Cold Regions Science and Technology 128 (2016) 32–37

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

The albedo of crushed-rock layers and its implication to cool roadbeds in permafrost regions

Yinghong Qin [a,b,*], Kanghao Tan [a,b], Haifeng Yang [a,b], Fanghua Li [c]

[a] College of Civil Engineering and Architecture, Guangxi University, 100 University Road, Nanning, Guangxi 530004, China
[b] Key Laboratory of Disaster Prevention and Engineering Safety of Guangxi, Nanning 530004, China
[c] The Science & Technology Division, Guangxi University, 100 University Road, Nanning, Guangxi 530004, China

ARTICLE INFO

Article history:
Received 24 December 2015
Received in revised form 23 April 2016
Accepted 14 May 2016
Available online 17 May 2016

Keywords:
Albedo
Reflectivity
Light-colored aggregate
Highway
Highly reflective pigments

ABSTRACT

The construction of roadway embankments may destabilize the thermal stability of roadbeds in permafrost regions. One mitigating strategy is to face the embankment side slopes with a crushed-rock layer, which promotes convective cooling and cools the underlying permafrost. While research on the convective cooling of the crushed-rock layer is fairly plentiful, the solar absorption of this layer remains unknown in the current stage. Measuring the albedo of a crushed-rock layer is crucial to estimate the thermal performance of the roadway embankment. This study proposes the theory and procedure for measuring the albedo of crushed-rock layers. The albedo of crushed-rock layers with different sizes of aggregate is measured in sunny and cloudy weather. It was found that the albedo of crushed-rock layers decreases with the increase of the aggregate size. The reason for this correlation is that at a rough surface, some photons leaving the surface return to it, increasing its absorption. Incorporating light-colored aggregates on a highway surface or side slope layer may raise the highway albedo and cool the underlying permafrost.

1. Introduction

Roadways in permafrost regions usually need embankments to disperse the traffic loadings to the underlying layer. The embankment modifies the pre-existing ground-surface conditions and consequently, negatively varies the heat convection, the vegetation coverage, and the solar absorption (Cheng et al., 2008; Ma et al., 2009; Qin et al., 2015a). Over the last decades, many techniques have been applied to mitigate the permafrost thawing under the embankment, including the use of air ducts, thermosyphons, and convective embankments. One type of convective embankments is to face the embankment side slopes with a layer of crushed rocks (Lai et al., 2009; Mu et al., 2010; Qian et al., 2012; Sun et al., 2007, 2014; Wu et al., 2008; Zhang et al., 2006a, 2006b). The cavities of the crushed-rock layer allow cold air sink and warm air float up circularly while the reverse procedure negates, an air circulation that cools the roadbed (Goering, 2003; Goering and Kumar, 1996; Lai et al., 2006b; Zhang et al., 2006b).

In addition to the convective cooling, the thermal radiation of this layer is primarily important to the cooling effect of this porous layer because the subsurface temperature is driven by solar radiation, especially during the summer months. Lebeau and Konrad (2016) found that great long-wave radiative transfer near the surface of a crushed-rock layer during the summer months tends to keep the layer warmer than that simulated without considering the radiative transfer. Although white paver surfaces have been applied to the roadways and airfields in permafrost regions (Bjella, 2013a, 2013b; Reckard, 1985), rare studies have been devoted to understand the crushed-rock layer solar absorption, which is the product of local solar irradiance to the absorptivity. As the solar irradiance incident on the embankment surface is uncontrollable, decreasing the absorptivity, or increasing the albedo, of the crushed-rock layer enhances its cooling capacity. Dumais and Doré (2016) proposed a simple model for calculating the surface temperature of pavements as a function of albedo, which is measured by the ASTM 1918-06. But the use of the ASTM 1918-06 to measure the albedo of a crushed-rock layer can cause some errors to the measurement (as illustrated in the study). Qin et al. (2016) proposed the theory and procedure for measuring the albedo of an embankment prototype. As a typical prototype is an isosceles trapezoid, the method cannot be directly adapted to measure the albedo of a crushed-rock layer. A technique for measuring the albedo of the crushed-rock layer is thus necessary to estimate the solar absorption of the embankment with crushed-rock layer revetment.

This study proposes the theory and procedure for measuring the albedo of the crushed-rock layer. The albedo of crushed-rock layers with different sizes of aggregate, which was set as 1 cm, 2 cm, 3 cm,

---

* Corresponding author.
E-mail address: yinghong231@gmail.com (Y. Qin).

http://dx.doi.org/10.1016/j.coldregions.2016.05.004

and 5 cm, was measured respectively. The proposed method was compared to the standard ASTM E1918-06. The techniques to increasing the albedo of the embankment were specified.

2. Theory for measuring the albedo of a heterogeneous surface

Albedo, or reflectivity (albedo and reflectivity are used interchangeably through this paper), is quantified as the proportion of solar radiation of all wavelengths reflected by a body or a surface to the amount incident upon it. The albedo, ρ, of a homogeneous surface is

$$\rho = \frac{\int_{\lambda_0}^{\lambda_1} i(\lambda) \times r(\lambda) d\lambda}{\int_{\lambda_0}^{\lambda_1} i(\lambda) d\lambda} \tag{1}$$

where i represents the incident solar spectrum, W/m^2/nm; λ(m)is the wavelength; r is the spectral reflectance of the homogeneous surface; $\lambda_0 = 280$ nm and $\lambda_1 = 2500$ nm are usually considered.

The albedo of a crushed-rock layer cannot be directly measured by Eq. (1) because the surface of this layer is rough and heterogeneous. Centering and leveling one pyranometer over the layer to measure the diffuse reflection (R) and another pyranometer to measure the arriving global horizontal solar radiation (I_h), one gets an albedo, R/I_h, which is the weighted albedo of the crushed-rock layer and of the surroundings. To eliminate the contribution of the surrounding albedo, the crushed-rock layer must fill the pyranometer's field of view. Paving such a large surface is costly and in some cases is impossible.

To circumvent this problem, we can prepare a small-size crushed-rock layer and eliminate the influence of the surrounding albedo. For simplicity, the size of this layer is 1 m × 1 m. We can center and level an albedometer, which integrates two pyranometers back to back, over the crushed-rock layer, with the lower one down-facing the target area to measure the diffuse reflection R_t (W/m^2) and the upper one up-facing the sky to log the arriving global horizontal solar radiation I_{ht}. This reflection and radiation obey

$$R_t = [\rho_t F + \rho_s(1 - F)] I_{ht} \tag{2}$$

where ρ_t is the albedo of the crushed-rock layer; ρ_s is the weighted albedo of the material surrounding the target area; F is the view factor from the lower pyranometer to the target area.

Both ρ_s and F are unknown, so ρ_t in Eq. (2) cannot be found. To get ρ_s and F, we can introduce two additional equations. The target area can be sequentially covered with a solar-opaque white mask and a solar-opaque black mask; the reflected radiation and the arriving global horizontal solar radiation are recorded simultaneously. The reflection and radiation obey

$$R_w = [\rho_w F + \rho_s(1 - F)] I_{hw} \tag{3}$$

$$R_b = [\rho_b F + \rho_s(1 - F)] I_{hb} \tag{4}$$

where R_w (W/m^2) and R_b (W/m^2) are the solar irradiance reading from the lower pyranometer when the white mask and the black mask cover the target area correspondingly; I_{hw} (W/m^2) and I_{hb} (W/m^2) are the global horizontal solar irradiance reading from the upper pyranometer.

In Eqs. (3) and (4), the albedo of the white and black masks is assumed as a constant. According to Eq. (1), this assumption means that the spectral reflectance $r(\lambda)$ is unselected to the wavelength λ of the solar radiation. That is, $(r(\lambda) = r)$. In Eqs. (3) and (4), we also assume that the ρ_s is a constant during the replacement of the white mask, black mask, and the crushed-rock layer. According to Eq. (1), this assumption satisfies only if the arriving solar irradiance is perfectly stable during a specific measurement cycle. In practice, a slight variation of the solar irradiance is acceptable because it is technically difficult to get a rigidly stable solar radiation over time. According to Akbari et al. (2008), when the maximum difference among I_{hw}, I_{hb}, and I_{ht} is greater than 20 W/m^2, the measurement must be redone. When both assumptions satisfy, one can find ρ_t as

$$\rho_t = \frac{\left(\frac{R_t}{I_{ht}} - \frac{R_b}{I_{hb}}\right)\rho_w - \left(\frac{R_t}{I_{ht}} - \frac{R_w}{I_{hw}}\right)\rho_b}{\left(\frac{R_w}{I_{hw}} - \frac{R_b}{I_{hb}}\right)}. \tag{5}$$

In theory, the target area is not necessarily of 1 m × 1 m but other shapes because the view factor, F, is eliminated from Eq. (5). The view factor, however, may influence the albedo of the target area because the diffuse reflections R_t, R_b, and R_w vary with F. That is, the height of the lower pyranometer to the center of the target area affects the measurement of the albedo of the crushed-rock layer. A schematic diagram for the setup of the lower pyranometer can be referred to Fig. 1. F can be calculated by:

$$F = \int_{-l/2}^{l/2} \int_{-w/2}^{w/2} \frac{h^2}{\left(x^2 + y^2 + h^2\right)^2} dxdy \tag{6}$$

where x and y are the coordinates; w and l are the width and length of the rectangular target area; h is the height from the center of the target area to the lower pyranometer. In practice, the target area is set as 1 × 1 m^2 and the height is 0.5 m. With this setup, F is approximately equal to 0.5 so the values in the bracket of Eqs. (2)–(4) are of the same magnitude.

3. Experiments

In cold regions, some embankment side slopes are faced with a single-size crushed-rock layer to maximize the inter-aggregate cavities and the convective cooling. In this study, we prepared crushed-rock layers with a single size of 1 cm, 2 cm, 3 cm, and 5 cm, respectively, in order to mimic the impact of different sizes of aggregate on the reflectivity of the crushed-rock layers. The aggregates passing through the 5 cm sieve and retaining by 4 cm sieve were deemed as the size of 5 cm. Considering that the maximum aggregate size was 5 cm, a 1 × 1 m^2 square shallow wooden box with a depth of 5 cm was fabricated to pile the single-size aggregate. The used aggregate was produced from crushed limestone. A 1 × 1 m^2 crushed-rock surface is sufficient to represent the roughness, color, texture, and reflectance of a crushed-rock layer with an infinite length and width because the size of the aggregate is order of magnitude less than the square of the wooden box. The spectral reflection of a flat crushed aggregate was measured by a Lambda 750 spectrophotometer; and the albedo of the fresh crushed limestone surface was 0.435, in which the clear sky AM1 (air mass = 1) global horizontal solar irradiance was used (Fig. 2).

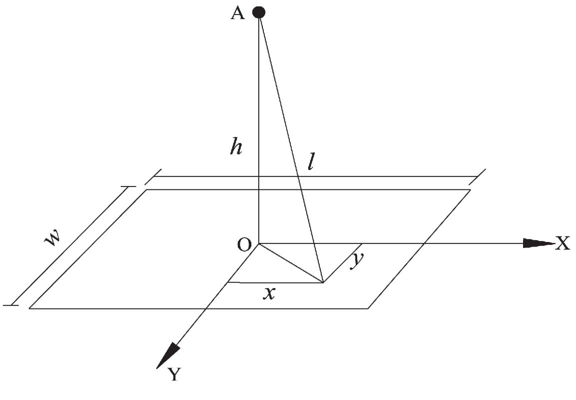

Fig. 1. A schematic diagram of the setup of the pyranometers to measure the albedo of a heterogeneous surface.