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An albedo based model for the calculation of pavement surface temperatures in permafrost regions

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ABSTRACT

High albedo road surfaces can be used to reduce the amount of heat absorbed by a pavement in order to limit the degradation of the permafrost under paved embankments. A model based on a simplified energy balance at the surface of a pavement is proposed to calculate the temperature of high albedo surfaces in order to assess their effectiveness. The model is validated using data from a test section built on the Alaska Highway near Beaver Creek, Yukon, Canada. The temperatures of four surfaces with different albedo were monitored for a year at the test section. The input data required for the model are the albedo of the surface, the incoming solar radiation, the air temperature and the wind speed. A set of design charts based on the radiation index and supported by the model are presented.

1. Introduction

High albedo pavement surfaces have been studied for several decades as a mitigation technique for permafrost degradation under paved embankments. High albedo surfaces can effectively reduce the surface temperature of a pavement by reflecting more solar radiation than traditional pavement materials, thus reducing thaw penetration and thaw settlement of the embankment (Berg and Quinn, 1977; Jorgensen and Ingeman-Nielsen, 2008; Miller, 1975). A general absence of simple and reliable calculation tools used to assess the thermal benefits related to high albedo surfaces partially explains their limited use in current practice.

Previous studies have proposed empirical relationships based on field data between the albedo and the n-factor of a road surface (Berg, 1985) or between the albedo and the thaw depth below the pavement (Bjella, 2013). These empirical relationships are site-specific and cannot be used for sites where weather conditions differ from those of the site studied (Berg, 1985). Furthermore, several studies have proposed models to estimate the surface temperature of pavements based on the calculation of surface energy balance (Hall et al., 2012; Hermansson, 2001, 2004; Qin et al., 2013; Solaimanian and Kennedy, 1993). These models were mainly developed to determine the daily maximum and minimum temperatures within a hot mix asphalt layer. They allow for an accurate estimation of pavement temperature but their complexity makes them difficult to use in practice. The soil's thermal properties are required as inputs in these models. However, these data are not always readily available, especially not in the early stages of the embankment design process, a time during which the use of high albedo surfaces is being evaluated. Moreover, hourly temperature data are used by these models, which significantly increases calculation time. Finally, most of these models were not validated for high albedo surfaces, but for typical asphalt or concrete albedo values. It will be demonstrated here that these models can be adapted and greatly simplified by limiting the input data to a few climatic data and the albedo of the surface. They will also ensure that the use of daily, weekly, monthly or seasonal average weather data yields reliable estimates of surface temperatures to assess the benefits of using high albedo surfaces in permafrost regions.

The objective of this paper is to propose a model based on a simplified energy balance at the surface of a pavement to calculate the surface temperature of pavement in Nordic regions. Surface temperature can subsequently be used to evaluate the impact of the albedo of a pavement on the permafrost degradation. The model can easily be solved using any spreadsheet software with a solver function and does not require the use of finite element modelling. The output of the model quickly provides engineers with an accurate estimate that can help guide their evaluation of the benefits of using high albedo surfaces for a specific site.

A test section built along the Alaska Highway near Beaver Creek in Yukon, Canada will first be described. Then, the equations of the model will be introduced and the model will be validated using the data from the test section. The input data of the model are limited to incoming solar radiation, air temperature, wind speed and the albedo of the surface. The limitations and range of validity of the model will

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be discussed in the validation section. Finally, a set of design charts based on the radiation index metric and supported by the model will be presented along with suggested usages of the model output.

2. Site description and data

In order to evaluate the effectiveness of high albedo pavement surfaces, a test section was built along the Alaska Highway on the Beaver Creek test site in Yukon, Canada. The Beaver Creek test site was built in 2008 in order to assess the performance of different permafrost degradation mitigation techniques applied to highway embankments. The test section used in this study is presented in Fig. 1 and it consists of four road surfacing materials having different albedo values.

The first test surface is a bituminous surface treatment with light coloured aggregates (L-BST) covering the whole width of the road. This surface was initially applied in 2008 during the construction of the Beaver Creek test site. The rest of the Beaver Creek test site is paved with a traditional bituminous treatment surface using locally available dark aggregates (BST).

The other three surfaces used in this study were installed in August 2012. First, a 5 cm thick patch of cold mix asphalt covering a 3 m by 9 m rectangular area was applied to the existing BST. The cold mix asphalt patch covers the whole width of the northbound lane. This patch was then divided into three equal square sections with side lengths of 3 m. The first patch was used as a control section and will be referred to as "coldmix". The two other sections were covered by two different proprietary high albedo surface coating products. The first one is a coating product named PerfectCool A from the Japanese company Nippo Corporation. This section will be referred to as the "Nippo" section. This product has a high reflection in the infrared spectrum but low reflection in the visible spectrum. The surface is thus perceptibly dark but presents a high global albedo value. It should be noted that sand is mixed within the Nippo coating product prior to application on the road surface to increase skid resistance. The last section is a coating product from the company Lafrentz. It is a white product manufactured for road marking. This section will be referred to as the "Lafrentz" section.

The four surfaces were instrumented with a single thermistor placed 5 cm below the pavement surface in August 2012. For the surfaces installed in 2012, the thermistors were placed at the interface between the existing BST and the cold mix asphalt layer prior to the application of the cold mix. For the L-BST section, the thermistor was installed in a groove made with a saw. The thermistor was then covered with pitch and rocks to accurately reproduce the reflective properties of the L-BST. The temperatures recorded at a depth of 5 cm were directly used as the surface temperatures in this study (Berg, 1985). The surface temperatures of the four surfaces were then recorded every four hours continuously from August 15th, 2012 at 13:24 (GMT-7:00) to July 25th, 2013 at 17:24 (GMT-7:00). The air temperature, wind speed and solar radiation data were recorded hourly by a weather station located nearby. In addition to the thermistors used to measure surface temperatures, data provided by a string of thermistors that measured temperatures at 0.3 m, 0.9 m and 1.2 m beneath the centerline of a section of BST installed in 2008 were used in this study.

Fig. 1. Beaver Creek test site with surfaces from top to bottom: L-BST, Coldmix, Lafrentz and Nippo.

The data from the Beaver Creek test sections are presented in Fig. 2 as monthly average values. Fig. 2 includes superficial temperatures from the four surfaces of the test section, air temperature as well as solar radiation. It is important to note that the data for August 2012 and July 2013 represents only a partial monthly average of the days for which data was available.

Fig. 2 highlights interesting characteristics of the behaviour of high albedo surfaces. First, the temperature difference between each surface is negligible when the solar radiation is low (October to February). Second, the surface temperatures are slightly higher than the air temperature during the first three months of winter. However, it is unlikely this difference is due to the absorbed solar radiation, which is very small. Third, the temperature difference between each surface is strongly correlated with the solar radiation and seems to be less correlated with the temperature of the air. As a matter of fact, the temperature difference between the surfaces is almost the same from April to August when solar radiation is relatively similar but air temperature is very different. It may then be justified to develop the surface temperature prediction model based on solar radiation rather than on air temperature.

2.1. Albedo of the test section

In summer 2013 and summer 2014, the albedo of each surface was measured using a second-class pyranometer with the test method ASTM-E1918 (1997). These values are presented in Table 1. The pyranometer was placed 40 cm above the surface instead of 50 cm as proposed by the ASTM-E1918 test method because of the relatively small surfaces. Some degradation of the surface was visibly noticeable when the albedo was measured in summer 2013, as the surfaces were initially installed in summer 2012. Nevertheless, the albedo of the newly applied surfaces presented in Table 1 could be determined through back calculations. For the L-BST, it was assumed that the value of the albedo was constant between summer 2012 and summer 2013 as the albedo measured in summer 2013 was the same as the albedo measured one year later in summer 2014. For the Coldmix, a sample was used to measure the albedo of new hot mix asphalt in laboratory and this value was used as the albedo of the Coldmix in summer 2012. The sample was prepared using a single wheel French roller compactor usually used to prepare samples for asphalt rutting tests. A surface course layer hot mix asphalt presenting similar reflective properties as the cold mix asphalt was used for preparation of the sample. The laboratory measurements of the albedo were done using direct sunlight and the alternative pyranometer technique proposed by Levinson et al. (2010a, 2010b) (Dumais, 2014). For the Nippo product, laboratory samples were prepared by applying the product to asphalt samples similar to the ones used to measure the albedo of the Coldmix. The albedo of these samples is considered to be representative of a freshly applied product at the Beaver Creek test section. The albedo of the Lafrentz product could not be measured in the laboratory because the product was not available. The albedo of the Lafrentz product for summer 2012 was consequently estimated by analysing the degradation of the surface from photographs taken in summer 2013. Due to snowplowing operations, the surface of the road was partially abraded thus removing the white product and exposing the underlying cold mix. The percentage of degradation of the white paint was calculated using image treatment software by selecting the pixels of the picture presenting the same