Mechanical characterization of asphalt tear-off roofing shingles in Hot Mix Asphalt

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Highlights

- Investigation on physical properties of the extracted binder from the tear-off shingle.
- Evaluation of mechanical performance of shingle-mixed HMA.
- Development of an optimum mix design for the shingle-mixed HMA.

Abstract

In the USA, asphalt tear-off roofing shingle is one of the largest productions in the municipal solid waste (MSW) stream. Applications into road construction materials can be an alternative to recycle these tear-off shingles. This paper discusses the beneficial use of tear-off shingles in Hot-Mix Asphalt (HMA) by presenting: (1) the physical properties of tear-off shingles and the extracted binder, (2) the mechanical behaviors and properties of shingle-mixed HMA, (3) an optimum mix design for the shingle used in HMAs. The tear-off shingles obtained from the states of Florida and Minnesota (but main study on the Florida’s shingles) were used for the sample preparation that involves varied amount of shingle addition (ranged from 0% to 6% with 1% increment) for three different virgin binder contents. Laboratory testing methods include a reflux extraction and recovery and penetration tests for the extracted binder and a modified Marshall stability, moisture susceptibility, and asphalt pavement analyzer (APA) tests for the mixtures. The shingle addition causes stiffer binder in the mixture, resulting in the increase of material stiffness, stability, and rutting resistance. A visual inspection of the fractured surface of samples was also conducted to investigate the location of the crack surface either through the aggregates or in the asphalt binder, which is a good indicator of sufficient level of asphalt film in the mixture. Testing results were used to identify the optimum mixing proportion of the tear-off shingle and asphalt binder in HMAs.

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1. Introduction

Construction wastes are defined as the wastes from the construction, repairing, and remodeling of residences, buildings, and other civil infrastructures and demolition wastes are defined as the wastes from razed buildings [1–8]. Construction and demolition wastes frequently constitutes between 15% and 20% of municipal solid wastes (MSW) in Taiwan [3,9]. Bossink and Brouwers [10] reported that these amounts vary from 13% to 29% worldwide. In general, the construction demolition and debris (C&D) wastes includes asphalt shingle, dirt, bricks, stones, blocks, gypsum wallboard, glass, steel, concrete, plastics, plumbing, heating and electrical parts [2,11,12].

In the US, approximately 11 million tons of asphalt shingle waste (out of about 250 million tons of MSW) is generated each year and it consists of roughly 90% representing post-consumer scrap (or tear-off shingles) and 10% comprising post-manufacture scrap [13–15]. California is one of highly shingle generating states and approximately produces 1.2 million tons per year, and 1.1 million are tear-off shingles from reroofing jobs [16]. Most roofing shingle scrap has been disposed by landfilling. Estimates of the cost for disposing shingles in a landfill may be between $18 and $60 per ton [17]. These shingle materials are composed of crushed aggregate, high viscosity asphalt, fillers, and fibers. These components may be beneficial to the production of HMA pavements. Vermont Agency of Natural Resource [18] reported that benefits of recycling asphalt shingles include reduced cost in the HMA production, potentially lower disposal costs for shingle scrap
manufacturers, and conservation of landfill space and virgin asphalt material. Dan Krivit and Associates [19] developed a best management practices manual for recycling asphalt shingles. There are two types of roofing shingle scraps: (1) manufacturer scrap (or called as roofing shingle tabs) and (2) tear-off roofing shingles. Manufacturer scraps are generated during production by trimming new asphalt shingles to required sizes or from “out-of-specification” shingles. These scraps created during the manufacturing process are generally uniform and homogenous. These materials typically contain 20–30% asphalt cement. The content can be certified and free of debris [20]. On the other hand, tear-off roofing shingles are typically generated from construction, demolition, or renovation and replacement of existing roofs. The quality of tear-off roofing shingles can vary and the tear-off shingles may contain debris such as nails, wood, paper, and plastic that is removed through processing and is quite variable in quality and composition [21]. The aggregate in roofing shingles can be lost due to weathering process over their service life. As a result, tear-off shingles generally include more than 30% asphalt by weight. The aged binder in tear-off shingles is likely harder and more brittle compared to the manufacturer scrap, but the tear-off shingle is easier to shred [22].

In Florida, construction and demolition (C&D) debris were produced about 6.6 million tons in 2009 and about 2 million tons were recycled [23]. Fig. 1a shows the components of C&D produced in Florida. It was estimated that about 7% (weight basis) of C&D debris consists of asphalt shingles and the majority consists of materials removed from roofs (tear-off shingles). Assuming the asphalt content of 20% from the processed shingles, the addition of 5% shingles may contain debris such as nails, wood, paper, and plastic that is removed through processing and is quite variable in quality and composition [21]. The aggregate in roofing shingles can be lost due to weathering process over their service life. As a result, tear-off shingles generally include more than 30% asphalt by weight. The aged binder in tear-off shingles is likely harder and more brittle compared to the manufacturer scrap, but the tear-off shingle is easier to shred [22].

The objective of this study is to understand the current status of asphalt shingle recycling and to evaluate the beneficial uses of tear-off shingles in HMA applications. The conducted research consists of following five tasks: (1) literature review on the beneficial use of roofing shingles in HMA, (2) the characterization of a physical property of extracted binder from the obtained tear-off shingles, (3) HMA mixture designs with and without shingles, (4) the evaluation of engineering properties (i.e. strength, moisture susceptibility, and rutting resistance) of the HMA mixtures, and (5) the determination of the optimum mixture design for the shingle–combined HMAs. One of the research scopes was to investigate the effect of shingle addition on mixture’s mechanical properties as the shingle addition increases, thus a softer asphalt binder of PG 52–28 was used in this research to better observe the stiffness change, which is more suitable being used in colder regions such as the states of Alaska and Minnesota. Study on the influence of stiffer binder (i.e. PG 67–22) is underway so that an optimum PG can be identified for the shingle use but the findings are not included in this paper due to the out of scope.

2. Review on shingle studies

Due to the existence of bitumen in shingles, using these shingle materials in HMA is a good application to save the amount of virgin binder. Although several previous studies have shown the satisfying results with respect to the mechanical behavior of shingle–combined HMA, many highway authorities have not formally approved the shingle in HMA applications. Table 1 shows the list of states in the US that allow the use of recycled shingles as pavement materials and also their material specifications for the use of shingle in HMAs.

Sengoz and Topal [15] evaluated the performance behavior of HMA when post-manufactured shingles (or manufacturer scrap) were added. Based on the results of Marshall stability and flow testing, it was concluded that adding more than 1% of shingle would result in a reduction of Marshall stability and the asphalt mixture with 1% shingle exhibited good flow resistance. Hansan et al. [24] also reported that using manufacturer scraps in HMA improves the rutting resistance of the mixture and results in cost savings in road paving projects by reducing the asphalt binder demand and shingle disposal. Janisch and Turgeon [25] investigated the in situ performance of HMA containing manufacturer scraps. The in situ pavement exhibited good condition after 6 years of the construction but the air voids of in-place test sections are 4% greater than the specification of Minnesota DOT. In addition, laboratory testing results showed no significant difference in moisture resistance between conventional and shingle–combined HMAs.

On the other hand, the beneficial uses of tear-off shingles have been investigated. Newcomb et al. [26] investigated the effects of both tear-off shredded shingles and manufacturer scraps in HMAs. In the study, the percentages of shingle addition were 0%, 5% and 7.5% by the weight of aggregate. It was found that adding 5% and 7% shingle could reduce the optimum binder content by 10%
and 25%, respectively. In addition, using post-manufactured fiber-glass shingle in HMA can increase the tensile strength of mixtures. Maupin [27] reported that the volumetric properties of HMA containing tear-off shingles met the specification of Virginia Department of Transportation (VDOT) and their rutting resistance is comparable with conventional HMA mixtures. The results of fatigue tests on the tear-off RAS-mixed HMA also exhibited satisfactory performance compared with the conventional HMA s. The Polk County Waste Resource Management Division for Florida Department of Environmental Protection (FDEP) studied economical benefits of using the tear-off shingles [28]. This report addressed that 7% of construction and demolition (C&D) debris in the state of Florida is tear-off shingle and using the shingle in HMA can reduce the amount of virgin binder demand, resulting in significant cost savings.

3. Materials descriptions

3.1. Asphalt binder

The asphalt binder commonly used in the state of Florida is PG 67-22 so that the high viscosity minimizes rutting. Adding tear-off shingles to HMA mixtures increases the stiffness of the total binder in the mixture because the shingle includes more aged binder. Along with the added shingle, PG 67-22 may be too stiff to observe changes in the mechanical behavior of the mixtures, thus less viscous binder of PG 52-28 was used in this study to better characterize the effect of the shingle.

3.2. Aggregates

Aggregates used in this study were from three different limestone stockpiles produced by a local supplier in Orlando, Florida. The first, second, and third stockpiles involve the maximum sizes of 19 mm, 2.36 mm, and 0.6 mm, respectively. A sample from each stockpile was tested according to the sieve analysis (ASTM C 136 [29]). Aggregate blending has been made so that the aggregate meet the criteria of Superpave method. The blend was composed of 50% large-size coarse aggregate, 30% small-size coarse aggregate, and 20% fine aggregate (sand). Bulk and apparent specific gravity of aggregate was determined based on ASTM C 127 [30] (for coarse aggregates) and ASTM C 128 [31] (for fine aggregates), respectively. The results were used to determine the effective specific gravity of both coarse and fine aggregates. By multiplying appropriate coefficient of bulk specific gravity (based on job mix formula) the overall bulk specific gravity of aggregate was calculated as Gb = 2.455. To determine bulk and apparent specific gravities, two repetitions were tested based on quartering method.

3.3. Asphalt roofing shingles

Manufacturer scraps tend to have more uniform properties while tear-off shingles are generally harder and more brittle and typically include asphalt content more than 30%. Table 2 shows the typical physical properties of recovered asphalt binder and the gradation of mineral particles from post-manufacturing shingle scrap. Asphalt binder in old roofing shingles undergoes oxidative age hardening and stearic hardening. The stearic hardening is a hardening process in which solid compounds separate from volatile oils in the asphalt cement. The stearic hardening process can be reversible by reheating and solubilizing, oxidative aging cannot be reversible [32]. As a result, the asphalt binder in older tear-off shingles is harder than the asphalt in manufacturer scrap.

4. Plan of laboratory testing

Laboratory testing was performed to evaluate the effect of tear-off shingles on the engineering properties of HMA mixtures. The testing plan includes the following steps.

Step 1. Extract asphalt binder from the tear-off shingles and measure its penetration property

This section includes reflux extraction (ASTM D 2172 [33]) and rotary evaporator (ASTM D 5404 [34]) methods. Solvent vapor generated by hot plate passes through the mixture placed in two wired mesh cones. After the extraction, asphalt binder was separated from its solvent using the rotary evaporator. Due to the high stiffness of the extracted binder, the penetration test was feasible.

Step 2. Perform the Superpave method and determine the optimum binder content

The optimum binder content for control mixtures (0% shingle) was determined so that the range of virgin binder content is determined for the shingle combined HMA mixtures. This task involved several standard procedures of AASHTO T84 [35], AASHTO T85 [36], ASTM D 2726 [37], and ASTM D 2041 [38] and concluded that the optimum binder content is 5.77% for targeting 4% air void. The binder at 5.77% was used for the control mixtures.

Step 3. Prepare the Superpave gyratory pills containing 1–6% tear-off shingles

To evaluate the effect of tear-off shingle on the Superpave HMA, the shingle ranged from 0% to 6% with 1% increment was added to the HMA mixtures.

Step 4. Modify the Marshall apparatus for the Superpave gyratory pills

Marshall stability testing is simple and quick, and it was used as a mixture performance test in this study. The Marshall testing apparatus designed for the Marshall method was modified by installing 6-in. diameter breaking head so that Superpave gyratory pills are tested. In addition, new data acquisition system was installed to monitor the load–displacement curve at smaller sampling rate (10 Hz).

Step 5. Characterize the mechanical properties of shingle combined HMA mixtures

Three sets of shingle-mixed HMA samples were prepared at 5.77%, 4.77% and 3.77% binder content. The Florida shingle was added from 0% (control sample) to 6% by the weight of aggregate with 1% incremental rate. Three identical samples were made for each mix. Testing was conducted based on ASTM D 6927 [39]. Sampling rate at 10 Hz was used while the load was applied at the rate of 2 in/min.
Typical physical properties of recovered asphalt cement and gradation of recovered mineral material from manufacturing shingle scrap [41].

<table>
<thead>
<tr>
<th>Properties</th>
<th>Manufacturing scrap (new organic felt)</th>
<th>Manufacturing scrap (new fiberglass felt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder content (%)</td>
<td>Approx. 28%</td>
<td>Approx. 28%</td>
</tr>
<tr>
<td><strong>Binder Properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Softening point, °C (°F)</td>
<td>52–102 (125–215)</td>
<td>52–102 (125–215)</td>
</tr>
<tr>
<td>Penetration, dmm (25 °C)</td>
<td>23–70</td>
<td>23–70</td>
</tr>
<tr>
<td>Ductility, cm (5 cm/min, 25 °C)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Flash Point, °C (°F)</td>
<td>&gt;260 (500)</td>
<td>&gt;260 (500)</td>
</tr>
<tr>
<td>Cumulative percent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passing</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>4.75 mm (No. 4)</td>
<td>69</td>
<td>69</td>
</tr>
<tr>
<td>2.36 mm (No. 8)</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>1.0 mm (No. 20)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>0.63 mm (No. 50)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0.3 mm (No. 100)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.15 mm (No. 100)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Step 6. Investigate the moisture susceptibility by indirect tensile testing

Indirect tensile testing (ASTM D4867 [40]) was conducted to investigate the moisture susceptibility of HMA mixtures with and without shingles. Two sets of HMA specimens were made containing 4.77% and 3.77% virgin asphalt binder. Amount of added shingle was 0%, 3%, and 6% by the weight of aggregates and no anti-strip materials were used. These tests provide the ratio of peak load of wet-conditioned subset to dry one expressed as Tensile Strength Ratio (TSR).

Step 7. Evaluate rutting resistance by asphalt pavement analyzer (APA)

Total six samples were made containing the shingle from 1% to 6%. The virgin binder content of 4.77% (optimum binder content for the shingle-mixed HMAs) was used for all six samples. APA testing was conducted following AASHTO TP 63–03. With 6-inch diameter HMA specimen with 4 ± 1% air voids, rutting performance can be evaluated after 8000 cycles of wheel-load repetition.

5. Testing results

5.1. Extraction and recovery of binder from roofing shingles

The asphalt binder was extracted from the tear-off shingles and the asphalt content and its property were measured. Four shingle samples were tested and its average asphalt content was 34.77% (see Table 3). In general, new shingles (manufacturer scrap) involve 20–30% asphalt content while tear-off shingles include 30–40% asphalt content. This 34.77% asphalt content falls within the typical asphalt content of 30–40% for the tear-off shingles and a large variation is also observed. The high percentage of aged binder in the tear-off shingle is potentially beneficial to the HMA mixtures especially in warmer regions. The aged binder increases the overall stiffness of asphalt binder in HMA and results in increasing rutting resistance. In the meantime, using the recycling materials will reduce the demand of virgin (or liquid) asphalt. The extracted binder was too stiff to conduct other binder tests except a penetration test. Considering high pavement temperature during the summer in Florida, the researchers performed the penetration tests at different temperatures of 45 °C and 60 °C. The results of penetration testing are shown in Table 3. The results indicate that tear-off shingles are much stiffer than manufacturer scraps of which penetration is in the range of 23–70 dmm.

5.2. Mixture designs: Marshall stability and flow testing

Although state-of-art testing technologies have been introduced over a decade, the Marshall stability and flow testing device is still a powerful tool as a performance testing device which estimates the structural capacity and rutting resistance of bituminous materials. Marshall stability and flow testing is simpler and quicker compared to newer mixture testing methods such as Superpave IDT or Dynamic Modulus tests that require more sophisticated labor skills in preparing a specimen and setting and operating the test. Moreover, most highway agencies keep this testing device and still utilize it. For a large amount of samples to be tested, Marshall testing can provide a quick assessment of finding the optimum amount of shingle to be added into HMAs. In addition, the results of Marshall stability testing were used to identify the mixture designs for further investigations (moisture susceptibility and APA tests).

In this project, the mixtures were made following the Superpave method, resulting in 6-in. diameter HMA specimens (or called as gyratory pills). The stability and flow values of these gyratory pills were determined by using the modified Marshall apparatus that accommodates 6-in. diameter breaking head. Table 4 shows the results of the mix design for the shingle addition from 0% to 6% as well as the virgin binder content of 3.77%, 4.77%, and 5.77%. The testing results are graphically shown in Fig. 3. The performance of Florida and Minnesota shingles are also compared in Fig. 4.

As the percentage of the tear-off shingle increases, the observations from Table 4 are summarized as below:

- For a given virgin binder content, the Marshall stability increased with increasing the shingle. The maximum stability for each set was observed at 6% shingle. The mixture with 6% shingle at 3.77% virgin binder resulted in the maximum stability of 78.6 kN.
The Marshall flow slightly increased. Due to the large variation, it is difficult to draw a clear conclusion from the flow result. However, in general, flow values show an upward trend with increasing the shingle.

The Marshall quotient (stability/flow) is an indicator of stiffness and it also increased. Figs. 3 and 4 show the load–displacement curves of the Marshall test with the Florida shingle at 5.77%, 4.77%, and 3.77% and it clearly indicates the mixtures become stiffer with increasing the shingle.

Florida shingles show higher stability and stiffer slope than Minnesota shingles (see Fig. 4). Aging of asphalt binder in hot climate regions may cause stiffer binder in the shingles.

### 5.3. Indirect tensile testing

Indirect tensile tests were performed to evaluate the effect of shingle on the moisture susceptibility of HMA mixtures. Anti-strip was not used to better observe the effect of shingle in the dry- and wet-conditioned specimens. Testing results are shown in Table 5. The results indicated that samples with 4.77% binder content had higher strength compared to the other set with 3.77% binder content. Compared to the control mixtures (samples with 0% shingle), adding 3% and 6% shingles to the HMA mixtures at 4.77% binder content increased the tensile strength ratio (TSR) by 53% and 61%, respectively. The Supersave specifications address that the TSR should not be less than 0.8 and the samples with lower TSR are considered as unacceptable mixtures. All sample sets with 3.77% binder content did not meet the requirement although TRS values increase with increasing the shingle. The maximum TSR was observed for the sample set with 4.77% binder content and 6% shingle, and was equal to 0.855 which is above the minimum acceptable value of 0.8. The sample set with 4.77% binder content and 3% shingle did also meet the criteria with a 0.826 TSR value. TSR values of the moisture susceptibility test are shown in Fig. 5.

In addition, after the completion of IDT tests, the fractured surfaces of HMA mixtures were investigated to evaluate bonding between aggregate and binder. This bonding condition determines the location of the failure plane under indirect tensile loads. Fig. 6 shows the fractured surface for the specimens at 3.77% and 4.77% binder content. With 3.77% binder content, all specimens containing the shingle from 0% to 6% illustrated that the fracture surface occurred between aggregates and binder and the aggregates (shown as white spots in the figure) are not clearly observed. On the other hand, the dry samples at 4.77% binder content (see Fig. 6b) shows many white spots in the fracture surface because the failure occurred through the aggregates. As shown in Fig. 6c, the wet samples at 4.77% showed some of aggregate breakage in the fracture surface but its bonding condition appears poorer than the dry samples at 4.77%.

### Table 3
Properties of recovered asphalt binder from roofing shingles.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Sample 4</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt content (%)</td>
<td>46.96</td>
<td>32.36</td>
<td>35.54</td>
<td>24.23</td>
<td>34.77</td>
</tr>
<tr>
<td>Penetration at 25 °C</td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Trial 3</td>
<td>Trial 4</td>
<td>Average</td>
</tr>
<tr>
<td>2 dmm</td>
<td>2 dmm</td>
<td>1 dmm</td>
<td>1 dmm</td>
<td>1.5 dmm</td>
<td>1.5 dmm</td>
</tr>
<tr>
<td>Penetration at 60 °C</td>
<td>4 dmm</td>
<td>5 dmm</td>
<td>6 dmm</td>
<td>5 dmm</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4
Results of Marshall stability and flow tests.

<table>
<thead>
<tr>
<th>Added shingle (%)</th>
<th>3.77% Virgin binder</th>
<th>4.77% Virgin binder</th>
<th>5.77% Virgin binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability (kN)</td>
<td>Avg. stability (kN)</td>
<td>Flow (mm)</td>
<td>Avg. flow (mm)</td>
</tr>
<tr>
<td>0</td>
<td>41.5</td>
<td>38.6</td>
<td>4.9</td>
</tr>
<tr>
<td>1</td>
<td>46.6</td>
<td>42.6</td>
<td>5.5</td>
</tr>
<tr>
<td>2</td>
<td>52.1</td>
<td>45.1</td>
<td>5.0</td>
</tr>
<tr>
<td>3</td>
<td>53.3</td>
<td>54.2</td>
<td>5.5</td>
</tr>
<tr>
<td>4</td>
<td>70.4</td>
<td>61.5</td>
<td>4.9</td>
</tr>
<tr>
<td>5</td>
<td>70.5</td>
<td>76.9</td>
<td>5.1</td>
</tr>
<tr>
<td>6</td>
<td>79.8</td>
<td>79.6</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Note: 1 decimilimeter (dmm) = 0.1 mm.
5.4 Rutting test

Rutting test was performed by using the Asphalt Pavement Analyzer (APA) based on AASHTO T 340-10. The APA is designed to evaluate the rutting resistance of HMA mixtures. Constant moving loads were repeatedly applied onto the top a gyratory pill through a pressurized hose. This cylindrical test specimen was 150 mm in diameter and 115 mm in height. The target air void range was 4% ± 0.5%. The procedure of APA testing used in this study is summarized below:

1. Preheat the specimens (gyratory pills) in the APA chamber at 64°C (147°F) with a minimum of 6 h but not more than 24 h prior to the test.
2. Pressurize the hose to 100 ± 5 psi.
3. Calibrate each wheel with the load cell to read a load of 100 ± 5 lbs.
4. Secure the preheated specimen in the APA, close the chamber doors and allow about 10 min for the temperature to stabilize.
5. Apply 25 load cycles and measure the initial reading.
6. Place the specimen back to the APA chamber and allow about 10 min for the temperature stabilizing.
7. Restart APA testing and continue the load repetition up to 8000 cycles.

The difference between the initial and final rut depth were calculated and averaged. The result of APA test is presented in Table 6. Testing results shown in Fig. 7 indicate that rut depth decreases with increasing the amount of tear-off shingle in the mixtures. The average rut depth for the control sample (0% shingle) was 3.7 mm after 8,025 cycles while the averages of rut depth for 3% and 5% RAS are 2.9 mm and 1.4 mm, respectively. This decrease in rutting depth is due to the increase of stiffer binder contributed by the shingle to the HMA. Increasing the amount of RAS in the HMA decreases the rut depth with a given load repetition.

6. Discussion

This study aimed at evaluating the effects of tear-off roofing shingle in HMAs by investigating three key performance criteria of stability, moisture resistance, and rutting resistance. The key observation through testing results is that higher stability values occur with higher shingle added and lower virgin asphalt content but a lack of virgin asphalt content exhibited weak moisture resistance. Our findings suggest that the optimum binder content is 4.77% and the tear-off shingle can be added up to 6% in HMAs.

The beneficial use of tear-off asphalt shingle in HMAs can be explained by the aged binder in the tear-off shingle. First of all, considering the optimum binder content of 5.77% with no shingle, adding shingle may cause “overflow” of binder in the mixture. For a given amount of the shingle, increasing virgin binder content allows for easier movements (“lubricating” effect) and results in the stability reduction. Second, unlike the findings of Sengoz and Topal (2004) [15] utilizing post-manufacturer scrap in HMAs, the addition of tear-off shingle up to 6% increases the stability of HMA mixtures and also rutting resistance. Over the service life of roofing shingle (about 10 to 15 years), the shingle has gone through more weathering and aging, resulting in higher viscosity. This can explain the test result that Florida’s shingle exhibits higher stability than Minnesota’s shingle because of higher temperature and heat radiation in Florida than those in Minnesota. Lastly, for a decent amount of virgin asphalt binder given, the aged binder of the shingle may fill in inter-aggregate with higher viscosity, resulting in improved moisture resistance in HMAs. The use of tear-off shingles would be more beneficial to lower PG binders.

In this study, fatigue cracking performance of the tear-off shingles was not evaluated. Although the shingle has demonstrated significant improvements in stability and rutting performance as well as material savings, the aged binder in the shingle has potential of fatigue cracking issue. Therefore, the recommendations from this study are the continued study on: (1) evaluation of the fatigue performance of the shingle-combined HMAs and (2) their fracture-mechanics properties and behaviors at varied temperature. Another research recommendation is that combination of tear-off shingles and waste aggregate (i.e. crushed concrete aggregate, bottom ash, etc.) be used in HMAs. In general, these waste aggregates contain higher porosity (referred as light weight aggregate) and requires...
higher amount of asphalt content because of its higher binder absorption. Considering significant amount of binder in the tear-off shingle (about 35% in this study), the use of tear-off shingles can reduce significant amount of virgin asphalt binder content without sacrificing overall mechanical performance; rutting performance would be enhanced. As a result, reusing tear-off shingles can enable low construction budget as well as sustainable transportation infrastructure.

7. Summary and conclusions

Different percentages of shredded tear-off shingles were added into the HMA mixtures and its effect on the mechanical behavior was evaluated by several laboratory testing methods. The optimum design for the shingle-combined HMA mixtures was evaluated. Through the Superpave method, it was found that the optimum binder content is 5.77% for the mixture without shingle.

Table 5

<table>
<thead>
<tr>
<th></th>
<th>3.77% Virgin asphalt binder</th>
<th>4.77% Virgin asphalt binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample's condition</td>
<td>Tensile strength (kPa)</td>
<td>Ave. tensile strength (kPa)</td>
</tr>
<tr>
<td>0% Shingles Dry</td>
<td>463.6</td>
<td>488.7</td>
</tr>
<tr>
<td>Wet</td>
<td>503.5</td>
<td>498.8</td>
</tr>
<tr>
<td></td>
<td>120.1</td>
<td>147.3</td>
</tr>
<tr>
<td>3% Shingles Dry</td>
<td>1121.7</td>
<td>1173.8</td>
</tr>
<tr>
<td>Wet</td>
<td>1137.7</td>
<td>1262.0</td>
</tr>
<tr>
<td></td>
<td>583.9</td>
<td>516.5</td>
</tr>
<tr>
<td>6% Shingles Dry</td>
<td>1242.2</td>
<td>1155.5</td>
</tr>
<tr>
<td>Wet</td>
<td>1151.7</td>
<td>1072.5</td>
</tr>
<tr>
<td></td>
<td>1072.5</td>
<td>790.8</td>
</tr>
</tbody>
</table>

Note: TSR = tensile strength ratio.
In the sample preparation, the shingle from 0% to 6% was added with 1% increment at three virgin binder contents of 5.77%, 4.77%, and 3.77%. In addition, moisture susceptibility and rutting performance of the shingle-combined HMA specimens were evaluated. Findings from this study and conclusions from the findings are summarized as below.

- The average asphalt binder extracted from the tear-off shingle is 34.77% which falls into a typical range of 30–40%. The average penetration depth is 1.5, 2, and 5 dmm at 25°C, 45°C, and 60°C, respectively while the typical range of manufacturer scrap is between 23 and 70 dmm at 25°C.
- The stability and flow values increase with increasing the shingle at a given virgin binder content. The maximum stability appears with the mixture with the 3.77% virgin binder and 6% shingle. The slope of linear portion of the load–displacement curve (indicator of mixture stiffness) increases with the shingle addition. The steepest slope was observed in the mixture with 6% shingle and 3.77% virgin binder.
- In the comparison of Florida and Minnesota shingles, the Florida shingle shows higher stability and stiffness. Florida's climate condition may cause more binder aging, resulting in the stiffening of the asphalt binder in the shingle over their service life.
- The TSR ratio increases with increasing the shingle amount. The visual inspection in the fracture surface indicates that 3.77% binder content does not provide sufficient coating for the aggregate.
- APA testing results show that rutting resistance increases with increasing the shingle. Adding 5% shingle (FDOT's maximum) decreases its average rut depth from 3.7 mm to 1.4 mm after about 8000 load cycles.

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- The Superapve method provides the optimum binder content of 5.77% without the shingle. Adding the tear-off shingle up to 5% may reduce the optimum virgin binder content from 5.77% to 4.77%.

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