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Original Research Paper

Recycled Asphalt Shingle Modified Asphalt Mixture Design and Performance Evaluation

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Highlights

- Study aims at determining binder availability from RAS material in asphalt mixtures
- Virgin and RAS mixtures were designed with identical volumetric parameters and asphalt contents were compared
- Binder availability was determined to be approximately 100% for RAS mixtures
- Performance-based tests were used to characterize RAS mixtures
- Field observations of mixtures with RAS were reported

Abstract

The inclusion of recycled asphalt shingles (RAS) in asphalt mixtures has become increasingly common; however, the underlying design principles vary significantly by agency. The primary objectives of this study included: (1) evaluating the 'binder availability' concept for RAS mixtures through a carefully designed laboratory experiment; (2) demonstrating a balanced mixture performance testing approach for the design of RAS mixtures; and (3) evaluating the field data of RAS mixtures placed in the Midwest region of the U.S. Three asphalt mixture designs with RAS contents of 0.0, 2.5 and 5.0%, which were designed to have nearly identical volumetric characteristics, were investigated. The binder availability was determined to be approximately 100% in the two RAS mixtures considered. In addition, Hamburg wheel tracking and disk-shaped compact tension tests were conducted to evaluate the high- and low-temperature mixture performance. As expected, the addition of RAS significantly improved the rutting resistance. DC(T) test results demonstrated that a soft base binder effectively permitted the design of thermal-crack-resistant RAS mixtures. Field investigations indicated that the performance of pavement surfaces containing RAS was similar to that of surfaces containing only reclaimed asphalt pavement or virgin materials. This study also highlights a performance-engineered mix design approach, which is currently being adopted by several agencies in the Midwest (e.g. Illinois Tollway, Missouri DOT, etc.) and can provide mix designers a reliable approach for designing innovative asphalt mixtures with higher recycling levels and a modern, heterogeneous composition. Furthermore, the proposed approach may prove to be a simpler, more mixture-centric alternative to the primary method suggested in AASHTO PP78-17, which recommends arbitrary VMA bumping plus binder extraction, recovery, and advanced binder testing.

Keywords:

Recycled Asphalt Shingles; RAS; DC(T); Cracking; Pavement

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1 Introduction

The sustainability revolution in the paving industry over the past twenty years has led to a proliferation of approaches toward meeting standards and goals pertaining to asphalt mixture design, performance, and sustainability. Modern asphalt mixtures are considerably more heterogeneous than previously used ones, and they contain multiple recycled materials and other additives such as binder modifiers, rejuvenators, and chemicals to enhance the mixture workability, performance and sustainability. Sustainability in asphalt pavements, in terms of material recycling, focuses on the incorporation of recycled construction materials such as recycled asphalt shingles (RAS), reclaimed asphalt pavement (RAP), and ground tire rubber (GTR) into asphalt paving mixtures. RAS is attractive due to the high content of asphalt cement present within the material (approximately 5 to 6 times that of RAP); however, it must be carefully engineered into the mixture to account for its significant stiffness and high melting point. Approximately 11 million tons of shingle waste is produced in the United States annually (CIWMB, 2005; CMRA, 2007). According to Brock (1998), a savings of $1 billion dollars annually could be realized by engineering RAS into asphalt mixtures in a comprehensive manner (Brock, 1998). Owing to the regional use of RAS worldwide (most prevalent in the Midwest and East Coast United States (Buttlar et al., 2019; Rath et al., 2019; Williams et al., 2018; Buttlar and Wang, 2016)), somewhat limited research and field data regarding RAS are available compared to research on RAP.

Asphalt shingles are composed of 20–40% asphalt, 40–70% aggregate granules, and 1–25% base materials (Arnold, 2014). Before being manufactured into asphalt shingles, the asphalt binder is oxidized by an air blowing process to increase the viscosity to reduce high temperature deformations. In addition, considering the aging and hardening experienced during service life, tear-off shingle asphalt is considerably stiffer than the asphalt used in the traditional asphalt mix design. For instance, it was found that the Superpave performance grade of shingle asphalt recovered from a particular source of RAS in Illinois was PG 112+2, which represents a stiffness notably higher than that of the PG 64-22 grade commonly used in paving mixtures in Illinois (Lippert and Brownlee, 2012). Aggregate granules in roofing shingles help to shield the asphalt from sun damage, improve the functional characteristics, and facilitate color variation for architectural purposes. Ceramic granular, headlap granules, backsurfacer sand and stabilizer are typical granular components in shingles, which possess a similar quality level as fine aggregates in paving materials. Base materials, typically categorized as either organic or fiberglass bases, provide a matrix to support the other component materials.

Early RAS studies demonstrated that the addition of RAS did not have an evident effect on the volumetric properties and served to only improve the compactability. Watson et al. (1998) and Mallick et al. (2000) showed that the gradation and volumetric properties of RAS-modified mixtures did not change appreciably in comparison to those of the control mixtures (Watson et al., 1998; Malik et al., 2000). Foo et al. (1999) confirmed that voids in the total mixture (VTM), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA) of RAS mixtures were similar to those of conventional HMA mixtures (Foo et al., 1999). Newcomb et al. (1993) and Sengoz et al. (2005) found that the optimum total virgin asphalt content for RAS mixtures reduced in comparison to control mixtures without RAS, implying that a certain amount of shingle asphalt participates as a binder in the mixture (Newcomb et al. 1993; Sengoz et al., 2005).

Binder characterization has been conducted to investigate RAS participation in the asphalt binder and to characterize the effect of RAS on the binder system. Paulsen et al. (1986) evaluated roofing waste from five different states (Paulsen et al., 1986). The binder test results indicated that the inclusion of RAS generally decreased the penetration and increased the viscosity of virgin asphalt, depending on the source. Maupin et al. (2010) found that 25% RAS binder by weight created a 2–3 Superpave PG high temperature ‘grade bump,’ along with an upward bump of one PG low-temperature grade (Maupin, 2010). You et al. (2011) investigated the influence of 5% and 10% RAS on PG 52–34 binder (You et al., 2011). Bending beam rheometer test results demonstrated that the creep stiffness of the binder increased with the increased usage of RAS. Similar to RAP mixtures, a softer virgin binder is typically used to counterbalance the rheological effects of the stiffer RAS binder. Cooper et al. (2015) evaluated the asphaltene content of the extracted binder from RAS and virgin PG 64–22 binder using gel permeation chromatography (Cooper et al., 2015). As expected, the asphaltene contents of the two studied RAS sources were noted to be considerably higher than that of the virgin binder, and the extremely different molecular weights distribution of the associated asphaltenes from RAS and the virgin binder suggested that binder compatibility should be considered.

A number of mixture performance studies have been performed to evaluate temperature susceptibility, moisture susceptibility, permanent deformation, low temperature behavior and fatigue cracking resistance in RAS mixes. Testing performed by Newcomb et al. (1993) showed that RAS had no distinct effect on the moisture susceptibility of the asphalt mixtures investigated (Newcomb et al., 1993). Wu et al. (2016) conducted a Hamburg wheel tracking test to characterize the rutting resistance of RAS mixtures, and the results showed that the rut depths of RAS-modified asphalt mixtures were lower than those of the control mixture due to the presence of the stiffer RAS binder, which is consistent with the results pertaining to binder research (Wu et al., 2016). Other studies similarly concluded that RAS increases the asphalt mixture rutting resistance (Mallick et al., 2000; Maupin, 2010).

While RAS is generally beneficial for high-temperature rut resistance, the higher binder stiffness present in RAS suggests that cracking behavior should be carefully evaluated and addressed in the mix design. The disk-shaped compact tension fracture test, or DC(T) as specified in ASTM D7313, and an acoustic emission technique were utilized by Arnold (2014) to examine the low temperature behavior of RAS mixtures. It was found that the inclusion of RAS decreased the fracture energy and increased the embrittlement temperature of the mixtures evaluated. A softer virgin asphalt binder was required to restore the low temperature properties of the mixture to those of the control mixture (Arnold, 2014). The fatigue cracking resistance of RAS modified HMA was studied by Cascione et al. (2015) and Wu et al. (2016). Cascione et al. (2015) conducted four-point bending beam testing on several asphalt mixtures and found that both RAS and non-RAS mixtures performed well with respect to fatigue performance, and, in fact, the RAS modified asphalt mixtures performed slightly better than the control mix (Cascione et al., 2015). Similarly, Wu et al. (2016) evaluated the fatigue performance of asphalt field cores containing RAS via monotonic fatigue testing and noted that the fatigue resistance of the mixtures was not significantly affected by the addition of RAS (Wu et al., 2016). This finding was consistent with field surveys that showed that the test sections were in excellent condition after three years of service.

2 Objectives

The primary objectives of this RAS study were to evaluate the availability of asphalt cement from RAS by considering the volumetric properties of RAS mixtures, and to evaluate the effectiveness of RAS mixtures using laboratory performance tests. In the initial phase of the study, a total of six asphalt mixtures with RAS contents of 0.0%, 2.5%, and 5.0% under two mixing regimes (standard laboratory mixing, and manual, full binder blending) were designed and evaluated. These mixtures were designed to have identical volumetric parameters so that their pavement performances were comparable. After mixture design phase was completed, the amount of asphalt cement provided by the RAS material was calculated, and the 'available RAS binder' percentage was computed. Finally, disk-shaped compact tension (DC(T)) and Hamburg wheel tracking tests were conducted to examine how the designed mixtures performed in relation to performance thresholds, for various combinations of virgin and RAS binder under two mixing regimes.

3 RAS Mix Design Approaches and Their Implications

Asphalt mix designers have grappled with the question of how to treat the stiffer, higher melting point asphalt materials present in RAP and RAS in the mixture design process. Research studies have demonstrated that neither RAP nor RAS binders fully blend with a virgin binder in production (Buttlar and Dave, 2005; Buttlar, 2005). For RAS mixtures, one of several approaches described below is typically used to 'discount' a portion of the RAS binder. This is based on the assumption that RAS binder only partially fulfills the binder's role to coat the aggregate, to facilitate the consolidation of aggregate during compaction, and to provide mixture durability. These approaches include: (a) the use of a 'binder availability factor', or; (b) adjustment of volumetric mix design targets such as raising VMA requirements or lowering the target air void level. Research by Cooper et al. (2014) determined that binder availability of up to 100% from RAS is possible with the introduction of rejuvenators in a polymer modified stone matrix asphalt (SMA) mixture (Cooper et al., 2014). However, research to date has not addressed the asphalt binder availability in a dense-graded asphalt mixture with a grade-bumped neat asphalt binder. AASHTO PP78-14 (2014), developed by a Federal Highway Administration (FHWA) asphalt mixture expert task group (ETG) recommends a binder availability factor of 70% to 85% (AASHTO PP78-14, 2014). However, the scientific problem with this approach is that the remaining percentage of RAS asphalt binder is considered as part of the aggregate skeleton, which is physically incorrect and leads to arbitrary aggregate gradation and specific gravity adjustments. As a result, AASHTO PP78-17 (2017) was modified to remove the binder availability factor; it now suggests an arbitrary VMA bump of +0.1% for each percent of RAS used, along with advanced low-temperature binder testing on the recovered binder (AASHTO PP78-17, 2017). The advanced low temperature binder testing suite involves the use of the bending beam rheometer to obtain the so-called 'ΔT-critical', or 'ΔTc' parameter (AASHTO PP78-17, 2017). AASHTO PP78-17 includes a provision for the designer to conduct mixture performance testing in lieu of binder extraction, recovery, and advanced low temperature testing. It is possible that mix designers will continue to use a binder availability approach for a number of years before AASHTO PP78-17 is widely adopted. This possibility, along with the impractical and inexact nature of binder extraction, recovery, and advanced low temperature testing in the mix design process, has motivated researchers to evaluate an alternative approach, as presented herein.

A central question addressed in this study is: What exactly is 'binder availability' from a mix design and performance standpoint? This study seeks to determine the answer through rigorous laboratory mix design and performance testing. The first phase of the study involved the investigation of RAS binder availability for a dense-graded mixture with a neat binder and two commonly used levels of RAS (2.5% and 5% by weight of mixture). These mixtures were designed to have similar VMA, VFA, and percent effective asphalt binder (P_{be}) values. Once the mixture designs were completed, the amount of asphalt cement provided by the RAS material was inferred from the volumetric measurements, and the 'available RAS binder' percentage was determined. The second part of the study involved the evaluation of the RAS asphalt mixtures via low- and high-temperature performance tests. DC(T) and Hamburg wheel tracking tests were performed to examine how the designed mixtures perform in relation to specification thresholds, for various combinations of virgin and RAS binder and under two mixing regimes (standard laboratory mixing, and manual, full binder blending). This was accomplished to evaluate a possible mixture performance testing approach for RAS mixtures, as permitted in AASHTO PP78-17, as a rigorous-yet-practical approach to the standard method proposed in the standard. Lastly, field data from RAS mixtures in the Chicago, IL vicinity were used to validate the proposed mixture performance approach for RAS mixture design. Furthermore, the extension of this approach to modern, heterogeneous mixtures with RAP, GTR and other components/additives is discussed.

4 Testing Methods and Mixture Designs

In this study, the development of asphalt mixture designs followed the Superpave and Illinois Department of Transportation (IDOT) standards. The mixing and compaction temperatures satisfied the IDOT standards for laboratory production of PG 58-28 asphalt binder. The bulk and maximum specific gravity measurements for compacted asphalt mixtures followed ASTM D2726 and ASTM D4021, respectively. The aggregate stockpiles were evaluated in terms of the specific gravity, absorption, etc., by considering the IDOT standards. The effective asphalt cement associated with the binder from RAS was determined by maintaining all other mixture variables constant and determining if additional virgin asphalt binder was required to obtain 4% air voids in RAS mixtures as compared to the virgin control asphalt mixtures.

4.1 Materials and Experimental Methodology

The components of the asphalt mixtures studied included PG 58-28 asphalt cement, RAS sourced in Chicagoland, along with crushed dolomitic limestone coarse aggregate, crushed dolomitic limestone sand and natural sand. The aggregates were sampled from Open Road Paving in Champaign, IL. The RAS mixtures used in the study did not contain any RAP material to allow the evaluation of the availability of the asphalt binder provided by RAS only. The mixture design phase was separated into two parts:

- First, traditional shingle mixture designs were developed to control volumetric properties such as VMA, VFA, and air voids. The portion of RAS asphalt binder that is active in mixing could be estimated by comparing the RAS mixtures to the virgin asphalt mixture in terms of the total asphalt content of the mixture.
- Second, initially, the RAS material was subjected to an extraction-recovery process to obtain the RAS binder and RAS pulp. Subsequently, a combination of extracted RAS pulp and virgin asphalt binder was added to the virgin mix instead of directly adding RAS material to the mixture. This substitution and subsequent comparison with the binder content measurements of mixtures following traditional design methods allowed the determination of the amount of available asphalt binder from

the RAS.

A detailed process flow of the abovementioned methodology is shown in Fig. 1.

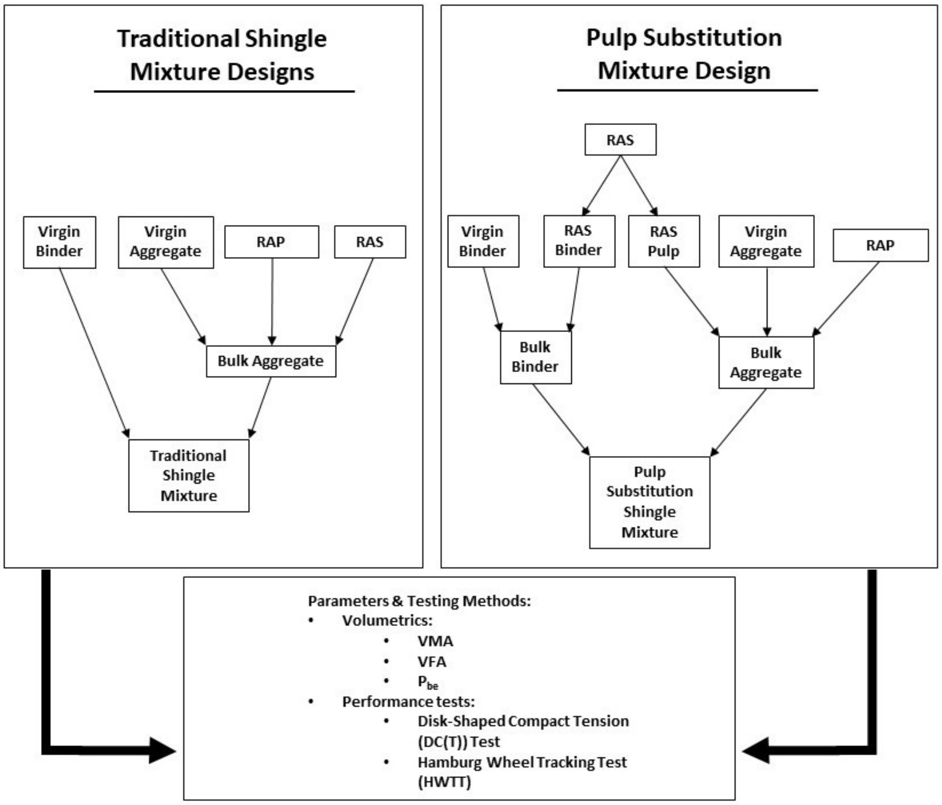

Fig. 1 Process flow of the proposed experimental methodology.

4.1.1 Traditional RAS Mixture Designs

Mixing and compacting of asphalt mixture specimens was performed at a temperature of 150°C in accordance with IDOT specifications. All aggregate and asphalt cement samples were heated for approximately four hours prior to mixing to ensure temperature consistency. The RAS present in each mixture sample was thoroughly mixed with virgin aggregate prior to placement in the oven to avoid RAS clumping in the mixture. To develop comparable mixtures, it was ensured that the VMA, VFA, and P_{be} in the finalized designs were nearly equivalent. The final mixture design gradations are listed in Table 1.

Table 1 Mixture Design Gradations.

Sieve	**Virgin Mix**	**2.5% RAS Mix**	**5.0% RAS Mix**
25.0 mm	100.0	100.0	100.0
19.0 mm	100.0	100.0	100.0
12.5 mm	100.0	100.0	100.0
9.5 mm	99.2	99.3	99.4
4.75 mm	72.9	74.6	76.3
2.36 mm	45.9	47.9	50.3
1.18 mm	27.7	29.2	31.5
0.60 mm	16.7	17.9	20.1
0.30 mm	9.4	10.9	13.4
0.15 mm	6.2	7.6	10.1
0.075 mm	5.3	6.4	8.5

The mixture designs considered in this study satisfied the 3 million equivalent single axle load requirement, owing to the use of 90 design gyrations. The mixtures contained 0.0, 2.5, and 5.0% RAS, which were respectively equivalent to an asphalt binder replacement (ABR) of approximately 0, 10, and 20%. The optimum asphalt content of 6.6% was obtained by changing the amount of virgin asphalt content using similar aggregate blends (as presented in Table 1) until the volumetric parameters were obtained. The volumetric properties of the asphalt mixtures are listed in Table 2. These results demonstrate that the total asphalt content of 4.0% air voids remains constant when VMA, VFA, and Pbe are maintained to be nearly constant. Therefore, the asphalt binder provided by the RAS was approximately 100% active in this case. The total activity of the complete virgin plus RAS binder system demonstrates that the material is completely functional as a soft binder in terms of facilitating mixing and compaction. To fully evaluate the binder availability, extracted RAS pulp and 100% virgin asphalt binder were substituted for the RAS product, as discussed previously. It should be noted that the dust-to-asphalt ratios in some mixes slightly exceeded those mentioned in the Superpave and IDOT criteria. This aspect was considered acceptable for the purposes of this study, in which maintaining VMA and other mixture volumetrics was assigned priority. The state of Illinois employs a maximum dust-to-total-binder ratio of 1.0 in design and one with a range of 0.6–1.2 during mix production. The slightly high ratio helps reduce VMA such that it remains approximately equal to 15.3%. In practice, the control and 5% RAS mixture are likely to be designed in a slightly different manner to satisfy the dust-to-asphalt specification requirement.

Table 2 Mixture Volumetrics.

Volumetric Property	**Mixture**				
	Virgin	**2.5% RAS**	**2.5% Pulp**	**5.0% RAS**	**5.0% Pulp**
Total Asphalt Content (%)	6.6	6.6	6.6	6.6	6.7
Asphalt Binder Replacement (%)	0.0	10.6	10.6	21.2	21.2
Air Voids (%)	4.0	4.0	4.0	4.0	4.0
VMA (%)	15.2	15.3	15.3	15.2	15.4
VFA (%)	74.0	73.8	73.7	73.7	73.2
Effective Asphalt Content (%)	4.9	4.9	4.9	4.9	4.9
Dust/Total AC	0.8	1.0	1.0	1.3	1.3
Dust/Effective AC	1.1	1.3	1.3	1.7	1.7

4.1.2 Pulp Substitution Mixture Designs

This portion of the study substituted the RAS material in the asphalt mixture with RAS pulp and PG 58-28 virgin asphalt binder to evaluate the RAS binder availability. For e.g. the mix with 2.5% RAS traditionally is modified with 2.5% RAS particles measured by the weight of the mixture; with RAS pulp substitution method, the weight of binder available in 2.5% RAS particles (by weight of the mixture) was computed and that much weight of the virgin PG 58-28 binder was added to the mixture with the corresponding RAS pulp – in other words, this method substitutes the RAS binder with the virgin PG 58-28 binder in the mixture. The same proportions of virgin aggregate gradation were used as in the traditional RAS mixture designs. This consistency in aggregate proportioning allowed for appropriate volumetric comparisons between all mixtures. Once again, the optimum asphalt content of 6.6% was optimized with the RAS pulp substitution till volumetric and densification parameters were met. The difference between the total asphalt contents for the pulp substitution and traditional RAS mixtures allowed calculation of the binder availability factor. The volumetric properties of the mixtures are shown above in Table 2.

As seen in Table 2, even with the pulp substitution method, as asphalt content was optimized to target volumetrics and densification parameters, the total asphalt content remained similar as in the traditional mixing technique, indicating a binder availability factor of approximately 100%. Thus, all RAS binder was active and therefore acted as asphalt binder in the mixtures. As shown in the table, in the RAS pulp mixture total asphalt content was 0.1% higher than the traditional RAS mixture. However, the VMA in the RAS pulp mixture was also slightly higher in this case, which likely led to a slight increase in asphalt content from 6.6 to 6.7%. Had the VMA remained unchanged, the total asphalt content would likely have been 6.6%, which would have yielded identical asphalt contents for the 5.0% RAS and 5.0% RAS pulp mixtures.

The 100% RAS availability factor carefully measured in this study does not agree with the suggested binder availability factor range of 70-85% recommended in AASHTO PP78-14. This value is also higher than that presented in the research findings of Cooper et al. (2014). The current study considers a dense graded asphalt mixture with a softer virgin asphalt grade. The results found by Cooper et al. (2014) considered a polymer modified SMA, a different RAS sample, and a different experimental approach, which may have led to the difference in findings (Cooper et al., 2014). The results obtained in this study demonstrate that 100% RAS availability is possible and that the elimination of the binder availability factor in AASHTO PP78-17 was appropriate.

It must be noted here that there is difference between recycled binder availability and recycled binder blending, and this study is only addressing the binder availability from RAS. Recycled binder blending depends on variables like mixing temperature and contact (mixing) time (Rad, 2013). In this study, the mixtures were carefully designed in a lab environment to achieve optimum blending and the results show a 100% availability of the recycled binder. Thus, this study addresses the fact that although incomplete blending of virgin and recycled binder likely occurs in both RAP and RAS mixtures, the recycled binder is ‘available’ from the standpoint of both mixture volumetric design and compaction. After all, a key contribution of the binder from a compaction and mixture volumetric standpoint is its lubricating effect, which is responsible for the concave upward VMA versus asphalt content curve. Although aggregate mass remains constant, additional binder (up to a point) leads to additional densification of the aggregate structure via lubrication. Thus, even if incompletely blended, the recycled and virgin binder appear to work together to create similar compaction and volumetric characteristics as compared to virgin mixtures. This begs the question: should all mixtures with soft, recycled materials, i.e., RAP binder, RAS binder, GTR, etc., be evaluated such that even if a portion of the recycled material exists in an imperfectly blended state, it should nevertheless be treated as a component of the binder system from a volumetric standpoint? Moreover, can a uniform design procedure be developed for mixes with recycled materials?

Ultimately, as the industry moves towards adopting Balanced Mix Design methods, performance testing is needed to determine if a mixture, when designed with standard volumetric design procedures, can withstand mechanical and environmental loads (West et al., 2018). The next phase of the study investigated a mixture-performance-based design alternative for RAS mixtures, which was recently introduced in AASHTO PP78-17 as an alternative binder extraction, recovery, and advanced binder testing to obtain ΔTc.

4.2 Performance Testing Methods

To characterize the rutting and cracking resistance of asphalt mixtures, Hamburg Wheel Tracking and DC(T) fracture testing were performed. The Hamburg Wheel Tracking test was used to evaluate the permanent deformation characteristics of the asphalt mixtures investigated. All gyratory specimens, 130 mm in height, were cut in half, and sawn along one edge to produce a flat face to produce a geometry suitable for the Hamburg test (using the cylindrical geometry option). All Hamburg tests were conducted until either 20,000 passes were reached or 20.0 mm of rut depth was achieved (AASHTO T324, 2017).

Wagoner et al. (2005) developed a DC(T) geometry for asphalt mixtures to create a mode-I fracture (Wagoner et al., 2005). This configuration contains sufficient fractured surface area to produce good repeatability and can be easily fabricated from both laboratory-compacted specimens and field cores. In addition, a low-temperature cracking pooled fund study, along with research by Dave et al. (2008), demonstrated that the DC(T) fracture energy parameter correlates well with the thermal cracking resistance of asphalt concrete mixtures (Marasteanu et al., 2007; Marasteanu et al., 2012, Dave et al., 2008). For both tests, specimens were compacted to approximately 7.0% air voids to comply with AASHTO T-324 standards, and four replicates per mixture were tested.

The Hamburg test, specified in AASHTO T-324, is conducted in a water immersed state at 50°C to induce both permanent deformation and moisture damage, as shown in the Fig. 2(a). A steel wheel applies a load of approximately 71kg to each specimen and external linear variable differential transducers (LVDTs) measure the rut depths at regular intervals during each pass of the wheel. PG 58-28 mixtures are considered satisfactory in terms of permanent deformation resistance if they can withstand 5,000 wheel passes prior to reaching a 12.5mm rut depth in order to conform to IDOT standards. The presence of stripping can be validated by visually examining the tested material. Finally, the maximum rut depth is defined as the rut depth present at the end of the test.

The DC(T) test evaluates the fracture energy associated with propagating a crack perpendicular to the applied load through the asphalt mixture. Fracture energy can be calculated by measuring the area under the load-crack mouth opening displacement (CMOD) gauge curve, shown in Fig. 2(b), and normalizing it by the fractured surface area. Researchers in this study tested all specimens at -12°C which corresponded to the ASTM recommendation for asphalt mixtures with a -22°C low temperature PG grade. Furthermore, all tests were run at the standard CMOD opening rate of 1.0 mm/min (ASTM D7313, 2013).

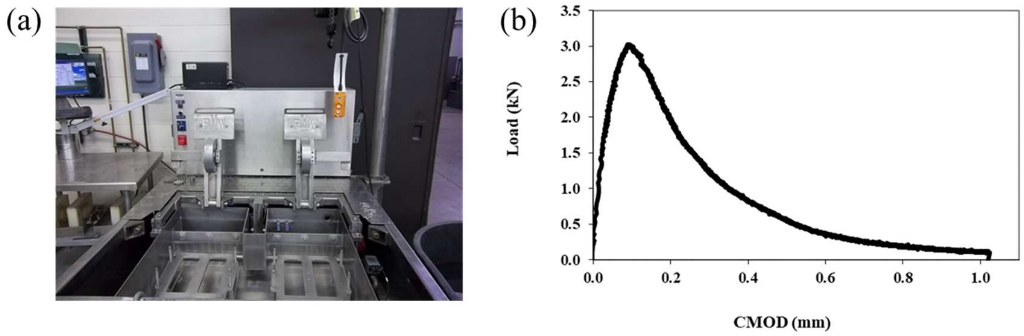

Fig. 2 Performance tests: (a) Hamburg wheel tracking device; (b) Typical DC(T) load-CMOD plot.

5 PERFORMANCE TESTING RESULTS

The mixtures in this portion of the study included PG 64-22 and PG 58-28 virgin control mixtures, 2.5% and 5.0% traditional RAS mixtures, and 2.5% and 5.0% RAS pulp mixtures. Unlike the mixture design portion of the study, the 2.5% and 5.0% mixed binder mixes (RAS pulp mixtures) contained RAS pulp plus virgin binder and recovered RAS asphalt binder with 10.6% and 21.2% ABR, respectively. This was done to examine the effects of complete RAS binder blending in the asphalt mixtures and compare it to the traditional RAS mixtures. The two control mixtures used in this study allowed examination of the effects of binder grade bumping.

5.1 Hamburg Wheel Tracking Test Results

As shown in Table 3, the virgin asphalt mixtures did not meet the Hamburg testing requirement developed by IDOT. On the other hand, the RAS mixtures both exceeded the minimum requirement of 5,000 wheel passes prior to reaching 12.5 mm (1/2”) rut depth. The improvement in Hamburg wheel tracking performance from 2.5% RAS to 5.0% RAS showed that an increase in ABR (from RAS) from 10.6% to 21.2% significantly improved rutting resistance.

The 2.5% and 5.0% RAS mixed binder Hamburg results demonstrate the increased rutting resistance created by artificial, complete mixing of virgin and extracted RAS binder. Research by Mogawer et al. (2013) found that the complex modulus of traditional RAP-RAS mixtures yielded a lower modulus as compared to a fully mixed RAP-RAS binder mixture (Mogawer et al., 2013).

Thus, if it happens that unblended RAS binder continues to mix with virgin binder during service life, this phenomenon would have a positive effect on rutting resistance.

Table 3 Hamburg Wheel Tracking Test Results.

Mixture	**No. of Passes to Failure (12.5mm)**	**Required Passes**	**Pass/Fail**
Virgin PG 58-28	3030	5000	Fail
Virgin PG 64-22	5860	7500	Fail
2.5% RAS PG 58-28	5110	5000	Pass
5.0% RAS PG 58-28	14,430	5000	Pass
2.5% RAS Mixed Binder	7370	5000	Pass
5.0% RAS Mixed Binder	15,850	5000	Pass

5.2 DC(T) Fracture Test Results

The DC(T) results are shown in Fig. 3. The PG 58-28 virgin asphalt binder was used in this study to evaluate the counterbalancing effect of using a softer base binder with RAS. The use of PG 58-28 and either level of RAS (2.5% or 5.0%) led to passing results in the DC(T) test. As shown, all three PG 58-28 mixtures met the medium traffic threshold developed during the FHWA Pooled Fund Low Temperature Cracking of 460 J/m^2 (Marasteanu et al., 2012). Furthermore, the RAS mixtures outperformed the PG 64-22 virgin asphalt mixture in terms of fracture energy. It was interesting to note no major difference between the fracture energies of 2.5% and 5.0% RAS-modified mixtures. Perhaps, testing at a lower temperature would bring out differences in those mixtures.

Additional DC(T) tests (shown with red bars) were completed on mixtures containing RAS pulp and mixed virgin plus extracted RAS binders. In both of these RAS mixtures produced with idealized, complete binder blending (for the sake of research) led to decreases in fracture energy, as expected. However, the resulting fracture energies measured still met the low traffic level DC(T) requirement of 400 J/m^2. Furthermore, the mixed binder mixtures exhibited higher DC(T) fracture energy as compared to the reference virgin PG 64-22 mixture. Thus, even if the asphalt binders achieve complete blending with time in the field, grade bumping in this case allowed the mixtures to meet the bracketed performance requirements for the Hamburg and DC(T).

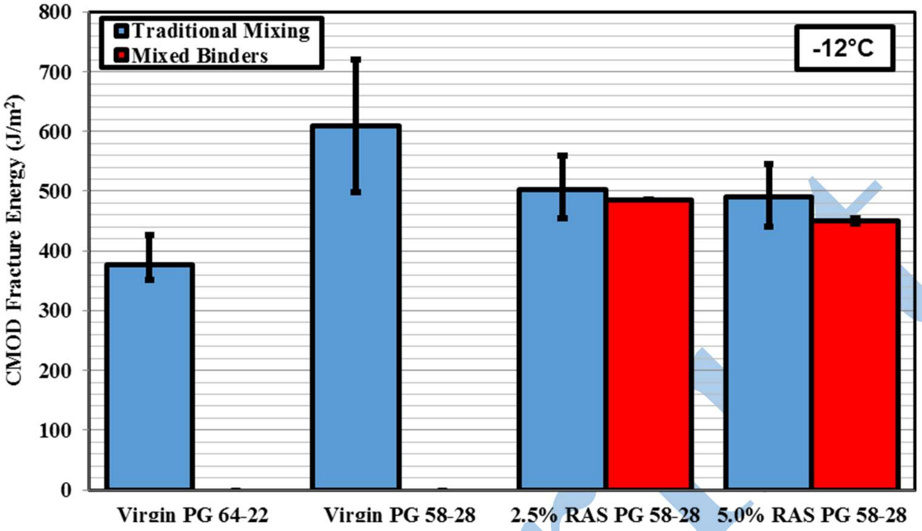

Fig. 3 DC(T) test results at -12°C.

This combination of the Hamburg and DC(T) test represents a possible mixture performance testing approach for RAS mixtures, as permitted in AASHTO PP78-17. This would provide a rigorous-yet-practical, mixture-centric alternative to the primary method suggested in AASHTO PP78-17 (arbitrary VMA bump plus extraction, recovery and advanced binder testing/analysis to obtain ΔTc). The use of a mandatory VMA bump specified in AASHTO PP78-17 should be revisited and, if deemed appropriate, dropped. Rather, the mix designer should be given the flexibility to lower the void target, increase VMA, etc., for RAP or RAS mixes, as needed to pass mixture performance test result criteria.

The extension of this approach to modern, heterogeneous mixtures with RAP, GTR, and other components/additives is suggested by the results obtained in this study as well as others studies (Buttlar et al., 2019; Rath et al., 2019; Buttlar and Wang, 2016). Currently, RAP and RAS mixtures are designed using different principles by most agencies, for instance, using a binder availability approach or VMA bumping plus advanced binder testing for RAS, but not RAP mixes. The approach explained herein provides a simple, unified design system involving classic mixture volumetric calculations with recycled materials, along with high and low temperature performance tests. The designer may wish to target a slightly lower design air void level for high ABR mixes, perhaps 3.0 or 3.5%, applying this principle for mixtures containing both RAP and RAS.

6 Field Observations

In 2014, a 2.5” lift of N30 surface course was paved as an overlay on an existing pavement at a pavement recycling facility in Pulaski, Illinois, near Chicago. The mixture featured nearly two-thirds (66.2%) ABR, which achieved by using 45.3% RAP and 7.5% RAS in the mixture. A very soft base binder (PG 46-34) was used to offset the stiffness imparted by RAP and RAS, and the mixture was designed at 3% air voids to enhance durability. Bracketed performance testing was added to the mix design stage, which involved the aforementioned Hamburg and DC(T) tests. After three years in service, three specimens were fabricated from field cores and tested at -12°C using the DC(T) fracture test to evaluate residual thermal cracking resistance in this highly recycled mixture. The DC(T) reported an average fracture energy of 564 J/m^2, with a coefficient of variation of 6.0%, which easily met the 460 J/m^2 threshold for medium-traffic roads (Marasteanu et al., 2012). A visual examination of the 250-meter test section (Fig. 4) revealed only one transverse crack and two localized areas of load-induced cracking, both likely caused by reflective cracking mechanisms. The section receives heavy truck loading, as fully loaded trucks enter and leave the asphalt and concrete recycling center at regular intervals, carrying 20 or more tons of payload.

A study conducted by Buttlar (2014) investigated 12 mixtures placed in locations with low, medium, and high traffic levels and varying age (between 1 and 7 years of service) around Chicago and northern Illinois (Buttlar, 2014). Of the 12 mixtures, six mixtures contained both RAP and RAS, while four contained only RAP recycling content and two used only virgin materials. Similar trends in DC(T) fracture energy values, as measured from field cores taken in 2014 were found, and similar field cracking performance of the various mixture investigated was observed in 2014 field performance evaluations. This demonstrates that careful design of mixtures with RAS can lead to good performing, highly sustainable pavement surfaces, even in demanding climates such as the Midwest United States. The long-term performance of these and more newly constructed sections will continue to be monitored.

The performance-engineering mix design approach presented herein is being formalized and specified in various agencies in the Chicago area and Midwest, and appears to provide mix designers and agencies a reliable approach for designing innovative asphalt mixtures with higher recycling levels, and moreover, modern, mixtures with heterogeneous binder and mixture compositions.

Fig. 4 Surface condition of Pulaski test site in July 2017, after 3 years of service.

7 Summary and Conclusions

This study evaluated mixture designs and performance results for virgin, 2.5% and 5.0% RAS modified asphalt mixtures, which allowed evaluation of the binder availability concept. The test results also demonstrated a robust and attractive mix performance testing approach that can be accomplished by following an allowed provision in the recently approved AASHTO PP78-17 document. A careful volumetric mix design process was used, involving binder extraction and recovery of RAS binder and RAS pulp, along with careful blending and volumetric analysis of virgin and recycled mixtures. Performance testing in the Hamburg wheel tracking and DC(T) device was performed, and field performance data was presented. Several conclusions can be drawn from the findings reported herein:

1. The asphalt binder available from RAS was found to be approximately 100%. This result was

arrived at by creating mixture designs with equal VMA, VFA, and P_{be} and virtually identical total asphalt contents. This supports the decision to drop the binder availability concept in the new AASHTO PP78-17 document.

2. The inclusion of RAS led to improvements in Hamburg wheel tracking performance. In particular, relatively weak virgin aggregates such as those used in this study benefitted from the inclusion of RAS to meet the wheel tracking requirements.

3. RAS mixtures met and exceeded the 460 J/m^2 requirement from DC(T) testing for low and medium traffic roads, and exceeded the fracture energy of the PG64-22 control mixture, with the use of a PG 58-28 virgin binder (softer base binder). The RAS mixtures in the current study were the only mixtures which passed the bracketed performance thresholds set for Hamburg and DC(T) tests.

4. This study also serves to demonstrate a balanced mix design approach that is being formalized and now specified in various agencies in the Chicago area and Midwest. This appears to provide mix designers and agencies a reliable approach for designing innovative asphalt mixtures with higher recycling levels, and moreover, those with modern, heterogeneous binder and mixture compositions. This also serves as a simpler, and more mixture-centric alternative to the primary method suggested in AASHTO PP78-17, which entails arbitrary VMA bumping plus binder extraction, recovery, and advanced binder testing to obtain ΔTc.

In light of these findings, it is recommended that the next revision of AASHTO PP78 be revised to give priority to the mixture performance-based design approach over the arbitrary VMA bumping and advanced binder testing approach, and not vice-versa. The use of a mandatory VMA bump should also be dropped; rather, giving the mix designer flexibility to lower the void target, increase VMA, etc., for RAS mixes, as guided by mixture performance tests. In addition, it is recommended that designers of modern, heterogeneous asphalt mixes containing RAP, RAS, GTR, and other additives begin to employ modern mixture performance tests as a supplement to volumetric mix design, and that, uniform procedures be developed. Currently, RAP and RAS mixtures are designed using different principles by most agencies, for instance, using a binder availability factor approach or VMA bumping plus advanced binder testing for RAS, but not RAP mixes. The approach explained herein provides a simple, unified design system involving classic mixture volumetric calculations in the design of mixes with recycled materials, along with high and low temperature performance tests. The designer may wish to target a slightly lower design air void level for high ABR mixes, perhaps 3.0 or 3.5%, applying this principle in an identical fashion for mixtures containing RAP and/or RAS.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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