International Communications in Heat and Mass Transfer 87 (2017) 14–21

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Enhancement of convective cooling of the porous crushed-rock layer in cold regions based on experimental investigations

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ARTICLE INFO

Keywords:
Crushed-rock layer
Convective heat transfer
Geotemperature control
Thickness optimization
Cold regions

ABSTRACT

A crushed-rock layer, because of its pore-air convective cooling effect, has been widely used to adjust the geotemperature of the permafrost stratum in cold regions. To optimize the control measure, a series of experiments have been conducted. The convective heat transfer capability of crushed-rock layers with different thicknesses is evaluated. The experimental results indicate that: 1) forced convection occurs during warm period and mixed convection occurs during cold period. The cooling performance is mainly determined by the forced convective heat transfer process; 2) pore-air flow pattern can change thermal resistance of the crushed-rock layer. Larger thermal resistance can reduce heat accumulation during the warm period and smaller thermal resistance can strengthen heat transfer during the cold period; and 3) there exists an optimal thickness to enhance the convective cooling effect. Under the experimental conditions, the optimum thickness is close to 1.3 m. These findings are helpful to the construction of cold regions engineering. If the thickness of crushed rock revetment could be reasonably designed, the well convective cooling effect can be achieved and the construction costs will also be reduced.

1. Introduction

Permafrost is widely distributed in cold regions of the world, especially in Eurasia, North America, and Antarctica [1,2]. In China, permafrost regions constitute about 22.4% of the land area [1,3,4]. Permafrost is, however, very sensitive to temperature changes caused by the existence of ground ice [5,6]. Engineering activity and climate warming accelerate permafrost degradation [3,5]. Permafrost degradation has become an international concern due to its impact on the environment and engineering stability [6,7]. Proactive cooling embankment with crushed-rock layer is a key approach to reduce the underlying geotemperature [3,8–10]. Engineering paradigms using the crushed-rock layer include the Qinghai-Tibet Highway and Qinghai-Tibet Railway in China (Fig. 1), the Alaska Highway in the USA and the Baikai-Amur Railway in Russia [9,11–14]. Researches show that the crushed-rock layer can adjust and control the geotemperature of the underlying permafrost effectively [9,15–17].

The crushed-rock layer can be taken as a highly porous medium without inner hot source [3,8,18,19], which allows air to flow through it when unstable pressure gradient exists [8,11]. Experiments and numerical simulations were also conducted to explore the heat transfer mechanism and strengthen the convective heat transfer in porous media [20,23–25]. Enhancement of convective heat transfer processes can increase the cooling performance of the crushed-rock layer. Bejan et al. [26,27] proposed the objective of the minimum entropy production theory to optimize the convective heat transfer. Chen et al. [21] suggested that changing velocity distribution is one of the most direct and effective approaches to reduce thermal resistance and enhance heat transfer based on the minimum thermal resistance theory. The geometric and physical parameters of crushed-rock layer, such as thickness, particle size, porosity and boundary, can affect its cooling performance on the underlying frozen soil. Lai et al. [28] experimentally investigated the influence of boundary conditions (i.e. air-permeable and air-impermeable tops) on cooling effect of crushed-rock layer. The effect of particle size on the cooling performance of crushed-rock layers under air-permeable and air-impermeable tops was reported by Zhang et al. [22]. They also distinguished the heat transfer process between the crushed-rock layer and concrete-sphere layer [8]. Sun et al. [29] concluded that the porosity reduction of crushed-rock layer resulted from cyclic loading decreased its convection cooling effect. Numerical method is also a key tool to analyze the flow characteristics inside porous medium with micro convective velocity. Zhang et al. [30]

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.06.019

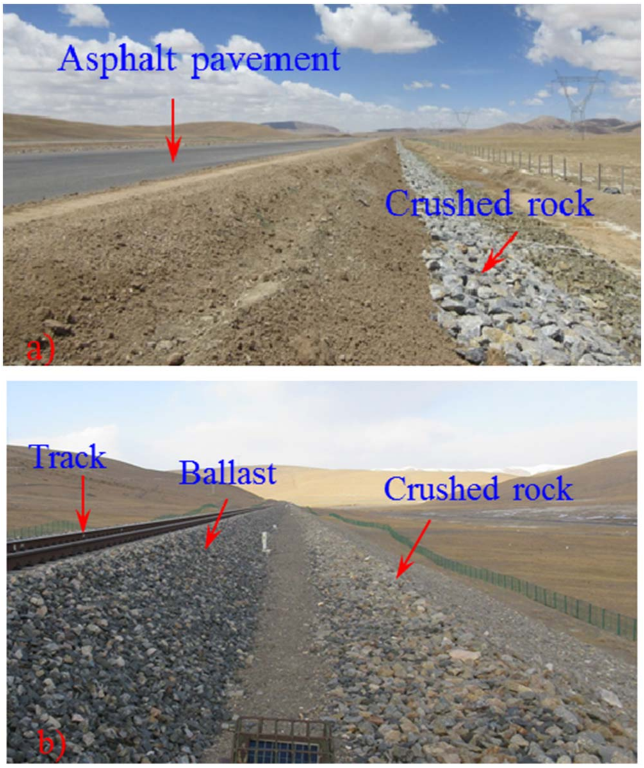

Fig. 1. Applications of crushed-rock layer in embankment engineering in permafrost regions of the Qinghai-Tibet Plateau. a) Highway embankment; b) railway embankment.

simulated the influence of geometrical parameters (i.e. slope angle and aspect ratio) on natural convection cooling effect of the crushed-rock revetment. Sun et al. [31] numerically evaluated the influence of thickness on cooling effect of crushed rock revetment according to the Nusselt percentage. However, the forced convection is ignored for the air-permeable boundary.

The thickness of crushed rock revetment is one of the most important parameters in engineering design which can not only affect the convective cooling performance but also influence construction costs. In present study, a series of laboratory tests are carried out to study the geotemperature control performance of crushed-rock layers with different thicknesses under air-permeable boundary. To analyze the convective heat transfer processes and cooling performance, the air convection characteristics, transient heat flow characteristics, and temperature characteristics are comprehensively evaluated for three models with 1.6-m, 1.3-m and 1.0-m crushed-rock layers, respectively. It is hoped that an optimal thickness can be obtained to enhance the convective heat transfer and reduce engineering costs in permafrost regions.

2. Experimental work

2.1. Experimental setup

Fig. 2 shows the schematic of the experimental setup. The main parts of the setup are the temperature controlling system, the ventilated system and the data-collection system. The apparatus consists of a box with dimensions of 1.84 m × 8.0 m in the horizontal plane and a vertical height of 2.7 m (Fig. 3). The wall of the modeling box is made up of 10-cm insulation layer.

The temperature controlling system is comprised of a double-head compressor named SANYO (7.5 kW), an automatic temperature controller with the precision of ± 0.1 °C, pipes for the Freon circulation and an evaporator. The controlled temperature ranges from − 60 °C to + 50 °C.

The ventilated system consists of the cooling fans, the speeding fans, the velocity controlled instruments and a wind-circulation passage. The wind direction is parallel to the longitudinal direction of the box.

The data-collection system is composed of temperature sensors with precision of ± 0.05 °C, heat flow sensors, wind speed sensors, data acquisition and logging instruments, and a computer. Data were collected by the data loggers at an interval of 20 min.

2.2. Experimental methods and conditions

In order to investigate the influence of thickness on the cooling performance of crushed-rock layer, three models with different thicknesses of crushed-rock layer were performed under air-permeable conditions. Thickness of crushed-rock layer in three models was designed as follows:

Model 1: 1.6-m crushed-rock layer and 0.2-m soil layer (Fig. 3a).
Model 2: 1.3-m crushed-rock layer and 0.2-m soil layer on an insulation layer (Fig. 3b).
Model 3: 1.0-m crushed-rock layer and 0.2-m soil layer on an insulation layer (Fig. 3c).

Three models have the same dimension of 1.5 m × 1.2 m × 1.8 m. The mean particle size of crushed rock is nearly 20.0 cm. Three models are separated by 10.0-cm polyurethane insulation board. The water content and dry density of the soil layers are all about 12% and 1.59 g/cm^3, respectively. The layouts of sensors in three models are shown in Fig. 3a–c. The installing process and testing field are shown in Fig. 4.

According to the in-situ measured data and related references [32], the ambient temperature in the model box varied as Eq. (1):

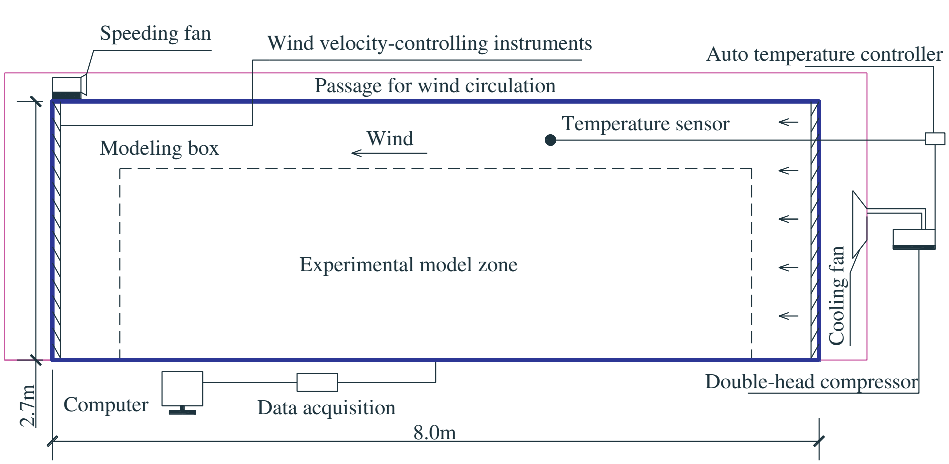

Fig. 2. Schematic of the experimental setup.