Road pavement condition mapping and assessment using remote sensing data based on MESMA

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Abstract. Remote sensing can be used to monitor changes of asphalt pavement condition because of the spectral change of aged asphalt material. However, owing to coarse spatial resolution of images and the limited width of roads ambient land cover types (e.g. vegetation, buildings, and soil) affect the spectral signal and add significant variability and uncertainty to analysis of road conditions. To overcome this problem, Multiple Endmember Spectral Mixture Analysis (MESMA) was tested to map asphalt pavement condition using WorldView-2 satellite imagery with eight bands spanning from visible to near infrared. Results indicated that MESMA run in a three-endmember model models mixed-pavement pixels well with a low average RMSE (0.01).

1. Introduction
Asphalt roads, consisting of the mixture of bitumen and gravel, play a crucial role in the transportation system. However, asphalt quality deteriorates gradually over time because of a variety of factors, such as temperature, oxidation, loads, and water [1]. Generally, the aging process can be divided into four stages: preliminary aging, moderate aging, heavy aging, and the distress stage. Road departments need to detect pavement condition in advance so as to prolong road life. Currently, the common practice is field inspections by engineers evaluating physical measures such as the Pavement Condition Index (PCI) and Structural Index (SI) [2]. Additionally, an advanced Pavement Management System (PMS) mounted on a vehicle has recently been applied for road maintenance. PMS can provide exhaustive road condition information with a set of sophisticated subsystems [3, 4]. Nevertheless, these methods are labor intensive and time consuming, and many cities only inspect the main highways, while the secondary highways are neglected or rarely inspected.

Remote sensing, bearing the advantages of wide spatial coverage and spectrum, offers the possibility to map asphalt pavement condition [5]. However, mixed pixels are very common in coarse resolution images, especially for those captured in the heterogeneous urban areas. Moreover, it is difficult to map pavement condition because of the limited width of roads. As a consequence, pure asphalt pavement pixels are rare, and ambient land cover types add significant variability and uncertainty to analysis of road conditions. To overcome this problem, multiple endmember spectral mixture analysis (MESMA) was employed to map asphalt pavement condition using WorldView-2 satellite imagery with eight bands spanning from visible to near infrared.

2. Data and method
2.1. Study area and remote sensing data
To investigate the spectral features of aged asphalt road pavement, several asphalt roads located in southwest Beijing City were selected (figure 1). Baiyang East Road in the south of the image has three lanes in each direction, marked in red polygon. The Yangguang South Street marked in yellow polygon and the East Ring Road marked in green polygon are located in the west and east of the image respectively. In the middle part of the image, there are two successively narrower roads, Liangxiang East Area 14th and 16th roads. According to our field investigation, the narrowest road is Liangxiang East Area 16th Road, with two lanes. The widest one was East Ring Road with ten lanes, which contained six lanes in the main road area, three in each traffic direction, and four lanes in the side road area. The width of the narrowest road was about 20 meters wide while the widest one was up to about 60 meters. In terms of the pavement condition, the Liangxiang East Area 14th Road was recently repaved and is in the preliminary aging stage, while Liangxiang East Area No. 16 Road and Yangguang South Street showed a worse condition because they were built in 2006 without any later maintenance. By contrast, most of the pavement in both Baiyang East Road and East Ring Road is in the moderate aging stage, showing loss of bitumen and some outcrops of gravel.

Worldview-2 satellite imagery with eight bands spanning from visible to near infrared wavelengths was selected to map the asphalt pavement condition (figure 1). The imagery was captured on September 21, 2013 with 2m spatial resolution. Preprocessing was applied to the image, including radiometric calibration and atmospheric and geometric correction. The FLAASH module was employed to remove the effect of atmosphere on the land reflectance. In order to diminish the impact of non-road areas on the results, we simply delineated the road areas using five Polygonal Vector files by GIS tools. These polygons were delineated through visual interpretation of WorldView-2 high resolution images, each of which covered a segment of road in our study area (figure 1).

2.2. Spectral analysis of asphalt pavement
A spectrometer was used to make three field spectra measurements in the study area between April and July of 2015. The pavement reflectance was gauged with a semi-automatic MATLAB spectral post-processing Toolbox released by NERC Field Spectroscopy Facility (http://fsf.nerc.ac.uk/).

Asphalt pavement generates different spectral patterns at different aging stages because of changes in composition and structure of the road surface. Figure 2 illustrates some representative asphalt pavement spectra in the first three aging stages. The pavements marked with P1, P2 and P3 were in the preliminary stage. Their spectra show that global reflectance was significantly low (under 10%) between 0.35μm and 2.5μm wavelength. I1, I2 and I3 represented pavement in the moderate aging
stage, in which the gravel was exposed at the road surface. Total reflectance rose in this stage, as expected, and an absorption feature appeared at the wavelength of 2.33 μm, which was dominated by mineral characteristics. Moreover, the slope in spectral signature within visible bands saw a slight increase. Moving on to the heavily-aged stage (e.g. L1, L2 and L3 in figure 2), overall reflectance rose considerably (e.g. a peak at approximately 24% for L3), and the slope in visible wavelengths was increasingly steeper as aging increased. The distress stage was excluded in our experiment because there was no agreed trend found for different types of distress.

In sum, it is clear that the asphalt pavement in different aging stages presented different spectral features from 0.35 to 2.5 μm, especially in the visible and near infrared bands, and this makes it possible for the WorldView-2 imagery with only eight bands from visible to near infrared to map the asphalt pavement condition.

2.3. Asphalt pavement condition mapping using MESMA

Multiple endmember spectral mixture analysis was based on the principle of Linear Spectral Mixture Analysis, as the following equation (1) presents.

\[ \rho'_\lambda = \sum_{i=1}^{N} f_i \ast \rho_{\lambda i} + \varepsilon_\lambda \]  

Where \( \rho'_\lambda \) is the corrected reflectance acquired by remote sensor in band \( \lambda \) while \( \rho_{\lambda i} \) is the true reflectance of the endmember \( i \); \( f_i \) represents the fraction of the endmember \( i \) in mixed pixel; \( N \) is the number of endmembers, and \( \varepsilon_\lambda \) refers to the residuals produced by the model. Sometimes two constraints should be taken into account as below (2).

\[ \sum_{i=1}^{N} f_i = 1 \quad \text{and} \quad 0 \leq f_i \leq 1 \]  

And the accuracy of the model can be evaluated by the Root Mean Square Error (RMSE).

\[ \text{RMSE} = \sqrt{\frac{\sum_{\lambda=1}^{M} (\varepsilon_\lambda)^2}{M}} \]  

Where \( M \) is the total number of bands.

Endmembers can be derived either from the image directly, or from a spectral library from field spectral measurements. To remain the same scale as the image, only image endmembers were considered in this study, and ‘VIPER-tools’ (www.vipertools.org) integrating with MESMA were used. Using field observation and GPS information, a spectral library was built using the VIPER tools from several Regions of Interest (ROIs) in the Worldview-2 image. The library contains around 40 pixels for each representative surface type. The library was optimized on the basis of the Endmember Average Root Mean Square Error (EAR), a metric proposed by Dennison and Roberts [6], to select the most representative endmembers with lowest EAR value for each class. Considering an evolutionary range within every aging stage, a reasonable number of endmembers, containing five health endmembers for each type of aged pavement and three common endmembers for every other object were exported in this study. Figure 3 shows the number and types of endmembers that were used to run the MESMA model.

The VIPER tools provide a maximum of four spectral libraries, each of which refers to one type of endmember in mixed pixel. Subsequently, 180 three-endmember models with 15 asphalt pavement endmembers in the first library, 12 endmembers of other objects in the second library and one photometric shade in the third library were run in a full constrained mode with a set of parameters.
recommended by Roberts [7] (-0.05 and 1.05 minimum and maximum fraction constraints, 0.8 shade constraints, 0.025 RMSE and 0.025 residual constraints).

3. Results and discussion
Table 1 indicates the number and percentage of different mixed models in the image. In the three-endmember models almost every pixel (98.5% of valid pixels except for the background pixels) could be modeled with a low average RMSE (about 0.01) apart from those pixels covered by vehicles (e.g. black pixels in area A), and the three-endmember models provided a more detailed spatial distribution of the road surface condition.

Figure 2. The spectra and corresponding digital photos of the asphalt pavement in preliminary aging stage (P1, P2 and P3), moderate aging stage (I1, I2 and I3) and heavily-aged stage (L1, L2 and L3)
Table 1. The number and percentage of mixed models in the image

| No. | First Endmember     | Second Endmember | Third Endmember | Number of Pixels | Percentage (%) |
|-----|---------------------|------------------|-----------------|------------------|----------------|
| 1   | Preliminary aging   | Vegetation       | shade           | 11247            | 3.776          |
| 2   | Preliminary aging   | TrafficLine      | shade           | 6007             | 2.017          |
| 3   | Preliminary aging   | Soil             | shade           | 2031             | 0.682          |
| 4   | Preliminary aging   | Sidewalks        | shade           | 3549             | 1.191          |
| 5   | Moderate aging      | Vegetation       | shade           | 9425             | 3.164          |
| 6   | Moderate aging      | TrafficLine      | shade           | 3089             | 1.037          |
| 7   | Moderate aging      | Soil             | shade           | 2397             | 0.805          |
| 8   | Moderate aging      | Sidewalks        | shade           | 2955             | 0.992          |
| 9   | Heavily aged        | Vegetation       | shade           | 18986            | 6.374          |
| 10  | Heavily aged        | TrafficLine      | shade           | 1795             | 0.603          |
| 11  | Heavily aged        | Soil             | shade           | 2695             | 0.905          |
| 12  | Heavily aged        | Sidewalks        | shade           | 2900             | 0.974          |
|     | **Total**           |                  |                 | **67076**        | **22.519**     |

Notes: The classification image (756*394) has 297864 pixels in total, including 229770 pixels located in the background (outside the road area).

Figure 4 displays the fraction image showing heavily aged pavement in red, preliminary-aging pavement in green, and moderate-aging pavement in blue. The classification image showed good agreement between the road surface condition modeled and the actual situation. For example, much pavement in Liangxiang East Area No.14 Road was classified as preliminary aging (bright green pixels), as the scene A proved. The Yangguang South Street that had been in service about nine years without any maintenance was mostly categorized as late aging pavement (bright red pixels and scene C). Scene B refers to a portion of moderately-aged pavement in the intersection between East Ring Road and Baiyang East Road.

We also calculated the area and percentage of the pavement in three aging stages for every road segment (table 2, figure 5). The statistics indicate that Liangxiang East Area No.14 Road was in the best condition with 52.42% of pavement being in the preliminary aging stage. By contrast, Yangguang South Street and Liangxiang East Area No.16 Road showed heavily-aged pavement at 52.79% and 46.33% respectively, indicating a poor road surface condition. In East Ring Road, the amount of the
pavement in the heavily-aged stage was relatively higher (35.53%) than that in Liangxiang East Area No.14 Road (22.74%). As for Baiyang East Road, most of the pavement was in the preliminary stage (37.78%) and moderate stage (34.81%), which was an example of fair pavement condition.

![Image of fraction image for pavement stages](image)

**Figure 4.** The fraction image for the heavily-aging pavement, the preliminarily-aging pavement, and the moderately-aging pavement as RGB (above) and the scene A, B and C refer to three parts of corresponding road.

| Roads                      | Preliminary-aging Pavement($m^2$) | Moderately-aging Pavement ($m^2$) | Heavily-aging Pavement ($m^2$) |
|----------------------------|-----------------------------------|----------------------------------|-------------------------------|
| Liangxiang East Area No.14 Rd | 9230.966                          | 4375.746                          | 4003.996                      |
| Baiyang East Road          | 23547.13                          | 21700.47                          | 17083.90                      |
| East Ring Road             | 12553.03                          | 12815.21                          | 13981.21                      |
| Liangxiang East Area No.16 Rd | 2798.578                          | 2754.538                          | 4792.827                      |
| Yangguang South Street     | 7073.529                          | 6958.992                          | 15691.25                      |

**Table 2.** The area of pavement in three aging stages

4. Conclusions
This paper presents an experimental study of road pavement condition mapping, using WorldView-2 multispectral data and multiple endmember mixture analysis (MESMA). Analysis of the field spectral measurements of pavement spectra shows that various aging stages are characterized by different spectral features from 0.35\textmu m to 2.5\textmu m. The results show that three-endmember models give more reliable results, with good success in identifying roads with preliminary aging, moderate aging and heavy aging. Moreover, MESMA provides a credible fraction image so that we can count the area and percentage of different surface conditions, which could be useful as support data for road maintenance departments. For example, in this study, Yangguang South Street and Liangxiang East Area 16th Road showed the largest proportion of later aging pavement (around 50%), which means that maintenance should be carried out urgently to prevent further aging and deterioration for these roads. It is also observed that there are several important spectral features beyond the visible and near infrared range, such as the change of the absorption intensity at around 2.3\textmu m, which might be another alternative
approach for detecting varying pavement conditions. It suggests that hyperspectral images with higher spectral resolution and wider band coverage should be obtained, which is key work we will do in the future.

![Figure 5. The percentage of aged pavement in different roads](image)

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