

Use of coarse aggregate materials to protect embankments located in permafrost regions

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This paper describes the physical principles, monitoring and application of porous filling materials used in embankments located in permafrost regions. The use of crushed rock and jackstones in slopes of roads and railways in the Tibetan plateau are studied. The mean diameter of crushed rocks and jackstones is a key parameter for the appropriate performance of an embankment, i.e. to prevent settlements due to permafrost thawing. Embankment settlements can seriously damage the performance of a road or railway. From experimental results, it was found that the thermal conductivity coefficient of a crushed rock layer during winter was around twelve times larger than that during summer. This can be explained by the presence of air convections in the porous crushed rock layer which mainly occur with the change of air temperature and density only during winter. As a consequence, it is believed that the crushed rock layer plays an important heat shield role in the protection of the permafrost under a road. According to the embankment construction conditions and the air convection properties in the porous crushed rock materials, the best diameters for crushed rocks are between 10 cm and 15 cm and the thickness of the crushed rock layer is about three to four times that of the crushed rock diameters.

El artículo describe los principios físicos, monitoreo y aplicaciones de materiales porosos de relleno usados en terraplén ubicados en regiones con permafrost. Se estudia el uso de chancado y gravilla redondeada en taludes de caminos y líneas férreas en el altiplano del Tibet. El diámetro medio del chancado y buevillo es el parámetro principal para un apropiado funcionamiento de un terraplén, es decir, para prevenir asentamientos debido al deshielo del permafrost. Asentamientos del terraplén pueden dañar seriamente el desempeño de un camino o línea férrea. A partir de resultados experimentales, se encontró que el coeficiente de conductividad térmica de bases de chancado fue alrededor de doce veces mayor en invierno que en verano. Esto se puede explicar por la presencia de convecciones de aire en la base porosa de chancado, convección que ocurre principalmente con el cambio de la temperatura y la densidad del aire, lo cual sucede sólo en invierno. En consecuencia, se cree que la base de chancado juega un rol muy importante como coraza contra el calor y así proteger el permafrost bajo un camino. Dependiendo de las condiciones constructivas del terraplén y las propiedades de convección del aire en los materiales porosos de roca chancada, los mejores diámetros para roca chancada están entre 10 cm y 15 cm y el espesor de la base de este material resulta alrededor de tres o cuatro veces el diámetro del chancado.

Keywords: crushed rock, air convection, embankment in permafrost regions, permafrost protection, thermal conductivity coefficient

Palabras clave: roca chancada, convección del aire, terraplén en regiones con permafrost, protección del permafrost, coeficiente de conductividad térmica

Introduction

During the last forty years, the mean annual ground temperature of the permafrost in the Tibetan plateau has been rising. This can be attributed to global warming and human activity increase. As a consequence, the thickness of the permafrost active layer has been increasing, i.e. the permafrost is in a situation of degradation and disintegration. An embankment, by itself, also alters the natural temperature since

it can act as a barrier or transmit the atmospheric temperature into the permafrost soil. Under these conditions a road sub-base or base can become unstable, leading to settlements which can affect seriously the performance of a road. Methods have been developed to prevent or reduce settlements of the sub-base and base in regions with permafrost.

One method consists in the control of the quantity of heat accumulation, i.e. to decrease heat transfer into

the sub-base and base. There are mainly three forms of controlling the accumulation of heat in a road:

- a) Changing the thermal resistance of the embankment, for instance, using thermal barriers which can increase the embankment thermal resistance, decreasing the conductive heat from the upper layer.
- b) Insulating against radiation heat, for example, using shelters or covers over the road to stop the heat from the sun radiation reaching the embankment.
- c) Using thermal sinks, to store temporarily heat and prevent freezing or thawing outside of the sink.

A second method considers actively cooling of the sub-base, base and embankment by:

- a) Mechanically freezing
- b) Natural convective systems
- c) Thermosyphon
- d) Using nitrogen to freeze

A third method is simply the control of the heat transfer process. For example, the use of heat insulation materials, whose coefficient of thermal conductivity are small during melting and large during freezing, so the freezing energy input can increase and the heat energy input can decrease.

The first and second techniques were mostly used in the past engineering practice. They proved to be efficient in decreasing the heat energy input, hence protecting the permafrost. However, these techniques have some shortcomings, since on one hand thermal barriers insulate the input of heat energy during warm seasons; on the other hand they insulate the input of freezing energy during cold seasons. The other techniques presented above are difficult or too expensive; therefore, they are not used extensively.

The third method is more suitable, because it can essentially protect the permafrost and simultaneously enhance the embankment stability. During the past decades the Chinese governmental institutions of public works have paid a lot of attention to the use of the third method for the construction of roads and railways, incorporating crushed rock in the embankments. The protection mechanism of the permafrost using embankments made of crushed rock and jackstones has not yet been sufficiently studied.

This paper presents the physical principles related to heat energy transmission on which is based the use of crushed rock and jackstones. Crushed rock and jackstones can increase the freezing energy input in winter and decrease the heat energy input in summer resulting in an appropriate material to protect the permafrost soil.

Physical principles

Crushed rocks represent large porous materials, which are definitely different from normal soils in terms of heat energy transmission. In general, two types of convective heat-transfer processes can occur in crushed rocks, plus the conductive transfer which also occurs in normal soils. The first corresponds to forced convection driven by air pressure gradients and the second corresponds to free convection occurring as a result of temperature-induced variations in air density. In a layer of porous crushed rocks, free convection is most likely to occur during periods of cooling from above, *i.e.* during winter. In this situation, cooling at the upper surface increases the density of the pore air, thereby generating a density stratification, which leads to free convection, with warmer air circulating upwards whilst cooler pore air descending because it is denser.

Forced convection associated with the movement of pore air may be important in porous systems, provided that significant pressure gradients are present in the crushed rock layer to drive the flow. In the case of pore air, forced convection may occur in the upper portion of the crushed rock layer due to the influence of the surface winds. This effect will be significant at depths below the surface that are lesser than the surface roughness length, and will usually be limited to pore diameters. Perhaps, the largest impact of wind-induced pore air convection will be associated with the establishment of convection boundary conditions at the upper surface of the crushed rock layer, rather than with enhanced heat transfer beneath the surface. This causes that crushed rock layer may decrease the temperature beneath the crushed rock layer (the soil surface temperature), protecting the permafrost under the sub-base from thawing.

The attention of researchers on coarse-grained and fine-grained interbedding embankments and crushed rock revetment embankments have focused on thermal characteristic measurements, design calculation methods and the integration application of crushed rock

revetments (Goering, 1998; Goering *et al.*, 2000).

Experimental studies

Research on trial embankments have been carried out in Reshui (Wang *et al.*, 1996; Cheng, 2003), in Beiluhe (Sun *et al.*, 2005), in the Qinghai-Tibet plateau, in the Fenghuoshan mountains and in the Great Xingan ridges of the northeast of China (Yang, 1985). From the results obtained in these areas and also from the working conditions of the Baikal-Amur railway, in the former Soviet Union Siberia, it is possible to conclude that there are several advantages in using coarse aggregate materials, especially crushed rock materials, such as jackstones and block stones, as embankment filling and protection filling. Since they can provide a cold reserve in winter and take advantage of the convection characteristics of the cold and hot air in summer to maintain the thermal balance of the permafrost upper limit, keeping the permafrost upper limit under the sub-base unchanged or even higher.



Figure 1: In situ experimental railway section with crushed rock slope protection

The protection technique referred to as Air Convection Embankment (ACE) uses crushed rock materials or any highly porous and uniformly graded material to construct the base or the shoulder of a road embankment. The high permeability of this type of material offers natural convection of the pore air in the embankment during winter months, when unstable air density gradients exist (Goering, 1998). As mentioned above in the physical principles, during winter months, cold air from the upper part of the embankment will tend to settle downwards due to its greater density. At the same time, warm air from the base of the embankment will rise, which will result in circulation of the pore air and enhanced heat transfer by speeding the cooling and refreezing of the underlying permafrost. During summer, the warmer air will stay in the upper part of the embankment since the air density gradients are stable, resulting in the absence of circulation.

Figure 1 shows the crushed rock embankment of a railway used for monitoring. It can be observed that the crushed rock layer forms the embankment slopes. The stones used were various in shapes and the rock layer was built with ripped stones except for those on the top surface, where rocks were oriented with the flat surface upwards for convenience in construction and maintenance. The thickness of the crushed rock layers were 3 to 4 times the mean diameter of crushed rocks, resulting in thickness of 80 cm for mean crushed rock diameters of 15 to 20 cm. In some sections, the mean diameters were about 40 cm to 50 cm. The height of the trial embankment was between 3.91 m and 4.25 m, each trial section length was 50 m. The experimental section included six boreholes for temperature monitoring in order to obtain representative and reliable measurements of temperature changes. Arrangement of the six boreholes considered a natural borehole away from the embankment, a borehole in the middle of the embankment, two boreholes in the side slope corners and two boreholes on both lateral sides of the road surface.

Another trial embankment was also made of crushed stones and it was constructed in Reshui from March to July in 1973. The site is located on the thick underground ice district around the permafrost lower limit. It is 11 m long from east to west, 7.5 m wide from south to north and 2.7 m high. The main body of the embankment is directly carved out from pieces of slice rock of diameter larger than 30 cm. After the embankment was completed, ground temperatures were measured and analysed in terms of mean annual ground temperature of the embankment. The adequate ventilation provided by the crushed rock resulted in lower temperatures than that measured in embankments made of general gravely soils. The permafrost upper limit under the ventilated embankment ascends faster and cooler. On the contrary, using the general gravely soil embankment, the permafrost upper limit does not change or ascends very little after recovering the original natural upper limit. Therefore, from these results it was concluded that the ventilation offered by the crushed rocks protect effectively the permafrost.

Recently, scientists in China have started research on slope protection along the Qing-Zang railway collecting a lot of data. In addition to the investigation carried out in Reshui, Muli district, the Northwest Research Institute of China of the Academy of Railway Sciences (NRICARS) has also performed

field measurements during the 1960s and the 1970s. They studied the convective heat transfer in jackstone embankments and found that the thermal conductivity modulus of jackstone layers change between winter and summer. The thermal conductivity coefficient can be expressed as:

$$\lambda_f = \frac{I_u}{I_f} \lambda_u \quad (1)$$

where λ_f and λ_u are thermal conductivities in the crushed rock layer in winter (frozen) and in summer (unfrozen) respectively, and I_f and I_u are the freeze index and the thaw index on the earth surface, in winter and summer respectively. Based on results from experiments, He *et al.* (2000) determined the values of the thaw index and the frost index as $I_u = 40.5$ and $I_f = 3.31$. Therefore, the thermal conductivity coefficient of a crushed rock layer in winter is around twelve times larger than that in summer, $\lambda_f = 12.2 \lambda_u$. Moreover, the values of the summer and winter thermal conductivity modulus are 1.006 W/mK and 12.271 W/mK, respectively. In the early 1980s, the NRICARS tested in the laboratory model embankments with coarse materials. In 1999, the NRICARS and the State Key Laboratory of Frozen Soil Engineering carried out tests of crushed rock for the embankment side slopes. The results showed that a crushed rock embankment was effective in protecting the underlying permafrost.

Sun *et al.* (2005) found out that the crushed rock layer with particle diameters between 40 and 50 cm had a good cooling effectiveness for the foundation soil based on heat exchange. Further research is needed to determine the optimal diameter and thickness of the crushed rock layer from field trials and laboratory experiments. The results from field trials are very important, since they allow, under similar conditions, a better understanding of laboratory results and the calibration of numerical models.

In general, ventilated embankments using crushed rock or jackstones, are cost-effective materials which can cool permafrost naturally. Therefore, ACE embankment is an appropriate method to protect permafrost in regions with thick ice layers, low level of precipitation and high evaporation due to high sun radiation as in the region of Qinghai-Tibet plateau. The use of crushed rock and jackstones in embankments results in an effective solution to avoid settlements due to thawing, which would cause serious problems for the railway in Qinghai-Tibet region.

Diameters of crushed rocks and jackstones

Crushed rocks are mined from hills and afterwards crushed to form coarse aggregates. It is required that the longest diagonal of each crushed surface should not be shorter than its diameter.

Crushed rocks were sorted into three groups according to size:

- 1) Standard: stones between 2.0 cm and 7.0 cm in diameter, used for newly-built or repairing of embankments
- 2) Medium: stones between 1.5 cm and 4.0 cm in diameter, used mainly for maintenance
- 3) Granule: stones between 0.3 cm and 2.0 cm in diameter, used for maintenance

Jackstones were initially used to protect the side slopes underwater, since they are also used to protect riverbeds and sub-bases from washout. In railway constructions, jackstones are mainly used for side slope reinforcement. The stone material should be hard and from anti-airslaked rocks (chemically resistant to atmospheric agents). Table 1 shows that the stone mean diameter, generally between 15 cm and 50 cm, is determined by the velocity of water flow and the depth under water. The higher the depth underwater and the higher the water flow velocity are, the larger the stone diameters are. In general, the stone thickness is between 3 and 4 times its diameter.

Table 1: Relationship between jackstone diameter and velocity of flow

Diameter of jackstone, cm	Velocity of flow, m/s				
	depth underwater, m				
	0.4	1.0	2.0	3.0	5.0
15	2.70	3.00	3.40	3.70	4.00
20	3.15	3.45	3.90	4.20	4.50
30	3.50	3.95	4.25	4.45	5.00
40	—	4.30	4.85	4.80	5.05
50	—	—	—	5.00	5.40

The results from studies (He *et al.*, 2000; Sun *et al.*, 2005) have indicated that the protective effect of crushed rock or jackstone layers on permafrost and the efficiency depends on the size of crushed rocks or jackstones and the depth of their layers. The right election of the crushed rock or jackstone size and layer depth can effectively reduce the thawing rate and stop the anthropogenic rise of the permafrost upper

limit, leading to the stability of roads and railways in permafrost areas. Since the presence of water is generally not considered in railway construction, it can be preliminary proposed a material of 10 cm to 15 cm in size and 30 cm to 50 cm in layer depth. The thickness of a crushed rock slope protection should be 3 to 4 times the mean diameter of crushed rocks. A pad should be installed below the slope. The desirable material is gravel or sand and an ideal depth is between 10 cm and 20 cm. However, in cases where the slope material is consistent with the construction requirement the pad material may not be necessary.

Final remarks

A crushed rock layer acts as a highly porous material, allowing strong air convection to occur within the layer during winter due to air density gradients. During summer, the density gradient becomes relatively stable; therefore, air circulation does not occur or is negligible. As a consequence, crushed rock layers act as a one-way heat transfer device which provides an effective cooling for the soil beneath it during winter and becomes an obstacle for heat flow during summer. The cooling effectiveness can prevent the underlying permafrost from thawing and eliminate hence thaw settlement.

From laboratory and field data analysis and observations, the following conclusions can be drawn:

- 1) The average temperature under a crushed rock layer is lower than that under a gravel layer for the same depth
- 2) The crushed rock layer has a better cooling effectiveness on the foundation soil based on the heat exchange
- 3) Further laboratory and field experimental research is needed to find the optimal diameter and thickness of the crushed rock layer. These results can be used to calibrate numerical models on permafrost engineering.

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