ABSTRACT

The type, shape, and gradation of aggregate have significant influence upon surface texture and its durability. The properties of reclaimed asphalt pavement (RAP) are different from virgin aggregate. Previous research found that the presence of RAP influenced negatively the pavement surface terminal friction value and surface polishing rate. The objective of this research is to assess the impact of high content of RAP on pavement surface texture after five years of environmental and traffic loading.

Field pavement textures were measured on sections with various percentages of RAP. The sections have been in service for five years at the time of testing. The three-dimensional (3D) surface texture is recovered by using a portable line-laser scanning device which has the ability to scan an area of 100 mm \times 100 mm of pavement surface with a horizontal resolution finer than 0.05 mm, and vertical accuracy better than 0.1 mm. The recovered 3D texture heights are decomposed into five levels by using discrete wavelet transform to separate macro-texture from micro-texture. 3D texture indices were calculated and analyzed. These 3D texture parameters are indices of texture size both at macro-level and micro-level, spacing, distribution, and texture direction. Texture analysis showed that the macro-texture indices were better for sections with high RAP content than those with low RAP content at the time of testing, while micro-texture parameter shows equal or slightly higher value compared to control mixture. It was also found that the texture durability was slightly worse for high RAP content (50\%) sections than those of lower RAP content sections.

Pavement core samples were collected and characterized through creep compliance, indirect tensile test and resilient modulus. Laboratory results showed that as the amounts of RAP increases the rutting resistance increases, however, the resistance to low temperature cracking decreases as expected.

Key words: Reclaimed asphalt pavement (RAP), macro-texture, micro-texture, three-dimensional texture indices, laser scanning technique, asphalt core test.

INTRODUCTION

Use of recycled asphalt pavement (RAP) in asphalt pavement is generally accepted and extensively used in asphalt pavement construction. Numerous studies (Shu et al. 2008, McDaniel et al. 2012, Mogawer et al. 2012) found that dynamic modulus, resilient modulus and indirect tensile test usually increase by increasing RAP. Increase in RAP content results in increase in stiffness of the asphalt mixture due to the influence of aged binder. Other studies (McDaniel et al. 2000, Silva et al. 2012, Karlsson and Isacsson 2006) showed that an asphalt mixture resistance to rutting improves especially at intermediate and high temperature as amount of RAP increases in hot mix asphalt (HMA). Kowalski et al. (2010) investigated the influence of RAP on pavement surface friction by evaluating the polishing properties of laboratory specimens. Very limited documentation is available regarding the impact of RAP on pavement surface texture.
In this research, pavement texture was measured by using a portable line-laser scanner to recover the surface texture in three-dimensional (3D) manner. The recovered 3D texture heights were decomposed into five levels by using discrete wavelet transform to separated macro-texture from micro-texture. 3D texture indices were calculated and analyzed for the tested pavement sections including various percentages of RAP.

The test sections were part of a study which evaluated the effect of high RAP content on pavement performance (Hajj et al. 2011). The mixtures contained 0%, 15%, and 50% RAP. The virgin binder of three out of the four tested sections had a performance grade of PG 58-28 (specified as penetration grade 150-200); the other section was constructed with a softer binder PG 52-34 (specified as penetration grade 200-300) to alleviate the effect of high aged RAP binder.

PAVEMENT SURFACE TEXTURE MEASUREMENTS AND ANALYSES

Test Site

The tested pavement sections were constructed in September 2009 on provincial truck highway (PTH) 8 between Gimli and Hnausa in Manitoba, Canada. The pavement consisted of two 2-inch lifts with conventional HMA and various percentages of RAP as shown in Table 1. The aggregate gradations are shown in Figure 1. The traffic information of the pavement was provided by Manitoba Infrastructure and Transportation and is shown in Table 2.

Strict quality control measures were in place during the construction of these test sections. The same hot plant, truck type, paver, crews, and compaction equipment were employed for all the sections. Identical compaction effort was applied to all the test sections (Hajj et al. 2011).

**TABLE 1** Tested Pavement Sections with Various Percentages of RAP and Different Binder

<table>
<thead>
<tr>
<th>Section</th>
<th>RAP content (%)</th>
<th>Virgin binder used</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%RAP</td>
<td>0</td>
<td>Pen 150-200 (PG 58-28)</td>
</tr>
<tr>
<td>15%RAP</td>
<td>15</td>
<td>Pen 150-200 (PG 58-28)</td>
</tr>
<tr>
<td>50%RAP</td>
<td>50</td>
<td>Pen 150-200 (PG 58-28)</td>
</tr>
<tr>
<td>50%RAP200</td>
<td>50</td>
<td>Pen 200-300 (PG 52-34)</td>
</tr>
</tbody>
</table>

**FIGURE 1** Aggregate gradation of tested sections.
TABLE 2 Traffic Information of Tested Pavement Sections (Source: Hajj et al. 2011)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-Directional average daily traffic</td>
<td>25,395</td>
</tr>
<tr>
<td>Truck percent of ADT, %</td>
<td>7.6</td>
</tr>
<tr>
<td>Two-Directional average daily truck traffic</td>
<td>1,930</td>
</tr>
<tr>
<td>Directional split, %</td>
<td>50/50</td>
</tr>
<tr>
<td>Annual growth rate, %</td>
<td>2.0</td>
</tr>
<tr>
<td>Annual one-directional design equivalent single axle load</td>
<td>80,000</td>
</tr>
<tr>
<td>20 year one-directional design ESAL</td>
<td>1,950,00</td>
</tr>
</tbody>
</table>

Three-Dimensional Texture Measurement

As shown in Figure 2, surface texture was measured by using a portable line-laser scanner with horizontal resolution finer than 0.05 mm and vertical accuracy better than 0.1 mm. The scanner measures texture of a 100 mm × 100 mm area of the surface in one pass. The measured area was recovered into a 3D texture height map with 2448 × 2048 data points. Figure 3 shows an example of the pavement surface and its recovered 3D texture heights. Ten replicate measurements were conducted on the outer wheelpath of tested pavement sections.

![Figure 2](image)

Figure 2  A portable line-laser scanner employed for the research.

Three-Dimensional Texture Parameters

The recovered 3D texture heights were detrended to remove the average elevation and slope, if any. The detrended texture heights were decomposed into five levels by using discrete wavelet transform (DWT) (Daubechies 1988) to define its micro-texture and macro-texture. The Daubechies mother wavelet denoted by db3 was adopted for this research for its usefulness in data analysis (Liu and Shalaby 2013, Zelelew and Papagiannakis 2009). The equivalent wavelengths from level 1 through level 5 are 0.06, 0.12, 0.24, 0.49, and 0.98 mm. Level 1 to level 4 represent micro-texture, and level 5 represents macro-texture. Texture parameters for micro-texture and macro-texture were calculated independently. The definitions and their calculations of the proposed 3D texture parameters are shown in Table 3.
FIGURE 3 Recovering surface texture (a) image of pavement surface (b) recovered 3D texture heights.

Texture Analyses and Discussions

The averaged texture parameters of the 10 replicate measurements of each section are presented in Table 4. Figure 4 shows the averaged SMTD and $S_q$ of the tested sections. SMTD is a parameter to simulate the mean texture depth of pavement surface as defined and calculated by sand patch method (ASTM E965 2006), while $S_q$ indicates the standard deviation of the texture heights of pavement surface. Previous studies by the authors found that SMTD and $S_q$ are good indicators representing the amplitude and its variation of macro-texture (Liu and Shalaby 2014).

Researchers found that factors affecting pavement macro-texture are maximum aggregate dimensions, coarse aggregate types, fine aggregate types, mix gradation, mix air voids, and mix binder (Henry 2000, Hall et al. 2009, PIARC 1995, AASHTO 1976). The gradations of all the four mixtures of the sections are almost identical, as can be seen in Figure 1. The asphalt binder of 0%RAP150, 15%RAP150, and 50% RAP150 has an identical source and performance grade. The only variable among sections of 0%RAP150, 15%RAP150, and 50% RAP150 is the RAP content. Higher percentage of RAP content increased SMTD and $S_q$. Studies have found that the amplitude of macro-texture is positively related to pavement friction and thus safety (Hall et al. 2009, Henry 2000). The RAP content in this research
resulted in better pavement surface macro-texture at the time of testing. However, the slightly larger standard deviation of SMTD and $S_q$ for high RAP content (50%) sections in Figure 4 implies higher surface macro-texture variability. Use of softer binder in mixtures containing 50% RAP did not show significant change on pavement macro-texture.

### TABLE 3 Texture Parameters and Their Calculation

<table>
<thead>
<tr>
<th>Texture parameter</th>
<th>Calculation formula</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated mean texture depth (SMTD, mm)</td>
<td>$SMTD = h_{max} = \frac{1}{A} \sum_{i=1}^{M} \sum_{k=1}^{N} \frac{1}{3} a h_{ik}$</td>
<td>Macro-texture</td>
</tr>
<tr>
<td>Root mean square roughness ($S_q$, mm)</td>
<td>$S_q = \sqrt{\frac{1}{A} \sum_{i=1}^{M} \sum_{k=1}^{N} a h_{ik}^2}$</td>
<td>Macro-texture</td>
</tr>
<tr>
<td>Skewness ($S_{sk}$, unitless)</td>
<td>$S_{sk} = \frac{1}{A S_q^3} \sum_{i=1}^{M} \sum_{k=1}^{N} a h_{ik}^3$</td>
<td>Macro-texture</td>
</tr>
<tr>
<td>Kurtosis ($S_{ku}$, unitless)</td>
<td>$S_{ku} = \frac{1}{A S_q^4} \sum_{i=1}^{M} \sum_{k=1}^{N} a h_{ik}^4$</td>
<td>Macro-texture</td>
</tr>
<tr>
<td>Normalized power spectra energy (NPSE, mm^2/mm^2)</td>
<td>$NPSE = \sum_{j=1}^{L} NE_j$</td>
<td>Micro-texture</td>
</tr>
<tr>
<td></td>
<td>$NE_j = \frac{1}{A} \sum_{i=1}^{M_j} \sum_{k=1}^{N_j} \left( c D_{ij}^d \right)^2$</td>
<td></td>
</tr>
</tbody>
</table>

Where

- $h_{max}$ = the highest elevation of the macro-texture heights after DWT;
- $h_{ik}$ = the elevation of any data point of the macro-texture heights after DWT;
- $A$ = the area of the recovered surface;
- $a$ = the area of each data point of the macro-texture heights after DWT;
- $M$, $N$ = the number of data points in each direction of the macro-texture after DWT.
- $NE_j$ = normalized energy for decomposition level $j$;
- $c D_{ij}^d$ = the diagonal detail coefficients at decomposition level $j$;
- $M_j$, $N_j$ = the number of data points in each direction of the micro-texture at decomposition level $j$;
- $L$ = the maximum decomposition level.

### TABLE 4 Texture Parameters of Tested Sections

<table>
<thead>
<tr>
<th>Section</th>
<th>SMTD (mm)</th>
<th>$S_q$ (mm)</th>
<th>$S_{sk}$</th>
<th>$S_{ku}$</th>
<th>NPSE (mm^2/mm^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%RAP</td>
<td>150</td>
<td>0.77</td>
<td>-0.01</td>
<td>4.57</td>
<td>0.0615</td>
</tr>
<tr>
<td>15%RAP</td>
<td>150</td>
<td>0.84</td>
<td>-0.01</td>
<td>4.74</td>
<td>0.0635</td>
</tr>
<tr>
<td>50%RAP</td>
<td>150</td>
<td>1.07</td>
<td>-0.21</td>
<td>4.93</td>
<td>0.0666</td>
</tr>
<tr>
<td>50%RAP</td>
<td>200</td>
<td>1.07</td>
<td>-0.18</td>
<td>5.14</td>
<td>0.0645</td>
</tr>
</tbody>
</table>
Figure 5 shows Ssk and Sku of the four test sections. Kurtosis (Sku) is a measure of the spread of the texture heights distribution. Kurtosis also provides a measure of the spikiness of the surface. A spiky surface will have a high kurtosis value and a flatter surface will have a lower kurtosis value (Davim 2010). The higher the kurtosis, the more peaked the distribution. Higher kurtosis means more texture variability due to a few extreme differences from the mean, instead of being caused by more but smaller differences from the mean. The high peak indicates the distribution is more clustered around the mean than in a normal distribution, and the standard deviation will be relatively smaller. A normal distribution has a kurtosis of 3. If a distribution has a kurtosis below 3, the probability density function is flatter than a normal distribution. For example, the kurtosis is 1.8 for a uniform distribution of texture heights.
As shown in Figure 5 (a), the kurtosis of the tested sections are all greater than 3, which indicates that the surface is dominated by some sharp peaks or valleys due to either the method of construction (paving and compaction), voids created by raveling, or environmental conditions to the surface. There is no significant difference of $S_{ku}$ among the tested sections which indicates that the variation of RAP did not have a significant impact on texture kurtosis.

Skewness ($S_{sk}$) is a measure of the lack of symmetry in a statistical distribution. Recommended by ISO 4287 (1997), skewness is used to assess the directionality of the surface texture to differentiate the contribution of positive texture from negative texture. A negative value of skewness indicates that the left side of the probability density function is longer than the right side. In other word, more texture smaller than the mean value. As can be seen from Figure 5 (b), the $S_{sk}$ of 0%RAP150 and 15%RAP150 are close to zero, which means the texture distribution is or nearly symmetric. For the sections of 50%RAP150 and 50%RAP200, the distribution of texture is slightly negatively skewed. As can be seen from Figure 6, negatively skewed surface indicates that the surface has less positive texture than Gaussian surface where the texture follows normal distribution or the texture distribution is nearly symmetric.

**FIGURE 5 $S_{ku}$ and $S_{sk}$ of tested sections.**
A reasonable explanation of the negative skewness of 50%RAP150 and 50%RAP200 is that the positive textures of these two sections were slowly worn out by traffic loading during the 5 years of service. In other word, the high content of RAP in these two sections makes the texture durability slightly worse than those of lower RAP content sections. As can be seen from Figure 5 (b), the change in binder for sections containing 50% RAP did not have significant impact on texture skewness.

Figure 7 shows the micro-texture indices, normalized power spectra energy (NPSE), of tested sections. The NPSEs of the tested sections are very similar although the high RAP content (50%) sections show slightly higher NPSE compared to mixture with 0% RAP. This indicates that RAP did not have negative influence on micro-texture of the asphalt mixture. The change in binder for sections of 50%RAP150 and 50%RAP200 did not have significant impact on surface micro-texture as well.
LABORATORY TESTS AND DISCUSSIONS

In addition to assess the pavement surface texture, the sections were also evaluated for their physical and mechanical properties.

Pavement core samples were extracted to characterize the impact of RAP in asphalt mixtures. Creep compliance test as a non-destructive test was applied on the core samples to evaluate the low temperature resistance of the mixtures. The test temperature which is function of binder performance grade was -20°C, -10°C, and 0°C in accordance with AASHTO T 322-07 (2011). Figure 8 shows the creep compliance results from the core samples at three temperatures.

As shown in Figure 8, as RAP content increases, creep compliance decreases as expected. This means the high RAP mixture is stiffer at low temperature. Samples of 0% RAP and 15% RAP show very similar stiffness at lower temperature. In addition to creep compliance, indirect tensile test (IDT) was conducted on the samples to measure the strength of the RAP mixtures at low temperature. IDT was applied on core samples at -10°C which is the middle temperature of creep compliance test (AASHTO T 322-07, 2011). As can be observed from Figure 9, the IDT strength increases as RAP content increases in the mixtures. This result matches with creep compliance test result which showed high stiffness at low temperature for high RAP mixtures. The high stiffness at low temperature means less resistance to thermal cracking. This result agreed with the previous study which predicts the low temperature cracking using the Mechanistic-Empirical Pavement Design Guide software (Esfandiarpour et al. 2013).

![Figure 8: Creep compliance for different RAP mixtures tested at (a) 0°C (b) -10°C (c) -20°C.](image)

FIGURE 8 Creep compliance for different RAP mixtures tested at (a) 0°C (b) -10°C (c) -20°C.
FIGURE 9  Indirect tensile strength for different RAP mixtures.

The resilient modulus was run for temperatures at 5°C and 25°C to determine the stiffness of RAP mixtures. The resilient modulus decreases when temperature increases since at higher temperature asphalt becomes softer. As can be seen from Figure 10, the presence of RAP improves the resilient modulus at almost all temperatures. This means RAP enhances the rutting resistance at intermediate and high temperature.

FIGURE 10  Resilient modulus for field core samples tested at (a) 5 °C (b) 25 °C.
CONCLUSIONS

This paper presented a side-by-side comparison of micro-texture and macro-texture of asphalt pavement sections with various percentages of RAP content and two types of binders. It was found that, after five years of traffic loading and environmental conditions, the presence of RAP resulted in better macro-texture represented by simulated mean texture depth and root mean square roughness. However, high RAP (50%) section showed more macro-texture variability and less durability compared to the lower RAP content sections. The presence of RAP did not have negative impacts on micro-texture of the pavement surface. The change of binder from Pen 150-200 (PG 58-28) to Pen 200-300 (PG 52-34) did not have significant impact on either macro-texture or micro-texture of the pavement with 50% of RAP content.

High RAP mixtures showed less resistance to thermal cracking at low temperature due to high amount of aged binder. High RAP mixtures showed about 50% improvement in resilient modulus at intermediate and high temperature compared to control mixture (0%RAP). The section with 15% RAP shows similar performance compared to the section with 0% RAP.

These findings are based on onetime assessment of pavement texture with various RAP contents after 5 years of service. Since pavement surface texture will decrease with traffic loading, long-term texture monitoring is recommended to adequately evaluate the impacts of the presence of RAP on pavement texture.

ACKNOWLEDGEMENT

The authors acknowledge the assistance of Manitoba Infrastructure and Transportation in facilitating the research.

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