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Hyperspectral Imaging for Moisture Content Measurement in Ballast: A Feasibility Study

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Abstract

One of the significant aspects of the railroad substructure that governs the performance of the superstructure is the moisture content of the ballast material. Although emerging non-destructive technologies (NDTs) are being employed to assess moisture content, these techniques are time-consuming and demand skilled operators. The current study proposes the use of hyperspectral imaging for rapid assessment of moisture content measurement in the ballast material. Experiments are performed for thirteen different moisture contents, and the reflectance and absorbance spectra are obtained. Results revealed that the spectral profile of dry ballast material is distinguishable from that of wet ballast material. However, the overall shape of the spectral profile for all the moisture contents was noticed to remain similar. The range of wavelengths for which the reflectance/ absorbance intensities varied from that of a dry sample is found to be 1375 nm -1550 nm. While a positive linear correlation was found for the absorption, a negative linear correlation was observed for the reflectance.

Keywords: moisture detection, railroad ballast, hyperspectral imagery, non-contact sensing

1 Introduction

Railway owners carry out periodic inspections of the railroad substructure (ballast, sub-ballast, and subgrade) to ensure the integrity and safe operation of the superstructure (rails and sleepers) [1]. Essential functions of substructure include dissipation of large and dynamic loads, drainage of water, structural stability, maintaining the alignment of track etc. [2]. Among the various characteristics of a substructure, ballast material's moisture content significantly contributes to the railroad's performance [3]. For instance, the maximum shear strength of ballast is found to decrease with an increase in the moisture content [4]. According to Qian et al. [5], the ballast samples reached significantly lower maximum deviator stress values rather quickly at a relatively small axial strain level and remained at the same level as the axial strain was increased. Traditional human inspection and emerging non-destructive technologies (NDTs) such as Ground Penetrating Radar (GPR) [1], Nuclear Magnetic Resonance (NMR) [6], seismic/vibration etc., were carried out for assessing the moisture content in ballast material, these techniques can be time-consuming, and dependent on skilled operators. To circumvent the limitation of the existing practice, the authors hypothesized using reflectance properties of the ballast medium using hyperspectral imaging (HSI).

Hyperspectral imaging is a non-contact spectroscopy technique that captures the physio-chemical information of the material's surface in the form of an Electromagnetic (EM) spectrum. Unlikeconventional imaging, which provides the intensity information in the broad range of spectral bandwidth (e.g., red (R), green (G), and blue (B) channels) of the visible EM spectrum, HSI provides the reflectance intensity within the narrow range of spectral bandwidth of the EM spectrum (e.g., 2.5 nm).

Examples of fields wherein the HSI gained popularity include medicine, precision agriculture, forensics analysis, and the food industry. In this study, we aim to assess the moisture content in a ballast sample with varying moisture content. We hypothesize that the ballast material's light reflection characteristics (spectral signature) are distinctive for different moisture content. The rest of the paper is organized as follows: detailed methodology is provided in Section 2, results are described in Section 3, and conclusions are provided in Section 4.

2 Methods

This section briefly describes the experimental methodology adopted to detect moisture in the rail ballast.

A coarse aggregate sample weighing 15kg was prepared in the Laboratory. The sample With a 1-inch maximum size aggregate (MSA) was obtained from the local supplier to experiment (see Figure 1). The aggregates were washed in distilled water to remove contamination and oven-dried for 24 hours to ensure dry condition (ASTM C127- 15 [7]). The sample's particle size distribution (PSD) was selected following the guidelines provided by American Railway Engineering and Maintenance-of-Way Association (AREMA) [8]. The detail of grading is shown in Table 1.

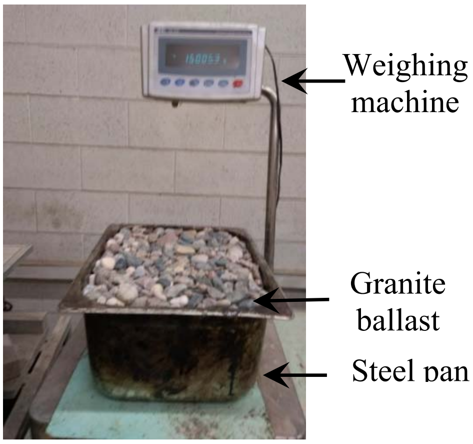

Figure 1: Image of sample prepared for testing

Sieve designation	Percent passing	Mass Retained (Kg)	Percent retained	Percent passing
1 1/2″	100	0	0	100
1 ″	90-100	0	0	100
3/4 ″	40-75	4.5	30	70
1/2″	15-35	6	40	30
3/8″	0-15	3	20	10
No. 4	0-5	1.5	10	0

Table 1: Compliance of sample's grading in this study with AREMA grade specifications

The dry sample was scanned by a hyperspectral camera with specifications shown in Table 2. for specifications. Subsequently, certain amount of water was evenly sprayed on the surface of the sample to represent the wet conditions after precipitation and the sample was scanned again. The experiment was carried out for water content of 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550 and 700 mg. The collected raw hyperspectral data was saved in 336 spectral channels for each scan (corresponds to spectral resolution of the camera).

Pika NIR640	900 - 1700 nm
Spectral Channels	336
Spectral Bandwidth	2.5 nm
Spectral Resolution (FWHM)	5.6 nm
Spatial Pixels per Line	640
f/#	1.8
Dimensions	27.0 x 11.4 x 8.9 c
Weight	3.21 kg
Max Frame Rate	249 fps
Interface	GigE
Bit Depth	14
Pixel Size	15 µm
Binning	spectral and spatial available
Sensor Type	InGaAs
Sensor Cooling	TEC
Operating Temperature (non-condensing)	-20 - +50oC
Recommended Temperature (non-condensing)	5 – 40o C
Objective Lens Mount	CS-mount
Objective Lens Field-of-View Options	5°, 7°, 11°, 22°, 77°

Table 2: Compliance of sample's grading in this study with AREMA grade specifications

The raw hyperspectral data was calibrated using a white reference and a dark reference. A sheet of Teflon was scanned by the camera to present the white reflectance (I_{WHITE}). A scan was performed with the camera's lens covered (no incoming light) as the dark reflectance (I_{DARK}). The calibration was performed on each raw scan (I_{SAMPLE}) using Equation (1)

$$\mathrm{I} = \frac{I_{SAMPLE} - I_{DARK}}{I_{WHITE} - I_{DARK}} \tag{1}$$

3 Results

In this section the NIR spectral profile of the granite ballast material for 13 different water contents, including the dry condition (see Section 2) is provided. Additionally, the correlation between the water content and the maximum reflectance (I)/ absorption (A) (see Eq. 2) characteristic of the ballast material is also investigated.

$$\mathrm{A} = -\log_{10}(\mathrm{I}) \tag{2}$$

A spectral profile represents the variation in the magnitude of surface reflectance/ absorption as a function of the wavelength of the light. It represents the physical, chemical, and morphological characteristics of the surface of a material. In other words, the spectral profile is a unique signature that distinguishes one object from the other. In the current study, the reflectance/ absorption characteristic of the ballast material subjected to different water contents is obtained (see Figure 2). Herein, the spectral profile associated with the dry ballast material is referred to as a "0 mg". From Figure 2(a) it can be deduced that the spectral profile (reflectance) of the wet ballast sample is distinct from that of a dry sample (0 gms. water content). Specifically, the reflectance intensity of a wet ballast material is found to decrease for the wavelengths ranging from 1375 nm to 1550 nm. At this juncture it is important to note that the shape of spectral profile (reflectance and absorbance) remained similar for all the water contents investigated in this study (see Figure 2(a)-(b)). The maximum decrease in reflectance intensity was associated with wavelength of 1450 nm which corresponds to standard spectral reflectance of water [9]. From Figure 2(b) it can be inferred that an increase in the water content resulted in an increase in the absorbance intensity.

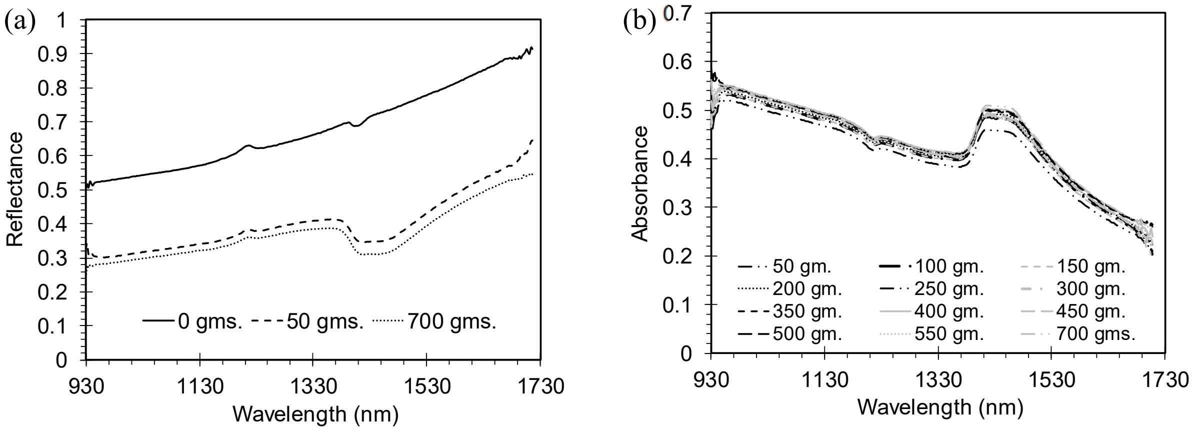

Figure 1. Spectral profiles of granite ballast material for different water contents (a) reflectance and (b) absorbance.

The correlation between the water content and the reflectance/ absorption intensities is obtained shown in Figure 3. An average of the magnitude of the reflectance/ absorption intensities (between 1375nm to 1550nm) were used for this purpose. Fitting a linear regression model to the data shown in Figure 3 indicated that water content in ballast can be related to the reflectance/ absorption characteristics of the ballast material. While a positive linear correlation was found for the absorption, a negatively linear correlation was observed for the reflectance (see Figure 3). While the absorption spectra yielded a R2 value of 0.6146, the reflectance spectra yielded a R2 value of 0.5609. Further investigation is being carried out by repeating the experiments with a greater number of samples to further formulate the observed deviation.

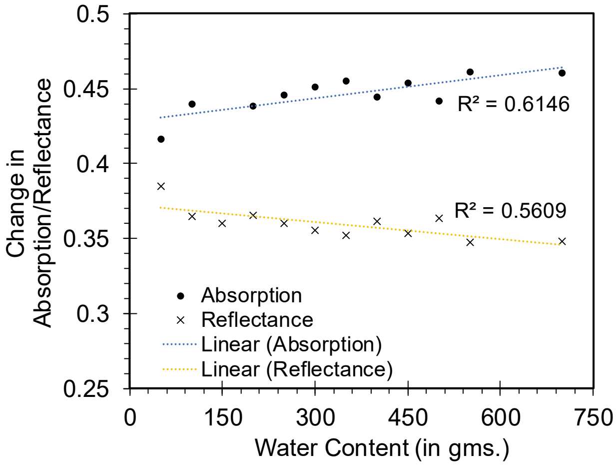

Figure 2. Influence of water content on the reflectance/ absorption magnitude of granite ballast material

4 Conclusions and Contributions

The reflectance/ absorption characteristics of the ballast material subjected to 13 different water contents were investigated in this study. For the first time, hyperspectral imaging is employed in this study with 336 spectral channels ranging from 900 to 1700nm and a resolution of 5.6nm. For the experimentation, the chosen water contents ranged from 50 to 700 mg.

The conclusions drawn from the experiments performed in this study are as follows:

1. The overall shape of the spectral profile for all the moisture contents was noticed to remain similar.

2. The spectral profile of wet ballast material is distinct from that of dry ballast material. Specifically, the reflectance characteristics are found to decrease for the near-infrared wavelengths ranging from 1375 nm to 1550 nm. The maximum decrease in reflectance intensity was associated with a wavelength of 1450 nm, which corresponds to the standard spectral reflectance of water

3. The reflectance intensity was found to decrease with an increase in the water content.

The correlation between the water content and the reflectance/ absorption intensities is obtained. While the reflectance intensity of the ballast material exhibited a negative linear correlation (r-square=0.5609) with increasing water content, the absorption intensity exhibited a positive linear correlation (r-square=0.6146).

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