Monitoring of Moisture Content in Paste Tailings using Hyperspectral Cameras

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ABSTRACT

Chile produces large amounts of tailings daily which must be safely disposed on the earth's surface. There are a series of strategies that have been successfully used in our country to store tailings, among them are thickened and paste tailings. Paste tailings are an advantageous technique that allows for greater recovery of water while improving physical stability of the structure. Although challenges are faced worldwide when large production rates are tried to be thickened, the technique seems promising for countries like Chile where there is an ongoing water crisis.

The stability of paste tailings facilities is highly influenced by water content or saturation. As consolidation occurs the tailings loses water. However, as the evaporation front takes place, the material goes from a saturated to a non-saturated state. Unsaturated paste has shown improved resistance, e.g. liquefaction resistance almost double when saturation drops below 90%.

A well planned facility operation should consider the monitoring of the water content of the paste. However, this is sometimes difficult, due to the large areas that must be controlled and the danger associated with manual moisture measurements in the field. In this context, we proposed the use of hyperspectral cameras to obtain a relationship between the paste moisture content and light reflectance. This would allow to generate moisture surface map and to the use of this data to monitor for instance evaporation rates or water balance in tailings storage facilities. This article summarizes laboratory main findings and proposes a series of procedures to implement the technique in the field.

INTRODUCTION

The Chilean mining industry produces more than five hundred million tons of tailings annually, which challenges engineers to improve disposal techniques ensuring stability and safety the resulting facilities. The most common type of storag facility in Chile are tailings dams which are constructed using the coarse fraction of the tailings (i.e. sand dam tailings). However, the economic and environmental risks associated with failures and subsoil seepage, in addition with the need to reduce water consumption, have led the industry to shift to the use of other type of techniques such as thickened tailings. One of these alternatives are paste tailings, which reduce water consumption due to large thickening of the full stream tailings and increasing water retention in the pore space.

Tailings storage facilities (TSF) must be physical and chemical stables, avoiding phenomena such as such as erosion, overtopping, liquefaction slope instability, settlements, etc. One of the conditions that most challenges tailings engineers in ensuring stability of the facility is the proper management of water, not only on the surface of the reservoir but also the water retained in the tailings. For instance, it has been shown that cyclic resistance (through the cyclic resistance ratio) almost doubles when saturation drops to the range 80 to 95%. In other words, a slight decrease in water retained by thickened tailings can significantly decrease the risk of experiencing liquefaction related phenomena in the material. This is likely one of the reasons behind the rule of thumb that indicates that shrinkage limits must be attained in the facility prior to deposition of additional tailings. Monitoring water contents allows also to explore other phenomena such as changes in evaporation and infiltration rates, cracking, acid mine drainage, etc.

Recognizing that saturation is a key parameter in tailings facilities we have committed to long term research on characterizing the effects of water content on the global stability of the structure, and on developing ground-breaking technologies for the continuous monitoring of surface and indepth water contents. In this last point, the use of remote sensing and image processing methods are an attractive technology compared to ground-based observation that can be costly and can interfere with the operation. These techniques have had great development in the last decade due to advances in plant monitoring and crop health in agricultural engineering (Hassan-Esfahani et al. 2015). Remote thermal and optical detection (visible and infrared) has proven to be a good predictor of natural soil moisture. For example, the use of the normalized difference vegetation index (NDVI) has shown good results when differentiating vegetated soil from non-vegetated, or by detecting plants under stress (Taktikou et al. 2016).

Araya et al. (2018) explored the monitoring of TSFs using hyperspectral cameras in the laboratory and in the field by using a UAV vehicle. These authors found that there is a good relationship between the tailings moisture content and reflection of light in a given range of wavelengths. However, this study did not consider the effects of variables such as density, grain size, mineralogical content, among others, in the resulting reflectance (and in moisture content prediction).

Based on the above, this article continues the investigation of Araya et al. (2018) by exploring the effects of fines content, shrinkage limit and saturation on light reflectance.

METHODOLOGY

The light from the sun is irradiated over the surface of different material where one part is absorbed and the other is reflected. This reflection/absorption behavior of the material (like on the surface of tailings) is function of wavelength and the properties of the surface. As has been previously proved, it is possible to find a relationship between light reflection and other phenomena e.g, the relation between the reflection and the soil moisture in near infrared (NIR) and visible (VIS) range (Dalal, H. 1986). When the light is reflected, it can be captured by a sensor, like a camera. In general, the cameras work with three bands of channels, R (red), G (green) and B (blue). Each channel stores a fraction of the incident light spectrum in their pixels in a range from 0 to 255, where 0 is shadow and 255 is saturated, as seen in Fig.1

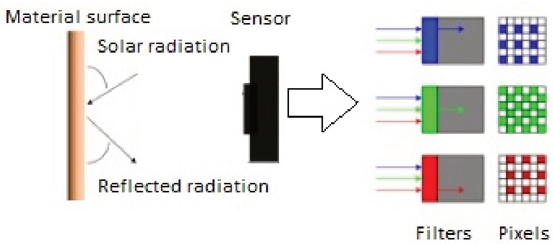

Figure 1 Reflection and capture scheme in conventional camera.

Light coming from the sun has energy in the entire wavelength spectrum. The incident light $I_l(\lambda)$is filtered by the sensor according to the transfer function of each channel ($r(\lambda)$, (λ) , $b(\lambda)$), these functions are presented in figure Fig.2. Integrating the incident light multiplied by the transfer function of each channel in the entire spectrum, according to Eq. (1), results in the value of intensity R, G and B for each pixel in the image captured.

$$(R, G, B) = \int_{-\infty}^{\infty} I_l(\lambda)\big(r(\lambda), g(\lambda), b(\lambda)\big)d\lambda \tag{1}$$

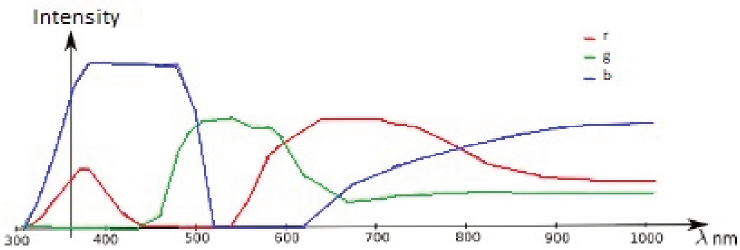

Figure 2 Transfer function at channels cameras.

The soil reflection depends on the physical structure of the material, mineralogical composition, and other soil's variables of state, the surface roughness and the type of lighting. If the other characteristics are assumed constant, thinking that in a tailings deposits those characteristics are relatively homogenous, a relationship between light reflection and moisture content should be found, as proved by Araya et al. (2018).

Laboratory tests

The study was conducted at geotechnical laboratories of the Federico Santa Maria Technical University. The test considered paste tailings material from an iron ore mine. In addition, clean natural sand and clays were mixed creating solid with different fines contents (from 100% sand to 100% clay). The samples properties are shown at Table 1.

Table 1 Soils used in the research.

Sample	Moisture work range [%]	Fine content [%]	Saturation moisture w_{sl} [%]	Shrinkage limit w_s [%]	Plastic limit w_P [%]	Liquid limit w_l [%]
0% sand	0-70	100	67.3	35.2	36.2	48.5
25% sand	0-60	75	54.6	24.5	25.2	33.2
50% sand	0-35	50	31.4	-	-	-
75% sand	0-25	25	19.8	-	-	-
100% sand	0-15	0	13.5	-	-	-
Tailing	0-40	85	35.3	19.2	19.9	24.8

Each sample was molded in cylindrical specimens with a diameter of 7.5 cm and 2.3 cm in height (Fig. 3). The specimens were then illuminated with ambient light and artificial light using a 980 [nm] laser.

Figure 3 Sample test

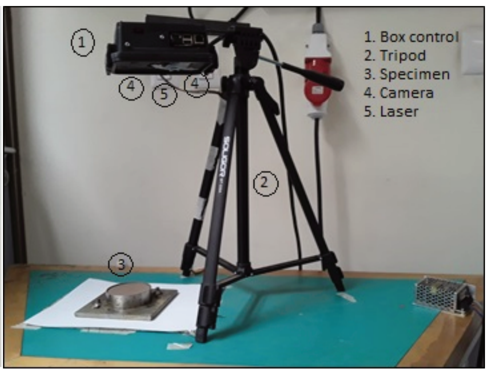

Figure 4 Test scheme.

Reflected light was captured by two cameras, located at 38 cm from the sample surface, one for the visible range (VIS, 400-700 nm) and one for the infrared range (NIR 700-1100 nm). The testing setup is shown in Fig. 4. The specimens where dried out from initial moisture content (above saturation) by oven dry them at intervals of 10 [min], until dry state was reached. Photographs were taken continuously at intervals of 1 minute.

For image processing, a homogeneous section of sample surface of "n pixels" was selected. Then, the index of total spectral intensity I_{ti} (R, G, B) for each channel (Red, Green and Blue), was defined which corresponds to average intensity in the selected zone, as shown in Eq. (2). This process was repeatead for all images obtained.

$$I_{ti(NIR,VIS)}(R,G,B) = \frac{1}{n}\sum_{j=1}^{n} I_j(R,G,B) \tag{2}$$

Measurements were conducted at different times during the day, which leads to variations of ambient light intensity. To eliminate that effect, the intensity obtained by the NIR image $I_{ti(NIR)}(R,G,B)$ without the laser light illumination is subtracted to the intensity obtained in the NIR image $I_{ti(NIR)}(R,G,B)$ with laser light ilumination, as shown in Eq. (3).

$$I_{ti}(R,G,B) = I_{ti(NIR)}(R,G,B)(LASER) - I_{ti(NIR)}(R,G,B)(NONLASER) \tag{3}$$

Then, in order to standardize the results, the intensity of all the measurements $I_{ti}(R,G,B)$ was normalized by the intensity at dry condition $I_{tn}(R,G,B)$ following Eq. (4).

$$I_{Ti}(R,G,B) = \frac{I_{ti}(R,G,B)}{I_{tn}(R,G,B)} \tag{4}$$

Finally, the normalized difference vegetation index (NDVI) was calculated, according to Ec. (5).

$$NDVI_i(R,G,B) = \frac{I_{i,NIR} - I_{i,VIS}}{I_{i,NIR} + I_{i,VIS}} \tag{5}$$

RESULTS AND DISCUSSION

The results from the Blue channel are presented, because the light coming from 980[nm] laser is mainly captured by the Blue band according to the transfer function of the camera, as shown in Fig. 2. In Fig.5 the light reflection obtained for the tailings at each water content is presented. A quadratic relationship between light reflection and moisture content was found which is consistent with Araya et al. 2018.

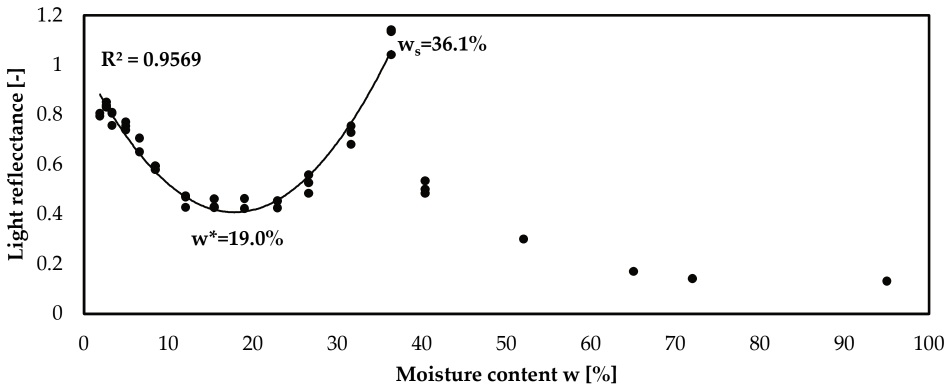

Figure 5 Results for light reflectance versus moisture content

From this relationship, the inflection humidity (w*) is defined, which corresponds to the humidity associated to the minimum light intensity captured. The w* is in good agreement with the tailings shrinkage limit (w_{sl} = 19.2%). Thus, w* may be related to the point when soil starts to experience changes at volume due to the increase the moisture. For moisture contents lower than w*, light reflection decreases with increasing moisture. Conversely, when w increases beyond w* light reflectance increases until moisture content at saturation is reached (w_s=36.1%), after this, light reflectance falls abruptly, like is show at Fig. 5. This phenomenon is associated with a greater absorption light due to the water layer formed on top of the specimen. Our current research shown that beyond w_s image processing can help to estimate volume of supernatants ponds.

NDVI results are presented in Fig.6, where it is observed that a break in the curve occurs at w*. At water content below w*, NDVI increases. However, as w* is super passed, NDVI remains relatively constant. It must be mentioned that the NDVI has no apparent physical meaning in tailings, however, it helps to use in practice the quadratic relationship in Figure 5, i.e. it helps to discern if water content is greater or smaller than w*.

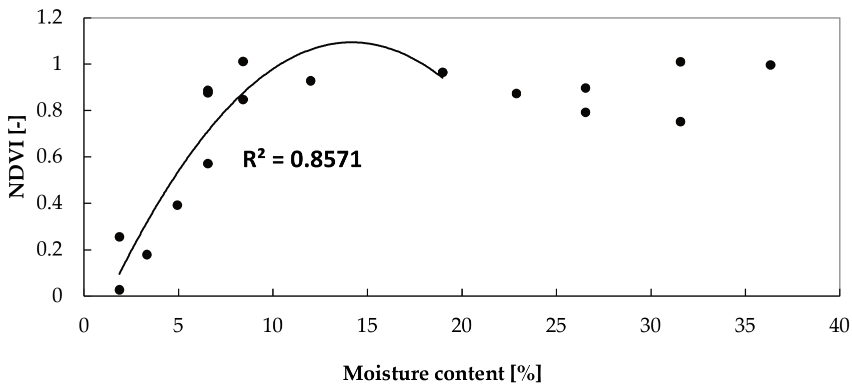

Figure 6 Results for NDVI versus moisture content

Fines content effects on reflectance

In order to explore the influence of particle size distribution on the relationship between moisture content and light reflectance, tests were performed in artificial soils by mixing clean sands and clays in different proportions. The results obtained are presented in Fig.7. where it is observed that decreases in fines content decreased w*. In addition, for 0% sand and 25% sand, the minimum reflectance for each curve (w*) coincides approximately with the shrinkage limit observed in the laboratory (shown in Table 1). On the other hand, for all soils and tailings tested, reflected light intensity drops abruptly after w_s. It is also observed that light intensity for sand-clay mixtures is in a bounded range of 0.7 to 1. For the tailings sample the intensity is in a wider range between 0.4 to 1. We believe that changes in intensity is due to the effects of mineral content of tailings. This is part of an ongoing research for the mineral characterization of abandoned TSFs.

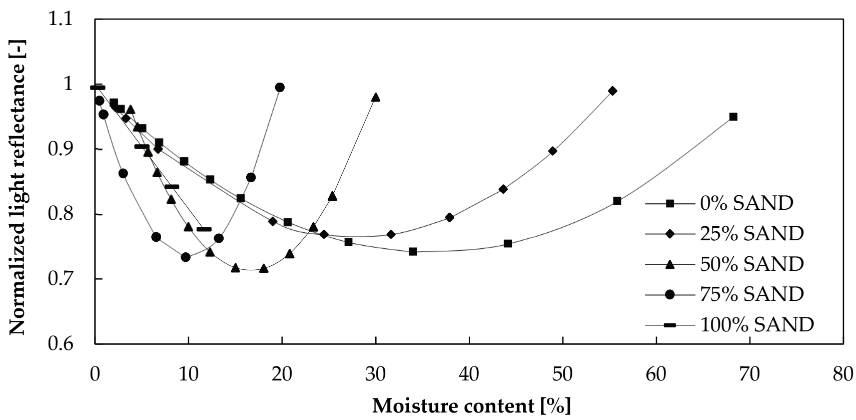

Figure 7 Granulometry effect

Fig. 8 shows the relationship between fines content and the inflection humidity (w*), where the higher the fines content the greater is w*. This is expected since at increased fines content the Atterberg limits likely increases, modifying the shrinkage limit which we showed is related to w*.

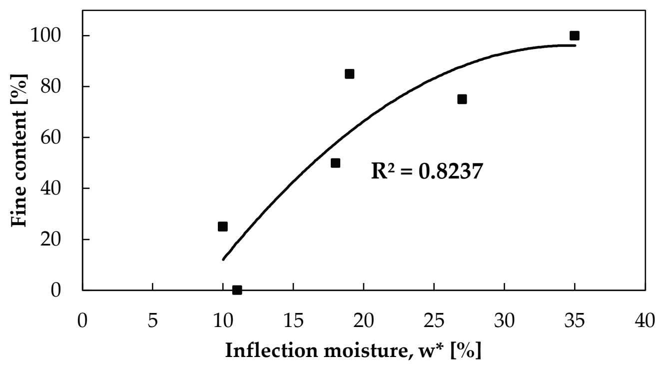

Figure 8 Fine content influence

CONCLUSION

This article presents a relationship between light reflection, captured using hyperspectral images, and tailings moisture content. Samples of iron tailings and soils prepared at different particle sizes were tested. A good correlation was observed with a clear inflection point in the moisture content versus reflectance curve, i.e. the so-called inflection moisture (w *). The w* was found similar to the shrinkage limit. In other words, the shrinkage limit was easily picked by image processing.

On the other hand, a clear effect of fines content in the moisture-light reflection relationship was observed. The smaller the particle size, the greater the inflection point (w*). In addition, it is interesting to observe that fines content did not affect light intensity (reflection). However, it is observed that tailings significantly affect intensity level which can be attributed to mineral effects. One question that remains unanswered is if hyperspectral images can identify residual minerals in TSFs, or how other variables can affect the behavior of the light reflectance. This will be taken as a research challenge for the future.

ACKNOWLEDGEMENTS

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NOMENCLATURE

w_s	saturation moisture
w_{sl}	shrinkage limit
w*	inflection moisture
I_{ti}	total spectral intensity for channel i
I_{Ti}	total spectral intensity normalized for channel i
NDVI	normalized difference vegetation index

REFERENCES

Araya, V., Suazo, G., Villavicencio, G., and Silva, M. (2018) 'Use of UAV and Satellite Images for the Monitoring of Water Content in Tailings Storage Facilities', *5th International Seminar on Tailings Management, Santiago, Chile, 2018*,10.

Hassan-Esfahani, L., Torres-Rua, A., Jensen, A., and Mckee, M. (2015) 'Assessment of Surface Soil Moisture Using High-Resolution Multi-Spectral Imagery and Artificail Neural Networks', *Remote Sensing*, 7(3),2627-2646.

Taktikou, E., Bourazanis, G., Papaioannou, G., and Kerkides, P. (2016) 'Prediction of Soil Moisture from Remote Sensing Data', *Procedia Engineering*, The Author(s),162,309-316.