Jurnal Teknologi

Full paper

A Review of Crumb Rubber Modification in Dry Mixed Rubberised Asphalt Mixtures

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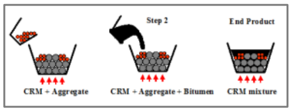
Article history

Received :26 May 2014
Received in revised form :
25 July 2014
Accepted :6 August 2014

Graphical abstract



Dry process method

Abstract

This paper provides an overview of crumb rubber modified asphalt mixtures with particular reference to the dry process. The dry process involves the blending of crumb rubber with hot aggregates prior to mixing with bitumen. In comparison to the wet process (process of incorporating crumb rubber into bitumen prior to mixing with aggregates), this mixture type has a number technical issues. The lack of standards and inconsistent performance have resulted in scepticism among practitioners and researchers in accepting the dry process for rubber modification even though it has the potential to recycle more crumb rubber compared to the wet process. This has resulted in the overwhelming majority of asphalt paving projects involving crumb rubber using the wet process. Therefore, to better understand the mixture, details pertaining to dry mixed rubberised asphalt are discussed in this paper with sufficient information from previous research. The discussions highlight several critical issues regarding its modification concept (the function and behaviour of rubber particles within the mixture), mixture design criteria and mechanical performance of this mixture type. This is necessary in order to identify the factors that play a significant role in improving the mixtures properties for future studies. Additionally, the review will be a positive step in the direction of achieving an appropriate design standard for dry mixed rubberized asphalt mixtures.

Keywords: Crumb rubber; dry process; wet process; rubberised asphalt mixture

■1.0 INTRODUCTION

For decades, waste tyre rubber has been used as an additive for constructing asphalt pavements. The use of rubber in asphalt materials started in the 1960's when it became of interest to the paving industry because of its elastic properties which had the potential to improve the skid resistance and durability of asphalt mixtures [1-3]. The additional benefit of using rubber in asphalt mixtures was that it created an alternative or additional use of recycled waste tyres. Evidence from literature reveals that crumb rubber has been used to modify asphalt mixtures usually by employing two different processing methods. The first is the 'wet process', whereby fine rubber is blended with hot bitumen to produce a 'rubberised bitumen' binder (Figure 1). The second means of rubber modification is through the 'dry process' which substitutes a proportion of the mix aggregate with coarse rubber, thereby causing the rubber to function essentially as an elastic aggregate within the mixture (Figure 2) [4-6]. In this paper, any mention of a rubber modified asphalt mixture or 'CRM mixture' is made in reference to the dry process mixture. Until recently, the design of CRM mixtures has been accomplished without any specification or official standard documentation. The asphalt mixture design approaches mentioned earlier, came into prominence as a result of several previous field trials and laboratory experiments. Previous studies evaluated the mechanical properties of dry mixed rubberised mixtures in terms of temperature susceptibility, moisture sensitivity, permanent deformation and fatigue behaviour [7-10]. Generally, both laboratory and field results show that dry process CRM mixtures exhibit poor performance or show little improvement compared to wet process or conventional asphalt mixtures. Several laboratory studies have been conducted to determine an appropriate aggregate gradation, design bitumen content or mixture preparation procedure capable of improving the consistently and performance of a dry process originated mix [11-12]. These studies found that the mechanical properties of the mixtures formed through the dry process method are very sensitive to changes in rubber content. Design criteria such as aggregate gradation, bitumen and air voids content were highlighted as the keys to success in designing a CRM mixture. Additionally, there are claims that a good laboratory mixture design is critical to obtain an optimum mixture with low air voids content and adequate stability. A lack of adequate space or gaps for the rubber particles to manoeuvre themselves within the mixture could result in large variations in air voids content due to the 'rubber swelling' phenomenon. This in turn has the potential to reduce the mixture mechanical performance as a result of specimen expansion following compaction. Although decades of research have been dedicated to the study of CRM mixtures, results produced have been largely inconsistent.

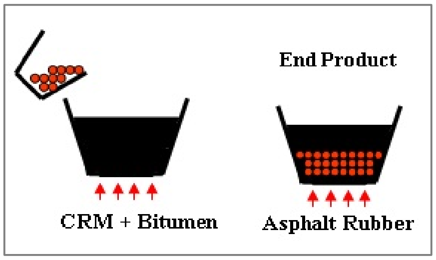


Figure 1 Wet process method

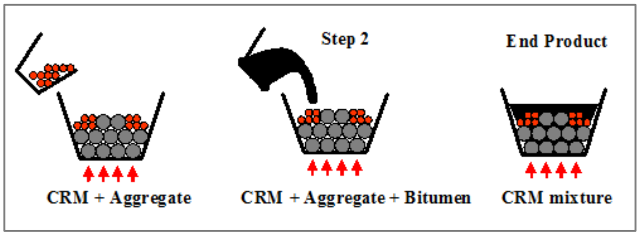


Figure 2 Dry process method

■2.0 CRUMB RUBBER COMPOSITION AND PHYSICAL PROPERTIES

Crumb rubber is made of tyres or vulcanized rubber. Tyres are basically formed by combining natural and synthetic rubber and carbon black. The tyres are shredded into smaller particle sizes to remove wire and fabric reinforcement. The actual chemical composition of crumb rubber derived from tyres is difficult to assess because of the large variation in tyre types produced by different manufacturers. However, crumb rubber is typically referenced by its size together with basic compositions such as natural and synthetic rubber, steel, fibre and carbon black. In tyre production, the vulcanization process increases the number of cross-links in a rubber's molecular structure and enhances its elasticity and strength properties. During vulcanization, the rubber is treated with sulphur at temperatures between 140°C and 180°C, at which point the long chain molecules are crosslinked together with sulphur molecules [13]. The resulting product then becomes incapable of being re-softened by further heating. Physical properties of rubber such as type, quantity, shape, gradation are said to affect the performance of rubber modified asphalt mixtures [5]. The size, shape and texture of the rubber particles used to modify the mixture vary with the proposed applications to ensure expected performance is achieved. Different sizes of crumb rubber produced for recycling purposes are shown in Figure 3.

Figure 3 Different sizes of crumb rubber

Rubber particles with irregular shapes and relatively high surface area are more likely to react with bitumen at elevated temperature to produce a modified binder. Cubical shaped rubber particles with a relatively low surface area are typical of aggregates and desirable for use in the dry process as an elastic aggregate as they are easily integrated into the aggregate mix. There are two main methods for processing scrap tyres, namely ambient granulating (crackermill process) and cryogenic grinding. Both processes essentially reduce the size of the tyre and separate the steel belting and fibre from the rubber compound. The ambient granulating using a crackermill process is currently the most common and most productive means of producing crumb rubber. The process comprises a series of granulators for tearing the scrap tyres, screeners, conveyors, and various magnets for steel removal. The end product of the crackermill process is an irregularly shaped particle with a large surface area, 'spongy surface' and varies in size from 0.425 mm to 4.75 mm as shown in Figure 4. Cryogenic grinding is accomplished at extremely low temperatures (-87 to -198°C) by submerging the scrap tyre in liquid nitrogen. Below the glass transition temperature, the rubber is very brittle and easily fractured to the desired size (0.85 mm to 6 mm). The surface of rubber obtained from cryogenic grinding is glasslike with a lower surface area and elastic recovery compared to ambient granulated crumb rubber of similar gradation (Figure 4). Ambient granulated crumb rubber results in a higher binder viscosity than any of the modified binders produced with an equal amount of cryogenic crumb rubber [14-15]. This is possible due to the very high surface area and irregular shape of the ambient rubber particles which permits a faster reaction of the bitumen with the rubber than when cryogenic rubber is utilised. The above explanation demonstrates that the method used to manufacture crumb rubber has an influence on the extent to which the properties are enhanced.

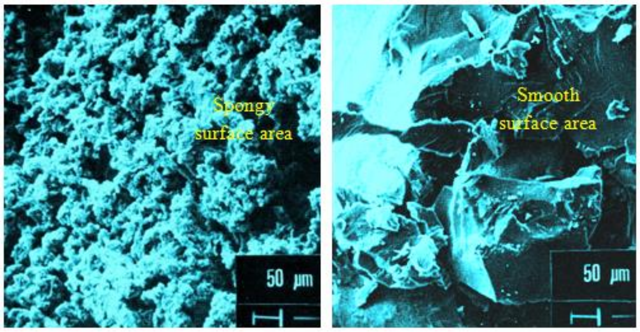


Figure 4 SEM of crumb rubber (left) ambient granulating synthetic tyre rubber (right) cryogenically crushed synthetic tyre rubber [16]

■3.0 MODIFICATION CONCEPT OF DRY MIXED RUBBERISED ASPHALT MIXTURES

Dry mixed rubberised asphalt mixture was developed in Sweden where relatively large rubber particles were incorporated into asphalt pavements. The original purpose was to increase skid resistance and pavement durability. This mixture type was distributed under the European trade names 'Skega Asphalt' or 'Rubit' in Scandinavia (Northern Europe). The technology was then patented for use in the United States in 1978 under the trade name PlusRide[17]. With this modification, the coarse rubber particles act as elastic aggregates to increase the mixture's flexibility under loading. The finer rubber particles were reported to react partially with the bitumen, increasing its viscosity to make the binder more flexible at low temperatures, while maintaining high stiffness at high temperatures [18-21].

3.1 Rubber as an Elastic Aggregate

In the dry process, normally around 1% to 3% coarse rubber by weight of the total mixture is added to the aggregate gradation having sizes between 2.0 mm and 6.3 mm [22, 23]. The idea of adding the rubber particles is to substitute a small portion of aggregates with rubber, for the rubber to function just like the aggregates but with additional benefit of possessing elastic properties as illustrated in Figure 5. By limiting the reaction time between bitumen and rubber particles and specifying a coarse granulated rubber with low surface area, the rubber particles are able to retain their physical shape and rigidity. In a gap graded mixture, the gaps provided between the fine and coarse aggregate is allocated to the rubber particles within the mixture. On the other hand, in a densely graded mixture, the aggregate gradation must be on the coarser side of the specification to permit the rubber modification. Initially, the dry mixing method of incorporating crumb rubber into gap graded mixture was targeted at controlling the effects of snow and ice on pavement surfaces. The rubberised asphalt mixture was expected to have the advantage of breaking up ice and providing better skid resistance during icy conditions than conventional asphalt mixtures. Esch [24] reported a higher skid resistance on an icy pavement constructed with the PlusRide mixture as well as a significant reduction in vehicular stopping distance. Furthermore, the Cold Regions Research Engineering Laboratory (CRREL) as reported by Federal Highway Administration, Washington, in 1992 investigated the effect of dry process mixtures for debonding ice on pavements using various amounts of coarse rubber with a particle size range from 4.75 mm to 12.5 mm. They observed that incidences of ice cracking increased when the percentage of coarser rubber added to the mixture was increased. However, testing to prove the above theory was confined to the laboratory without any field trials being undertaken.

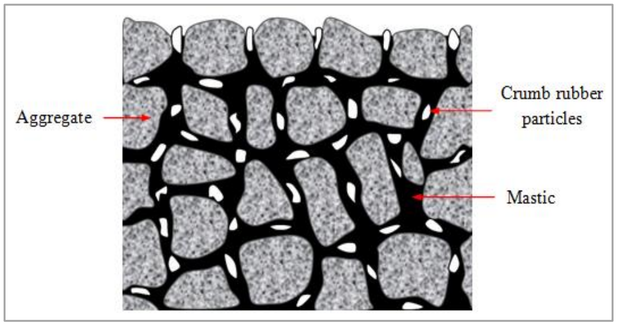


Figure 5 Rubber particles distribution within a gap graded rubberised mixtures [26]

In a similar vein, the theory discussed above was applied in the production of a mixture with enhanced elastic recovery properties under repeated loading. This enhanced the mixture's resistance against fatigue cracking. Previous laboratory tests indicate major increases in fatigue life and crack reflection control due to an increase in pavement flexibility [9]. However it was later found that the rubber particles can lose some of their elastic behaviour at temperatures in the region of -6°C resulting in a reduced fatigue life [25]. Several factors contribute significantly to the extent to which rubber functions as an elastic aggregate. These include the rubber gradation, rubber content and aggregate gradation. The way rubber particles perform under stress is illustrated in Figure 6. The figure shows that the rubber particles are able to recover their shape after the load is released. This is because when the load is applied the rubber particles absorb the energy of impact by deforming but after the load is released the rubber releases the absorbed energy and in the process recovers physically. By virtue of the aforementioned flexibility, rubber modification is considered to have potential to improve fatigue resistance and ice control in pavements.

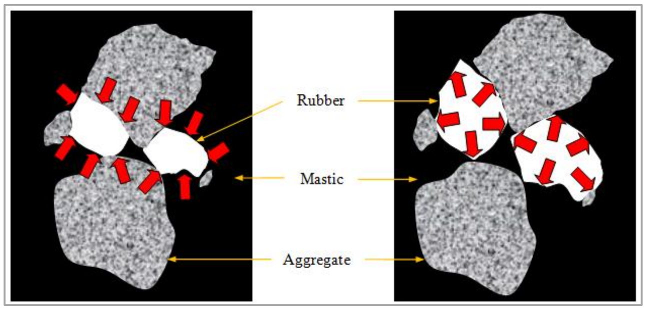


Figure 6 Rubber particles elastic behaviour before (left) and after (right) releasing the load

3.2 Rubber-Bitumen Interaction

While the utilisation of crumb rubber in asphalt mixtures has significantly evolved in the past few decades, there are aspects that have been continuously studied to better explain the effect of rubber on asphalt mixture properties. One such aspect relates to the interaction between the rubber and bitumen, which is considered vital to better understand the concept of rubber modification in both wet and dry process methods. The term 'interaction' used in this study refers to the diffusion of the lighter bitumen fractions (aromatic oils in the maltenes) into the rubber which leads to the swelling of the rubber particles. The swelling of the rubber as a result of the rubber-bitumen interaction is shown schematically in Figure 7.

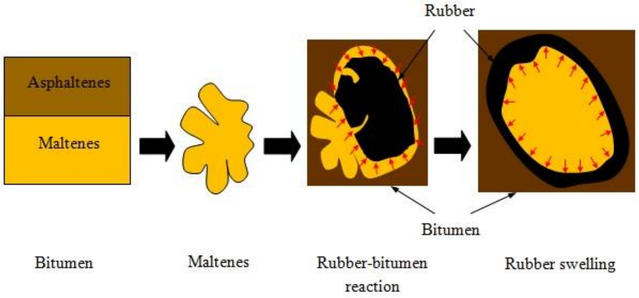


Figure 7 Schematic of rubber swelling in rubber-bitumen interaction

When rubber gets in contact with bitumen, it generally absorbs the maltenes fraction (which has low molecular weight) and leaves the residual bitumen containing a higher portion of asphaltenes (of high molecular weight) which increases its viscosity [15]. The maltenes fraction diffuses into the rubber particles, increasing the dimensions of the rubber network until equilibrium swelling is achieved. Factors such as the temperature and time of rubber-bitumen contact, chemical composition of bitumen, rubber type and size were all found to affect the rate of rubber swelling [27]. With sufficient heat and time, a higher degree of interaction between the bitumen and rubber can be increased to cause depolymerisation of the rubber particles [28]. Furthermore, the lower the molecular weight of the maltenes fraction, the more readily it will diffuse into the rubber [29]. Airey *et al.* [30] conducted a binder absorption test using the Basket Draining Method to investigate the rubber-bitumen interaction by measuring the amount of bitumen absorbed and the rate of absorption. They found that using higher penetration grade bitumen (rich in aromatic oils) seemed to increase the rate of absorption and the rate of rubber swelling. In the aspect of rubber properties, the greater the number of cross-links in the rubber, the shorter the average length of rubber chains between the cross-links and the lower the degree of swelling. This is because, strong cross-links between the elastomer chains in the rubber's molecular structure prevent the rubber particles from being completely dissolved in the bitumen. In addition, another study reported that small rubber particles could swell to three to five times their original size on reacting with bitumen [31].

Generally, it has been suggested that there is a greater degree of rubber-bitumen interaction with greater enhanced properties in the wet process than the dry process, thereby making the wet process the preferred method for modification. The rubber-bitumen interaction in the wet process is well established as it is considered as a major reaction that inevitably occurs within the mixture. In contrast, little has been documented regarding the rubber-bitumen interaction that occurs in the dry process. The majority of research conducted, pertaining to the dry process, generally assumes that the reaction between the rubber and bitumen in the mixture is insignificant. This assumption is based on the perception that only a minor interaction can occur within a limited mixing time at elevated temperature. The aforementioned assumption was refuted by Takallou and Hicks [26], who using PlusRide determined that it was possible for dry process mixtures to achieve a greater binder modification, by adding fine rubber particles in the mixture [28]. Fine rubber particles have higher surface area and hence are more reactive with bitumen. Consequently, introducing fine rubber particles reduces the binder's temperature susceptibility by enhancing the elastic and resilient properties of the bitumen at low temperature. Epps [32] reported on a series of laboratory tests that evaluated the resistance of a dry mixed rubberised mixture to fatigue failure by adding an extra 2% of fine rubber (0.850 mm). By providing 45 minutes curing period at 204°C in the loose form before undergoing compaction, the mixtures showed an increase in fatigue life by up to 450%. The improvement in the fatigue life was expected to be caused by the reaction between bitumen and the rubber particles. The reaction increased the bitumen's viscosity and resulted in a thicker film of bitumen coating on the aggregate particles which provided better resistance to oxidative aging and fatigue cracking. The curing period seemed necessary as to provide a sufficient time for the rubber to swell and partially dissolve in the bitumen prior to compaction. In addition, allowing optimum rubber swelling in a loose mixture should prevent major swelling of the compacted specimen once the mixture is being compacted. Without the interaction time, Pinheiro and Soares [33] found greater differences in the air voids content of rubberised mixture compared to conventional asphalt mixtures. As the curing period extended up to 2 hours, the mixtures showed an increase in resilient modulus and consistency in density but a decrease in their fatigue life [3, 28]. This shows that better performance can be achieved by providing a long interaction time between the rubber and bitumen but not in excess of 2 hours. A possible reason could be a reduction in the bitumen fraction of the cured specimens. It must be noted that further diffusion of oils into rubber particles will adversely affect the cohesive and adhesive properties of the bitumen and reduces the binder's ability to bond with the aggregate particles. Therefore, it was recommended to use higher design bitumen contents as compared to conventional mixtures or bitumen with higher penetration grade in the mixture design of rubberised mixtures [30]. A light oil, petroleum-based product was recommended as a pretreatment agent that should be compatible with the bitumen to pretreat the rubber before mixing in order to control the bitumen absorption [6,12].

■4.0 MIXTURE DESIGN CRITERIA OF DRY MIXING

Currently, there is no official guideline or detailed specification for preparing dry mixed rubberised asphalt mixtures. However in North America, PlusRide (gap graded) and Generic mixtures (dense graded) are two major dry process techniques that are widely practiced. This section reviews the differences in the mixture design considerations recommended by researchers and industry practitioners. The design of CRM mixtures is typically accomplished using the conventional Marshall method. Based on previous research work, the gradations of aggregate and crumb rubber, bitumen content as well as low air voids content is thought to be the keys to success in designing CRM mixtures [17,24,26,30,33-35,37]. The importance and role of these design elements used to form CRM mixtures are considered in turn in subsequent sections for both PlusRide and Generic mixture types.

4.1 Aggregate Gradation

4.1.1 PlusRide Mixture

Aggregate gradation must be selected by first identifying whether or not the crumb rubber can be incorporated into the air void spaces provided by the existing aggregate gradation. Consideration must also be given to the fact that the rubber particles will swell when in contact with the hot bitumen during mixing and compaction. Kandhal and Hanson [34] reported that PlusRide mixture types have high coarse aggregate content to provide spaces for the rubber particles to form a dense, durable and stable mixture upon compaction. The Alaska Department of Transportation and Public Facilities was one of the first agencies to use the PlusRide mixtures in the United States. Three different aggregate gradations were recommended namely; PlusRide 8, PlusRide 12 and PlusRide 16. Figure 8 shows the gradation curves (log scale) for the recommended PlusRide mixtures. The most important difference between the rubber modified and conventional asphalt mixture is evident from the shape of the aggregate gradation curves as shown in Figure 9 (0.45 power gradation graph).

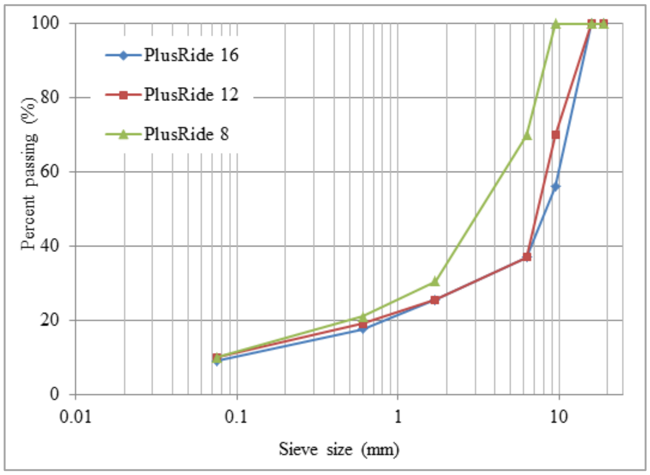


Figure 8 Aggregate gradation curves for PlusRide 16, 12 and 8 [26]

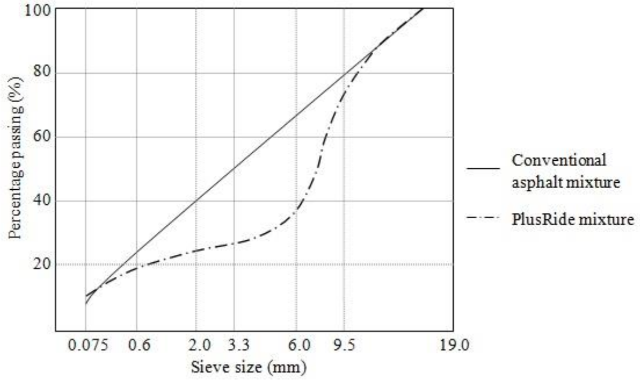


Figure 9 Aggregate gradation curves for conventional and PlusRide [24, 26]

The gap in the aggregate gradation curve for PlusRide mixture is created to provide space for rubber particles of sizes ranging between 3.175 mm and 6.35 mm. The aforementioned size range is chosen on the basis that the rubber particles that are usually used in the dry process are within this size range. Laboratory work by Chehovits *et al.* [35] revealed that if the spaces are inadequate, the rubber will resist compaction and the resultant pavement will have excessively high air voids content and lack durability. Such a problem could potentially result in minor expansion of the compacted rubberised mixture. Therefore, by opening up the aggregate gradation, the problem could be reduced.

4.1.2 Generic Mixture

Generic mixture alters the conventional dense aggregate gradation. There are three recommended aggregate gradations for Generic mixtures, namely Generic 9.5, Generic 12.5 and Generic 19 [35]. With the Generic mixture, a conventional dense aggregate gradation is used but with some adjustment made in the percentages of selected aggregate sizes to accommodate or facilitate the inclusion of the rubber particles. Figure 10 displays a comparison of the aggregate gradation curves (log scale) for the different Generic mixtures. The rubber particles added, substitute the percentage of aggregate that would have been taken out to produce a dense graded CRM mixture.

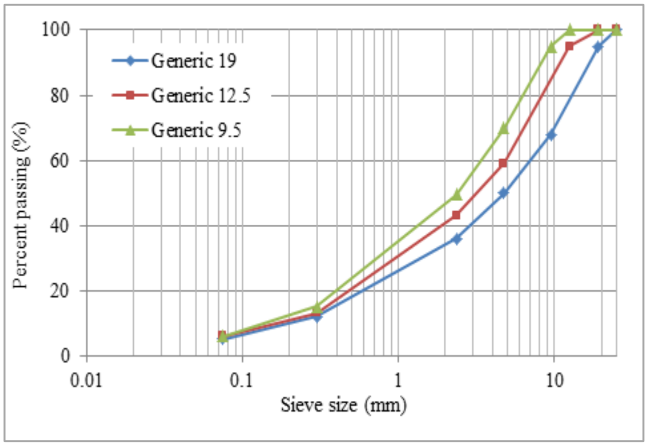


Figure 10 Aggregate gradation curves for Generic 19, 12.5 and 9.5 [35]

4.2 Crumb Rubber Gradation

In past practice, only the coarse rubber particles of granulated rubber from waste tyres (passing 6.3 mm sieve size) in a rough cubical form were added to modify mixture properties. However, further experiences with CRM mixtures have shown that better durability results can be achieved by increasing the fine rubber content. Hence, after 1981, 20% of the originally used coarse rubber grading was replaced with fine crumb rubber passing 0.85 mm sieve size (Table 1). Xiao *et al.* [26] specified a size range of 0.425 mm to 2.0 mm of fine rubber for replacing 20% of the original coarse rubber within the CRM mixture. In addition, Gallego *et al.* [36] observed that mixtures with fine rubber gradation (0.15 mm to 1.18 mm), performed better with respect to permanent deformation in comparison to conventional asphalt mixtures due to the binder modification. Pinheiro and Soares [33] identified that rubberised mixtures with fine rubber in the size range of 0.075 mm to 0.42 mm could achieve lower air voids content after compaction. The crumb rubber used in PlusRide mixtures vary from 1% to 6% by weight of the total mixture with 3% being the most commonly used. Esch [24] evaluated the PlusRide mixture’s sensitivity to the rubber content. The study indicated that a 0.5% change in rubber content can cause a 1% change in the air voids contents for the same bitumen content added to the mixture. Therefore close attention needs to be paid to the addition of the rubber. This is essential to obtain consistent mixture properties, especially in relation to getting low air voids content, which can vary considerably with small changes in the rubber content. For Generic mixtures, the percentage of crumb rubber used is slightly lower (1% to 3%) and the rubber particle size, finer compared to the PlusRide. However Generic mixtures adopt the same concept of modification of adding coarse and fine rubber fractions to the mixture (Table 2). The premise behind the technique is for the coarse rubber to serve as an elastic aggregate and fine rubber could react with bitumen to produce a modified binder in the mixture.

Table 1 Crumb rubber gradations for PlusRide (by patented company) and recommended by Minnesota DOT [34, 37]

Passing sieve size (mm)	Original PlusRide	Current PlusRide	Alaska	Minnesota
6.3	-	100	100	100
4.75	100	76-88	76-100	76-100
1.70	28-40	28-42	28-36	28-42
0.850	-	16-24	10-24	16-24

Table 2 Recommended rubber gradations for Generic mixtures [35]

Sieve size (mm)	Percent passing (%)
4.75	100
2.36	70-100
1.18	40-65
0.6	20-35
0.3	5-15

4.3 Bitumen Content

Previous studies have specified that higher bitumen content (between 1% and 2% higher) is needed for the rubberised mixture compared to the conventional mixture for the same aggregate type and gradation [38]. The approximate range of the bitumen content recommended for PlusRide and Generic mixtures are given in Table 3.

Table 3 Bitumen contents used for PlusRide and Generic mixtures [17, 26]

Mixture type	Optimum bitumen (% of total mix by weight)
PlusRide 8	8.0-9.5
PlusRide 12, 16	7.5-9.0
Generic	7.5

As noted earlier in the rubber and bitumen interaction section, some of the bitumen fraction in rubberised mixture may be absorbed by the rubber particles. As a result, replicate specimens containing rubber could end up with high variations in air voids content, for the same mixture design [30]. Figure 11 shows that as bitumen content in the rubberised mixture decreases, air voids content will increase. Therefore, to counter the absorbed bitumen fraction into rubber particles, the optimum bitumen content is selected at low target air voids content, with 3% usually desired in the design rubberised mixture. Furthermore, higher bitumen content is significant to ensure the workability of the mixture. In addition, both PlusRide and Generic mixtures yield lower stabilities and higher flows due to their elastic properties, compared to conventional mixtures. Therefore, a proper laboratory mixture design is critical to produce a mixture with low air voids content and adequate stability. Several researchers recommended additional design criteria for the PlusRide and Generic mixtures as shown in Table 4 [35].

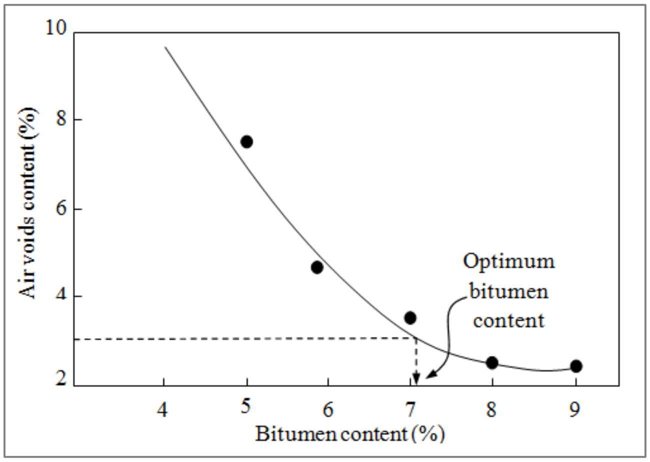


Figure 11 Determination of bitumen content on the basis of air voids content [24]

5.0 MECHANICAL PERFORMANCE OF DRY MIXED RUBBERISED MIXTURES

The majority of mechanical testing was undertaken to evaluate mixtures' performance in terms of stiffness modulus, permanent deformation and fatigue resistance. In turn, the aforementioned measures of performance are reviewed to attain a better understanding of the effect of different mixture variables on CRM mixtures compared to conventional asphalt mixtures. The mixture variables discussed include rubber content, rubber gradation and mixing procedures.

5.1 Resilient Modulus

A resilient modulus testing program is typically used to evaluate the ability of mixtures to bounce back upon releasing the applied stresses. Resilient modulus can be measured as the ratio of the repeated stress to the corresponding resilient strain (by the recoverable deformation). Pinheiro and Soares [33] and Xiao *et al.* [39] found the resilient moduli of rubber modified mixtures to generally increase with increasing rubber content demonstrating the increased elasticity of the mixtures. However, deformation was mostly recoverable indicating that the mixture's lower stiffness and greater flexibility had resulted in less stress being absorbed by the pavement surface compared to a conventional mixture. Takallou and Hicks [26] compared three different rubber gradations; fine, medium and coarse. They found that mixtures with fine rubber had the highest modulus, which is thought to have been caused by the rubber-bitumen interaction.

5.2 Tensile Strength

The indirect tensile strength test can be conducted to evaluate the tensile strength of CRM mixtures under static or repeated compressive loads. The test measures the horizontal displacement to calculate the horizontal strain corresponding to the load applied parallel to the vertical diametral plane of the specimen. Stroup Gardiner *et al.* [40] tested the tensile strength of rubber modified asphalt specimens at low temperatures (-18,-10, 1°C). They found that, increasing the rubber content led to reductions in the tensile strength of the mixtures, which indicated that the structural capacity of the rubberised mixtures had been deleteriously compromised. The corresponding horizontal strains showed a substantial increase in strain potential at low temperatures. Pinheiro and Soares [33] and Gowda *et al.* [41] also reported a reduction in the tensile strength of the rubberised mixture tested at 25°C.

5.3 Fatigue Resistance

Fatigue behaviour can be characterised by relating the strain of a mixture to the number of load applications to failure. Fatigue testing can be conducted by either controlling the load (stress) or the deformation (strain). Researchers have identified several mixture variables believed to influence the fatigue life of CRM mixtures. The mixture variables found from various published literature include rubber content, rubber gradation, aggregate gradation, mixing temperature and curing time prior to compaction (for rubber-bitumen interactions). Studies undertaken have shown that CRM mixtures have a much greater fatigue life than conventional asphalt mixtures. Increasing the rubber content of an asphalt mixture having a gap graded particle size distribution with coarser rubber gradation was shown to result in better fatigue resistance compared to rubber-modified dense graded mixtures [42]. Furthermore when a higher mixing temperature and curing time (1 hour at 150°C) was considered, the results showed an extended fatigue life [33]. It was also found that increasing curing time by up to 6 hours did not make a significant difference to the fatigue performance of the mixture [30]. According to Takallou *et al.* [26], conditioning the CRM mixture at a higher temperature of 190°C or more for 2 hours before compaction decreased the fatigue life due to binder oxidation.

5.3 Permanent Deformation Resistance

The potential of permanent deformation at high temperatures for CRM mixtures can be determined from the permanent strain accumulated at the end of the testing under vertical compressive stresses. Researchers claim that the addition of rubber to asphalt mixtures will enhance the mixture's elasticity allowing recover at higher service temperatures to counter the permanent deformation experienced on road surfaces. Olivares *et al.* [16] evaluated the rutting resistance of a CRM mixture at 60°C using the Wheel Tracking Test to simulate the effect of traffic. They discovered that increasing the rubber content and allowing sufficient curing time improved rutting resistance. A higher number of cycles had to be applied to the CRM mixture for it to reach the same target rut depth as the conventional mixture. Creep tests were conducted by Lee *et al.* [8] and Fontes *et al.* [9] to characterise permanent deformation in terms of creep modulus under static axial load. Their results suggest that CRM mixtures have lower creep resistance than conventional asphalt mixtures. The creep resistance was found to improve as fine rubber was added to the mixture. In a further study, Airey *et al.* [43] used a Confined Repeated Load Axial Test to evaluate the rubberised mixture by measuring the total strain and strain rate of the test on the mixture after the application of load cycles. The inclusion of rubber as additional aggregate was found to increase the permanent strain and the strain rates over that of a conventional asphalt mixture. On the other hand, strain rates were found to decrease as the rubber content in the mixtures was increased. This demonstrates that higher rubber content could potentially improve the permanent deformation resistance of rubber-modified asphalt mixtures.

■6.0 PROPOSED MIXTURE DESIGN AND MIXTURE PREPARATION GUIDELINES BASED ON THE REVIEW OF LABORATORY AND FIELD PRACTICES

On the basis of the reviews, several mixture design and mixture preparation guidelines have been identified based on previous research recommendations. The following general guidelines are suggested for use in the design of dry mixed rubberised asphalt mixtures.

a. Gap graded aggregates and coarse densely graded aggregates are preferred for modification.
b. Use the same bitumen grade as used in conventional asphalt mixtures or a higher penetration grade.
c. Add higher bitumen content (1-2%) compared to conventional asphalt mixtures.
d. Combination of coarse and fine rubber is significant for better performance.
e. Low design air voids content on the compacted mixture is critical and desirable (approximately 3%).
f. Use higher mixing temperatures than conventional asphalt mixtures.
g. Mix the rubber with the aggregate prior to adding the bitumen.
h. Provide a curing period after mixing (in a loose form) of about 2 hours (between 1 and 2 hours is recommended).
i. Remix the mixture prior to compaction to 'warm-up' the mixture after the long curing period.
j. Apply a surcharge load after compaction to counter the rubber swelling in the specimen prior to extrusion. However, this step is limited to laboratory prepared specimens and may not necessarily reflect the real in-situ conditions in a road. Therefore for field practice, it was suggested by Esch [44] that the compaction (refers to rolling action) should commence as soon as possible after placement to the highest possible density with minimal air voids.

■7.0 CONCLUSIONS

The review has provided detailed insight and a better understanding of dry mixed rubberised asphalt mixtures. This is necessary to justify the function and behaviour of the rubber particles within the mixture prior to performance evaluation. Thus, it would be possible then to identify the factors that play a significant role in improving the CRM mixtures properties. From the review, the following general conclusions can be made:

a) The use of crumb rubber in asphalt mixtures is often considered to improve the performance of asphalt mixtures and benefit the environment. It has been used to modify both gap and dense graded mixtures by means of gradation modification or substitution.
b) Rubber particles have two main functions in the context of asphalt mixture's modification. Firstly, they perform as part of the aggregate component of the mix but exhibit greater elastic recovery characteristics. Secondly, they partially modify the binder properties through a rubber-bitumen interaction. These aforementioned functions have been found to improve the asphalt mixture's resistance to fatigue cracking and permanent deformation.
c) The mixture design guidelines identify aggregate gradation, rubber gradation, bitumen content and air voids content as critical design criteria. They are considered important for the production of CRM mixtures.
d) There are slight modifications in the mixing and compaction procedures adopted for preparing the CRM mixtures compared to conventional asphalt mixtures. This is for the purpose of achieving the target mixture design and enhancing the mixture's properties.

Acknowledgement

The support provided by Universiti Teknologi Malaysia in a form of scholarship for this study is very much appreciated

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