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Thermal properties of mine tailings and tire crumbs mixtures

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HIGHLIGHTS

- Thermal properties of dry mixtures of mine tailings and tire crumbs are studied.
- Increase in tire crumb reduces thermal conductivity and volumetric heat capacity.
- A multiple linear regression model for predicting thermal conductivity is proposed.
- An analysis chart for estimating volumetric heat capacity is established.

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ABSTRACT

This paper describes thermal and packing behaviors of the dry mixtures of mine tailings and tire crumbs, which has significant relation to engineering applications in utilizing recycled tire particles as lightweight fill materials with improved thermal insulation. The thermal properties and packing measurements of mine tailings and tire crumbs mixtures with different mixing ratios are presented, which are then analyzed to examine their correlations with respect to the volumetric mixing ratio of tire crumbs as well as the porosity of the mixtures. A statistical study using multiple linear regression analysis is also performed to establish a prediction model for the thermal conductivity and an analysis chart for estimating the volumetric heat capacity, as a function of the volumetric mixing ratio of tire crumbs and porosity.

1. Introduction

In geotechnical engineering practice, geomaterials, including natural soil, crushed rock and tailings from mining activities, and cement concrete, are commonly used as fills of earthworks. On the other hand, waste and by-product materials such as scrap tire, coal fly/bottom ash, sewage sludge ash, and rice husk ash, are often applied to enhance the physical and chemical properties of the fill materials. These materials are often required to have specific thermal properties depending on their applications. For instance, good insulating fills are needed for oil and gas pipelines and underground storage tanks of liquefied natural gas (LNG). In contrast, geothermal heat pumps and high-voltage power cables require fill materials to dissipate heat readily. Hence, suitable selection of fill materials is very important for energy savings.

In the mining industry, substantial tailings are generated worldwide after extraction of valuable metals and minerals from ore body. The tailings are the finely ground rocks, and can be either reactive (generating acid mine drainage, AMD hereafter) or non-reactive, depending on the mineralogical composition. Recently, the utilization of mine wastes by modifying the physical and chemical properties of tailings has been practiced, for example, as the backfill of cemented tailings [1] and as the raw material of building bricks [2]. These applications have advantages from technical, economic and environmental perspectives. Nevertheless, most tailings have traditionally been disposed on site in the form of impoundments. The surface impoundments of high water content tailings allow for their consolidation and desiccation. The impoundments may be in water or dry, depending on the disposal history and site conditions. Some tailings may be applied as construction materials on the mine site for infrastructures when natural soils are not available in ample quantity near the site and underwater disposal is not essential to control AMD [3]. Moreover, the use of such tailings can be beneficial for the reduction in tailings accumulation and costs associated with constructing and reclaiming tailings dykes and other infrastructures on the mine site.

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More than one billion scrap tires are produced each year worldwide, and the handling of these scrap tires has become a serious environment problem over past decades. As a possible alternative for their disposal, the scrap tires are used in civil engineering applications. The scrap tires are usually grinded to particles. According to ASTM D 6270 [4], they are classified into three distinct groups in particle sizes: tire shreds (50–305 mm), tire chips (12–50 mm) and particulate rubber (less than 12 mm), often known as tire crumbs [5]. The rubber tire particles are lightweight and durable, and display favorable drainage characteristic, good thermal insulation and high energy absorption. They are also comparatively cost effective when used as fills compared to other materials. Owing to these advantages, tire particles can be applied alone or mixed with other geomaterials as backfills of embankments, retaining walls, bridge abutments, leachate collection layers in landfills, subgrade thermal insulators and vibration attenuation media [6,7].

Studies on tire particles and soil-tire particle mixtures have been carried out extensively, including characterization of mechanical properties such as the strength, compressibility, compactivity and permeability, as related to the size and shape of tire particles, soil type and mixing ratio [5,8]. Meanwhile, a variety of field and laboratory studies for evaluating toxicity of leachates from scrap tires have been conducted [7,9]. A comprehensive overview on the environmental impacts of scrap tires is given in ASTM D 6270 [4]. However, the thermal properties of scrap tires and their mixtures with geomaterials, which are important in the design as insulation fills, have not been addressed in detail in the literature. For instance, in the work of Humphrey et al. [6], the thermal conductivity of tire chips was back-calculated by using one dimensional heat flow theory and measured temperature profile of an in situ three-layer (soil-tire chip-soil) system under steady state conditions. Therefore, more information on thermal properties of tire particles and their mixtures with geomaterials will be beneficial for practical applications.

This study is directed to the beneficial use of tire particles as lightweight fill materials with improved thermal insulation. Tailings from a mining site and tire crumbs were selected for the study for reasons discussed in the previous section. The thermal properties and packing densities of tailings mixed with tire crumbs in dry state were measured to investigate the roles of tire particles inclusion in amending the thermal and packing behaviors of mineral aggregates. The results of thermal conductivity and volumetric heat capacity measurements on the mixtures are presented to demonstrate their correlations with the volumetric mixing ratio of tire crumbs as well as the porosity of the mixtures. Based on the experimental results, a multiple linear regression model for predicting the thermal conductivity of the mixtures is established as a function of two variables, i.e., the volumetric mixing ratio of tire crumbs and porosity. The volumetric heat capacity diagram is presented, which enables the volumetric heat capacity to be determined for the mixtures at known porosity and volumetric mixing ratio of tire crumbs.

2. Heat transfer in geomaterials

Heat transfer takes place through conduction, convection and radiation. Of the three mechanisms, conduction prevails in solids and is the predominant mechanism for heat transfer in most geomaterials [10]. The thermal properties of a geomaterial are affected by the volumetric fractions of its constituents (air, water, minerals and organic matter). The thermal properties of constituents of geomaterials vary in a broad range, as shown in Table 1.

The thermal conductivity λ (W/m K) is defined as the heat flux under a unit temperature gradient under steady state, one dimensional conditions, as stated in the Fourier's law:

$$\lambda = -\frac{q}{dT/dx} \tag{1}$$

where q (W/m^2) is the heat flux which is the amount of thermal energy transferred per unit time in the x (m) direction per unit area perpendicular to the transfer direction, and T (K) is the temperature.

The volumetric heat capacity C_v (J/m^3 K) is the amount of heat required to change a unit temperature per unit volume of material:

$$C_v = \frac{dQ}{dT} \tag{2}$$

where Q (J/m^3) is the thermal energy per a unit volume and T (K) is the temperature. De Vries [13] suggested that the volumetric heat capacity of a geomaterial can be estimated as the arithmetic mean of the volumetric heat capacity C_i of each constituent in the geomaterial, using the volumetric fraction V_i as weight:

$$C_v = \sum_i V_i C_i = V_a C_a + V_w C_w + V_s C_s \tag{3}$$

where C and V denote the volumetric heat capacity and volumetric fraction of each constituent: air (a), water (w), and soil solid (s), respectively. Note that the solid constituents include various minerals and organic matter, which are not separated. When a dry mixture of tailings and tire crumbs is considered, Eq. (3) can be rewritten as

$$C_v = V_a C_a + V_m C_m + V_t C_t \tag{4}$$

where C_m and C_t are the volumetric heat capacities, and V_m and V_t are the volumetric fractions of mine tailings and tire crumbs, respectively. Eq. (4) can be expressed in terms of the porosity and volumetric mixing ratio of tire crumbs in the mixture R_{mV}:

$$C_v = nC_a + (1-n)(C_m - R_{mV}C_m + R_{mV}C_t) \tag{5}$$

where n is the porosity of the mixture and R_{mV} is the volumetric mixing ratio of tire crumbs in the mixture.

3. Particle packing characteristics

The term of packing may be defined as any manner of arrangement of solid units, in which each constituent unit is supported

Table 1

Densities and thermal properties of basic geomaterial constituents.

Material	Particle density ρ (g/cm^3)	Thermal conductivity λ (W/m K)	Volumetric heat capacity C_v (MJ/m^3 K)
Air	0.00125[a]	0.025–0.026[a] (283 K)	1.25×10^{-3}[a]
Water	1[a]	0.57–0.58[a] (283 K)	4.18[a]
Quartz	2.66[a,b]	8.8[a] (283 K)	2.01[a] 2.13[b]
Other minerals	2.65[a,b]	2.0[a,†] (298 K) 3.5[a,‡] (298 K)	2.01[a] 2.39[b]
Organic matter	1.3[a]	0.25[a] (–)	2.51[a]

[†] and [‡]: Values are for feldspar and mica, and amphibolite, respectively.

[a] Balland and Arp [11].

[b] Bristow [12].