Sustainability of using reclaimed asphalt pavement: based-reviewed evidence

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Abstract. The concept of sustainability is considered essential in the development of the asphalt mixtures industry, due to its economic and environmental benefits. This study attempts to highlight the potential benefits of sustainability using Reclaimed Asphalt Pavement (RAP). It reviews previous studies conducted on RAP to obtain the most important characteristics in how to use the optimal content of RAP and its effect on some basic properties such as resilient modulus, susceptibility to moisture, permanent deformation, and fatigue. This study mainly focuses on the advantages of using RAP materials in hot mix asphalt (HMA). The results indicated that adding 30% of RAP to virgin asphalt mixtures gives the best performance in terms of the most studied characteristics.

Keywords: Moisture susceptibility, reclaimed asphalt pavement, resilient modulus, permanent deformation

1. Introduction

The construction of paving roads (flexible or rigid) consumes huge quantities of raw materials (aggregate and asphalt), therefore, saving the natural resources of these materials is an important concern [1-3]. Reclaimed asphalt pavement (RAP) is constructed from milled asphalt that tore apart the old asphalt surface course. It is generally obtained in a loose granular form as a pavement rehabilitation or restoration as a by-product and is used as commonly as new pavement courses (i.e., base/subbase courses) if crushed, hot recycling, or cold recycling [4]. The incorporation of RAP materials into new asphalt mixtures has been increased recently, because it reduces the demand for new raw materials (aggregate and asphalt binder), which in turn reduces the construction cost and preserves the natural resources. On the other hand, the use of RAP in Hot Mixing Asphalt (HMA) could reduce the cost of disposing waste resulting from old pavements. RAP inclusion in HMA has become more and more popular recently all over world due to previously mentioned aspects. The evaluation of the mechanical...
properties and performance of RAP-asphalt mixtures have been part of several studies in the literature. Emphasis was placed on the advantages and disadvantages of incorporating RAP into HMA and optimal properties of RAP were investigated [5].

Several studies have been conducted to explore the effect of adding RAP to HMA in terms of mechanical and volumetric properties of such mixes [4, 6]. Daniel and Lachance [7] revealed that the volumetric properties (VMA and VFA) of the RAP asphalt mixtures were increased. It was observed that the quality of the asphalt mixes is highly depended on how well the new asphalt binder interacts with the RAP asphalt binder. Izaksa et al. [8] showed that the addition of RAP materials to asphalt mixtures did not significantly affect the mechanical and volumetric properties of the recycled hot mix asphalt in terms of Marshall stability and flow. ValdÁ et al. [9] examined the mechanical response of bituminous blends with high rates of 40% RAP and 60% RAP for a surface layer. Their results showed that a high RAP content could be incorporated into new asphalt mixes, and it was also found that 10% and 30% RAP contents had similar properties to conventional asphalt mixes.

Colbert and You [10] examined the effect of fractionated RAP materials on the performance of asphalt mixtures containing different proportions of RAP (50%, 70%, and 100% RAP). The results indicated that the increasing in the RAP concentration led to an increase in the viscosity of RAP asphalt mixtures, contributing to the more stiff mixture. Mogawer et al. [11] found that the asphalt mixtures containing low amounts of RAP quantities (less than 30 percent) performed similarly to those asphalt mixtures made from virgin materials. TabakoviÁ et al. [12] evaluated the mechanical performance of asphalt mixture containing diverse percentages of RAP (i.e., 10%, 20%, and 30%). RAP materials replaced the fine and coarse aggregates. A clear improvement was observed in the mechanical performance of RAP-containing asphalt mixes compared to conventional asphalt mixes.

Kodipilly et al. [13] assessed the effects of adding RAP and polymer-modified asphalt on the performance of HMA. The study included preparing six mixtures containing different percentages of RAP and polymer-modified asphalt. The aggregate extracted from RAP replaced the raw aggregates in various percentages (0%, 15%, and 30%). The results showed that the asphalt mixture comprising a high percentage of RAP (30%) and polymer-modified bitumen met the standard requirements of mechanical properties and sustainability resistance of highways development in New Zealand. Shen et al. [14] evaluated the volumetric properties and ITS of 12 asphalt mixes of ten contained recycled materials. The use of two types of rejuvenating agents, including one commercially available oil in the US and low viscosity liquid asphalt. Aggregate replacement with (15%, 30%, and 40%) of coarse and fine RAP gradation. The results showed that the volumetric criterion of recycled mixes has been met and that ITS passed the specifications of recycled mixtures with 30% of RAP.

Widyatmoko. [15] studied the effect of adding the RAP (10%, 30%, and 50%) to asphalt concrete and a base course on mechanical properties and durability. It was found that the mixtures containing RAP performed at least equivalent or better performance than the control mixture (without RAP). Moreover, it was found that 10% and 30% of RAP behaved equivalent to the control mixture for most characteristics.

The current research aims to refine the best technique for adding RAP to HMA by investigating the effect of particle sizes of aggregate in RAP on volumetric and mechanical properties of HMA. The work included comparative replacement from coarse aggregate, fine aggregate, and total aggregate. HMA is designed as a wear layer of pavement that include different percentages of RAP.

2. Pavement sustainability

Sustainability requires addressing consumer needs and developments in technology at the lowest reasonable environmental and economic cost. The greatest demand of human beings is the transportation and the establishment of safe transport services. With approximately 83.5% of total pavement in the US, asphalt is the primary characteristic of road network infrastructure [19]. To provide sustainable pavement, environmental impacts, and economic gains, efficiency must be taken into consideration.
Around 1.6 billion tons of asphalt were manufactured worldwide in 2007 [20], which requires fuel consumption ($1.4 \times 10^8$ m$^3$), energy use ($1.28 \times 10^8$ gigawatt hours), and CO$_2$ pollution of $46.08$ million tons, which it reflects $0.15\%$ of global CO$_2$ emissions. In comparison, pavements construction requires three sub-phases of transportation, paving, and compaction of asphalt mixtures. The last sub-phase can mitigate pollution if modification is applied for better compatibility. Also, energy use and pollution can be reduced during the operation, maintenance, and end-of-life by improving the performance of asphalt concretes. Another environmental aspect of producing asphalt mixtures is waste management. The use of recycled aggregates and the modification of the asphalt binder by polymer waste and by-products is a solution to conserve environmental resources and discourage dumping of hazardous and environmental wastes [16].

An optimal balance between the engineering (performance), environmental and economic aspects thus provide sustainable pavement as shown in Figure 1 [22]. Most of the studies that have been conducted have typically focused on three components: economic growth, social progress, and environmental conservation [23]. Figure 2 illustrates the waste hierarchy applied to pavement materials. The most preferred option is to reduce waste production, while landfilling is the least preferred choice [24].

The asphalt mixture is a compound containing large amounts of aggregates, asphalt and cement binders, and additives that improve performance to meet the ever-increasing requirements for axle loads and frequency of traffic. There are two explanations for the use of waste asphalt materials: either to save resources or to improve material properties [25]. Many researchers have explored the techniques to save natural resource by reusing or recycled aged asphalt pavement, aged concrete aggregate, aged asphalt shingles, construction and demolition, steel furnace slag, scrap tire rubber, waste glass, and low-quality marginal materials in reducing the need to use new raw materials for asphalt concrete production.

**Figure 1.** Sustainability of pavement materials [22].
3. Reclaimed Asphalt Pavement (RAP)

The main factors that can be attributed to weak asphalt paving are likely avy traffic loads, harsh climate change, and poor construction. Thus, the maintenance of these pavements leads to the removal of a lot of damage materials and replacing them with new ones. Recycling of deteriorated asphalt pavements results in a recyclable mixture of aggregates covered with an aged asphalt binder called RAP [26]. Recycling is a process with environmental and economic benefits that produces a sustainable strategy for the paving industry. Whereas, the reuse of RAP with the new HMA reduces the quantities of new materials used (binder and aggregate) and stops their disposal in landfills. Although aged asphalt pavements have been degraded and reached the end of their service life, both the aggregate and aged binder are still useful and can be reused again. For decades, RAP materials have mainly been used with raw materials to create new asphalt pavements, indicating that they are economical and contribute to improving the environment [27,28]. Therefore, RAP methods have the advantage of reducing maintenance and rehabilitation costs as well as the environmental impact waste.

4. Evolution of Using RAP throughout History

Recycling asphalt pavements were first used in the USA in 1915 [29]. In 1979, the Federal Highway Administration (FHWA) adopted the implementation of Field Project No. 39 by including 50% RAP in the hot asphalt mixture and published a detailed report on this study entitled "Assessment of Recycled Asphalt Concrete Pavement" in 1982 [[17]].

At the end of the twentieth century, specifically in 1997, a subgroup of FHWA Asphalt Mixture ETG embarked on developing and issuing guidelines for incorporating RAP into a Superpave system based on the performance data for Marshall mixtures contained RAP materials [30]. In 2001, these guidelines were verified and developed by the National Cooperative Highway Research Program (NCHRP) in the context of significant research (Project 9-12) titled "Incorporation of Reclaimed Asphalt Pavement in the Superpave System," this study emphasized the benefits of applying stepwise approach using a RAP, supported the use of blending schemes, and suggested a modified stepwise approach to the use of RAP in hot asphalt mixtures [31].

In the US, the average RAP content in new asphalt mixtures is between 12 and 15%. The National Asphalt Paving Association (NAPA) aims to increase the average RAP content to 25% by the end of
2013. For a decade, there has been successful planning and production of quality RAP recycled mixes. The most recent studies done in the United State and Canadian provinces have shown that mixtures containing at least 30% RAP perform similar to those containing virgin materials [32]. According to the 2017 survey, European countries, Belgium, Finland, Great Britain, Hungary, and Slovakia recycled more than 90% of available RAP in the production of hot and warm asphalt mixtures for surface layers [33].

5. Characteristics of RAP

RAP is a product of removal and milling deteriorated asphalt pavement, which consists of aged aggregates covered with an aged asphalt binder that have been subjected to various impacts during its service life, and finally it has been stored for use in a new asphalt mixture. Therefore, it is essential to know the characteristics of RAP components because it is related to two main issues: limitations of RAP materials and performance of recycled asphalt mixtures.

Aging is one of the crucial characteristics of RAP asphalt binder. As a result of aging, RAP asphalt binder has subjected to physical changes during construction and service life, making it more stiff than virgin asphalt binder. Generally, the aging process occurs in two stages (short-term and long-term). Short-term aging occurs during the construction phase which leads a significant increase in the viscosity due to exposing the binder to hot air through the construction. Long-term aging occurs during service which leads to a gradual increase in hardness through several mechanisms. These mechanisms are categorized into six groups such as oxidation, volatilization, and polymerization of molecular elements by chemical reaction and synergy resulting from perfusion of the oily fraction and segregation by removal by absorption of aggregates of oily elements, resins and asphaltene [34, 26].

Finally, the stiffness of RAP asphalt binder mainly depends on the level of aging, which in turn affects the degree of blending between the virgin and RAP binders. If the RAP bitumen is too stiff, the mixture of RAP and virgin bitumen may not work as expected. In small percentages (up to 20%), the aged binder does not significantly affect the properties of the RAP binder and the raw material mixture [35]. However, when average to higher ratios is applied, an aged binder can greatly influence the behavior of the asphalt mixture and may influence the result of binder grade.

The major concern that directly affects the performance of the recycled asphalt mixture is related to the mixing degree between the virgin and aged asphalt binders. Also, the level of blending affects both the limitations of the maximum RAP content and the economic value of the recycling process [36]. In general, the previous literature indicated that the incorporation of RAP with the new asphalt mixture followed three theories about the behavior and how to mix aged binder and the virgin within the mixture. The first theory assumes that RAP materials behave like black rock, with the RAP binder being neglected and not mixed with the virgin binder. The second theory assumes that mixing occurs between RAP and virgin binders, in which the resulting asphalt binder is uniformly stiffer. The third theory posits that partial mixing takes place between the RAP and the virgin binders, in which a portion of the RAP binder becomes liquid and partially blends with the new asphalt binder. In this case there is an area of the mixed binder where the asphalt binder properties range from being identical to the virgin binder to a RAP coated solid binder. Also, part of the RAP particles are black rocks, as shown in Figure 3 [37].

Nowadays, it is known that the amount of mixing present between virgin asphalt binder and old RAP binder distinguishes either complete blending or no mixing [38]. However, there is currently no clear tool that can be accessed to specifically assess the degree of blending occurring. The forms in which the RAP binder is mixing with the virgin asphalt binder and the degree to which the mixing affects the properties and results of the final mixture is still unknown [39].
6. Rejuvenation of the RAP asphalt binder
To address concerns about RAP stiffness and aging and its effect on the performance of recycled mixtures, a recycling agent should be added to soften or dilute stiffness and restore the rheological properties of the RAP binder in the mixture [40]. Besides recycling agents, softer asphalt binder can also be used for the same purpose. Recycling agents fall into two groups, either softening agents or rejuvenating agents. Softening agents help relieve the stiffness by reducing the viscosity of the RAP binder, which includes asphalt flux oil, lube stock, and slurry oil. While rejuvenating agents help to restore the physical and chemical properties of RAP binder, which includes lubricant and extender oils that contain a high amount of maltene constituents [41].

Asphalt binder loses some of its oleic constituents during the period of construction and service life, so it becomes stiffer with aging. Adding rejuvenating agents leads to compensate for the missing constituents and restore the balance to the aged binder. Moreover, there must be compatibility between the aged asphalt binder and selected rejuvenator to ensure its effectiveness. Therefore, rejuvenating agents possess a high aromatic content of and a low saturation content that are usually compatible with the aged asphalt binder [26].

7. RAP Aggregate Properties
Current AASHTO guidelines reflect the same requirements for conventional or RAP mixtures to evaluate the performance of RAP asphalt mixtures. When evaluating mixture gradient and consensus characteristics, the aggregate of RAP should be taken into account except for the equivalent value of sand, which is excluded from its volatility in the tests [42]. To ensure that both recycled mixtures containing RAP materials perform the same performance as conventional mixtures, it is important to allow the same fractions of RAP aggregates to be used as those for virgin aggregates. Although, due to the milling process, unnecessary fines are produced and the graduation requirements are very difficult. This reduces the high content of RAP material to be included. Although RAP heterogeneity was a concern, a recent analysis by [18] of RAP heterogeneity showed that RAP gradation is usually more consistent than virgin aggregates. Zaumanis, Oga [19] showed that the variability of the cored sample allowed 20% of RAP in the mixture design, while the milling process raised the potential RAP content to 30% and the mixing of the stock by up to 40%. It is also crucial that RAP content is handled with care at an early stage as higher RAP content may adversely affect the performance of asphalt mixtures.

8. The effect of RAP materials on the properties of asphalt mixtures
In this study, the effect of using RAP materials on some characteristics of asphalt mixtures such as modulus of resilience, susceptibility to moisture, permanent deformation and fatigue, was studied.
8.1 Resilient Modulus

This parameter is one of the vital characteristics of asphalt mixtures and should be evaluated as it relates to several requirements during the mechanical design approach. Several researchers have used this procedure to evaluate the elastic properties of asphalt samples, even those containing RAP as shown in Table 1. The standard configuration for determining this factor is to use the load on a cylindrical sample, as shown in Figure 4. Measuring instruments (LVDT) are used to calculate the horizontal deformation of a sample as a result of repeated applied loads.

| The author(s) | % RAP | Effect |
|---------------|-------|--------|
| In 1990, Noureldin and Wood [20] | Use four mixes of the same gradation. The only difference between the mixes was that one was a virgin mixture using AC-20 binder, while the other three were RAP (AC-20) mixed with three different regenerators. | The modulus of resilience is lower than that of the virgin mixture. |
| In 2000, Bennett et al. [47] | The use of RAP with crushed aggregates. | Modulus of resilience is higher than RAP for crushed aggregates with similar gradations. |
| In 2002, Sondag, Chadbourn [21] | (0, 15, 30, and 40)% of RAP from two sources on the resilient modulus value for mixtures prepared with three types of virgin asphalt binders, stiff and soft binders. | The effect of RAP is less on the modulus of resilience at low temperatures compared to high temperatures. Besides, the percentage increase in the resettlement program led to increase of the coefficient; However, with a stiffer virgin binder, the increase is less significant than that of softer binders. |
| In 2006, Xiao [22] | Using RAP in rubber asphalt mixtures with various proportions of reclaimed materials and crumb rubber. | The stiffness and resilient modulus of a mixture was closely related to the RAP content and ratios of crumb rubbers, and the use of crumb rubber was also useful in reducing the stiffness of the mixed binder under long-term aging. |
| In 2007, Xiao, Amirkhanian [23] | Varying ratios of crumb rubber and RAP to their mechanical properties in terms of resilient modulus. | The rise in RAP improved the mechanical properties of the rubber asphalt mixtures. Reasonable workability was observed when RAP was combined with rubber asphalt mixtures since the aged RAP binder had relatively lower viscosity. |
| In 2008, Widyatmoko [24] | Using recycled mixtures with (10, 30, and 50)% of RAP. The cohesion grades of fresh asphalt binders (60/70) and (80/100) penetration grades were used with the virgin and recycled mixtures. | Recycled mixtures containing RAP showed an improvement in resilient modulus compared to similar mixtures without RAP. |
| In 2011, MirA et al.,[11] | Use of bituminous mixtures of high modulus with bitumen low penetration and high RAP (0%, 15%, 50%, and 50%). | 30% of the RAP shows an improvement in the resilient modulus. |
| In 2012, Colbert and You [14] | (15%, 35%, and 50%) RAP with HMA. | The modulus of resilient decreases with increasing RAP. The acceptable value of RAP is 30%. |

Table 1. Effect of using RAP on resilient modulus by different studies.
In 2013, Pradyumna et al. [51] used virgin asphalt and 20% PAP under three temperature levels of 25, 35 and 45. The results show a 20% higher resilient modulus of RAP than virgin asphalt, however, the resilient modulus decreases with increasing temperature.

In 2014, Dong and Huang [52] used the use of RAP with crushed limestone and crushed gravel prepared with the same gradient and equivalent compression works. The results showed that RAP tends to have a higher resilient modulus when tested as unbound aggregate.

In 2018, Arshad et al., [13] used RAP (15%, 25%, 35%) with HMA. The modulus resilience decreases with increasing RAP ratio.

In 2020, Kareem and Al-jumaili [53] used 12.5, 25, and 50% of RAP materials were added to two types of mixtures used in the surface and base layers. Recycled mixtures containing 25% RAP with a softening agent (VL5%) showed the highest resilient modulus values under similar environmental conditions regardless of the type of layer gradations.

As indicated in previous studies, the prevailing impression is that the addition of RAP materials can improve the stiffness of the asphalt mixture produced by the RAP asphalt binder. However, the magnitude of this stiffening also has some arguments. As reported in one NCHRP article, resilient modulus results are not the best option for evaluating recycled mixture as results between different laboratories are unclear and inconsistent [45].

![Figure 4. Configuration of resilient modulus test for asphalt concrete](image)

### 8.2 Moisture Susceptibility

When asphalt mixtures are exposed to water and moisture, their performance may be quite complicated, as noted in recent extensive studies to verify the moisture susceptibility of asphalt mixtures as shown in Table 2. Tests performed on compacted samples can usually be categorized as qualitative and quantitative tests. As for the previous group, there are various methods such as boiling water test, freeze-thaw test, quick bottle test, bottle rolling process, etc. Quantitative measurements focus on observing a variety of mixture characteristics that are influenced by moisture, including the immersion compression test, indirect tensile test, Marshal immersion test, double punching process, resilient modulus test, etc. Alternatively, uncompacted (loose mixtures) samples may also be checked. These tests are usually simpler and cheaper to perform when avoiding traffic, incorporating mechanical properties, and pore strain. The surface energy system, film stripping, and surface reaction experiments in this regard are better examples [54].
several studies have investigated and evaluated the durability of recycled mixtures using RAP or modified mixtures with crumb rubber to withstand moisture damage through a moisture susceptibility test as shown in Table 2. It has been observed that RAP mixtures are assumed to be less susceptible to water as the RAP aggregate is covered with an aged asphalt layer. In addition, the increase in the viscosity and the binder content resulting from the addition of crumb rubber and resulting in excellent adhesion with complete coverage of aggregates with the asphalt binder improved the resistance of the mixtures to moisture damage. As indicated in Table 2, the use of RAP improves the resistance to moisture damage by increasing the RAP up to 40%.

**Table 2.** Effect of using RAP on moisture in various studies.

| The author(s) | % RAP | Effect |
|---------------|-------|--------|
| Huang, Li [25]; Karlsson and Isacsson [26]; Guthrie, Cooley [27]; Schaertl and Edil [28]. | 20% RAP used with recycled mixtures. | Improving resistance to moisture damage; in addition RAP was less affected in the water due to the presence of an aged binder covering the old aggregate preventing water penetration into aggregate-binder interface and loss of bonding. |
| Al-Rousan, Asi [29][58]. | 30% RAP with recycled mixtures. | The 30% of the RAP was less affected by the effect of water than the virgin mixture. |
| Huang [59]. | Using of different ratios of RAP | The resistance to moisture damage is significantly reduced with RAP |
| Mogawer, Bennert [30] and Al-Qadi, Aurangzeb [31]. | Use (0-40)% RAP in the recycled mixture. | Resistance to moisture damage was enhanced with an increase in the RAP content in the recycled mixture. While mixtures with 40% RAP have better resistance to moisture damage than virgin mixtures. |
| Pradyumna et al., [51]. | 20% RAP mixes | Mixes made with RAP are less susceptible to moisture damage compared to the virgin mixes. |

### 8.3 Permanent Deformation

Permanent deformation or rutting is one of the critical failures occurred in asphalt pavement. Therefore, resistance to this distress is important for the asphalt concrete mixture. This test subjects the asphalt sample to a repeated dynamic load and measures its vertical-deformation. This process continues over a number of cycles or until the deformation of the sample exceeds a certain value. There are several investigations approach to study permanent deformation with the presence of RAP as shown in Table 3. One well-known approach is the implementation of repeated haversine uniaxial compression loads with a rest time between the cycles [62]. Rutting resistance can be determined in a steady height test or an accelerating pavement test simulator (track wheel) under the influence of repeated shear forces. The last technique has some benefits in that it simulates the movement of axles loading traffic on the pavement, and the rut profile is registered [63]. The uniaxial repeated load test or the so-called dynamic creep test is considered one of the most practical experiments that simulates the passage of moving traffic loads on the pavement to study the properties of permanent deformation of asphaltic materials and its ability to resist the creep under repeated load [64]. This test is performed by applying a repeated compression load in the form of haversine pulses with a load period of 0.1 s followed by a rest period 0.9 s for several thousand repetitions and recording the cumulative permanent vertical deformation and recoverable (resilient) deformation as a function of the number of cycles or time, as shown in Figure 5 [62].

Table 3 shows that with increasing RAP, the resistance of recycled mixtures to permanent deformation improves.
Table 3: Effect of using RAP on Permanent Deformation and Rutting by different studies.

| The author(s)        | % RAP         | Effect                                                                 |
|----------------------|---------------|------------------------------------------------------------------------|
| Al-Qahi,              | Two sources of RAP in four ratios (0, 30, 40, and 50%) and two-grade virgin asphalt binders were used to prepare the recycled asphalt mixtures. | The resistance to permanent deformation of recycled mixtures has improved. |
| Aurangzeb [31][61],  | Four RAP ratios in the asphalt mixture (0, 20, 40, and 100%).           | The stiffness increases with increasing RAP content, which reduces the permanent deformations and increases the flow number cycle. |
| Katicha [32]         | 30% of RAP reduces permanent deformation.                               |                                                                         |
| In 2011, MirA        | Using of bituminous mixtures of high modulus with bitumen with low penetration and high RAP (0%, 15%, 30%, and 50%). |                                                                         |
| Colbert and You [14] | (15%, 35%, and 50%) RAP with HMA                                      | The rutting resistance increases with increasing RAP ratio.             |
| Abo-Qudais,          | Using asphalt mixtures with different proportions of RAP (0, 5, 10, and 15%). | The creep strain decreased as the percentage of RAP in the mixture increased, making the recycled asphalt mixture more resistant to rutting. |
| Ibrahim [33],        | Using crumb rubber with asphalt mixture containing 40% RAP             | 40% RAP rubber asphalt mixture has better resistance to permanent deformation compared to rubber asphalt mixture without RAP under the influence of repeated loads. |
| Mogawer [34]        |                                                                           |                                                                         |
| In 2018, Arslad et al. [33] | Use RAP (15%, 25% and 35%) with HMA.                                  |                                                                 |
| Jie [68]             | 100% RAP can be mixed with virgin aggregate, stabilized by cement and fly ash, or confined with geocell to increase its strength and reduce its creep and permanent deformation. | The resistance of asphalt mixtures to permanent deformation is enhanced with an increase in the content of RAP materials. The permanent deformation is reduced in the chemically diluted RAP with an increase in the stabilizing agent content. The rate of permanent deformation decreased as the number of loading cycles increased. |
8.4 Fatigue cracking
As mentioned earlier, RAP is usually assumed to enhance the stiffness of the mixture, so resistance to fatigue cracking may be decreased by incorporating RAP into the mixture. This is one explanation of why RAP is used with softer binders when the RAP content rises from a certain value, following the results of the NCHRP study [69]. Table 4 essentially shows that using RAP improves fatigue resistance with 30% of RAP.

| The author(s) | % RAP | Effect |
|---------------|-------|--------|
| Al-Qadi, Aurangzeb [31] | Using two sources of RAP with four proportions (0, 30, 40, and 50)% and two grade of virgin asphalt binders. | Fatigue life improved slightly with the addition of RAP up to 30% and then have decreased at higher contents compared to virgin mixtures. The soft binder had a significant effect on the fatigue and stiffness properties of the recycled mixtures. |
| Chaitanyaa, Srib [35] | Use different proportions of RAP (0, 15, 25, 35, and 50%). Indirect tensile fatigue test was performed under controlled stress at 25 °C to assess the fatigue properties of virgin and recycled mixtures. | The results indicated that the fatigue performance was improved for recycled mixtures up to 35% RAP content to the virgin mixture, as fatigue life decreased thereafter due to the high stiffness resulting from the higher RAP contents. |
| Widyatmoko [24] | Use recycled mixtures with (10, 30, and 50)% of RAP produced with a softer binder, or rejuvenating agent | Better performance in the resistance to fatigue cracking compared to conventional asphalt materials. |
| Xiao and Amirkhanian [36] | Using crumb rubber found in rubberized binder and 30% RAP is added to modified asphalt mixtures. | The inclusion of crumb rubber was not an additional advantage of fatigue life when the modified mixture had a high RAP content. The presence of RAP in the modified mixtures had a significant effect on fatigue performance. |
| Amirhossein, et al. [72]. | Use of 50% to 21% RAP with HMA (a softer base binder). | It has been found that it is possible to design high-quality HMA with up to 50% RAP meeting preferred fatigue performance. The high percentage of RAP in the mixtures did not lead to a significant difference in fatigue resistance. |
| Umme et al. [73] | Beam fatigue tests were performed to investigate the fatigue behaviors of two asphalt mixes: one containing 35% RAP and the other without RAP. | An increase in the strain level leads to a decrease in the fatigue lives of both mixes and binders. Fatigue lives of binders from sweep time and LAS tests show a good correlation with the mix fatigue life. |

9. Conclusions
The main findings of this study can be summarized as follows:
1. According to previous studies that have been associated with different testing, the most important ratio of RAP is 30% which may be suitable for improving all characteristics of asphalt mix or within the lower limits of asphalt mix specifications. This percentage can be improved with other admixtures such as polymer and crumb rubber.
2. Since the RAP exceeds 30%, the resilient modulus decreases but the addition of additives such as rejuvenators and crumb rubber may improve this modulus. However, this parameter decreases with increasing temperature.
3. As for moisture susceptibility, the presence of RAP materials improves the resistances to moisture damage. At 30% of RAP, this mix with RAP is less susceptible to moisture when compared to the virgin mixes.
4. Increasing the ratio (from 10% to 50%) of RAP increases stiffness which reduces the permanent deformation.
5. Increasing the content of RAP materials in the asphalt mixture increases the resistance of the RAP asphalt mixtures to permanent deformation.
6. The addition of 30% RAP to virgin asphalt mixtures improves the resistance of the asphalt mixture to fatigue.

References

[1] Al-Humeidawi BH and Mandal P 2018 Experimental investigation on the combined effect of dowel misalignment and cyclic wheel loading on dowel bar performance in JPCP Engineering Structures 174 256-66.
[2] Al-Khuzaie MG, Al-Humeidawi BH and Ra'id F 2019 Assessment of Dowel Bars Performance in Concrete Pavement Containing Crumb Rubber of Tires Al-Qadisiyah Journal for Engineering Sciences 12 214-9.
[3] Al-Khuzaie MG, Al-Humeidawi BH and Ra'id F 2020 Assessment of Dowel Bars Performance in Concrete Pavement Containing Crumb Rubber of Tires Al-Qadisiyah Journal for Engineering Sciences 12 214-9.
[4] Copeland A 2011 Reclaimed asphalt pavement in asphalt mixtures: State of the practice.
[5] Croteau JM 2005 Performance and cost benefits of asphalt pavement recycling Semi-Annual meeting: Asphalt Recycling and Reclaiming Association (ARRA).
[6] Zhu J, Ma T and Dong Z 2020 Evaluation of optimum mixing conditions for rubberized asphalt mixture containing reclaimed asphalt pavement Construction and Building Materials 234 1-11.
[7] Daniel JS and Lachance A 2005 Mechanistic and volumetric properties of asphalt mixtures with recycled asphalt pavement Transportation research record 1929 28-36.
[8] Izsak R, Haritonovs V, Klasa I and Zamanis M 2015 Hot mix asphalt with high RAP content Procedia Engineering 114 676-84.
[9] Valdã©S G, PéRez-Jimã©N Fl, Martã©N A and Botella Rn 2011 Experimental study of recycled asphalt mixtures with high percentages of reclaimed asphalt pavement (RAP) Construction and Building Materials 25 1289-97.
[10] Colbert B and You Z 2012 The properties of asphalt binder blended with variable quantities of recycled asphalt using short term and long term aging simulations Construction and Building Materials 26 552-7.
[11] Mogawer WS, Austerman AJ, Bonaquist R and Roussel M 2011 Performance characteristics of thin-lift overlay mixtures: High reclaimed asphalt pavement content, recycled asphalt shingles, and warm-mix asphalt technology Transportation research record 2208 17-25.
[12] Tabakovič A, Gibney A, McNally C and Gilchrist MD 2010 Influence of recycled asphalt pavement on fatigue performance of asphalt concrete base courses Journal of materials in civil engineering 22 643-50.
[13] Kodippily S, Holleran G and Henning TFP 2016 Deformation and cracking performance of recycled asphalt paving mixes containing polymer-modified binder Road Materials and Pavement Design 18 425-39.
[14] Shen J, AmirKhbian S and Aune Miller J 2007 Effects of rejuvenating agents on superpave mixtures containing reclaimed asphalt pavement Journal of materials in civil engineering 19 376-84.
[15] Widyatmoko I 2008 Mechanistic-empirical mixture design for hot mix asphalt pavement recycling Construction and Building Materials 22 77-87.
[16] Notani MA, Moghadas Nejad F, Fini EH and Hajikarimi PJ JoTE, Part B: Pavements 2019 Low-temperature performance of toner-modified asphalt binder 145 04019022.
[17] Department MHAT 1982 Evaluation Of A Recycled Asphaltic Concrete Pavement Federal Highway Administration (FHWA).

[18] West RC 2015 Best practices for RAP and RAS management.

[19] Zaumanis M, Oga J, Haritonovs VJC and Materials B 2018 How to reduce reclaimed asphalt variability: A full-scale study 188 546-54.

[20] Noureldin A and Wood LEJTRR 1990 Laboratory evaluation of recycled asphalt pavement using nondestructive tests 1269 92-100.

[21] Sondag MS, Chadbourn BA and Drescher A 2002 Investigation of recycled asphalt pavement (RAP) mixtures.

[22] Xiao F 2006 Development of fatigue predictive models of rubberized asphalt concrete (RAC) containing reclaimed asphalt pavement (RAP) mixtures.

[23] Xiao F, Amirkhanian S and Juang CHJJoMICE 2007 Rutting resistance of rubberized asphalt concrete pavements containing reclaimed asphalt pavement mixtures 19 475-83.

[24] Widyatmoko I 2008 Mechanistic-empirical mixture design for hot mix asphalt pavement recycling 22 77-87.

[25] Huang B, Li G, Vukosavljevic D, Shu X and Egan BKJTRR 2005 Laboratory investigation of mixing hot-mix asphalt with reclaimed asphalt pavement 1929 37-45.

[26] Karlsson R and Isacsson UIJOccE 2006 Material-related aspects of asphalt recycling—state-of-the-art 18 81-92.

[27] Guthrie WS, Cooley D and Eggert DLJTRR 2007 Effects of reclaimed asphalt pavement on mechanical properties of base materials 2005 44-52.

[28] Schaeftl GJ and Edil TBJTRU 2007 Literature search and report on recycled asphalt pavement and recycled concrete aggregate.

[29] Al-Rousan T, Asl I, Al-Hattamleh O and Al-Qablan HJJJoCE 2008 Performance of asphalt mixes containing RAP 2 218-27.

[30] Mogawer W, Bennett T, Daniel JS, Bonaquist R, Austerman A, Booshiehrian AJRM and Design P 2012 Performance characteristics of plant produced high RAP mixtures 13 183-208.

[31] Al-Qadi IL, Aurangzeb Q, Carpenter SH, Pine WJ and Trepanier J 2012 Impact of high RAP contents on structural and performance properties of asphalt mixtures.

[32] Boriack P, Katicha SW and Flintsch GWJTRR 2014 Laboratory study on effects of high reclaimed asphalt pavement and binder content: Stiffness, fatigue resistance, and rutting resistance 2445 64-74.

[33] Abo-Qudais S, Ibrahim A, Al-Ramahi EJJoG and Engineering T 2016 Utilizing Reclaimed Asphalt Pavement in Asphalt Mixtures: Laboratory Performance and Environmental and Cost Impacts 2.

[34] Vahidi S, Mogawer WS and Booshiehrian AJJomec 2014 Effects of GTR and treated GTR on asphalt binder and high-RAP mixtures 26 721-7.

[35] Chaitanya G, Srib MR and reddyc KS 2015 Fatigue performance of bituminous mixes containing reclaimed asphalt pavement (RAP) material 3rd Conference of Transportation Research Group of India.

[36] Xiao F and Amirkhanian SN 2010 Laboratory investigation of utilizing high percentage of RAP in rubberized asphalt mixture 43 223.

[19] Hansen, K. and Copeland, A. J. (2017). Annual asphalt pavement industry survey on recycled materials and warm-Mix asphalt usage: 2016.

[20] EAPA 2011. The asphalt paving industry, a global perspective.

[21] Notani, M. A., Moghadas Nejad, F., Fini, E. H. and Hajikarimi, P. J. (2019). Low-temperature performance of toner-modified asphalt binder. 145, 04019022.

[22] Pouranian, M. R. and Shishehbor, M. J. (2019). Sustainability assessment of green asphalt mixtures: A review. 6, 73.

[23] D’Angelo, J., Harm, E., Bartoszek, J., Baumgardner, G., Corrigan, M., Cowsert, J., Harman, T., Jamshidi, M., Jones, W. & Newcomb, D. 2008. Warm-mix asphalt: European practice. United States. Federal Highway Administration. Office of Recycling Programs.
[24] Milan, A. A., Ali, A. S. and Yusoff, N. I. 2020. A Review of the Utilisation of Recycled Waste Material as an Alternative Modifier in Asphalt Mixtures. 6, 42-60.
[25] Poutikakos, L., Zaumanis, M., Cavalli, M. C., Fernandez, M. M., & Heeb, N. (2018). Sustainable Fully Recycled Asphalt Concrete.
[26] AL-Qadi, I., Elseifi, M. & Carpenter, S. 2007. Reclaimed asphalt pavement—a literature review.
[27] Oliveira, J. R., Silva, H. M., Abreu, L. P., Pereira, P. A. J. P. -S. & Sciences, B. 2012. Effect of different production conditions on the quality of hot recycled asphalt mixtures. 53, 266-275.
[28] Xiao, F., Amirkhanian, S., Shen, J., Putman, B. & Materials, B. 2009. Influences of crumb rubber size and type on reclaimed asphalt pavement (RAP) mixtures. 23, 1028-1034.
[29] Kandhal, P. S. & Mallick, R. B. J. P. S. R. B., REPORT NO. FHWA-SA-98-042, NATIONAL CENTER FOR ASPHALT TECHNOLOGY, AUNURN, AL, 1997. Pavement recycling guidelines for state and local governments.
[30] Bukowski, J. R. Guidelines for the Design of Superpave Mixtures Containing Reclaimed Asphalt Pavement (RAP). Memorandum, ETG Meeting, FHWA Superpave Mixtures Expert Task Group, San Antonio, TX, 1997.
[31] MCDANIEL, R. S. & ANDERSON, R. M. 2001. Recommended use of reclaimed asphalt pavement in the Superpave mix design method: technician's manual. National Research Council (US). Transportation Research Board.
[32] WEST, R. J. A., AL: NATIONAL CENTER FOR ASPHALT TECHNOLOGY, NCAT DRAFT REPORT 2010. Reclaimed asphalt pavement management: best practices.
[33] RATHORE, M., ZAUMANIS, M. & HARITONOVS, V. Asphalt Recycling Technologies: A Review on Limitations and Benefits. IOP Conference Series: Materials Science and Engineering, 2019. IOP Publishing, 012046.
[34] Karlsson, R. & Isacsson, U. J. J. O. M. I. C. E. 2006. Material-related aspects of asphalt recycling—state-of-the-art. 18, 81-92.
[35] Kennedy, T. W., Tam, W. O. & Solaimanian, M. J. 1998. Optimizing use of reclaimed asphalt pavement with the Superpave system. 67.
[36] Zaumanis, M. & Mallick, R. B. J. I. O. P. E. 2015. Review of very high-content reclaimed asphalt use in plant-produced pavements: state of the art. 16, 39-55.
[37] Cooley Jr, L. A., Williams, K. & Dennis, B. C. 2013. Development of laboratory mix design procedures for RAP mixes. Mississippi. Dept. of Transportation.
[38] Al-Qadi, I., Carpenter, S., Roberts, G., Ozer, H., Aurangzeb, Q., Elseifi, M. & Trepanier, J. 2009. Determination of usable residual asphalt binder in RAP. Illinois Center for Transportation (ICT).
[39] Roque, R., Yan, Y., Cocconcetti, C. & Lopp, G. 2015. Perform an investigation of the effects of increased reclaimed asphalt pavement (RAP) levels in dense graded friction courses. Florida. Dept. of Transportation. Research Center.
[40] Sondag, M. S., Chadbourn, B. A. & Drescher, A. 2002. Investigation of recycled asphalt pavement (RAP) mixes.
[41] Mihlongo, S., Abiola, O., Ndambuki, J. & Kupolati, W. Use of recycled asphalt materials for Sustainable construction and rehabilitation of roads. International conference on Biological, Civil and Environmental Engineering (BCEE-2014) March, 2014. 17-18.
[42] Shah, A., Mcdaniel, R. S., Huber, G. A. & Gallivan, V. L. J. T. R. R. 2007. Investigation of properties of plant-produced reclaimed asphalt pavement mixes. 1998, 103-111.
[43] West, R. C. 2015. Best practices for RAP and RAS management.
[44] Zaumanis, M., Oga, J., Haritonoys, V. J. C. & Materials, B. 2018. How to reduce reclaimed asphalt variability: A full-scale study. 188, 546-554.
[45] Mcdaniel, R. S., Soleymani, H., Anderson, R. M., Turner, P. & Peterson, R. J. N. W. D. 2000. Recommended use of reclaimed asphalt pavement in the Superpave mix design method. 30.
[46] Nouredin, A. & Wood, L. E. J. T. R. R. 1990. Laboratory evaluation of recycled asphalt pavement using nondestructive tests. 1269, 92-100.
[47] Bennett, T., Papp Jr, W. J., Maher, A., & Gucunski, N. (2000). Utilization of construction and demolition debris under traffic-type loading in base and subbase applications. Transportation research record, 1714(1), 33-39.
[48] Xiao, F. 2006. Development of fatigue predictive models of rubberized asphalt concrete (RAC) containing reclaimed asphalt pavement (RAP) mixes.

14
[49] Xiao, F., Amirkhanian, S. & Jiang, C. 2007. Rutting resistance of rubberized asphalt concrete pavements containing reclaimed asphalt pavement mixes. 19, 475-483.
[50] Widyanmoka, I. 2008. Mechanistic-empirical mixture design for hot mix asphalt pavement recycling. 22, 77-87.
[51] Pradyumna, T. A., Mittal, A., & Jain, P. K. (2013). Characterization of reclaimed asphalt pavement (RAP) for use in bituminous road construction. Procedia-Social and Behavioral Sciences, 104, 1149-1157.
[52] Dong, Q., & Huang, B. (2014). Laboratory evaluation on resilient modulus and rate dependencies of RAP used as unbound base material. Journal of Materials in Civil Engineering, 26(2), 379-383.
[53] Kanem, Y. N., & Al-Jumaili, M. A. (2020). Preliminary mechanical characteristics of asphalt concrete mixture containing RAP as the design of sustainable mixture. In IOP Conference Series: Materials Science and Engineering (Vol. 888, No. 1, p. 012042). IOP Publishing
[54] SOLAIMANIAN, M., HARVEY, J., TAHHORESSI, M. & TANDON, V. Test methods to predict moisture sensitivity of hot-mix asphalt pavements. Transportation research board national seminar. San Diego, California, 2003. 77-110.
[55] Huang, B., LI, G., Vukosavljevic, D., Shu, X. & Egan, B. K. J. T. R. R. 2005. Laboratory investigation of mixing hot-mix asphalt with reclaimed asphalt pavement. 1929, 37-45.
[56] Guthrie, W. S., Cooley, D. & Eggett, D. L. J. T. R. R. 2007. Effects of reclaimed asphalt pavement on mechanical properties of base materials, 2005, 44-52.
[57] SCHAERL, G. J. & EDIL, T. B. J. T.-R. U. M., MN/DOT CONTRACT 2009. Literature search and report on recycled asphalt pavement and recycled concrete aggregate.
[58] AL-Rousan, T., Asi, I. AL-Hattamleh, O. & AL-Qablan, H. J. J. O. C. E. 2008. Performance of asphalt mixes containing RAP. 2, 218-227.
[59] Huang, B., Shu, X., & Vukosavljevic, D. (2010). Laboratory investigation of cracking resistance of hot-mix asphalt field mixtures containing screened reclaimed asphalt pavement. Journal of Materials in Civil Engineering. Vol 23, No.11, pp.1535-1543.
[60] Mogawer, W., Bennett, T., Daniel, J. S., Bonaquist, R., Austerman, A., Booshehrian, A. J. R. M. & Design, P. 2012. Performance characteristics of plant produced high RAP mixtures. 13, 183-208.
[61] AL-Qadi, I., Aurangzeb, Q., Carpenter, S., Pine, W. & Trepianer, J. 2012. Impact of high RAP contents on structural and performance properties of asphalt mixtures.
[62] Witzczak, M. 2005. Simple performance tests: Summary of recommended methods and database, Transportation Research Board.
[63] Fontes, L., Triches, G., Pais, J., Pereira, P. & Materials, B. 2010. Evaluating permanent deformation in asphalt rubber mixtures. 24, 1193-1200.
[64] Mashaan, N. S. & Karim, M. R. (2013). Evaluation of permanent deformation of CRM-reinforced SMA and its correlation with dynamic stiffness and dynamic creep. 2013.
[65] Boriack, P., Katicha, S. W., & Flintsch, G. W. (2014). Laboratory study on effects of high reclaimed asphalt pavement and binder content: Stiffness, fatigue resistance, and rutting resistance. Transportation Research Record, 2445(1), 64-74.
[66] Abo-Qudais, S., Ibrahim, A., & Al-Ramahi, E. Utilizing Reclaimed Asphalt Pavement in Asphalt Mixtures: Laboratory Performance and Environmental and Cost Impacts. Journal of Geotechnical and Transportation Engineering, 2(1).
[67] Vahidi, S., Mogawer, W. S., & Booshehrian, A. (2014). Effects of GTR and treated GTR on asphalt binder and high-RAP mixes. Journal of materials in civil engineering, 28(4), 721-727.
[68] Jitendra K. Thakur & Jie Han (2015). Recent Development of Recycled Asphalt Pavement (RAP) Bases Treated for Roadway Applications. Transp. Infrastructure. Geotech. Vol 2:68–86
[69] West, R. C., Willis, J. R. & Marasteau, M. O. (2013). Improved mix design, evaluation, and materials management practices for hot mix asphalt with high reclaimed asphalt pavement content, Transportation Research Board.
[70] Chaitanya, G., Srib, M. R. & Reddy, K. S. (2015). Fatigue performance of bituminous mixes containing reclaimed asphalt pavement (RAP) material. 3rd Conference of Transportation Research Group of India. India.
[71] Xiao, F. & Amirkhanian, S. (2010). Laboratory investigation of utilizing high percentage of RAP in rubberized asphalt mixture. 43, 223.
[72] Amirmohsenin N., Mohammdazrae S., Richard, K. Y. (2014). Evaluation of the Fatigue Performance of High RAP Asphalt Mixtures . Journal of Taylor and Francis Group , pp 1069-1077.
[73] Umme A. M., Md R. L., Rafiqul A. T. (2015). Effects of recycled asphalt pavements on the fatigue life of asphalt under different strain levels and loading frequencies. International Journal of Fatigue vol. 78 pp 72–80
