynamic creep under three levels of test temperature that simulates cold, medium, and warm temperatures using three loading frequencies (1, 4, and 8 Hz). The obtained results indicated that increasing the content of

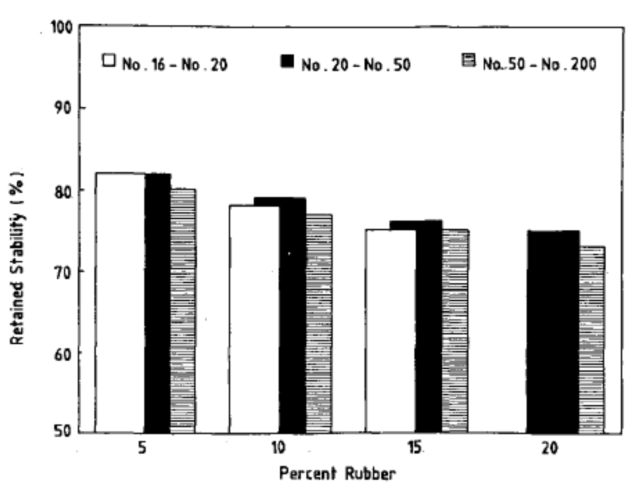

Fig. 16 Retained stability with different concentration of rubber content and particle size at 4% air void [29]

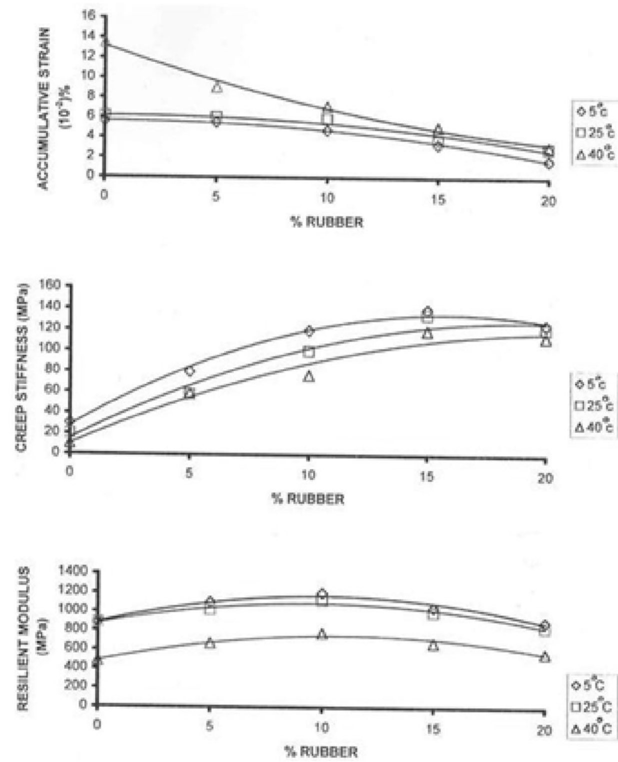

Fig. 17 Effect of adding rubber into asphalt mixture strain, creep stiffness, and resilience models [46]

waste tire rubber in the asphalt concrete mixture led to the increase of the resilience modulus and creep stiffness to an optimum value, and then, decreased and the optimum value were 10% and 15%, respectively. Also, they found that the accumulated strain of asphalt mixture decreases when the rubber content increases. Figure 17 shows the effect of adding rubber into asphalt mixture strain, creep stiffness, and resilience models.

It has been concluded that including waste tire rubber into asphalt concrete mixtures is a method for repurposing these wastes while also improving the stiffness, strength, resilience modulus, load and creep resistance, and hence the performance of asphalt pavements. The effect of adding waste tire rubber into asphalt cement using wet process can be summarized in Table 2.

6 Conclusions

Many enhanced characteristics of asphalt mixtures can be obtained by adding waste tire rubber to asphalt mixtures. This was demonstrated and reported by several researchers. These can be summarized in the following points as follows:

- The increase of rubber concentration in asphalt mixture reduces penetration, ductility, flash point, and specific gravity of the asphalt-rubber binder, and increases the softening point.
- Both ductility and specific gravity decrease with the increase of the size of added rubber.
- The characteristics of asphalt concrete mixtures were improved by adding waste rubber including Marshall stability, VMA and air voids, water sensitivity (RS), and creep resistance.
- The addition of 10 and 15% rubber to bituminous mixtures improves the resilient modulus and creep stiffness, respectively, by increasing the adhesive forces between asphalt and aggregate.
- The best performance of asphalt mixture can be obtained at 5–15% of added rubber with 10% being the optimum best performance.
- The optimum value of added rubber should be identified as exceeding it can make construction more challenging.
- Further studies into long-term durability are recommended especially in harsh climates and heavier traffic loads.

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Declarations

Conflict of Interest The authors declare that they have no conflict of interest,

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