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Review Article

Long-term performance of recycled asphalt mixtures containing high RAP and RAS

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HIGHLIGHTS

- The existing literatures on long-term performance of recycled asphalt mixtures containing high RAP and RAS are summarized.
- A critical comparison of durability between high RAP/RAS recycled mixtures and conventional asphalt mixtures is provided.
- Laboratory testing methods for better understanding of long-term performance of recycled asphalt materials are introduced.
- Insights into the effects of recycling agents on enhancing the performance of recycled asphalt mixtures are offered.
- Field data collection provides empirical evidence on the long-term viability of high recycled asphalt mixtures featured.

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ABSTRACT

The application of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) on asphalt pavement can reduce the asphalt paving cost, conserve energy and protect the environment. However, the use of high contents of RAP and RAS in asphalt pavement may lead to durability issues, especially the fatigue cracking and thermal cracking. It is necessary to conduct a series of analyses on asphalt mixtures containing high RAP and RAS, and seek methods to enhance their long-term performance. This paper provides a comprehensive over-view of the long-term performance of recycled asphalt mixtures containing high contents of RAP and RAS. The findings in this research show that rutting resistance of high recycled asphalt mixtures is not a concern, whereas their resistance to fatigue and thermal cracking is not conclusive. Recycling agents can be used to improve the thermal cracking resistance of high recycled asphalt mixtures. An optimum decision on recycling agents will improve the durability properties of high recycled asphalt mixtures. It is recommended that to use a balanced mixture design approach with testing of the blended asphalt binders will provide better understanding of long-term performance of recycled asphalt mixtures containing high RAP and RAS.

1. Introduction

1.1. Background

According to the U.S. government's World Factbook, there are over 20 million miles (over 33 million kilometers) of paved and unpaved roads in use worldwide today. In China, the mileage of asphalt pavement construction has exceeded 1.5 million kilometers. The paved roads and highways surfaced with asphalt concrete has more than 4.0 million kilometers in the United States. To maintain the service performance of those asphalt pavements, a regular maintenance and periodic rehabilitation/reconstruction needs to be conducted. The maintenance and rehabilitation/reconstruction requires to consume fresh asphalt binder and mineral aggregate. Therefore, there is growing interest in the use of RAP and RAS materials in the asphalt pavement production, which can help to preserve nonrenewable resources. It was reported in the FHWA's

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pavement industry survey that the average RAP content in recycled asphalt mixtures had increased from 15.6% in 2009 to 20.4% in 2014. The average RAS percentage had increased nearly 180% during the same period (Hansen and Copeland, 2014). In 2021, the pavement industry survey conducted by NAPA reported that the average RAP content in recycled asphalt mixtures had increased to 22%, which indicating an increasing interest in using RAP. In 2021, the asphalt industry utilized 85.3 million tonnes of RAP, leading to the conservation of around 4134 million liters of asphalt binder and the replacement of over 80.3 million tonnes of new aggregate. Additionally, the use of 613,360 tonnes of RAS contributed to significant cost savings, estimated to exceed $3.5 billion.

While protecting the environment is a primary concern, employing recycled asphalt mixtures containing RAP/RAS also offers the significant benefit of reducing asphalt paving costs (Feng et al., 2022; Sharma et al., 2022). The ascent in asphalt binder prices during the mid-1970s prompted the introduction of RAP in hot-mix asphalt (HMA) within the asphalt industry. Incorporating high levels of RAP into new asphalt mixtures presents challenges, particularly in assessing the blending effectiveness of recycling agents (RAs) with both aged and new asphalt binders. Furthermore, high RAP content can lead to diminished resistance to low-temperature cracking, as the aged binder in RAP tends to be more brittle. However, a comprehensive understanding of performance remains elusive. Research projects on evaluating performance of recycled asphalt mixtures containing RAP and RAS have been performed (Copeland, 2011; McDaniel and Anderson, 2001; West et al., 2013). Due to the ambiguity surrounding the long-term performance of these recycled mixtures, usage limits were often set based on factors like plant production capacity or anecdotal engineering experience, rather than robust scientific investigation. It was reported in the NCHRP Synthesis 495 that very few agencies use long-term aging procedure for performance evaluation (Stroup-Gardiner, 2016). This points to a pressing concern regarding the durability of recycled asphalt mixtures that incorporate RAP/RAS.

Furthermore, there exists the potential to use high contents of RAP and RAS in recycled asphalt mixtures without adversely affecting pavement performance. The amount of asphalt binder that can be substituted with RAP and RAS in these mixtures is notable (Bahia et al., 2020). Typically, RAP materials contain an average of around 4% aged asphalt binder, while RAS materials have between 18% and 32%. When the RAP content in a recycled asphalt mixture is increased from 15% to 40%, the conservation of fresh binder rises from 10% to 30%. A similar conservation rate is observed when the RAS content in the mixture is augmented from 2% to 5% (Robinette and Epps, 2010). While numerous studies have indicated that using elevated amounts of RAP and RAS in recycled asphalt mixtures can increase stiffness and potentially induce cracking (Hajj et al., 2012; Li et al., 2008; McDaniel et al., 2012; Stroup-Gardiner and Wagner, 1999), more recent research suggests that recycling agents can counteract the effects of the aged binders from RAP and RAS, thereby enhancing the performance of the recycled asphalt mixture (Epps et al., 2020; Reinke et al., 2017; Tran et al., 2012).

Recycling agents, including softening agents and rejuvenators, can reduce the stiffness and improve cracking resistance of recycled asphalt mixture. Softening agents such as asphalt flux oil, lube stock, and slurry oil, alter the viscosity of the aged asphalt binders found in RAP and RAS. On the other hand, rejuvenators aim to restore the chemical compositions and physical properties of these aged binders. Rejuvenators often contain lubricating oil extracts and extender oils, which have a high proportion of maltene constituents. These components are instrumental in rejuvenating the composition of the aged asphalt binders. Nonetheless, there remains a lack of information regarding the ideal type and dosage of recycling agents for various sources and contents of RAP and RAS. Furthermore, a standardized laboratory testing method to assess the performance of recycled asphalt mixtures containing these recycling agents remains undetermined.

Most damage to pavement performance manifests only after a long-term service of asphalt pavement. Throughout this service period, the properties of the binder undergo alterations due to factors like aging, moisture damage, and significant temperature fluctuations. Consequently, it's the properties of these aged asphalt binders that predominantly dictate their susceptibility to damage. For a comprehensive assessment of the durability of an asphalt mixture tailored to specific applications, it's imperative to understand how these binder properties evolve over time (Bahia and Anderson, 1995; Qin et al., 2014). However, much of our current understanding of the properties of blended asphalt binders and the performance of recycled asphalt mixtures hinges on limited aging procedures and small strain tests. Characterizations at longer aging terms and larger strain levels are very important to assess stiffness, cracking issues, and durability of recycled asphalt mixtures with various contents of RAP and RAS (Cavalli et al., 2018; Kilger et al., 2019).

To confidently use higher contents of RAP and RAS in recycled asphalt mixtures, further investigations are essential to fill the gap regarding durability of the recycled asphalt mixtures, especially when using recycling agents.

1.2. Objective

It is important to understand the long-term performance of recycled asphalt mixtures containing RAP and RAS. Engineers require this information to confidently increase RAP and RAS contents in the design and evaluation of recycled asphalt mixtures. In light of this, this paper offers a comprehensive review of the existing literature on the long-term performance of such mixtures, especially those with high contents of RAP and RAS. The insights from this review will guide the selection of appropriate recycling agents and laboratory testing methods for recycled asphalt mixtures. This paper is structured as follows.

- Asphalt binder aging in mixture and laboratory simulation.
- Properties of recycled asphalt mixtures.
- Research methods for recycled asphalt materials.
- Recycling agents for high RAP/RAS mixtures.
- Field data on pavement performance of recycled asphalt mixtures.

2. Asphalt binder aging in mixture and laboratory aging simulation

2.1. Aging of asphalt binder in mixture

The physical and rheological properties of the asphalt binder in pavement changed due to exposure to elements such as oxygen, UV light and extreme temperatures in the field (Bishara and McReynolds, 1996; Lu and Ulf, 2002; Marasteanu and Arindam, 2004). Such exposure, especially oxidation, results in the binder becoming stiffer and more brittle (Zupanick, 1994). Such exposure, especially oxidation, results in the binder becoming stiffer and more brittle (Asi et al., 1997; Jennings et al., 1980). Since RAP and RAS are highly aged materials, their aged asphalt binders can lead to significant fatigue and thermal cracking in pavements during their service life (Boriack et al., 2014; Hajj et al., 2009; West et al., 2009). Thus, it's essential to evaluate the performance of blended binders before incorporating them into recycled asphalt mixtures.

Both the binder composition and interactions with mixture design (e.g., gradation, and voids content) affect the aging rate of asphalt binder in the mixture. Furthermore, literature suggests that the climatic conditions of the pavement location and the source or mineralogy of the aggregates can impact the property changes of asphalt mixtures (Moraes, 2014). The changes of physical and rheological properties of asphalt binder in pavement production are due to two phases of aging: loss of volatile components and oxidation of asphalt binder during mixture production and construction stage with high temperatures, which is called short-term aging (STA); and in-field oxidation at ambient pavement temperatures, which called long-term aging (LTA) (Bell et al., 1994). Besides, researchers also found that the interaction between mineral aggregate and asphalt binder also significantly changes aging rate of asphalt binder (Moraes, 2014). It is generally agreed that pavement performance at high temperature range is benefit from the aging of asphalt binder, while pavement performance at intermediate and low temperature ranges are detrimentally affects by the binder aging.

Recent studies have employed dynamic shear rheometer (DSR) tests to analyze the rheological parameters of aged asphalt binders. Microstructure tests, including SEM and AFM, have established the relationship between viscosity, rheological properties and intermolecular forces in reclaimed asphalt binder (Lin et al., 2022). Notably, research found a "bee-like structure" in reclaimed asphalt binders, a microstructure that can be rejuvenated after adding a rejuvenator. This suggests that rejuvenators may dissolve and repair asphaltenes, thereby restoring the damaged "bee-like structure" of aged asphalt binders.

With increasing RAP and RAS binder content in recycled asphalt mixtures, there is growing emphasis on using recycling agents in the recycled asphalt mixtures to enhance their fatigue resistance and reduce thermal cracking. Yet, limited research has probed the long-term performance impacts of these recycling agents. The rejuvenation mechanisms in recycled asphalt mixtures, which are complex blends of virgin binder, aged binder, recycling agents, aggregates, and dust, remain poorly understood. Tran et al. (2012) reported that rejuvenating mechanism can be explained by the dispersion and diffusion of recycling agents in the recycled asphalt mixtures. However, the diffusion rate depends on not only types and dosages of recycling agents but also time and temperature during the interaction. As such, further studies are needed to understand the effects of aging on recycled asphalt mixtures containing recycling agents.

2.2. Laboratory aging of asphalt mixture

Laboratory testing protocols for investigating the effects of aging on pavement performance of asphalt mixtures is an ongoing research topic. The NCHRP 09-52 project, "Short-Term Laboratory Conditioning of Asphalt Mixtures" introduced predictive methods for assessing short-term aging (Newcomb et al., 2015). In contrast, the NCHRP 09-54 project "Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction" proposed methods for simulating long-term aging (Kim et al., 2018). The objective of WHRP 17-04 project (Bahia, et al., 2018) aims to determine the method that best predicts both short- and long-term aging of asphalt mixtures produced in the field.

Three mixture aging conditions were designed in WHRP 17-04 project. For short-term aging (STA), asphalt mixtures were heated to 135 °C and kept in the oven for 2 h. For long-term aging (LTA), asphalt mixtures were heated to 135 °C and kept in the oven for 6 h (LTA-6), and 14 h (LTA-14). In that study, effect of softening oils on performance of asphalt mixtures after aging was also investigated. The six asphalt mixtures with softening oils were compared to two normal mixtures with no oils. The main findings are shown below.

- Flexibility index (FI) is very sensitive to aging extent of asphalt mixtures and magnitude of FI parameter mainly depends on the post-peak slope during test.
- An obvious distinction of FI values between the STA and LTA-6 mixtures can be found. Therefore, it was recommended to use FI parameter to determine fatigue performance of asphalt mixtures after the short-term (2 h) and long-term (6 h) oven aging.
- The asphalt mixtures with re-refined engine oil bottom (REOB) showed the lowest FI values at three aging levels. The asphalt mixtures with bio-oils showed better fatigue performance after aging when compared to other mixtures.
- It is too severe for laboratory aging of asphalt mixtures by using 14 h aging (LTA-14) since it is not suitable to distinguish between various asphalt mixtures.

3. Properties of recycled asphalt mixtures

Many states in the United States permit the utilization of recycled asphalt mixtures with low RAP/RAS contents (RAP at a limit of 20%–25%, RAS around 5%) in surface course of asphalt pavement. The recycled asphalt mixtures with limited RAP/RAS have showed promising performance with sufficient scientific evidence. These mixtures, with limited RAP/RAS content, have demonstrated commendable performance, backed by robust scientific evidence and extensive field project experience. The FHWA specification recommends that RAP content in recycled asphalt mixtures should not exceed approximately 20% to guarantee asphalt pavement's enduring performance. According to the AASHTO M323 specification, when the rap content remains below 15%, one can choose the fresh asphalt binder without accounting for the addition of aged RAP binder. However, for mixtures incorporating 15%–25% RAP, the selected virgin binder should be a grade (using PG grading) softer than typically designed. Furthermore, an investigation on the use of RAP in asphalt pavement published in 2011 (Copeland, 2011) has compared the virgin mixtures and recycled asphalt mixtures containing up to 30% RAP from 18 practice projects. Remarkably, the recycled mixtures showcased equal or superior performance to virgin mixtures in various pavement attributes, including permanent deformation, cracking resistance, and raveling, in most projects that spanned 6–17 years of field service.

In one of NCAT's reports, successful experience on the use of RAP and RAS in recycled asphalt mixtures from several states has been summarized (West and Willis, 2014). It was highlighted that over 75% of asphalt mixtures produced for Florida DOT pavement projects contain RAP, with an average content of 22%. Those recycled asphalt mixtures containing RAP perform very well. The Minnesota DOT has more than 30 years' experience in maintaining RAP usage within the standard specifications for asphalt pavement design (Kuehl et al., 2016). The maximum content of RAP that local agencies are confident in applying in recycled asphalt mixtures is 30%. These lead to more attention on recycled asphalt mixtures containing higher contents of RAP and a combination of RAP and RAS together.

In the following sections, the rutting resistance, fatigue and thermal cracking of the recycled asphalt mixtures containing higher contents of RAP/RAS from literatures will be introduced.

3.1. Rutting resistance of recycled asphalt mixtures

Since aged binders typically have a higher stiffness, one would expect that the inclusion of RAP/RAS materials would enhance the rutting resistance of recycled asphalt mixtures. The NCHRP 9-46 project (West et al., 2013) investigated the long-term performance of recycled asphalt mixtures containing high RAP contents (between 25% and 50%). These mix designs utilized various RAP sources and virgin binders. The results showed that high RAP contents increased the dynamic modulus of the recycled asphalt mixtures. The study found that increased RAP content boosted the dynamic modulus of the recycled asphalt mixtures, thereby improving their rutting resistance. As a result, it is suggested that rutting resistance tests may not be necessary for such mixtures unless a recycling agent or a softer virgin binder is incorporated.

The improved rutting resistance of recycled asphalt mixtures high RAP/RAS content has been consistently confirmed by various studies. A study from Iowa (Lee et al., 2015) evaluated pavement test sections containing 30%, 35%, and 40% RAP using the Hamburg Wheel Tracking test. All tested mixtures exhibited rut depths of less than 3 mm, highlighting excellent rutting resistance. Other research findings (Al-Qadi et al., 2012; Williams et al., 2013) have also showed that rutting resistance of recycled asphalt mixtures containing higher RAP/RAS contents would be potentially improved. The newly completed NCHRP 9-58 project (Epps et al., 2020) was conducted to investigate the use recycling agents in recycled asphalt mixtures containing high RAP and RAS binder ratios. Their findings suggest that high RAP/RAS mixtures generally didn't experience rutting issues unless substantial amounts of recycling agents were added. However, fatigue and thermal cracking resistance remain concerns for such mixtures, given the brittleness of aged binders.

At the binder level, Zhou et al. (2019) used multiple stress creep recovery (MSCR) and linear amplitude sweep (LAS) test to examine the rutting and fatigue performance of blended binder with aged asphalt from RAP. The results indicated that RAP blended binder can improve the rutting performance through the J_{nr} parameter while the addition of RAP binder can lead to fatigue performance issue. Zhao et al. (2022) investigated the rutting and strain characteristics for rubberized asphalt rejuvenated reclaimed (RARR) asphalt pavement by adopting accelerated pavement tester (APT). The rutting resistance and strain recovery property of RARR was better than that of normal SBS modified AC and SMA pavement. Another study on rutting of recycled asphalt mixtures showed similar findings (Moghadas et al., 2014). In that study, Marshall tests and dynamic creep tests were performed to assess the impact of RAP on rutting resistance of HMA. The results showed that replacing up to 60% of the virgin aggregate with RAP materials improved rutting performance due to its high viscosity.

3.2. *Fatigue performance of recycled asphalt mixtures*

Fatigue performance at intermediate temperatures directly influences the asphalt pavement's susceptibility to alligator cracking. Given the strain sensitivity of aged asphalt binders, pavements tend to develop fatigue cracking after enduring years of traffic and environmental stress. Commonly, recycled asphalt mixtures with RAP/RAS content are anticipated to exhibit reduced fatigue performance. However, results from several state research initiatives present contrasting findings on this topic. McDaniel et al. (2011) assessed the fatigue performance of PG 58-58 and PG 64-22 mixtures incorporating 15%, 25%, and 40% RAP sourced from field projects. Among these, the PG 64-22 mixture outperformed the PG 58-28 variant. Interestingly, when 25% RAP was introduced, the PG 58-28 mixture displayed a more extended fatigue life than its PG 64-22 counterpart with the same RAP content, hinting that a softer binder might offer better fatigue resistance. This presents a contradiction in the fatigue performance results for the PG 64-22 and PG 58-28 mixtures containing 25% and 40% RAP. However, regardless of the virgin binder's PG grade, all recycled mixtures with 25% and 40% RAP demonstrated an enhanced fatigue life compared to mixtures without any RAP.

Another research project from Oklahoma DOT showed similar findings (Ghabchi et al., 2015). The research evaluated the fatigue performance of recycled asphalt mixtures containing varied quantities of RAS and RAP using four-point bending beam and cyclic direct tension tests. Eight types of recycled asphalt mixtures for surface course were investigated. Those mixtures were produced with two virgin binders (i.e., PG 64-22 and PG 70-28). It was founded that the recycled asphalt mixtures with a PG 64-22 binder showed improved fatigue performance with 30% RAP or a blend of RAP and RAS compared to the control mixture. The maximum increase in fatigue life was found at the recycled asphalt mixtures containing 5% RAP and 5% RAS together. However, it's noteworthy that mixtures incorporating 6% RAS demonstrated a shorter fatigue life than their virgin counterparts. Furthermore, mixtures with the PG 70-28 binder consistently registered a decline in fatigue life, irrespective of the RAP and/or RAS content. These results underscore the significant role virgin binders play in influencing the fatigue performance of recycled asphalt mixtures.

The transportation pooled fund (TPF) program TPF-5 (213) (Williams et al., 2013) was performed by a partnership group of several state agencies to investigate the effects of RAS on the pavement performance of HMA mixtures. The participated agencies include California, Missouri, Wisconsin, Minnesota, Colorado, Iowa, Illinois, Indiana, and the Federal Highway Administration. The flow number tests and four-point beam fatigue tests were performed on plant-produced mixtures from several practice projects. Laboratory test results showed that the recycled asphalt mixtures with RAS had good rutting resistance and fatigue performance. Pavement condition surveys were conducted on test sections for each project. The survey findings of pavement condition after two-year service were in line with the laboratory test results.

The fracture energy is intricately linked to the fatigue performance of mixtures containing recycled materials, particularly when considering performance under low-temperature conditions. Fracture energy reflects a material's resistance to crack propagation. Under fatigue loading, especially in low-temperature environments, materials may undergo multiple cycles of crack extension and contraction. Higher fracture energy may indicate a greater ability to resist crack propagation, contributing to improved fatigue performance. According to numerous studies (Al-Qadi et al., 2015; Bahia et al., 2016; West et al., 2013) indicated that recycled asphalt mixtures with high RAP contents often exhibited lower fracture energies at intermediate temperatures compared to control mixtures. This suggests a heightened vulnerability to fatigue cracking. It was also reported that the fatigue performance of RAS mixtures is poorer than the RAP mixtures due to the stiffer binder in RAS material (Foxlow et al., 2011). West (2019) employed indirect tension tests at a temperature of 10 °C to investigate the fatigue performance of four recycled asphalt mixtures containing 25%–50% RAP. The average fracture energy results showed that the virgin mixtures had better fatigue performance than recycled asphalt mixtures containing RAP. The 55% RAP mixtures had slightly higher fracture energy results than the 25% RAP mixture. To minimize the risk of pavement cracking at long-term period, careful attention should be taken for selecting the virgin binder grade of recycled asphalt mixtures with high RAP contents.

In another study, Al-Qadi et al. (2015) developed tests and specifications targeting recycled asphalt mixtures with high RAP and RAS contents. Their results indicated that an increase in RAP and RAS contents reduced the flexibility index (FI), pointing to a more brittle nature of recycled asphalt mixtures (Fig. 1). Furthermore, using both the semi-circular bend (SCB) tests and the accelerated loading facility (ALF) tests, they observed a strong correlation between the performance rankings of recycled asphalt mixtures. The ALF tests specifically highlighted the potentially adverse effects of high binder replacement levels (up to 40%) on fatigue performance, especially when excessive RAS contents (6%) were introduced.

In the NCHRP Project 9-57 (Zhou et al., 2016) the performance tests to eliminate brittle asphalt mixtures were summarized and compared. Since asphalt mix designs become more complex due to the addition of

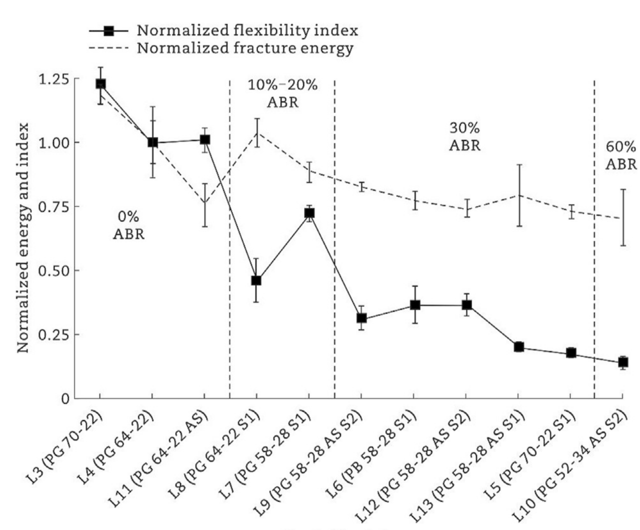

Fig. 1. Normalized fracture energy and flexibility index for laboratory produced recycled asphalt mixtures (Al-Qadi et al., 2015).

binder modifiers, recycled materials, and recycling agents, there is an urgent need to establish reliable test methods and specifications in a national level. The conflicting findings on fatigue performance of recycled asphalt mixtures containing high contents of RAP and RAS illustrate that more attentions should be given to fatigue cracking resistance of recycled asphalt mixtures.

3.3. Thermal cracking of recycled asphalt mixtures

The introduction of RAP and RAS, replacing virgin binder with aged binders, is anticipated to elevate the thermal cracking potential of asphalt mixtures. Common methods to assess the thermal cracking resistance of asphalt mixtures include the indirect tensile (IDT), semi-circular bend (SCB) and disc-shaped compact tension (DCT) tests. The increase of fracture energy at PG low temperatures indicates an improved thermal cracking resistance. In a national pooled fund research program centered on thermal cracking in asphalt pavements (Marasteanu et al., 2012), 11 asphalt mixtures collected from pavement test sections at Olmsted County (Minnesota) were measured by using the SCB and DCT tests. Both the results showed a similar range of fracture energy values, which were approximately between 170 J/m^2 and 380 J/m^2. In general, the performance ranking of tested mixtures according to the DCT and SCB results were in good agreement. The fracture energy measured by DCT tests showed a significant decrease when RAP was added. The SCB fracture energy showed a similar trend. On the contrary, the toughness results determined from the SCB tests indicates that adding RAP increased the fracture strength and toughness of the recycled asphalt mixture.

Johnson et al. (2013) found that the MnROAD field asphalt mixtures containing 0, 20%, 30% RAP had distinct fracture energies. Mixtures with elevated RAP contents displayed a higher susceptibility to fracturing. This finding was further corroborated by another study by Johnson, focusing on the fracture energy of mixtures containing RAP. The recycled asphalt mixtures containing higher contents of RAP (25%, 40%, and 55%) were measured by using the SCB tests. The results (Fig. 2) showed that the recycled asphalt mixtures with RAP had lower fracture energy compared to the control mixtures without RAP. Generally, the 50% RAP mixtures had the most reduced thermal cracking performance, in particular at the lower temperatures.

The negative impact of high RAP contents on the thermal cracking of recycled asphalt mixtures have also been reported by other researchers. Mensching et al. (2014) investigated the low-temperature cracking performance of mixtures produced in plants with varying RAP contents. IDT test results revealed that incorporating RAP enhanced the tensile strength of the recycled asphalt mixtures. However, mixtures with higher RAP concentrations exhibited elevated critical cracking temperatures, signaling a heightened vulnerability to thermal cracking due to the accelerated onset of thermal stress. It was also observed that the degree of binder blending played a role in improving the low-temperature cracking performance, particularly when softer grade binders were utilized. Lee et al. (2015) conducted SCB tests on mixtures containing 30%–40% RAP, with temperatures set at −18 °C and −30 °C. Their findings indicated that as the RAP content increased, the stiffness of the recycled asphalt mixtures rose, while their fracture energies declined. In the WHRP Project 0092-15-04 (Bahia et al., 2016), DCT tests were utilized to assess the fracture energy of recycled asphalt mixtures across various RAP contents and binder replacement ratios. The analysis revealed that mixtures with a 50% binder replacement ratio had lower fracture energy than those with a 15% binder replacement ratio.

Several researchers have observed that the fracture energy does not consistently decrease with the incorporation of RAP and RAS. For instance, the NCHRP Project 09-46 (West et al., 2013) highlighted that introducing up to 55% RAP did not lead to a significant alteration in the SCB fracture energy, as long as an appropriate grade of virgin binder was used. Such mixtures with high RAP content typically exhibited superior fracture toughness in comparison to their virgin counterparts. Similarly, Williams et al. (2013) found that the SCB fracture energies of recycled asphalt mixtures with RAS remained statistically consistent with virgin mixtures devoid of RAS across various state projects. Tang (2014) also used the SCB fracture energy parameter to determine the thermal cracking performance of recycled asphalt mixtures containing 30%, 40% and 50% of RAP. The fracture energy results did not show a good correlation with the increase of RAP contents. Furthermore, Al-Qadi et al. (2015) noted that the recycled asphalt mixtures containing different contents of RAP (30%–50%) showed no significant difference in the SCB fracture energies.

Stimilli's research showed that a recycled asphalt mixture with 40% RAP exhibited superior relaxation capabilities compared to a control mixture containing 25% RAP (Stimilli et al., 2018). Specifically, the mixture with 40% RAP was more effective in dissipating thermal stresses than its 25% RAP counterpart, suggesting it could potentially delay the onset of cracks at colder temperatures. Some research has reported that bio-asphalt binder can improve the low-temperature cracking resistance of asphalt mixtures (You et al., 2012). With an addition of 10% bio-asphalt binder, the critical cracking temperature of PG 64-22 binder showed a reduction of 4.6 °C–4.9 °C. It is recommended that the bio-asphalt binder may improve low-temperature performance of recycled asphalt mixtures with RAP. Ma et al. (2016) evaluated the thermal cracking resistance of recycled asphalt mixtures with various RAP

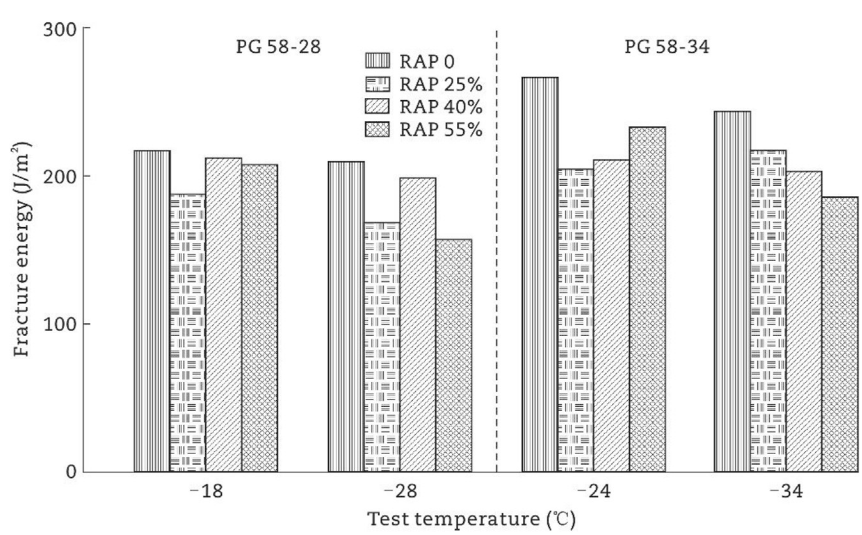

Fig. 2. SCB fracture energy of recycled asphalt mixtures with high RAP contents.

contents (20%–60%) through three-point bending tests. The results showed that increasing RAP content would decreased the low-temperature fracture strain of recycled asphalt mixtures (Fig. 3).

4. Research methods for recycled asphalt materials

4.1. Testing properties of blended asphalt binder

The NCHRP 09-12 project (McDaniel and Anderson, 2001) validated the concept of employing the linear blending charts to estimate the properties of blended asphalt binders that contain RAP binder. As recommended in AASHTO M323, when the RAP content ranges between 15% and 25%, it is advisable to select virgin binder that is one grade softer than normal binder. For RAP content exceeding 25%, linear blending charts should guide the selection of the virgin binder grade. However, as the increased use of binder modifiers and RAP binders, the effectiveness of linear blending charts is being questioned. Bonaquist (2011) observed that the blending chart for the binder's m-value becomes non-linear when the binder replacement level from RAS hits 30%. Additionally, the Transportation Pooled Fund Project TPF-5 found that the blending charts for binder properties measured by + PG + test methods (e.g., Multiple Stress Creep and Recovery) did not show linearity (Swiertz et al., 2019). Based on these findings, there's a recommendation to directly test blended asphalt binders to better characterize binder performance.

Many researchers have conducted DSR and BBR tests on blended asphalt binders to estimate the effects of RAP/RAS on performance of recycled asphalt mixture. Williams et al. (2013) found that introducing RAS binder increases both the high and low PG temperature grades of blended asphalt binders. Their average results revealed that adding 1% RAS binder elevates the low-temperature grade of the virgin binder by 1.9 °C, while a 1% addition of RAP binder results in a 0.3 °C increase. Lee et al. (2015) found that the addition of 30%, 35%, and 40% RAP stiffened the PG 64-28 virgin binder to PG 76-22, PG 76-16, and PG 82-16, based on the rheological properties of extracted binders from field mixtures. The recycled asphalt mixtures containing RAP showed a decrease of SCB fracture energy at low temperatures. Even though the binder testing results can help to determine low temperature properties of blended asphalt binders and the binder properties have certain correlation with the performance of recycled asphalt mixture. The impacts of RAP/RAS on mixture performance still uncertain, especially for low-temperature cracking resistance.

Foxlow et al. (2011) evaluated the performance of laboratory-prepared recycled asphalt mixtures containing RAP and RAS, as well as their respective recovered binders. Mixture tests revealed that the RAP mixture was stiffer than the three RAS mixtures, as evidenced by its higher dynamic modulus. However, all four recycled asphalt mixtures demonstrated similar low-temperature cracking resistance, as indicated by their failure temperature test results. In contrast, at high temperatures, the complex shear modulus of the recovered binders from the RAS mixtures exceeded that of the binder recovered from the RAP mixture. Moreover, the critical cracking temperatures of binders from the three RAS mixtures were lower than that of the RAP mixture's binder, suggesting superior low-temperature cracking resistance for the former. Interestingly, the findings from the mixture tests and binder assessments were not consistent.

In 2007, the Virginia DOT introduced a pavement design specification which allows to use up to 30% RAP in specified dense-graded asphalt mixtures for the surface course. This allowed the grade of virgin binder to be adjusted according to requirements. Nearly seven years later, a study evaluated the field performance of recycled asphalt mixtures produced following this specification (Diefenderfer et al., 2018). The study involved both field visits and laboratory evaluations of recycled asphalt mixtures from 23 operational pavements. All these mixtures had undergone initial laboratory evaluations, enabling the researchers to compare the performance data from the in-service pavements with the original laboratory test data. A notable finding was that, irrespective of the RAP content in the recycled asphalt mixtures, the binders from field cores after 6 years of service showed an elevation of one to two high-temperature grades compared to those collected at the time of construction. A similar trend emerged for the low-temperature grades. Additionally, the relationships between RAP content and low-temperature performance metrics (like continuous PG grade, stiffness, and *m*-value) were analyzed. This analysis suggested that the aging of binders in recycled asphalt mixtures was not influenced by the RAP content used.

In recent years, microscopic techniques have been employed to assess the blending degree between RAP binder and virgin binder. Jiang et al. (2019) carried out experiment of scanning electron microscope/energy dispersive spectrometer (SEM-EDS). The SEM-EDS images showed the partial blending in high RAP mixtures. The results indicated that with the increase of RAP content, the blending degree of virgin and aged asphalt binder decreased rapidly. The study also emphasized the necessity for adequate reaction time to facilitate the inter-diffusion between the aged and new asphalt binders. Li et al. (2022) applied Fourier transform infrared spectrometer (FTIR) to quantify the mobilization rate of aged asphalt binder and virgin binder. They further developed a blending chart that correlated RAP binder content with the carboxyl index (CI) of the blended binder, offering a method to gauge the blending efficiency

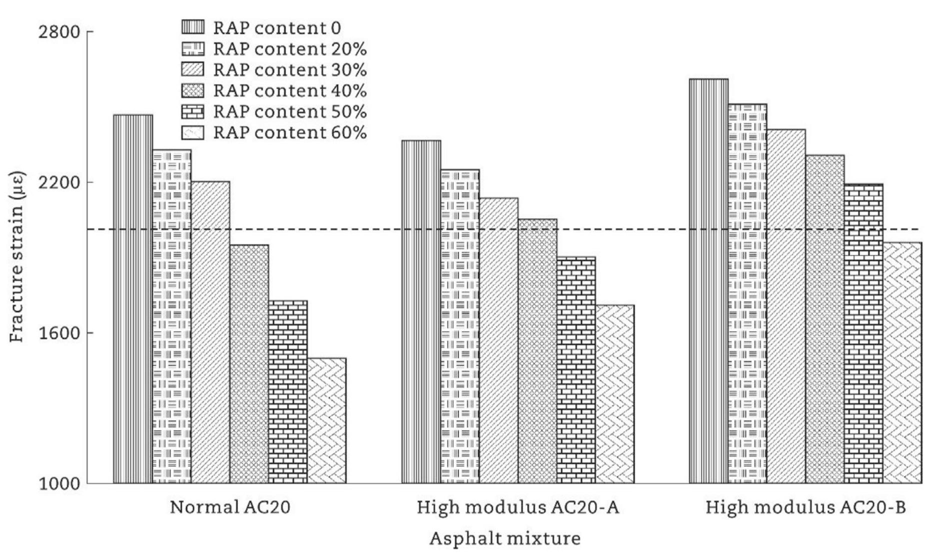

Fig. 3. Test results for thermal cracking resistance evaluation (Ma et al., 2016).

between RAP and virgin binders. There is a linear relationship between CI value and RAP binder content (α), expressed by Eq. (1).

$$CI = 0.0316\alpha + 4.76E{-5} \quad R^2 = 0.987 \tag{1}$$

They further developed a blending chart that correlated RAP binder content with the CI of the blended binder, offering a method to gauge the blending efficiency between RAP and virgin binders (Fig. 4).

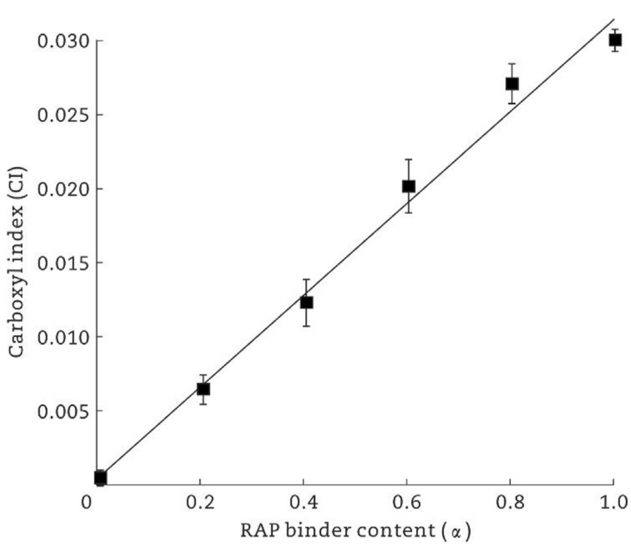

Fig. 4. Relationship between RAP binder content and CI of blended binder (Li et al., 2022).

4.2. Testing properties of fine asphalt mixture (FAM)

Although the binder testing can reveal the potential effects of RAP/RAS binders on performance of recycled asphalt mixtures, there are concerns about this research method. The primary issue arises from the use of solvents required to get asphalt binders from RAP/RAS materials or recycled asphalt mixtures. These solvents can alter the properties of the blended asphalt binders. Thus, when relying on the properties of recovered asphalt binders to discern the impact of high RAP/RAS contents on the performance of recycled asphalt mixtures, this solvent influence must be taken into account. In recent years, a new testing protocol using fine asphalt mixture (FAM) specimens has been proposed. This direct test on FAM specimens evaluates the interaction of RAP/RAS materials with virgin aggregates and asphalt binder eliminating the influence of chemical solvents. Typically, FAM specimens are prepared by combining virgin asphalt binder, fine aggregates, and fine RAP/RAS particles. When designing the FAM compositions, it is recommended to use the binder content and gradation of the fine portion of a fully-graded asphalt mixture. The complex shear modulus and fatigue behavior of the cylinder FAM specimens are normally measured by DSR tests (Fig. 5).

Kanna et al. (2014) prepared FAM specimens containing two types of RAS and virgin binders separately. The blended FAM specimens with three levels of RAS (0, 2.5%, and 7.1%) were compared for each RAS source. The complex shear modulus and shear fatigue life of FAM specimens were measured using the DSR with modified testing programs at intermediate temperatures. Both the complex shear modulus and fatigue properties of FAM specimens were sensitive to the changes of RAS contents and sources. Furthermore, the effects of increasing RAS content in FAM specimens were consistent for both measured properties. It was concluded that the FAM testing protocol is an effective tool for evaluate the effects of RAS on recycled asphalt mixtures.

Alavi et al. (2015) also prepared and tested FAM specimens containing fine RAP and RAS materials (passing the 2.36 mm sieves). The 12.5 mm-diameter FAM specimens were cored from a gyratory-compacted sample. Five virgin binders from three California refineries were applied in that study. The recycled FAM specimens including two RAP contents (25% and 40% at binder replacement ratio) and one RAS content (15% at binder replacement ratio) were evaluated, as well as the blended asphalt binders according to the corresponding fractions of tested mixtures. Comparison analysis of FAM testing results and blended binder results illustrated that the FAM testing protocol appears to be repeatable and reproducible. The representative results of FAM specimens can be used to characterize the performance-related properties of blended asphalt binders with high contents of RAP/RAS.

As expected, several factors influence the stiffness of FAM specimens, including the grade of the virgin binder, the content and source of RAP/RAS, and the recycling agent used. The content and type of aged asphalt binder in RAP and RAS materials, combined with the dosage and type of recycling agent, exert the most pronounced effects. Yan et al. (2018, 2019) implemented the FAM testing to characterize the impact of RAP materials on the actual grades of binder in recycled asphalt mixtures. They conducted DSR and BBR tests on FAM specimens to evaluate changes in performance-related properties of both virgin and RAP mixtures. Notably, these changes corresponded to specific virgin mixtures with adjusted binder grades. Analyzing the FAM testing results revealed that it's possible to accurately predict the PG grades of binders in the mixtures.

4.3. Testing performance of recycled asphalt mixtures

From the findings of section 3, it is noted that the moisture damage, along with fatigue and thermal cracking, are significant concerns for recycled asphalt mixtures with high RAP/RAS contents. Many testing methods have been used to study the impact of RAP/RAS on these involved mixture properties. This section will introduce the most commonly utilized testing methods and discuss their effectiveness as described in the literature.

4.3.1. Moisture damage tests

The tensile strength ratio (TSR) test is widely recognized as one of the primary methods for characterizing the moisture susceptibility of asphalt mixtures. It is also implemented as part of the Superpave mix design method in the United States. The standard TSR test method in AASHTO T283 requires the saturated specimens to be subjected to one freeze-thaw cycle. After conditioning, tensile strength is measured by applying load diametrically on the specimens at a displacement rate of 50 mm/min. The TSR value is the ratio of average tensile strength of conditioned specimens to that of unconditioned specimens. The NCHRP Project 09-46 (West et al., 2013) explored the influence of high RAP content on the tensile strength of recycled asphalt mixtures using TSR tests. It was observed that all the recycled asphalt mixtures exhibited greater tensile strengths than their virgin counterparts, whether conditioned or unconditioned. This can be attributed to the increased stiffness of the aged asphalt binder present in the RAP materials. In several cases, the TSR values of the recycled asphalt mixtures were lower than 0.80 (criterion required in AASHTO M 323), indicating an unsatisfied moisture damage susceptibility. To enhance moisture resistance, anti-stripping additives are commonly used. It's worth noting that certain states accept a lower TSR threshold provided both conditioned and unconditioned tensile strengths surpass a specified level. For example, both Georgia and Florida permit a TSR benchmark of 0.7 for designed asphalt mixtures as long as the tensile strengths of the evaluated specimens, pre-conditioning and post-conditioning, remain above 689 kPa. Especially for mixtures using softer-grade asphalt binders, a more lenient tensile strength criterion might be appropriate. Johnson et al. (2010) compared TSR values of recycled asphalt mixtures containing 10%, 15%, and 25% of RAP. The results showed that increased RAP content led to declining TSR values. All tested recycled asphalt mixtures had TSR values of less than 0.75, while the tensile strengths of all specimens were higher than 689 kPa.

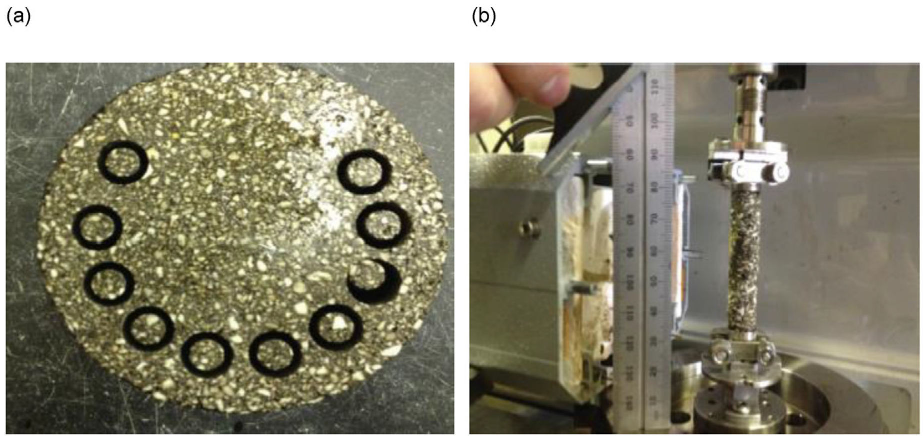

Fig. 5. FAM specimen preparation and testing. (a) Coring from compacted FAM specimen. (b) DSR test setup (Kanna et al., 2014).

Another method frequently used to measure moisture damage susceptibility of asphalt mixtures is the Hamburg wheel tracking (HWT) test. It was initially developed to determine the rutting resistance of asphalt mixtures at high temperatures. Since water bath is used for conditioning the samples during the tests, it was found also capable of investigating moisture damage. Due to its simplicity, practicality, and repeatability, the HWT test was introduced in the United States (Aschenbrener, 1995). As many state agencies started to use it, the HWT test has gained more and more popularity in evaluating both the rutting and moisture susceptibility of asphalt mixtures (Hand, 2013).

The AASHTO T324 specification for the HWT test doesn't stipulate a specific testing temperature. While some state agencies determine to use a single temperature of all local asphalt mixtures, others recommend to decide testing temperatures base on the PG grades of the asphalt binder used in the mixtures. Lee et al. (2018) evaluated the moisture susceptibility of the high RAP mixtures (30%–50%) from the field by using the HWT tests at 50 °C. The results of all recycled asphalt mixtures showed very little rutting and almost no stripping inflection point after 20,000 passes, which indicating excellent rutting resistance. It was therefore concluded that the high RAP mixtures were not susceptible to moisture damage in terms of HWT tests. The research of WHRP Project 0092-15-04 (Bahia et al., 2016) illustrated that the binder properties dominate most of the rutting behavior of Wisconsin asphalt mixtures at 50 °C. While the mixture design and mineral aggregate properties showed limited influence on the rutting response at that temperature. The statistical analysis indicated that a lower HWT testing temperature (45 °C) is better for Wisconsin mixtures. Both their rutting and moisture susceptibility can be characterized at 45 °C. Therefore, for recycled asphalt mixtures both the virgin binder grades and RAP contents should be considered when choosing their HWT testing temperatures.

Table 1 summarizes two commonly used methods for testing moisture susceptibility of recycled asphalt mixtures. The supporting references and major findings for both methods are also included. Results show that the incorporation of RAP has demonstrated a positive impact on the tensile strength of both conditioned and unconditioned specimens. In light of this, it is advisable to reconsider the threshold for the TSR when formulating recycled asphalt mixtures, suggesting a lower criterion. Furthermore, the study suggests that RAP materials may exhibit lower susceptibility to moisture damage compared to virgin asphalt mixtures, attributed to the existing binder absorption during the initial stage. Base on the HWT test, with 21 state agencies reporting its use. Research findings indicate that high RAP content in recycled asphalt mixtures correlates with reduced susceptibility to moisture damage. Optimal HWT testing should consider both binder grades and RAP contents.

4.3.2. *Fatigue performance tests*

The four-point bending beam test specified in AASHTO T321 is a controlled-strain fatigue test for asphalt mixtures. This test's efficacy in predicting in-service pavement performance was validated by the SHRP A-003A project (Deacon et al., 1995), which incorporated a variety of mixtures, climates, pavement structures, and traffic loads. However, other laboratory accelerated tests (e.g., laboratory wheel tracking and ALF experimentation) showed mixed results for predicting pavement performance. It has been observed that the flexible asphalt mixtures with lower stiffness perform better in controlled-strain fatigue tests. Williams et al. (2013) used the four-point bending beam tests to investigate the

Table 1
Testing methods for moisture susceptibility of recycled asphalt mixtures.

Testing method	Testing specimen and setting	Supporting reference	Major finding
Tensile strength ratio (TSR) test (AASHTO T283)	• Cylinder specimen of Ø100 mm or Ø150 mm with a thickness of 63.5 mm or 95 mm • To load diametrically at a displacement rate of 50 mm/min at 25 °C	Airamgzeb (2014); Al-Qadi et al. (2009); Johnson et al. (2010); West et al. (2013)	• The addition of RAP increased the tensile strength of both conditioned and unconditioned specimens. • A lower criterion of TSR should be considered for the designed recycled asphalt mixtures. • RAP materials might be less suspectable to moisture damage than virgin asphalt mixtures since the existing binder absorption at initial stage.
Hamburg wheel tracking (HWT) test (AASHTO T324)	• Slab specimens with dimensions of 320 mm × 260 mm × (38–100) mm or Ø150 mm cylinder specimen with a thickness of 62 mm • To apply moving wheel load of 705 N at a speed of 52 passes/min in water bath	Bahia et al. (2016); Lee et al. (2015); Lippert et al. (2012); Mohammad et al. (2015)	• Rutting specifications were discussed to relate mixture properties to field performance by rejecting mixtures that would fail in the field. • 21 state agencies reported the use of HWT test. • In several researches it was found that the recycled asphalt mixtures containing high contents of RAP were not susceptible to moisture damage. • Both the binder grades and RAP contents should be considered when choosing the HWT testing temperatures.

fatigue properties of recycled asphalt mixtures with RAS from various sources The results indicated that the recycled asphalt mixtures containing RAS had similar or better fatigue properties compared to virgin mixtures. Ghabchi et al. (2015) found that addition of RAP or a blend of RAP and RAS increased the fatigue life of tested asphalt mixtures in the controlled-strain tests. Furthermore, it was also reported that the four-point bending beam test results showed high coefficient of variation in the values of cycles to failure, indicating a poor repeatability of this testing method.

The loading cycles at the moment of that initial stiffness of the beam decrease 50% is typically defined as the failure criterion for four-point bending beam tests. However, Tang (2014) reported that this criterion might be misleading as the initial stiffness of tested asphalt materials can vary significantly in a wide range. Therefore, the use of a dissipated energy plot was suggested to better represent the fatigue resistance of asphalt mixtures. During the early loading cycles of four-point bending beam test, a higher dissipated energy is required for a stiffer mixture to achieve the same deformation than a softer mixture. The total cumulative energy integrated with loading cycles can be used to demonstrate the mixture's fatigue resistance. The results indicated that the recycled asphalt mixture with 40% RAP had better fatigue resistance than 30% and 50% RAP mixtures regardless of traditional stiffness and dissipated energy criteria. Although the four-point bending beam test has been widely used in the research of fatigue performance of asphalt mixtures, it is impractical as a routine test for design of asphalt mixtures. The fabrication of beam samples requires special equipment. The testing process is notably time-consuming, particularly for flexible asphalt beams.

Recently, several fatigue testing methods for asphalt mixtures have gained increasing popularity. These include the semi-circular bend test from Louisiana Transportation Research Center (SCB-LTRC), semi-circular bend–Illinois flexibility index test (SCB-IFIT), and indirect tensile cracking test (IDEAL-CT). The SCB-LTRC tests were first introduced by Mull et al. (2002) to characterize the fracture resistance of crumb rubber modified asphalt mixtures. Mohammad et al. (2004) employed the SCB-LTRC tests to determine the limits of critical strain energy release rate J_c of Louisianan asphalt mixtures. At intermediate temperatures, both SCB-LTRC and IDT testing results of various asphalt mixtures were compared. The strain energy release rate J_c values from SCB-LTRC tests showed good correlation with the IDT results. Furthermore, the SCB-LTRC results illustrated a good correlation with the field cracking data from Louisianan asphalt pavements as well. Bahia et al. (2016) also used the SCB-LTRC tests to characterize the fatigue resistance of recycled asphalt mixtures containing high percentages of RAP (at binder replacement ratios of 15%, 30%, and 50%). The results showed that there was no consistent trend between change in J_c values and RAP contents. In the results, the J_c value increased with a decrease of binder replacement ratio for only 3 out of 16 mixtures, which is as expected.

The SCB-IFIT test was developed by Al-Qadi et al. (2015) to evaluate the performance of recycled asphalt mixtures with high contents of RAP and RAS. The flexibility index was introduced to determine cracking resistance of recycled asphalt mixtures in SCB-IFIT tests. This parameter considers both the fracture energy and slope of the load-displacement curve after the peak load. The post-peak slope represents average crack propagation speed. Their study was aimed to identify, develop, and assess protocols, procedures, and specifications crucial for ensuring pavement performance of recycled asphalt mixtures with varying amounts of RAP and RAS. Consequently, they recommended a testing temperature of 25 °C and a displacement rate of 50 mm/min for the SCB-IFIT test. There findings suggest that the FI, when measured at intermediate temperatures, effectively reflects the impact of compositional changes and volumetric design variations in recycled asphalt mixtures on their cracking resistance. To validate the SCB-IFIT test's effectiveness, SCB specimens derived from plant-produced, laboratory-produced mixtures, and field cores were all examined. The FI measurements showed a strong correlation with the mixtures' cracking performance rankings, corroborating both the fatigue measurements and the pavement evaluations.

In the WHRP Project 0092-15-04 (Bahia et al., 2016) the SCB-IFIT and SCB-LTRC tests were compared by using them to differentiate recycled asphalt mixtures. The FI results derived from SCB-IFIT tests showed a wider range than the J_c results from SCB-LTRC tests. Thus, it could be considered more suitable for discriminating mixture variables. The results also indicated that the J_c parameter was not able to reliably capture effects of some mix design factors which intend to have influence on mixture cracking. Instead, the SCB-IFIT test allowing to use only one notch size and to include crack propagation analysis was considered as the best protocol for determining intermediate temperature cracking resistance.

The IDEAL-CT test is another fatigue testing method that gains the more interests and discussion in the past few years. It bears similarity to the indirect tensile strength test, where a diametrical load is applied to cylindrical specimens at a displacement rate of 50 mm/min at room temperature. For the purpose of Superpave mix design and laboratory mixture quality control/quality assurance (QC/QA), it was suggested to use the specimen dimensions of 150 mm diameter and 62 mm height. This is mainly because many state agencies and constructors are already adept at fabricating such specimens using a gyratory compactor. Moreover, due to its compatibility with regular IDT testing equipment, the IDEAL-CT test does not demand extensive training for routine operations, making it a practical choice (Zhou et al., 2017). The IDEAL-CT test has demonstrated effectiveness in differentiating among various mixture compositions and volumetric designs, including varying contents of RAP and RAS, binder content and type, levels of mixture aging, air voids, etc. The CT index results from these mixtures showed a strong correlation with field performance as measured by accelerated loading facility full-scale tests (Fig. 6). This analysis takes into account various types of cracks, such as fatigue, reflective, and thermal cracking. A detailed comparison of the IDEAL-CT test with other fatigue cracking measurements has been documented in the NCHRP Project 9-57 (Zhou et al., 2016).

The NCAT test track findings at phase VI (2015–2017) (West et al., 2019) reported a study of a group of cracking measurements for asphalt mixtures, including the SCB-IFIT and IDEAL-CT tests. The SCB-IFIT results showed a relatively wide range in FI results across the seven asphalt mixtures evaluated. This statistical spread in FI results would provide engineers better opportunities to improve mix designs and predict field performance of asphalt mixtures. The IDEAL-CT results showed the same performance ranking of measured mixtures as the SCB-IFIT results in most respects. Those two testing methods have the lowest equipment cost and shortest testing time as compared to other four cracking measurements. The NCAT report also highlighted the IDEAL-CT test's advantage of requiring a straightforward specimen fabrication process, further underscoring its practicality.

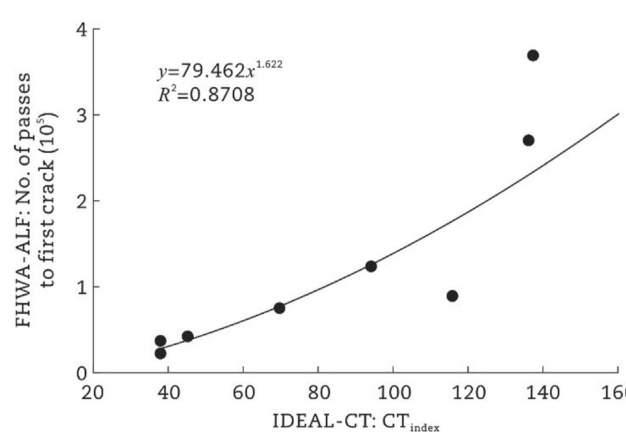

Fig. 6. Correlation between IDEAL-CT results of laboratory prepared mixtures and FHWA Accelerated Loading Facility Full-Scale Testing results of field performance (Zhou et al., 2017).

Table 2 summarizes commonly used fatigue cracking measurements for recycled asphalt mixtures from the literature search. Results showed that the RAS mixtures demonstrate comparable or superior fatigue properties, supported by high R^2 values in fatigue curves. However, the four-point bending beam tests reveal poor repeatability, challenging the method's reliability due to a high coefficient of variation in loading cycles to failure. Relying solely on loading cycles as a failure criterion lacks discriminatory power in evaluating fatigue resistance. Recommended critical J_c values (0.5–0.6 kJ/m^2) align with fatigue performance, correlating with toughness index values from IDT tests. Integrating high RAP in warm mix asphalt shows no noticeable impact on fracture resistance in SCB-LTRC testing. No consistent trends between changes in J_c values and RAP contents/binder replacement ratios are observed. Flexibility index results correlate well with the cracking performance rankings of recycled asphalt mixtures. SCB-IFIT proves superior to SCB-LTRC in determining fatigue cracking resistance. The fatigue behavior of blended binders explains rankings in FI values post-aging. The IDEAL-CT test emerges as a straightforward, practical, and efficient cracking test, demonstrating sensitivity to RAP and RAS. IDEAL-CT data aligns with SCB-IFIT data, with lower variability in CT index compared to FI values from SCB-IFIT tests.

4.3.3. Thermal cracking tests

Three commonly used thermal cracking tests for asphalt mixtures are the IDT creep and strength test (AASHTO T322), DCT test (ASTM D7313), and SCB tests at low temperatures (AASHTO TP105). In a national pooled fund study for characterizing low temperature cracking of asphalt pavements (Marasteanu et al., 2012), all those three tests were employed for evaluating thermal cracking of nine asphalt mixtures used in field projects. Those tested mixtures varied a lot in the materials, including RAP mixtures, PPA modified mixtures, and SBS and Elvaloy modified mixtures. The results of fracture energy measured by the DCT and SCB showed fairly good agreement in terms of the mixture ranking (Fig. 7). It was also found that the DCT and SCB fracture energy results of laboratory-produced specimens had a good correlation with field performance data. While the IDT results of laboratory specimens showed a relatively poor correlation with field results. It was concluded that the IDT test has an ability to discriminate rankings between different mixtures, but the stiffness is not well correlated to the IDT strength.

Wagoner et al. (2005) found that the fracture energy at low temperatures could be used to distinguish recycled asphalt mixtures according to their differences in binder properties. While the indirect tensile strength at low temperatures significantly underestimated the strength of highly ductile mixtures. Therefore, it was believed that the fracture energy is a much better indicator for discriminating the thermal cracking resistance of recycled asphalt mixtures than other indirect measures. It was also recommended to use the DCT geometry for fracture energy test configuration since it can provide larger potential fracture surface than the SCB geometry. A recent research reported that the DCT results for recycled asphalt mixtures containing RAP/RAS showed a decrease in fracture energy when the recycled material contents increased (Buttlar et al., 2017). The facture energy measured by DCT test is sensitive to the use of RAP and RAS. Furthermore, an increase of DCT fracture energy was observed for 45% RAP mixtures when virgin binder grade was decreased. The use of a PG 46-34 for 45% RAP mixture could result in equivalent fracture energy to the PG 64-22 virgin mixture without RAP.

However, it is also noted that many researchers reported their concerns about the DCT test on determining thermal cracking of recycled asphalt mixtures. The SCB test was recommended more frequently than the DCT test. Al-Qadi et al. (2009) found that both the DCT and SCB testing results showed less data spread and diminished ability to quantify the effects of RAP when testing temperatures were low. The DCT testing results could not discriminate thermal cracking resistance of various recycled asphalt mixtures at low temperatures. The SCB testing results

Table 2
Testing methods for fatigue cracking of recycled asphalt mixtures.

Testing method	Testing specimen and setting	Supporting reference	Major finding
Four-point bending beam test (AASHTO T321)	• Beam dimension of 380 mm × 50 mm × 63 mm • To apply flexural bending at a strain level between 250 and 750 with a frequency of 5–10 Hz at 20 °C	Deacon et al. (1995); Ghabchi et al. (2015); Tang (2014); Williams et al. (2013)	• The RAS mixtures showed similar or better fatigue properties than control mixtures with high R^2 values of both fatigue curves. • The high values of coefficient of variation of the loading cycles to failure illustrated poor repeatability of four-point bending beam tests. • To use loading cycles at certain moment as a failure criterion is not sufficient to discriminate the fatigue resistance.
Semi-circular bend-Louisiana Transportation Research Center (SCB-LTRC) Test (ASTM D8044-16)	• Semi-circular beam from cylinder specimen with Ø150 mm and 57 mm thick and three types of notch size • To apply load-head displacement at 0.5 mm/min at intermediate temperatures	Bahia et al. (2016); Kim et al. (2012); Mohammad et al. (2004); Mull et al. (2002)	• The recommended value of critical strain energy release rate J_c ranges from 0.5 to 0.6 kJ/m^2. • The J_c values showed good correlation with the toughness index values from IDT tests. • Incorporating high contents of RAP in warm mix asphalt did not influence the fracture resistance according to SCB-LTRC testing results. • No consistent trend between changes in J_c values and RAP contents/binder replacement ratios were observed.
Semi-circular bend-Illinois Flexibility Index Test (SCB-IFIT) (AASHTO TP124-16)	• Semi-circular beam from specimen of Ø150 mm and 50 mm thick and a notch depth of 15 mm • To apply load-line displacement at 50 mm/min at a temperature of 25 °C	Al-Qadi et al. (2015); Bahia et al. (2018); Chen et al. (2019); Ling et al. (2017)	• The flexibility index results of recycled asphalt mixtures were in very good agreement with the rankings of their cracking performance. • The SCB-IFIT test is a better approach for determining fatigue cracking resistance as compared to SCB-LTRC test. • The fatigue behavior of blended binders can well explain the ranking in FI values of corresponding mixtures after aging.
Indirect Tensile Cracking Test (IDEAL-CT) (ASTM D8225)	• Cylinder specimen with dimensions of Ø150 mm and 62 mm thick • To apply diametrical displacement at 50 mm/min at a temperature of 25 °C	West et al. (2019); Yan et al. (2020); Zhou et al. (2016, 2017)	• The IDEAL-CT test is a simple (no instrumentation, cutting, gluing, drilling, or notching to test specimen), practical (less training for routine operation), and efficient (short test time within 1 min) cracking test. • The change in CT index values clearly illustrated that it is sensitive to addition of RAP and RAS. • The IDEAL-CT data had similar trends as the SCB-IFIT data in most respects in NACT's study for comparing fatigue measurements. • It was found that the CT index from IDEAL-CT tests had lower variability compared to FI values from SCB-IFIT tests.

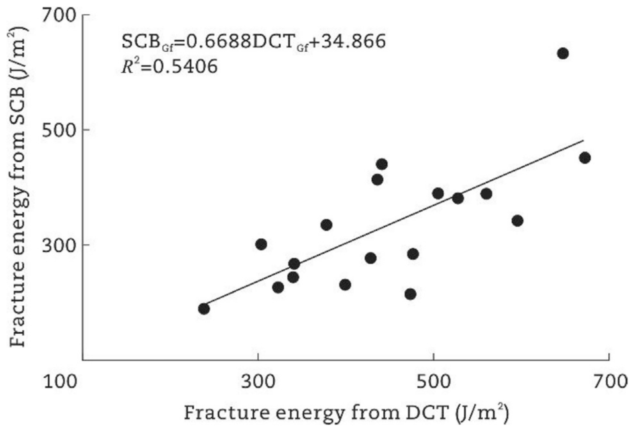

Fig. 7. Comparison of fracture energy from the DCT and SCB tests at low temperature (Marasteanu et al., 2012).

showed that the fracture energy decreased as the RAP contents were increased. The 40% RAP mixture with PG 58-28 virgin binder showed lower SCB fracture energy than the virgin mixture with PG 64-22 binder at testing temperatures of −12 °C and 0 °C, indicating a need of double bumping of virgin binder for the recycled asphalt mixtures. Johnson et al. (2013) also implemented the SCB tests on recycled asphalt mixtures containing up to 55% RAP. It was found that the fracture energy was decreased due to the addition of RAP, while the fracture toughness of recycled asphalt mixtures was increased. The 55% RAP mixtures had the most poor fracture performance among all recycled asphalt mixtures.

The SCB tests at low temperatures were conducted on the recycled asphalt mixtures containing high contents of RAS (4%, 5%, and 6%) by Williams et al. (2013). The SCB fracture energy measured for high RAS mixtures were correlated with the field evaluation results of test section. The 4% RAS mixture which had the highest fracture energy showed the least amount of cracking in the field. Whereas the control mixture with no RAS showed the greatest amount of cracking in the field since that mixture had the lowest fracture energy according to the SCB tests. Both the SCB fracture energy results and field evaluation data indicated that the addition of RAS increased the thermal cracking resistance of Iowa DOT mix design.

Table 3 summarizes commonly used thermal cracking measurements for recycled asphalt mixtures. A brief summary of related findings for those methods is also included. In summary, the addition of RAP and/or RAS enhances tensile strength, and the impact on pavement cracking temperature is notable, particularly with higher RAP percentages. Binder selection plays a crucial role in thermal cracking resistance for high recycled asphalt mixtures, as evidenced by DCT testing. SCB fracture parameters offer potential utility in thermal cracking prediction within the MEPDG framework. Additionally, the correlation between SCB fracture energy results for RAS mixtures and transverse cracking in pavement performance highlights the significance of these findings in practical applications.

5. Recycling agents for high RAP/RAS mixtures

5.1. Chemical compositions and rheological properties of recycling agents

Using a virgin binder with a lower PG grade is a common approach to improve the cracking resistance of recycled asphalt mixtures containing high RAP and/or RAS. Another alternative approach involves adding recycling agents without changing the binder grade. According to some researchers, these agents can be categorized into two types: softening agents and rejuvenating agents. Softening agents, such as flux oil, lube stock, lubricating oil, and slurry oil, are effective in lowering the viscosity of aged asphalt binders. Rejuvenating agents, which are supposed to contain a high proportion of maltene constituents, should able to restore the balance between maltenes and asphaltenes in aged asphalt binders. The typical rejuvenating agents are lube extracts and extender oils. It is believed that the addition of rejuvenating agents in recycled asphalt mixtures can improve the relaxation, ductile, cohesive properties of aged asphalt binders (Willis and Tran, 2015). Some proprietary products made from bio-based oils even have been traded in market as rejuvenating agents for high RAP/RAS mixtures. Table 4 provides a partial list of reported products of recycling agents from literature search.

Current specifications for recycling agents (such as AASHTO R14 and ASTM D 4552) mainly emphasize two characteristics: viscosity and flash point. A low viscosity of the recycling agent is crucial for ensuring thorough blending with the aged binders in the recycled materials. Simultaneously, a relatively high flash point is important for safety during production and application, preventing the agents from evaporating too rapidly either during the mixing process or in the early life of the pavement. The durability of recycling agents is commonly assessed by comparing the viscosity of the blended binder before and after conditioning. Therefore, understanding the long-term impacts of recycling

Table 3
Testing methods for thermal cracking of recycled asphalt mixtures.

Testing method	Testing specimen and setting	Supporting reference	Major finding
Indirect tensile creep and strength test (AASHTO T322)	• Cylinder specimen with dimensions of Ø150 mm and (38–50) mm thick • To apply a load at load-line displacement rate of 12.5 mm/min at the temperature of binder's low PG grade	Ghabchi et al. (2015); Marasteanu et al. (2012); McDaniel et al. (2011)	• The tensile strength was increased due to the addition of RAP and/or RAS. • 15%–25% RAP increased pavement cracking temperature by about 2 °C. 40% RAP doubled cracking temperature. • The pavement cracking temperature of high recycled asphalt mixtures can be lowed by using relatively softer binder.
Disc-shaped compacted tension (DCT) test (ASTM D7313)	• Disc-shaped specimen of Ø150 mm and 50 mm thick with one notch and flat surface at crack mouth • To apply tensile load with a constant crack mouth opening displacement rate of 0.017 mm/s	Bahia et al. (2016); Buttlar et al. (2017); Marasteanu et al. (2012); Wagoner et al. (2005)	• The DCT testing results showed the fracture energy had wider data spread than indirect tensile strength results. • The DCT fracture energy of high recycled asphalt mixtures could be reduced by using lower grade binder. • It was concluded that the DCT test is insensitive to factors affect thermal cracking resistance.
Semi-circular bend (SCB) test (AASHTO TP105)	• Semi-circular beam from Ø 150 mm and 24.7 mm thick specimen and a notch with a depth of 15 mm • To apply 3-point bending load for a crack mouth opening displacement rate of 0.0005 mm/s at binder's low PG temperature 10 °C	Al-Qadi et al. (2009); Johnson et al. (2013); Li et al. (2008); Li and Marasteanu (2004)	• The SCB fracture parameters will be able to used in the MEPDG for thermal cracking prediction model. • The fracture energy of recycled asphalt mixture at low temperatures decreased as the RAP content increased. • The results of SCB fracture energy for RAS mixtures correlated well with pavement performance of test sections with regards to transverse cracking.

Table 4
Recycling agent categories and types (Willis and Tran, 2015).

Category	Example	Description
Paraffinic oils	Waste engine oil (WEO) Waste engine oil bottoms (WEOB) Valero VP 165® Storbit®	Refined lubricating oils from engine repair factory
Aromatic extracts	Hydrolene® Reclamite® Cyclogen L® ValAro 130A+	Refined oil products with high aromatic oil components from petroleum industry
Naphthenic oils	SonneWarmix RJ™ Ergon HyPrene®	Engineered hydrocarbons for binder modification
Triglycerides & fatty acids	Waste vegetable oil Waste vegetable grease Brown grease Delta S	Derived from vegetable oils and few with other added chemical components
Tall oils	Sylvaroad™ RP1000 Hydrogreen®	Paper Industry byproducts (also used as liquid antistrip agents and emulsifiers)

agents on asphalt mixtures is essential for enhancing recycling efficacy.

The understanding of how chemical and rheological properties evolve in blended binders containing recycling agents during long-term service remains limited. More tests and field observations should be conducted with respect to this aspect. King et al. (2018) reported the characteristic changes of eight recycling agents after short-term and long-term aging conditioning. The involved recycling agents were aromatic extract (A1), paraffinic oil (P), tall oil (T1), vegetable oils (V2, V3), and bio-oils (B1, B2). The aging susceptibility of those recycling agents was determined by measuring the 15 °C complex viscosity of their RTFO, 20 h PAV and 40 h PAV aged residues (Fig. 8). An extreme change in complex viscosity was found for the tall oil T1 and vegetable oil V3 after the long-term aging (PAV conditioning), indicating potential poor durability of those two recycling agents. In that study, the aging and rheological response of blended binders containing RAP binders and recycling agents were investigated through the FTIR and DSR tests. The results illustrated that the paraffinic oil only played a part as a softening agent with poor compatibility; the aromatic extract A1 was sufficient for some blended binders at relative high dosage; both the vegetable oils and bio-oils acted like emulsifiers for blending but less rheological effect on binder properties; the tall oil T1 had no effect on changing binder properties after long-term aging. Therefore, it was suggested to set specifications for recycling agents in terms of their effects on long-term performance of aged binder blends. Haghshenas et al. (2018) also reported that the

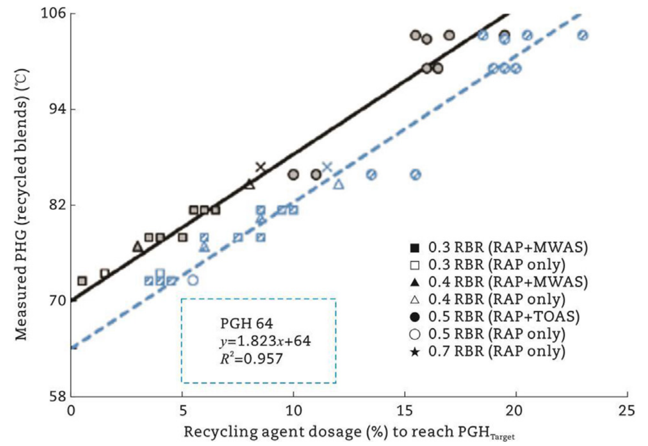

Fig. 9. Optimum recycling agent dosage to match the continuous high-temperature PG grade of the blended binder (Epps et al., 2020).

petroleum-based recycling agents could improve long-term performance of the blended binders through preserving their chemical components and performance stability, whereas the agriculture-based recycling agents might negatively affect long-term durability of the blended binders due to the aging issue caused by their high oxygen components.

5.2. Optimum dosage of recycling agents

In application of recycled asphalt mixtures with high contents of RAP and/or RAS, the addition of recycling agents plays a crucial role. The type and dosage of these agents significantly influence the cracking resistance and rutting performance of the recycled asphalt mixtures. While a higher dosage of recycling agents can effectively reduce the viscosity and brittleness of the RAP and RAS binders, an excessive dosage might lead to problems like poor adhesion and stripping in the blended binders of the recycled asphalt mixture. Consequently, it's essential to carefully determine the optimal dosage of recycling agents, taking into account the specific types and quantities of RAP/RAS materials involved. Traditionally, the dosage of recycling agents has been selected based on empirical experience and manufacturer recommendations, often without fully considering the unique characteristics of the recycled materials.

The NCHRP Project 09-58 (Epps et al., 2020) reported a design tool to estimate optimum dosage of recycling agent in blended binder using minimum laboratory efforts. In which, the type, source, and content of RAP binders, and the source and grade of virgin binder are both considered. Blending charts for the combination of RAP and virgin

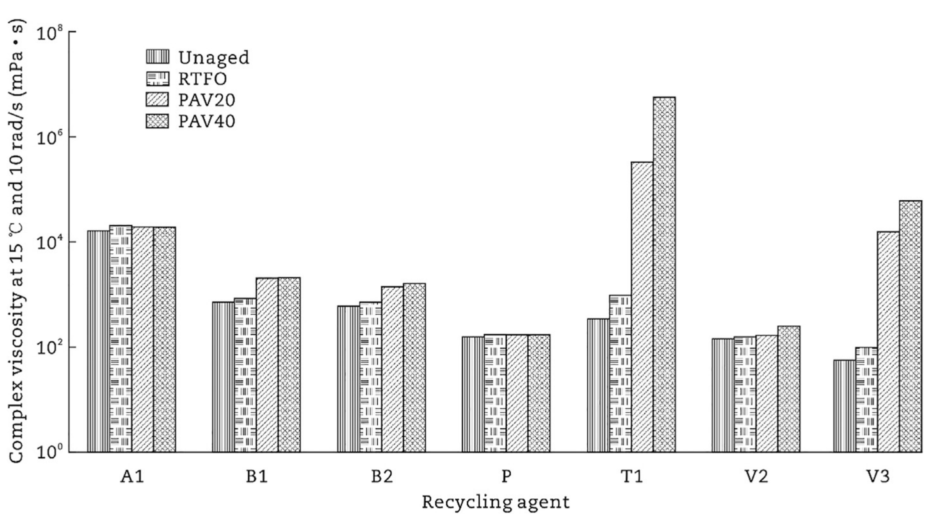

Fig. 8. Aging susceptibility of recycling agents (King et al., 2018).

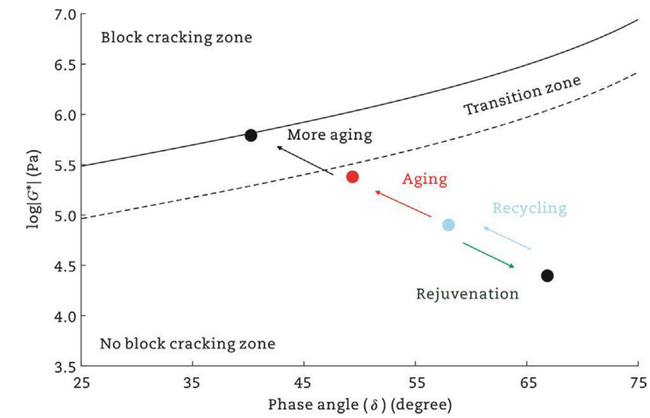

Fig. 10. Illustration of G^* and δ changing with recycling, aging, and rejuvenation in black space (Kaseer et al., 2018).

binders and recycling agent are established and then used to estimate the optimum dosage of recycling agent (Fig. 9). The principle is to match the continuous high-temperature PG grade of the blended binder to that required by the target climate of designed mixture for the pavement. It was investigated and verified that this dosage yielded the best performance for both blended binders and recycled asphalt mixtures.

Some researchers (Karki and Zhou, 2016; Kaseer et al., 2018; Lee et al., 2018) suggested the black space diagram of $|G^*|$ against phase angle to determine the cracking resistance of asphalt and to assess the effectiveness of recycling agents with long-term aging. The black space diagram of $|G^*|$ and phase angle of blend binders also can be used to evaluated restoration of the stiffness and flexibility by adding recycling agents. A fresh binder without modification generally has a relatively low $|G^*|$ and high phase angle. Therefore, it locates at the lower right corner of the black space diagram. The inclusion of RAP/RAS binders is represented as an increase in $|G^*|$ and decrease in phase angle. Conversely, rejuvenation by adding recycling agents is considered as the reversal of the impact of laboratory and field aging or the inclusion of RAP/RAS binders on asphalt. Concerning this aspect, the addition of RAs is expected to reduce $|G^*|$ and increase phase angle (Fig. 10).

The G-R parameter which is calculated from $|G^*|$ and phase angle at 15 °C and 0.005 rad/s has been employed to determine the durability of blended binders containing RAP/RAS binders and recycling agents. It was reported that the G-R parameter values between 180 and 600 kPa tied well with inadequate ductility of 5 to 3 cm, correlating to cracking onset and significant cracking of the pavements in the field, respectively. Karki and Zhou (2016) investigated the effects of recycling agents on the rheological and chemical properties of blended binders with recycling agents and later used the findings to recommend optimum dosages of recycling agents. According to the results of G-R parameter, to add recycling agent increased the extent of binder aging associated with more risk of significant cracking. The blended binders containing moderately aged binders appeared durability issues much later than the blended binders with severely aged binders. Lee et al. (2018) investigated the effects of various recycling agents through employing each product to blended asphalt binders and corresponding high RAP mixtures. The DSR testing results showed that all recycling agents lowered both high- and low-temperature PG grades of blended binders. The aged binder showed the highest G-R value and virgin binder had the lowest G-R value. The blended binders containing recycling agents exhibited intermediate G-R values. Overall, all recycling agents helped to decrease the aging level of blended binders at different extents. While, it is also noted that none of those recycling agents restored the properties of aged binder to those of corresponding virgin binder.

There are limited researches on investigating the link between the chemical compositions of recycling agents and their effectiveness in blended binders and recycled asphalt mixtures. Zhou et al. (2019) found that many bio-oils improved cracking resistance of recycled asphalt mixtures through a series of laboratory testing and field evaluations of 17 test sections. Some tested bio-oils performed more effectively than others. Both laboratory testing results and field data indicated that the content of total fatty acid in those bio-oils appeared to be a potential indicator for the performance of this type of recycling agent. The bio-oils which have a higher content of fatty acid perform more effectively. It was also recommended that bio-oils should contain more than 97% fatty acid and in which saturate fatty acid should be less than 50%. Meanwhile, the mass loss of bio-oils should be less than 5% during the RTFOT test. The DSR and BBR testing results further confirmed the findings for the total fatty acid content of oils.

In summary, the addition of recycling agents with proper dosage can effectively restore the rheological properties of aged asphalt binders and improve the intermediate and low temperature properties of the blending binders. However, a high recycling agent dosage may lead to rutting issues at high temperatures. Recent research recommended to use continuous high-temperature PG grade of blended binder to select the optimum recycling agent dosage.

5.3. Effects of recycling agents on performance properties of recycled asphalt mixtures

Over the past decade, many researches of evaluating the effects of recycling agents on aged binders have been published, while limited effort has been carried out for investigating the effects of recycling agents on recycled asphalt mixtures, especially for their long-term performance. In recent years, several researchers started to assess the performance properties of recycled asphalt mixtures containing recycling agents. One such study by Mogawer et al. (2013) explored how three different recycling agents could mitigate the stiffness increase in recycled asphalt mixtures with high contents of RAP and RAS. In this study, the agents were blended with virgin binders to produce mixtures that included 40% RAP, 5% RAS, and a combination of 35% RAP plus 5% RAS. The mixture test results indicated that the addition of recycling agents enhanced the cracking resistance of the recycled asphalt mixtures. However, there were negative impacts on rutting resistance and moisture susceptibility at the dosages of recycling agents used. It was also observed that the dynamic modulus of mixtures containing only RAP was more significantly altered by the recycling agents compared to those with RAS or a mix of RAP and RAS. This discrepancy could be attributed to the relatively stiffer binder present in the RAS material as compared to that in the RAP.

Zaumanis et al. (2014) conducted a research to investigate the effectiveness of recycling agents in the production of 100% RAP mixtures. In this study, the 100% RAP binder and mixture samples were both prepared by adding 12% of recycling agents by weight of total binder content. Binder testing results revealed that several recycling agents, including waste vegetable oil and grease, bio oil, tall oil, and aromatic extract, effectively lowered the PG grade of the RAP binder from PG 94-12 to PG 64-22. However, achieving comparable effects with waste engine oil required a higher dosage. The fatigue resistance of 100% RAP mixtures containing most of recycling agents was better than the virgin mixture at tested conditions, except for the RAP mixture containing waste engine oil. Furthermore, thermal cracking testing results showed that five out of the six recycling agents improved mixture's cracking resistance. Notably, waste vegetable oil and aromatic extract performed better than other agriculture-based recycling agents, decreasing critical cracking temperature of recycled asphalt mixture to similar extend of corresponding virgin mixture.

Lee et al. (2018) characterized the thermal cracking resistance of laboratory-produced recycled asphalt mixtures containing 27.6% and 70% of RAP. The DCT testing results illustrated that the recycling agents obviously improved the resistant to low-temperature cracking of recycled asphalt mixtures. However, the addition of recycling agents adversely impacted the moisture susceptibility and rutting resistance of recycled asphalt mixtures. Overall, the tall oil and vegetable oil were more effective than petroleum-based oils at their optimum dosages.

Haghshenas et al. (2019) compared three recycling agents (i.e., fatty acid, aromatic extract, and tall oil) by applying them in to the asphalt binders and mixtures with 65% of RAP/RAS. The flow number and SCB tests under dry and wet conditions were performed on the recycled asphalt mixtures. The recycled asphalt mixtures containing recycling agents showed improved SCB fracture energy than the control mixtures without recycling agents. While only one set of measured mixture showed rutting issue due to an excessive amount of RAS included. This finding highlighted the importance of accessing rutting performance of recycled asphalt mixtures with a combination of RAP/RAS and recycling agents.

In 2019, Zhou et al. (2019) recommended a four-step procedure for applying recycling agents for recycled asphalt mixtures containing high contents of RAP/RAS: 1) selection of recycling agent type, 2) determination of the range of recycling agent dosages required to satisfy the binder specifications, 3) determination of the range of recycling agent dosages required to meet mixture performance requirements, and 4) selection of optimum RAs dosage based on engineer judgement.

Liu et al. (2023) proposed a separation technology for asphalt and aggregates of RAP materials with bio-oil as a solvent. Considering the excellent compatibility between bio-oil and asphalt, as well as the rejuvenating effect of bio-oil on aged asphalt, bio-oil derived asphalt (BBOA) could serve as a viable raw material for the production of asphalt or liquid asphalt. Moreover, it has the potential to act as a rejuvenator for asphalt, facilitating the separation of oil and stone components in the asphalt mixture. Some research findings indicate that the separation of oil and stone components has a significant impact on the long-term performance of asphalt pavements containing reclaimed asphalt pavement (RAP). Yu et al. (2022) introduced a novel method, refined decomposition (RD), aiming to overcome the inefficiencies, safety concerns, and high costs associated with current separation methods. RD demonstrated a 30%–45% asphalt separation degree and a 20% reduction in agglomeration for coarse RAP, contributing to improved stability. The processed RAP exhibited enhanced strength, slightly reduced angularity, and minimal impact on sphericity and texture, making it a viable choice for pavement applications. RD offers an effective solution for oil-stone separation in RAP, positively impacting the long-term performance of asphalt pavements.

6. Field data on pavement performance of recycled asphalt mixtures

Laboratory studies on the effect of the recycled asphalt mixtures with high RAP/RAS contents in their rutting and cracking characteristics need to be verified with performance evaluations from the field projects. However, very few projects of using high RAP/RAS mixtures in the field have been conducted. This section summarizes the field data on pavement performance of the recycled asphalt mixtures.

Leiva-Villacorta and Grant (2020) evaluated six field projects containing high RAP mixtures after 5–6 years in service. Those projects were constructed in Alabama in between 2011 and 2012. The field cores were collected and measured for flexibility index by using the SCB-IFIT tests. The conditions of the existing pavements were evaluated, especially the cracking conditions. It was found that most pavement sections had little to no cracking except for the pavement section on US-29. Table 5 shows a summary of pavement performance and mixture properties about this study.

In 2014–2015, national center for asphalt technologies (NCAT) constructed seven pavement sections to investigate the pavement performance of 5% RAS mixture and 35% RAP mixture under NCAT test track cracking group experiment (phase VI). Ten million equivalent single-axle loads (ESALs) were applied on those sections over two years (2015–2017). The rutting depth, changes of international roughness index (IRI), changes of surface mean texture depth, and cracking characteristics of those sections were measured. The results are shown in Table 6.

In 2006, the NCAT test track cracking group experiment (phase III) had constructed four test sections with 45% RAP mixtures, two sections with 20% RAP mixtures, and one control section without RAP. West et al. (2009) reported that four different virgin binders were used for the 45% RAP mixtures, including PG 76-22 plus 1% Sasobit, PG 76-22, PG 67-22, and PG 52-28. For the 20% RAP mixtures, PG 67-22 and PG 76-22 binders were employed. Five trucks with 18K ESAL were driven on test sections for 2 years to simulate 10 million ESALs. Pavement performance of those test sections was monitored, such as the rutting depth, surface texture, roughness change, and cracking. None of test sections showed raveling and rutting distresses. Only the sections of 45% RAP mixture with PG 76-22 binder plus 1.5% Sasobit and 20% RAP mixture with PG 76-22 binder showed cracking. Those two sections experienced with moderate and low severity longitudinal cracking on wheel paths, respectively.

Furthermore, NCAT constructed two test sections with the HMA and WMA mixtures containing 50% RAP to compare with their control mixtures. Table 7 shows the results of cracking and rutting characteristics for all the sections. It was found that test sections with 50% RAP mixtures had significantly less cracking and rutting compared to two WMA sections with no RAP. It is worth noting that the control section with HMA mixture showed slightly higher cracking than the 50% RAP HMA. Based on the field data, it was concluded that high RAP mixtures could be utilized in the field with caution. Since the pavement performance of the recycled asphalt mixtures depends on both virgin binder type and activation extent of RAP binder during the production.

Virginia DOT recently published an investigation of pavement performance of high RAP mixtures after field service (Diefenderfer et al.,

Table 5
Summary of filed performance of six projects and their mixture properties (Leiva-Villacorta and Grant, 2020).

Mixture ID/location	Mixture variable	Age (year)	Field performance	FI (SCB-IFIT)-filed core (after 5–6 years)
AL-50, Lafayette, Chambers County	35% RAP mixture, fine-graded 12.5-mm NMAS, water injection (ASTEC)	6	Low-severity transverse cracking	0.73
I-65, Calera, Shelby County	35% RAP mixture, fine-graded 19.0-mm NMAS, water injection (Gencor)	6	No cracking or other distress	3.07
AL-137, Wing, Covington County	35% RAP, fine-graded 12.5-mm NMAS, water injection	6	No cracking or other distress	1.05
US-29, Troy, Pike County	32% RAP plus 3% RAS mixture, fine-graded 12.5-mm NMAS, water injection	6	Low-severity fatigue cracking on both wheel-paths	1.73
AL-35, Fort Payne, Chereokee County	35% RAP mixture, fine-graded 19.0-mm NMAS, Evotherm 3G	6	Low-severity raveling	3.84
US-80, Lowndes, Lowndes County	40% RAP mixture, fine-graded 12.5-mm NMAS, Evotherm 3G	5	Low-severity fatigue cracking	1.32

Table 6
Performance of tested sections in NCAT cracking group experiment after 10 million ESALs (West et al., 2019).

NCAT test track section	Mixture description	Rutting (mm)	Change in IRI (in./mi)	Change in mean texture depth (mm)	Cracking (% of lane area)
N1	Control	1.7	3	0.4	21.5
N2	Control, higher density	2.2	8	0.6	6.2
N5	Control, low density, low AC	1.2	15	0.5	5.0
N8	Control+5%RAS	1.2	17	0.7	16.9
S5	35%RAP, PG 58-28	1.5	4	0.5	0.0
S6	Control, HiMA binder	1.4	11	0.6	0.0
S13	Gap-graded, asphalt-rubber	2.8	6	0.1	0.0

2018). In the study, field visits and laboratory mixture investigations for 23 in-service pavements were included. Historical pavement performance and maintenance data were collected for analyzing the long-term performance of those pavements. Visual survey data indicated that test sections with low RAP mixtures (less than 20%) had no obvious difference in each pavement distress compared to test sections with high RAP mixtures (between 21% and 30%). The ride condition of most pavements were in acceptable range based on the distress data extracted from PMS. The dynamic modulus results illustrated that the applied RAP contents had no obvious influence on the mixture modulus, neither the virgin binder grade. The results of repeated load permanent deformation (RLPD) tests indicated that there is a correlation between RAP content and increasing of strain accumulation in the secondary portion.

7. Conclusions and recommendations

The main objective of this study is to provide a synthesis of existing researches on the long-term performance of recycled asphalt mixtures containing high contents of RAP/RAS. In addition, the current state of applying recycling agents in high recycled asphalt mixtures is summarized for future study. The following main findings are summarized.

- **Aging of asphalt mixtures**: The aging of asphalt binder in the mixture improves pavement performance within the high-temperature range, while it detrimentally affects the cracking performance at intermediate- and low-temperature ranges. This highlights the need for tailored aging mitigation strategies for different temperature ranges.
- **Properties of high recycled asphalt mixtures**: The rutting resistance of recycled asphalt mixtures is not a concern unless high dosages of recycling agents are applied. Inconsistent findings on fatigue cracking and low-temperature fracture energy indicate a need for further research to understand the complex interactions in high RAP/RAS mixtures.
- **Research methods for recycled asphalt materials**: To use linear blending charts in predicting the effects of high contents of recycled materials on rheological properties of blended binder has limitations. It is recommended to directly test individual binders for accurately determine the performance of RAP/RAS blended binders. FAM specimens are effective in evaluating RAP/RAS effects, avoiding biases from solvent-recovered binders. For testing, the HWT test assesses rutting resistance and moisture susceptibility, while the SCB-IFIT and IDEAL tests evaluate intermediate temperature fatigue cracking. The semi-circular bend test (AASHTO TP105) is preferred over the DCT test for measuring low-temperature cracking resistance.
- **Recycling agents for high recycled asphalt mixtures**: To know the long-term effects of recycling agents in asphalt mixtures is important for producing more effective recycled asphalt mixtures. Investigating the aging and rheological properties of binders blended with recycling agents helps in their selection. While literature shows recycling agents improve cracking performance in high RAP/RAS mixtures, high dosages may negatively impact rutting resistance and moisture susceptibility. Therefore, a balanced mix design approach is advised for these mixtures.
- **Pavement performance of high recycled asphalt mixtures**: Relatively few studies about the field performance of high recycled asphalt mixtures have been reported. The pavement performance of NCAT's test sections for the cracking group experiment showed that high RAP mixtures could be utilized in the field with caution. The performance of recycled asphalt pavements depends on both virgin binder type and the activation extent of RAP binder during the production.

Table 7
Comparison of cracking and rutting of test sections with high RAP and control mixtures at the NCAT test track (West, 2014).

Section	Cracking (%)	Rutting (mm)
Control HMA	2	2
50% RAP HMA	0	4
50% RAP WMA	3	5
WMA foam/No RAP	11	12

While significant insights were gained, several areas require further investigation.

- **Advanced aging models**: Develop and validate advanced aging models that more accurately predict the long-term performance of recycled materials in asphalt.
- **Optimization of mix design:** Based on the main findings of this study, the use of a balanced mixture design approach for high recycled asphalt mixtures with additional direct testing of corresponding blended binders is supported. Focus on optimizing the mix design of high RAP/RAS asphalt mixtures to balance performance with cost-effectiveness and environmental impact.
- **Eco-friendly and efficient recycling agents:** Investigate the development and application of more eco-friendly and efficient recycling agents that enhance the performance of high RAP/RAS mixtures without compromising environmental sustainability.
- **Impact of variability in RAP/RAS quality:** Examine how variability in the quality of RAP and RAS affects the performance of recycled mixtures and develop guidelines for field quality assessment and control.

Declaration of competing interest

Zhen Leng is editorial board member of Journal of Road Engineering, Yuan Zhang is a young academic editor of Journal of Road Engineering and they were not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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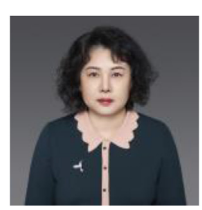

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