Spectral characteristics of asphalt road aging and deterioration: implications for remote-sensing applications

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We integrate ground spectrometry, imaging spectrometry, and *in situ* pavement condition surveys for assessment of asphalt road infrastructure. There is strong spectral evidence for asphalt aging and deterioration. Several spectral measures derived from field and image spectra correlate well with pavement quality indicators (e.g., a pavement condition index). However, the potential for mapping is limited by fine spatial resolution requirements (as fine as 0.5 m) and by the spectral confusion between pavement material aging and asphalt mix erosion on the one hand and structural road damages (e.g., cracking) on the other.   © 2005 Optical Society of America

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1. Introduction

The quality standards for transportation infrastructure have evolved considerably over the past three decades. The cost of frequent, comprehensive inspection is high, and many jurisdictions limit their surveys to major roads, with minor roads surveyed in 3-year cycles. For this purpose, a number of survey technologies have been applied to road-condition mapping. The common practice today is extensive field observations by experts who characterize a pavement condition index (PCI) and a structure index (SI) based on established physical parameters such as cracking, rutting, and raveling. Other technologies are evolving; they include the application of pavement management systems typically coupled with Global Positioning System receivers and geographic information system technology and with semiautomated *in situ* pavement health surveys facilitated by vans.[1] This technology produces detailed and georeferenced road condition reports, with PCI ratings for every ~10 m of road. Nevertheless, such surveys remain expensive and challenging, although cost and safety considerations require that they be made at regular intervals.

Previous studies of pavement condition mapping by remote sensing are rare. Early studies in the 1970s dealt with the visual interpretation of large-scale aerial photographs to map physical surface distresses (e.g., cracks).[2] Results showed that distresses are distinguishable but only on detailed map scales. Recent advances in imaging spectrometry provide the ability to derive physical and chemical properties of materials at a detailed level.[3] Consequently, one would raise the question: Can we map road surface conditions with imaging spectrometry? The utility of imaging spectrometry for transportation studies was discussed previously, but a generic study of the spectral effects of road surface aging and deterioration is lacking.[4,5] There is evidence that road properties such as aging and material composition result in distinct spectral characteristics.[6] However, it is unclear which spectral properties are associated with specific road surface characteristics and what remote-sensing data configurations are needed to map such phenomena.

An experiment was conducted in the vicinity of Santa Barbara and Goleta, California, to investigate the effects of road conditions on pavement spectra and evaluate the utility of imaging spectrometry for mapping road conditions. A comprehensive spectral library of road surfaces and distress types was acquired with an Analytical Spectral Devices (ASD;

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Boulder, Colorado; full-range) hand-held spectrometer. The roads were imaged with a HyperSpectir (HST; Spectir, Inc., Goleta, California) submeter sensor. For field reference, roads were surveyed with an automatic road analyzer (ARAN; Roadware Corporation, Ontario, Canada) survey vehicle that acquires a multitude of *in situ* road-condition parameters. Based on this comprehensive database, we investigated the spectral properties of road surface distresses and evaluated the potential of remote-sensing data for discriminating them. The ultimate goal was to explore relationships between remotely sensed parameters (i.e., spectral reflectance) and road-condition parameters such as the PCI. This relationship needs to be established if remote sensing is to support pavement health surveys.

2. Data and Methods

A. Study Area

The study focused on several urban roads in the Goleta, California, area, located 170 km northwest of Los Angeles in the foothills of the California Coast Range. Two roads with asphalt pavement, Fairview Avenue and Cathedral Oaks, were of main interest. Both are major urban roads with four lanes, two in each traffic direction. Most of Cathedral Oaks is well maintained and reflects good to very good road conditions. Parts of this road were resurfaced just before the study. Only the western part of this road has fair to poor conditions. In contrast, pavement on Fairview Avenue is in particularly poor condition. Along this road, the central divider is the boundary between two traffic management zones, in which rehabilitation efforts are funded and coordinated by two different institutions, resulting in delays and failure of necessary maintenance. Continued deterioration of the road surface was apparent during the study.

B. Road-Condition Data

Road-distress surveys provide information on the various distress types, their location, severity, and extent.[1,7] The pavement evaluation is performed *in situ,* and the road quality information is aggregated into a PCI and a SI. The PCI is a single road performance indicator aggregating a variety of individual road-condition characteristics with a scale usually from 0 and 100, with 100 being the best condition.[8] The SI works in a similar manner. The only difference is that it includes only distresses that are related to the structure, e.g., only alligator, block, and transverse cracking.[8]

In this study, an *in situ* survey technique provided detailed information about road distresses and their spatial distributions. The observations were performed in December 2002 with the ARAN system mounted on a specially modified vehicle that houses an extensive set of computers and sensors including lasers, inertial measurement units, accelerometers, ultrasonic transducers, digital cameras, and other advanced technology subsystems. Global Positioning System receivers on the vehicle and at a base station ensure accurate locational data. The survey provides geocoded road-distress information on more than 30 individual parameters aggregated for 50 m road segments. The individual road-distress measures were combined into a PCI and a SI available for each road segment. All road-condition information was integrated into a spatial database by use of the ARCGIS (ESRI, Redlands, California) geographic information system.

C. Asphalt Road Spectral Library

In February 2004, a ground spectra acquisition campaign was conducted in the study area. Ground spectra were acquired with an ASD full-range spectrometer. Full-range field spectrometer data are widely used and considered to provide high-quality spectral measurements. The full-range spectrometer samples the spectral range from 350 to 2400 nm. The instrument uses three detectors that span visible and near-infrared (VNIR) spectra and shortwave infrared (SWIR1 and SWIR2) spectra, with spectral sampling intervals of 1.4 nm for the VNIR detector and 2.0 nm for the SWIR detectors. The measurements were taken within 2 h of solar noon. Spectra of *in situ* materials were acquired from a height of 1 m by use of a bare fiber optic, with a field of view of 22° (0.147 m^2 at a height of 1 m). The road materials were measured in sets of five spectra for each field target. Four to six sets of spectra were bracketed by measurements from a Spectralon (Labsphere, North Sutton, New Hampshire) 100% reflective standard to convert the signals to reflectance values. All spectra were inspected for quality, and suspect spectra were discarded. All targets were documented and integrated into a spectral library. This library was acquired as part of the National Center for Remote Sensing in Transportation at the University of California, Santa Barbara, and is available online for research purposes from http://www.ncgia.ucsb.edu/ncrst/research/pavementhealth/urban/road_spec.htm. Some spectra show sensor-specific features with small-scale variations. High-frequency noise from 1100 to 1150 nm results from the transition between the VNIR and SWIR-1 detectors. Major water-vapor absorption bands (1340 to 1480 and 1770 to 1970 nm) were excluded from the analysis. Other sensor-induced spectral variations relate to the somewhat noisy signal in the SWIR region beyond 2300 nm, particularly evident in low-reflectance targets. The magnitude of the noise is less than 1% reflectance in any case and does not hinder the interpretations of spectral characteristics from this spectral library.

D. Remote Sensing Data

Imaging spectrometry observations were provided from Spectir, Inc. The new HST sensor samples 227 bands from 450 to 2450 nm. The main advantage of the HST is its fine spatial resolution. An onboard integrated stabilization system enables a very low flight altitude to produce a ground instantaneous field of view of ~0.5 m. Related investigations have

shown that a spatial resolution of 4 m ground resolution was insufficient to produce good results in comparing spectral data and pavement conditions.[9] Despite the spatial advantages of the HST data, the spectral calibration of the data was limited, and only the bands from 450 to 900 nm covered by the first spectrometer of the HST could be used for the analysis.

The analysis of the remote-sensing data considers only the actual visible road surfaces. We excluded all other land cover types by using an accurate road outline that is available in digital format. Vegetation and shadows obscuring the road surface were excluded from the HST data when they were clearly visible. The remote-sensing investigations applied a specific reflectance difference that is discussed below. The local variance in the omnidirectional 3×3 pixel neighborhood of the band difference was also calculated and is included in the analysis.

3. Spectral Analyses

A. Spectral Properties of Asphalt Road Surfaces and Pavement Aging

Asphalt pavements consist of rocky components and asphalt mix (or hot mix or bitumen). The mineral constituents of the crushed stone rocky components can vary depending on the geological region, but the usual major components in the aggregate are dominated by SiO_2, CaO, and MgO.[10] The asphalt mix is a complex substance that can vary in composition depending on the source of the crude oil and on the refining process. The chemical nature essentially is a mix of hydrocarbons with 50 to 1000 carbon atoms plus enough hydrogen, oxygen, sulfur, and nitrogen substituents to give some of the molecules a polar character. More specifically, the chemical components of asphalt mix are carbon $(80\%-87\%)$, hydrogen $(9\%-11\%)$, oxygen $(2\%-8\%)$, nitrogen $(0\%-1\%)$, sulfur $(0.5\%-1\%)$, and some trace metals.[11,12]

Diagram A in Figure 1 presents spectral samples from the ground spectral library of pure road asphalt with no obvious structural damages or cracks. The age of the pavement, the PCI, and the SI are shown, with photographs of each surface. Spectrum A shows a recently paved road. The surface is completely sealed with asphalt mix. The spectral reflectance is generally low, and hydrocarbon constituents determine the absorption conditions. The minimum reflectance is near 350 nm, with a linear rise toward longer wavelengths. Hydrocarbon compounds exhibit electronic transitions that arise from excitation of bonding electrons in the UV and the visible, causing this strong absorption. The absorption is broad, and there are no individual resolvable absorption bands in this spectral region because of the complex nature of bitumen. A decrease in absorption strength toward longer wavelengths results in a broad overall reflectance increase toward longer wavelengths, as is also seen in coals, oil shales, and chars.[13]

At longer wavelengths, spectrum A exhibits some obvious organic absorption features in the SWIR.

Fundamental absorption bands include an aromatic C—H stretch, symmetric and asymmetric stretches and bends of CH_3 and CH_2 radicals, the carbonyl–carboxyl C—O stretch and aromatic carbon stretch, and numerous combinations and overtones.[13] A low overall reflectance suppresses most of the distinct features except the most prominent ones near 1700 nm and from 2200 to 2500 nm. Various C—H stretching overtones and combination bands dominate the feature in the 1700 nm region. When this feature is well developed it is asymmetric and reflects a doublet, with the strongest absorption at 1720 nm and a second, less deep one at 1750 nm. The region from 2200 to 2500 nm is affected by numerous overlapping combination and overtone bands.[13] This causes the reflectance to decrease substantially beyond 2200 nm, with the strongest absorptions located in the 2300 nm region, including a well-developed doublet at 2310 and 2350 nm with the 2310 nm feature usually deeper.

Spectrum C shows an old, deteriorated road surface. The photograph of the surface shows that the asphalt seal is widely eroded and the remaining asphalt mix has undergone aging. The natural aging of asphalt is caused by reaction with atmospheric oxygen, photochemical reactions with solar radiation, and the influence of heat, and it has three major results[14]: loss of oily components by volatility or absorption, changes of composition by oxidation, and molecular structuring that influences the viscosity of the asphalt mix (steric hardening). The loss of oily components is relatively short term; the other two are longer-term processes. With the erosion and aging of the asphalt mix the road surface is less viscous and more prone to structural damages such as cracking.

The spectral effects represent a mixture of exposure of rocky components and asphalt aging. The loss of complex hydrocarbons causes a general increase in reflectance in all parts of the spectrum. This difference is highest in the near IR and the SWIR, resulting in an increase of more than 10% reflectance. The electronic absorption in the VNIR reflects the dominance of minerals and results in a concave shape with distinct iron oxide absorption features that appear at 520, 670, and 870 nm. The typical SWIR hydrocarbon absorption properties near 1700 and 2300 nm vanish for older road surfaces and are replaced by mineral absorptions. For example, there is a significant change in slope at the transition from hydrocarbon to mineral absorption. For older road surfaces the slope increases from 2120 to 2200 nm as the 2200 nm silicate absorption becomes more prominent. The slope is higher for new pavement materials at 2250 to 2300 nm, which correlates with the intensity of the 2300 nm hydrocarbon feature.

Spectrum B represents road pavement of intermediate age and condition. The surface exhibits both the asphalt mix and exposed minerals. The spectral characteristics reflect this intermediate stage by showing absorption features from hydrocarbons and minerals. The intensity and characteristics of the features are less distinct than for pure very new and very old road
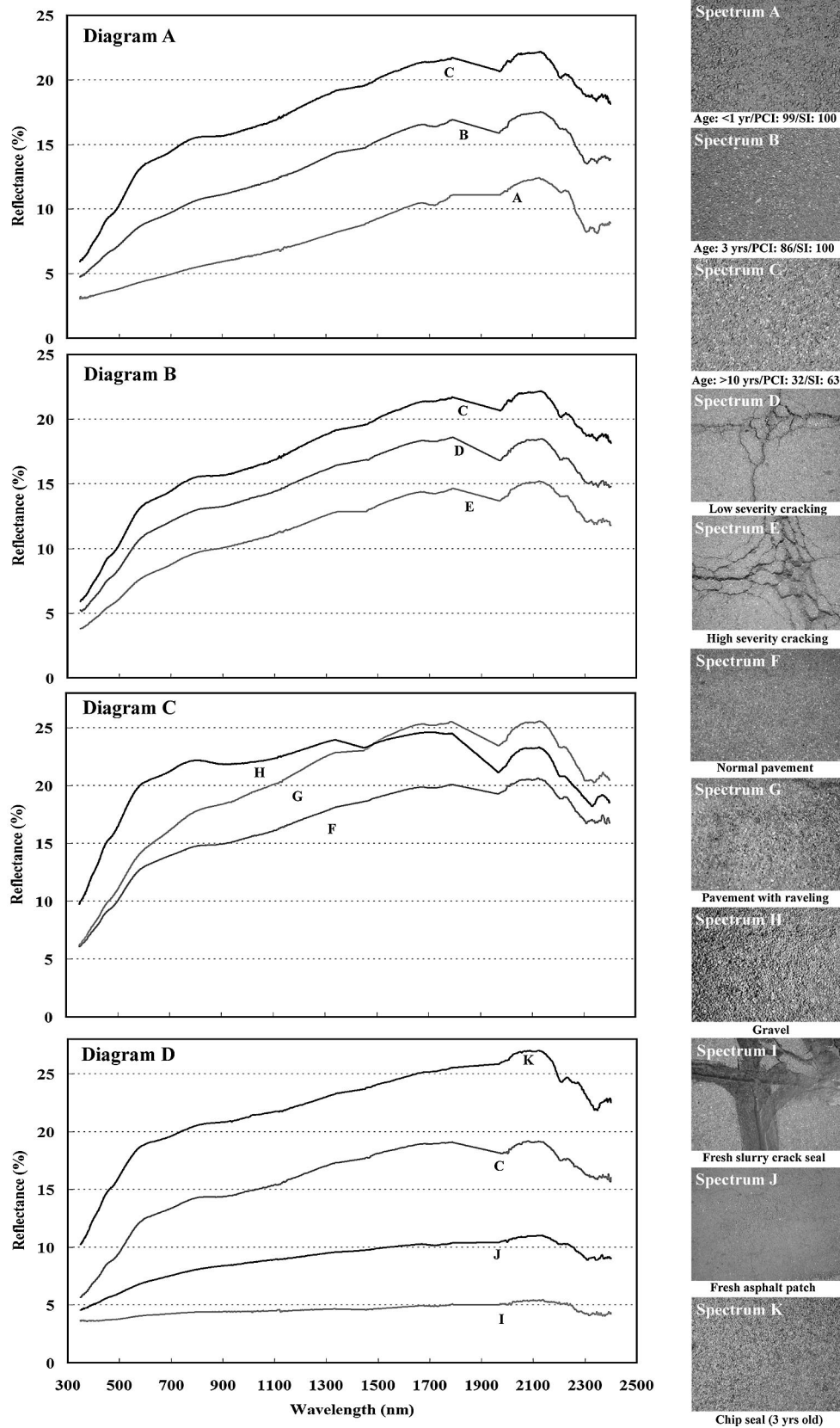
Fig. 1. Spectral effects of the asphalt surface characteristics of aging from the ASD ground spectral measurements (the major water-vapor absorption bands are interpolated). A, asphalt aging and erosion; B, structural road damages (cracks); C, structural road damages (raveling); D, pavement maintenance.

surfaces. Aging and deterioration are gradual, and there is strong spectral evidence that this transition in surface material properties can be mapped by imaging spectrometry. However, it should also be noted that the spectral signal is more sensitive to the early stages of aging and deterioration than it is for later stages. For example, the spectral differences between 1- and 3-year-old roads and a road that is 3 to 10 or more years old were approximately equivalent, although the PCI and SIs showed significant changes; i.e., the PCI decreased from 100 to 86 between 1 and 3 years and from 86 to 32 between 3 to 10 years or more. The structure index decreased from a constant of 100 between 1 and 3 years to 100 to 63 over the same age range.

B. Spectral Properties of Typical Asphalt Road Distresses and Surface Maintenance

The most common road distress and indicator of pavement quality is cracking. Diagram B in Fig. 1 shows the spectral effects of structural damages or cracks with different degrees of severity. The main spectral effect of cracking is a decrease in brightness in all on parts of the spectrum. The increasing surface roughness causes shadows and reflectance decreases of as much as 7%–8% in the near IR and the SWIR between the unshadowed pavement and high-severity cracks. The concave shape in the VNIR is more obvious for brighter, noncracked road pavements. There is also a subtle indication that the cracked surfaces have more-intense hydrocarbon absorption features in the 1700 and 2300 nm regions. The asphalt mix erosion and oxidations occur on the road surface. Cracking exposes deeper layers of the pavement with higher concentrations of the original asphalt mix, which are then manifested as an increase in the expression of hydrocarbon absorption features. This fact highlights the contrary spectral signal between road deterioration of the pavement itself (diagram A) and the severity of structural damages (diagram B). Whereas an aging road surface becomes brighter with decreasing hydrocarbon absorptions, structural distresses cause decreased reflectance but greater expression of hydrocarbon absorptions. Although the differences in reflectance and intensity of the hydrocarbon absorptions are less for cracks than for new asphalt surfaces, this fact indicates some limitations in spectrometry of road conditions.

A second common road distress is raveling. Raveling describes the progressive dislodgement of pavement aggregate particles. Spectra of normal pavement are compared with a raveled road surface in diagram C (Fig. 1). The spectrum with raveling exhibits larger amounts of rocky components and raveling debris (gravel) on the surface. This results in a general increase in the brightness of the surface caused by increasing mineral reflectance and less-prominent hydrocarbon absorptions. The raveling spectrum shows characteristics from both the normal pavement and Spectrum C. Spectrum C reflects a gravel parking lot surface. Compared with those of the pavement, the gravel surface has a higher reflectance in the visible and photographic near IR because of the missing hydrocarbon absorptions. The mineral composition is reflected in more-prominent features from iron oxide and other minerals, such as calcite feature near 2320 nm.

Besides rehabilitation treatments there are several maintenance methods to improve and maintain the quality of road surfaces. Their spectral characteristics are compared to those of a common asphalt road surface (diagram D in Fig. 1). Spectrum I shows a slurry crack seal that helps to prevent water or other noncompressible substances such as sand, dirt, rocks, and weeds from entering cracks. Slurry seal crack fillings are mixtures of emulsified asphalt or rubberized asphalt that are spread with a machine onto the asphalt surface. This treatment material has a constant low reflectance of the order of 5% reflectance. Only minor hydrocarbon absorption features, similar to those found for parking lot surfaces, are represented.[6]

Patches are used to treat areas of localized road distress. The material is similar to fresh pavement, and Spectrum J has similarity to a newly paved road (Spectrum A). Chip seal treatments include spraying an asphalt binder on the pavement and then immediately covering the binder with a single layer of uniformly sized chips. The new surface treatment is then rolled to seal the aggregate and broomed to remove any loose chips. Chip seal spectrum K has significantly higher reflectance than an untreated asphalt road surface with more-prominent mineral absorption features, similar to a raveled road surface (Spectrum G).

4. Remote-Sensing Data Analyses

The spectral interpretations of the road surfaces suggest several features that have utility for spectral identification of road aging and deterioration. The goal of the remote-sensing image analysis was to evaluate the generic spectral understanding of asphalt road conditions in a spatial mapping context. Given the fact that imaging spectrometers typically are coarser than spectral resolution, the image analysis focused on a band difference in the visible region. The difference describes the spectral difference between bands at 830 and 490 nm (VIS2 difference $= \rho_{830} - \rho_{490}$). This measure was selected because high-quality HST data were limited to a range of 450 to 900 nm. The band at 830 nm reflects a spectral peak between two iron absorption bands; 490 nm is located in the middle of an iron absorption band. The spectral difference between the two bands emphasizes the increasing spectral contrast between road surfaces dominated by hydrocarbon absorptions (new roads) and mineral signals (older and deteriorated roads), which show increasing brightness and a change toward a more-concave spectral shape in the VNIR for older roads (Fig. 1). This band difference is low for new asphalt surfaces and increases with age and level of deterioration, partially caused by increased iron oxide absorptions.
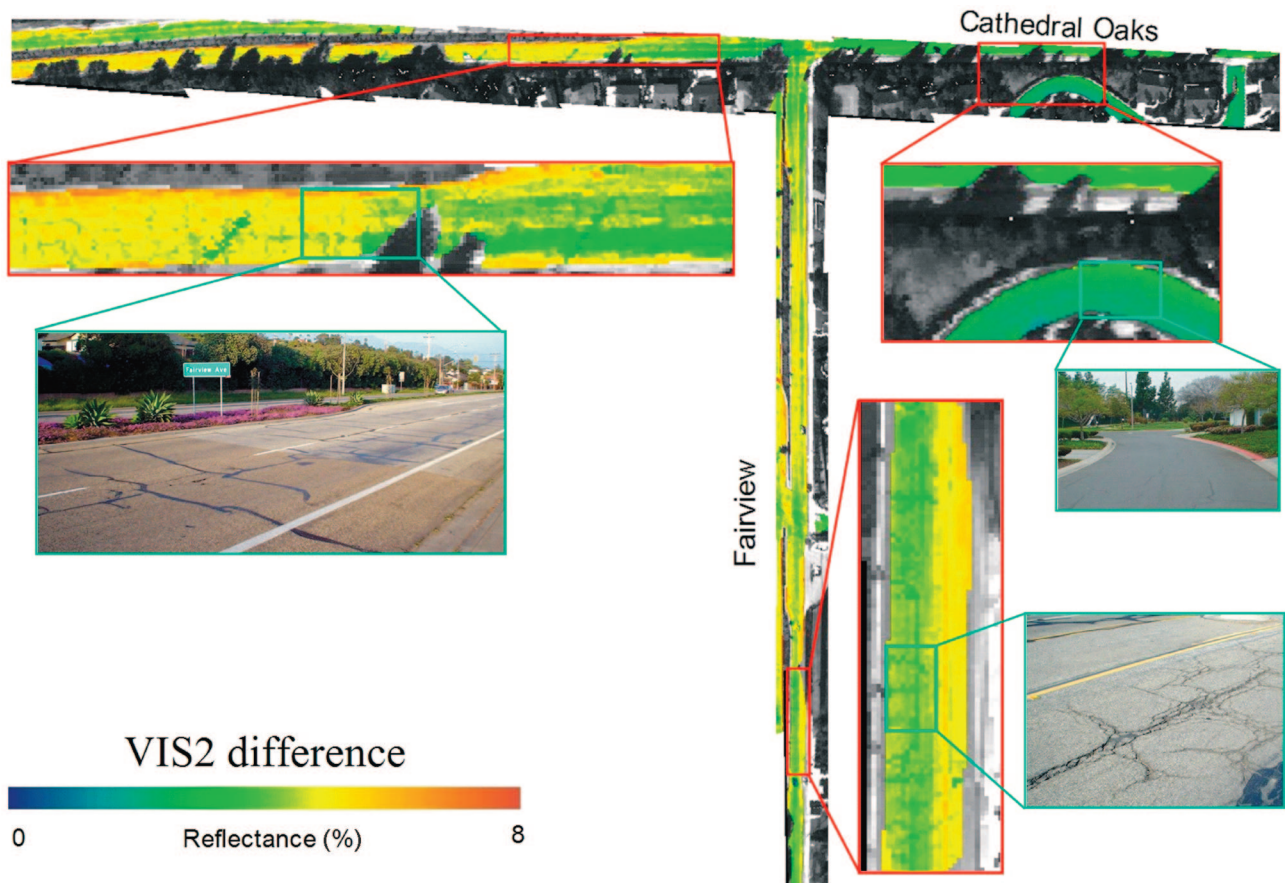
Figure 2 shows the VIS2 band difference calcu-

Fig. 2.   Spatial distribution of the VIS2 difference derived from the HST data.

lated for the HST sensor, showing expected patterns on surface roads. Roads with recently paved surfaces (upper left in Fig. 2; east Cathedral Oaks) show low difference values, of the order of 2%–4% reflectance (dark green and blue) between 830 and 490 nm. The highlighted part of west Cathedral Oaks presents the transition between a newer split-seal refurbished road (green–yellow) and an older part with several sealed transverse cracks (yellow–orange). The southern part of Fairview Avenue shows an area with severe alligator and block cracking. The crack patterns

are visible in the VIS2 difference and match expected patterns from field spectra. Such surface characteristics add spatial variance to the difference values and appear for roads with structural damage.

The HST VIS2 difference values show a significant correlation with the Roadware PCI and SI values (Fig. 3). Both regression relationships are statistically significant at the 0.0001 probability level. The relationship is quite distinct for roads in good condition because the scattering of values is quite low. The variability increases for high difference–low PCI val-
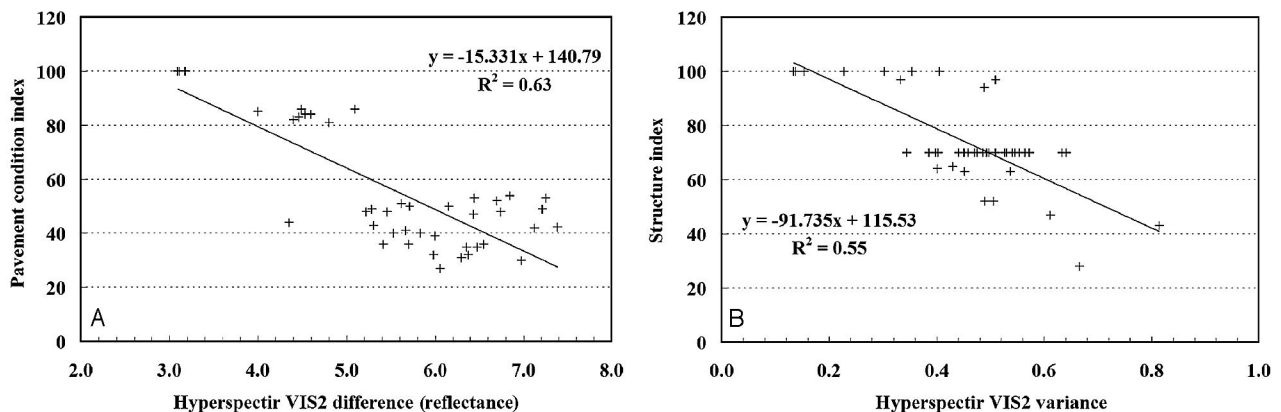

Fig. 3.   Comparison of the HST (HyperSpectir) VIS2 difference and the Roadware PCI and SI.

ues. The spectral signal of the roads in poorer condition become more complex, and the relationship is not so obvious. This result agrees with observations from the field spectra. *In situ* material aging and asphalt-mix erosion cause an increase in the VIS2 difference. In contrast, structural road damages such as cracks can reverse this spectral gradient. The VIS2 difference decreases if more numerous and more severe cracks are present (Fig. 1) and make a deteriorated road surface look more like a newly paved surface.

However, Fig. 2 also shows that structural road damage adds spatial heterogeneity to the road surface, given the 0.5 m spatial resolution of the HST data. A second remote-sensing measure, the spatial variance of the VIS2 difference in the 3×3 pixel neighborhood, was investigated and compared to the Roadware SI (Diagram B, Fig. 3). This relationship shows that structural road damage adds spatial complexity to the spectral signal. Diagram B highlights a significant amount of variability for high SI values. This effect is caused by false positives, basically other features that add variability to the spectral signal and do not represent road damage such as shadows from light poles, cars, and street paint. Despite this variability, the relationship between SI and the VIS2 variance is significant and emphasizes that the both the spectral signal and the spatial variance are important indicators of road damage in hyperspectral remote-sensing data.

5. Conclusions

In this study we combined field spectrometry, *in situ* road surveys, and imaging spectrometry to gain a spectral understanding of asphalt road aging and deterioration and to explore the possibility of mapping these conditions by using image spectrometry. For the first time we were able to provide spectral evidence of the aging and degradation of *in situ* asphalt pavements. New asphalt pavements are dominated by hydrocarbon absorptions. Pavement aging and erosion of the asphalt mix results in a gradual transition from hydrocarbon to mineral absorption characteristics, with a general increase in brightness and changes in distinct small-scale absorption features. Structural road damage (e.g., cracks) indicates a somewhat contrary spectral variation. Cracking decreases the brightness and emphasizes hydrocarbon absorption features.

The study used a band difference in the visible region and the local spatial variance to compare the remote-sensing signals to *in situ* pavement performance observations. The reflectance differences of the HST sensor data were compared to the PCI (R^2 = 0.63) and showed that imaging spectrometry has the potential for representing road conditions. The local variance correlated (R^2 = 0.55) with a SI describing structural road damage (e.g., cracks). Imaging spectrometry was successfully used to map roads in good condition. Older roads in poorer condition are more complex, and the map quality was lower. There are several reasons for this. The spectral effects of

asphalt aging are more sensitive to early stages of asphalt deterioration. Furthermore, material aging and asphalt mix erosion on the one hand and structural road damage on the other hand have opposite spectral effects. This results in less-clear spectral evidence for pavement quality. A measure of local variance further represents the spatial cracking pattern as an additional indicator of pavement condition. However, these measures are sometimes confounded by false positives.

This study provided a first investigation of this topic. It should be mentioned that the focus was on a small study area and on asphalt road surfaces. There were some problems with the spectral calibration of the high-resolution HST data that limited the spectral remote-sensing analysis to a VNIR band difference. With better-calibrated data it should be possible to explore other techniques that include the SWIR, small absorption features (continuum removed algorithms), and characteristics of spectral shape (match filter analysis) that were identified in the spectral library analysis, as well as improved spatial pattern analysis techniques. It would be of interest to extend spectral investigations to concrete road surfaces. Previous studies have shown that concrete road aging, unlike asphalt aging,[6] results in decreasing reflectance. Ultimately, the remote-sensing measurements should be compared to field expert observations of road quality and management suggestions to make this technology valuable to transportation asset managers.

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