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Joon Kyu Lee and Julie Q. Shang

The University of Western Ontario
Department of Civil and Environmental Engineering Faculty of Engineering Science

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Joon Kyu Lee[1] and Julie Q. Shang[2]

Abstract: This paper describes the thermal and packing behaviors of mine tailings and tire crumbs mixtures, which has significant relation to engineering applications in utilizing recycled tire particles as lightweight fill materials with improved thermal insulation. In the first part, the literature study on particle packing characteristics of spherical and granular materials is reviewed to comprehend the packing behaviors of mine tailings and tire crumbs mixtures that affect their thermal behaviors. In the second part, the thermal properties and packings measurements of dry mixtures of mine tailings and tire crumbs 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.

CE Database subject headings: Thermal factors; Tailings; Rubber; Fabrics; Porosity; Statistics.

Author keywords: Thermal conductivity; Volumetric heat capacity; Packing; Tailings; Tire particles; Statistics.

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[1]Research Fellow, Dept. of Civil and Environmental Engineering, Univ. of Western Ontario, London, ON, Canada N6A 5B9 (Corresponding author). E-mail: jlee962@uwo.ca

[2]Professor, Dept. of Civil and Environmental Engineering, Univ. of Western Ontario, London, ON, Canada N6A 5B9. E-mail: jqshang@uwo.ca

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, rice husk ash, etc, 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 mining tailings are generated worldwide after extraction of valuable metals and minerals from ore body. The mine 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 mine tailings has been practiced, for example, as the backfill of cemented tailings (Ercikdi et al. 2010) and as the raw material of building bricks (Yellishetty et al. 2008). These applications have advantages from technical, economic and environmental perspectives. Nevertheless, most mine 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 (Bussiere 2007). Moreover, the use of such mine 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.

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 (ASTM 2008), they are classified into three distinct groups in particle sizes: tire shreds (50 to 305 mm), tire chips (12 to 50 mm) and particulate rubber (less than 12 mm), often known as tire crumbs (Edincliler et al. 2010). 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 (Humphrey et al. 1997; Tweedie et al. 1998; Aydilek et al. 2006; Tandon et al. 2007; Hazarika et al. 2008).

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 (Hudson et al. 2007; Ozkul and Baykal 2007; Wartman et al. 2007; Tanchaisawat et al. 2010; Edincliler et al. 2010). Meanwhile, a variety of field and laboratory studies for evaluating toxicity of leachates from scrap tires have been conducted (Mclsaac and Rowe 2005; Sheehan et al. 2006; Tandon et al. 2007). A comprehensive overview on the environmental impacts of scrap tires is given in ASTM D 6270 (ASTM 2008). 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. (1997), 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.

Objective and Scope

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 mine 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 mixture samples were prepared in the laboratory by controlling the mixing ratio of the two materials and packing methods. 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.

The scope of the study includes a review of concepts from particle packing characteristics relevant to mixtures of mine tailings and tire crumbs, which will enhance the understanding of the thermal responses of the mixtures. Methods are addressed to estimate the loosest and densest packing behaviors of the mixtures from the theory and from experimental investigations, respectively. 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.

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 (Farouki 1986). 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. Furthermore, the fabric of geomaterials, which refers to the arrangement of particles of all size ranges, shapes and associated pores (Mitchell and Soga 2005), has an effect on their thermal properties (Carson et al. 2003; Cote and Konrad 2005).

The thermal conductivity λ (W/mK) 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. A high thermal conductivity signifies that heat easily propagates through a material. Several researchers (Farouki 1986; Brandon and Mitchell 1989) have pointed out that the thermal conductivity of geomaterials varies with temperature and pore fluid salinity, as well as the thermal conductivities and volumetric fractions of constituents.

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. A high volumetric heat capacity implies that a material has high capacity to store thermal energy. De Vries (1963) 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 mine 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.

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 and held in place in the Earth's gravitational field by tangent contact with its neighbors (Graton and Fraser 1935). The term *packing* is sometimes used interchangeably with the term *fabric* that describes the geomaterial particles and aggregates arrangement in soil mechanics. To comprehend the packing behaviors of particulate material mixtures, numerous theoretical and experimental studies have been performed. In general, the purposes of these studies are to minimize the void or maximize the density of the mixtures in ceramic, construction, food and polymer industries. In this section, a literature review on particle packing theories is presented in order to interpret the thermal behaviors of mine tailings and tire crumbs mixtures.

The porosity n, void ratio e and bulk unit weight γ_b, which are strongly related to the packing of granular materials, are correlated in the volume-weight phase relationships defined in soil mechanics:

$$n = \frac{e}{1+e} = 1 - \frac{\gamma_b}{G_s \gamma_w} \quad (6)$$

where G_s is the specific gravity of a mixture and γ_w is the unit weight of water. In addition, the arrangement of the packing is indirectly characterized by means of the coordination number N (defined as the average number of contact points that each particle has with surrounding particles).

The packings of uniform spheres provide insight for understanding the packing behaviors of granular materials. The regular packing arrangements of uniform spheres can be theoretically calculated using geometry. The porosity of uniform spheres ranges from a low of 0.260 for cubic packing to a higher of 0.476 for rhombohedral packing, and the corresponding coordination number is in the range of 6 to 12 (White and Walton 1937). However, random packings are more realistic to particulate materials. McGeary (1961) revealed that for packings of uniform spheres from 41 μm to 3 mm in size, the minimum porosity representing dense random packing lies within the range of 0.375 to 0.405. German (1986) summarized the reported porosities for randomly packed uniform spheres, and noted that the porosity for dense random packing varies from 0.333 to 0.390 with an average of 0.362, whereas the porosity of loose random packing of uniform spheres ranges from 0.375 to 0.440 with an average of 0.408. Murphy (1982) compiled the coordination number data from the literature and proposed an empirical relationship between the coordination number N and porosity n in a randomly packed assembly of uniform spheres, namely,

$$N = 27.03n^2 - 44.54n + 21.80 \quad (7)$$

Although this relation holds for $0.2 \le n \le 0.6$, it is obvious that the decrease in the porosity of random sphere packs increases the coordinate number, both being the result of denser packing.

The packing of granular materials is controlled by intrinsic factors such as the shape, size and gradation of particles, as well as by external factors such as the container wall effect and packing method. These factors, thus, have influences on the thermal properties of the mixtures.

Irregular particles tend to form looser packing than equivalent spheres. The porosity of natural sands with the same average particle size increases with decreasing the roundness and sphericity, resulting in lower coordinate number as well as lower stiffness (Cho et al. 2006). The greater the surface roughness is, the lower the packing density (Shinohara 1984). On the other hand, it was observed that the increase in the porosity with increasing particle irregularity leads to the decrease in the thermal conductivity (Carson et al. 2003; Yun and Santamarina 2008).

Fine particles likely exhibit looser packing than those of coarse particles due to surface effects. When the particle sizes approach to less than 50 μm, interparticle forces become prominent because of the increase in the specific surface area of particles (Samlley 1970). The factors such as frictional forces and bridging between fine particles contribute to the formation of loose or honeycomb structures with high pore space (Lade et al. 1998). Also, cementation between particles causes agglomeration and particles clusters, yielding high porosity (Fedors and Landel 1979). Norris (1977) pointed out that finer sands are generally more irregular and as a result, have higher porosity than coarse sands. Normally, the porosity of coarse-grained soils is within the range of 0.23 to 0.50, while fine-grained soils can have porosities greater than 0.50 (Budhu 2007). Meanwhile, it was shown that the thermal conductivity decreases as soil particles decrease in size (Tavman 1996; Smits et al. 2010).

Mixtures of non-uniform particles display a tendency to be denser than those of the same sizes since finer particles may occupy the voids between coarser particles. Panayiotopoulos (1989) noted that the influence of particle size distribution on packing efficiency is greater than those of particle size and shape. As the particle size ratio (i.e., the ratio of coarse particle to fine particle) increases, the coordinate number of coarse particles increases (Suzuki and Oshima 1983). On the other hand, it was found that the thermal conductivity of well-graded soils is greater than that of poor-graded soils (Brandon and Mitchell 1989; Cote and Konrad 2005).

The container wall effect is defined as the packing of particles being disrupted by the smooth wall of container, which leads to higher porosity near the wall. In a similar manner, the coarse particles dispersed or isolated within the fine particles may prevent truly random packing of fine particles at the interfaces of coarse and fine particles. The container wall effect on packing is less pronounced with rough walls and irregular particles. When the distance from the wall is at least ten times the particle size, the randomness of particles becomes constant (McGeary 1961). Meanwhile, the densest and loosest random packings are affected by packing procedures. In other words, the minimum and maximum porosities of a mixture depend on the methods employed for their determination (Lade et al. 1998), which may be estimated by procedures declared in ASTM D 4253 and D 4254 (ASTM 2006a, b). Additionally, other methods have been adopted by some researchers (Messing and Onada 1978; Al-Jarallah and Tons 1981).

For a mixture containing particles of two sizes, it can be idealized as a binary mixture, and its porosity variation against the volumetric mixing ratio of coarse particles to the total solids is illustrated in Fig. 1, where porosities at $R_{mV} = 0$ and 1 correspond to random packings of fine and coarse particles, respectively. The porosity decreases with an increase in the volumetric mixing ratio of coarse particles until it reaches a threshold value. This threshold value represents an optimal packing for a binary mixture, which is a point where the behavior of the mixture changes from fine-dominated to coarse-dominated. The trend is overturned with further increases in the volumetric mixing ratio of coarse particles. When the particle size ratio approaches infinity, the voids of the coarse particles are larger enough to allow for the random packing of fine particles, the porosity n_{opt} and volumetric mixing ratio R_{mV-opt} at the optimal packing can be obtained from the following equations, respectively (Lade et al. 1998):

$$n_{opt} = n_c n_f \tag{8}$$

$$R_{mV-opt} = 1 - \frac{1}{e_f}\left(\frac{n_f}{1/e_c + n_f/e_f}\right) \tag{9}$$

where n and e denote the porosity and void ratio of each particle in mixtures: coarse (c) and fine (f), respectively. The theoretical packing curve, i.e., the porosity behavior of mixtures n_{mix} in Fig. 1, is expressed as

$$n_{mix} = \frac{e_f(1-R_{mV})}{1+e_f(1-R_{mV})} \text{ for } R_{mV} \le R_{mV-opt} \tag{10}$$

$$n_{mix} = \frac{R_{mV}(e_c+1)-1}{R_{mV}(e_c+1)} \text{ for } R_{mV} \ge R_{mV-opt} \tag{11}$$

It is clear from these equations that the optimal packing point in binary mixtures is not unique because it relies on the packing characteristics of the host materials.

Experimental Study

To study the thermal and packing behaviors of mine tailings, tire crumbs and their mixtures, an experimental program was designed and carried out. A description of materials, apparatus, sample preparation and methodology is provided in this section, followed by discussion of experimental results and statistical analysis.

Materials

The materials used in this study are mine tailings and tire crumbs. Mine tailings were recovered from the Musselwhite mine, a gold mine located 500 km north of Thunder Bay, Ontario, Canada. Tire crumbs were supplied by a tire recycling facility located in Ontario. The index properties of two materials were determined following the recommended procedures by American Society of Testing and Materials (ASTM), and summarized in Table 2.

The specific gravity of mine tailings is 3.37, which is greater than that of typical soils owing to predominant amphibole minerals of high specific gravity (Wang et al. 2006), and the specific gravity of tire crumbs is measured as 1.19, which is comparable to those reported in ASTM D 6270 (ASTM 2008). The Atterberg limit tests on tailings particles finer than 75 μm revealed that the mine tailings are non-plastic. Scanning electron microscope (SEM) images of mine tailings and tire crumbs are displayed in Fig. 2. For mine tailings (Fig. 2(a)), particles are angular to subangular in shape, and typically consist of large bulky particles, platy particles and flocks (agglomeration of clay-sized particles). As shown in Fig. 2(b), the tire crumbs are angulated and roughened as they are produced through the mill process.

The particle size distributions of the mine tailings and tire crumbs are shown in Fig. 3. In Fig. 3(a), the shaded area indicates the typical grading of Canadian hard rock tailings as presented by Bussiere (2007). The mine tailings are made up of a wide range (0.42 to 138 μm) of particle sizes, characterized as a silt, with 9.4% sand, 83.2% silt and 7.4% clay (< 2 μm) sized particles. The size of tire crumbs ranges from 0.069 mm to 0.85 mm, as shown in Fig. 3(b). On the other hand, the textures of both the mine tailings and tire crumbs are quantified as the effective D_{10} and median D_{50} particle sizes, together with the coefficient of uniformity C_u and the coefficient of curvature C_c, as given in Table 2. Their textures can be further specified by using other statistical measures such as mode D_m, mean $\overline{D}$, standard deviation σ, skewness Sk and kurtosis K (see Appendix for the definition and statistical meaning of the measures) that are used to characterize the properties of geomaterials. As an example, Carrier (2003) pointed out that the $\overline{D}$ size of particles best represents the particle size for the estimation of the coefficient of permeability of a soil than the D_{10} size of particle. It is also noteworthy that the D_{50} almost never displays the same value as the $\overline{D}$ since the particle size probability density functions are likely to be skewed. Accordingly, the statistical measures of the mine tailings and tire crumbs were computed and are listed in Table 3. Based on the descriptive terminology of shapes suggested by Blott and Pye (2001), the mine tailings are poorly sorted (σ = 3.596), with fine skewed (indicating an excess of fines, Sk = -0.981) and mesokurtic

(K = 3.469) distribution, whereas tire crumbs is moderately well sorted (σ = 1.557), with fine skewed (Sk = -1.043) and leptokurtic (K = 3.810) distribution, as comparing to the log-normal distribution. As shown in Fig. 3(a), meanwhile, the particle size distribution of mine tailings used is characterized as the tertiary mode, which is attributed to the fact that ore has been artificially ground to a targeted particle size for liberating gold from the rock.

Wang et al. (2006) have studied the mineralogical and geochemical properties of the mine tailings used in this study. According to their results, the mine tailings contain 3% reactive minerals (i.e., pyrrhotite) and the remainder is composed of amphibole, quartz, mica or illite, and chlorite. The amount of pyrrhotite is small, comparing to that of other sulphide-containing mine tailings reported in the literature (e.g., 80% pyrrhotite: Amaratunga 1995; 49% pyrite: Ercikdi et al. 2010). This means that the mine tailings tested has low reactivity. Moreover, the mine tailings contain 1.2% carbonate, in the form of calcite and dolomite, which provide a pH buffer capacity. On the other hand, the pH of the mine tailings is measured as 8.4, which is slightly alkaline. This is mainly due to the addition of lime during the milling process and the presence of carbonates. Up to date, AMD has not been generated on the mine site.

Apparatus

In this study, all measurements of thermal properties were conducted using a thermal property analyzer (Model KD2 Pro, Decagon Devices Inc.). The methodology of the measurement is based on the transient line heat source theory (Bristow et al. 1998). This apparatus reproduces thermal properties of reference materials with ±5% accuracy within the temperature range of - 50 to 150 °C. The KD2 Pro analyzer comprises a hand-held unit and a sensor. The sensor has two-parallel probes of 1.3 mm diameter and 30 mm length at a spacing of 6 mm, which is inserted into the sample under testing. One of probes contains a heater and the other, a thermistor. A heat pulse is applied to the heater and, the temperature is simultaneously recorded at the thermistor. The thermal properties of the sample are automatically determined from the temperature response with time. A single measurement takes about 2 minutes including the temperature equilibrium period prior to heating and cooling.

Sample Preparation

In this study, samples tested include mine tailings, tire crumbs, and seven mixtures of the tailings and tire particles. The thermal conductivity and volumetric heat capacity of mixtures were measured and compared with those of pure mine tailings and pure tire crumbs. Nine samples with the rubber-to-tailings weight ratios of 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8 and 1.0 were prepared. The weight ratio was used instead of the volumetric ratio, because preparing samples is more readily performed using weight measurement. The weight mixing ratios were converted to the volumetric mixing ratios for evaluating packing and thermal behaviors of the samples in the analysis related to the volumetric terms. The volumetric mixing ratio of tire crumbs in the mixture R_{mV} can be calculated from the weight mixing ratio R_{mW}, knowing the specific gravities of tire crumbs G_{st}, and mine tailings G_{sm}, by using the following equation (Youwai and Bergado 2003):

$$R_{mV} = \frac{R_{mW}}{G_{st}} \left(\frac{1 - R_{mW}}{G_{sm}} + \frac{R_{mW}}{G_{st}} \right)^{-1} \quad (12)$$

It is intuitively recognized that the mixtures will form different fabrics under different particle sizes and shapes, which will influence the thermal properties of the mixtures, as discussed in the previous section.

Methodology

The tire crumbs and tailings at predetermined weight ratio were placed in a mechanical mixer and mixed until the samples were visually homogenous. The mixture was then packed following three different procedures: loosest packing, intermediate packing and densest packing. A standard Proctor mold of volume 943.7 cm^3 (101.6 mm diameter and 116.4 mm height), as described in ASTM D 698 (ASTM

2007), was used as the container. No surcharge and compaction were applied in the sample preparation to avoid crushing tailings particles and compression of tire particles.

A mixture with loosest random packing was achieved following the Method A specified by ASTM D 4254 standard (ASTM 2006b), in which a funnel was used to pour the mixture into the container. A mixture with the densest random packing was attained using an electromagnetic vibrating table (Model VP-51-D1, FMC tech.). A mixture with the intermediate packing was prepared following the same procedures for the densest packing, but the time and amplitude of vibration were attenuated. For each rubber-tailings weight ratio, one to three samples were prepared with various degrees of intermediate packing.

After packing, the extension collar on the mold was removed and the excess material was carefully trimmed off. The weight of the sample was measured for calculation of the bulk unit weight and porosity from Eq. (6). Lastly, the volumetric fractions of constituents in the sample (air, mine tailings and tire crumbs) were computed using Eq. (12) with the known porosity.

After the sample was prepared and its properties were measured, the KD2 Pro analyzer was vertically inserted into the sample. A total of three measurements, taken from 50 mm from the mold wall, were made and the average value and standard deviation were calculated. All measurements were carried out at the room temperature of 20 °C, with deviation less than ±0.5 °C.

Results and Discussion

A summary of results for all samples tested is tabulated in Table 4. One can notice that the measured bulk unit weight and porosity already capture the effects of the particle sizes, shapes and gradation as well as the container wall effect. In this section, the experiment results are presented and discussed to highlight the roles of coarse-gained tire particles inclusion in modifying the thermal and packing characteristics of fine-grained tailings.

Packing Behaviors of Mixtures

The minimum and maximum bulk unit weights (γ_{min} and γ_{max}) of the mixtures are plotted against the volumetric mixing ratio of tire crumbs, as shown in Fig. 4, in which the bulk unit weights corresponding to samples with intermediate packing are not included. The variation of the maximum bulk unit weight with the volumetric mixing ratio of the lightweight tire crumbs is greater than that of the minimum bulk unit weight. On the other hand, the results indicate that the inclusion of the lightweight tire crumbs decreases the bulk unit weight regardless of the packing density, and the trend is non-linear, which is due to the change in the amount of air-entrainment as influenced by the volume of tire crumbs in the mixture.

The minimum and maximum porosities (n_{min} and n_{max}) of the mixtures against the volumetric mixing ratio of tire crumbs are shown in Fig. 5, to compare with bulk unit weights in Fig. 4. Again, the porosities corresponding to intermediate packing are not presented in this plot. The porosity change in Fig. 5 represents the changes of air fraction in mixtures. The porosity of the mixtures decreases as packing density increases, while the variations of porosity are similar irrespective of packing states. As the volumetric mixing ratio of tire crumbs increases from 0 to 0.55, both the minimum and maximum porosities of the mixtures decrease gradually. As the volumetric mixing ratio of tire crumbs further increase from 0.55 to 1, the limit porosities of the mixtures increase significantly. This trend supports the fact that the decrease in the bulk unit weight of the mixtures with the increased portion of tire crumbs is caused not only by the reduced mixture weight, but also by the changes in entrained air in the mixture. The porosity of mine tailings ranges from 0.44 to 0.60, which is in the range of typical fine-grained soils, whereas the porosity of tire crumbs varies from 0.63 to 0.68, which are relatively large comparing to geomaterials. This may be attributed to the angular shape and rough surface of the tire particles. The observation shows the evidence that the porosity of materials is associated with the combined effect of particle size, shape and gradation.

The binary packing theory, modeled as Eqs. (8)-(11), is applied to the measured porosities of the mixtures of mine tailings and tire crumbs, as shown in Fig. 5. Based on particle size statistics of the two materials given in Table 3, the particle size ratios of the mode $D_{m\,t}/D_{m\,m}$ and the median $D_{50\,t}/D_{50\,m}$ (where the subscript t and m denote the tire crumbs and mine tailings, respectively) are computed to be 9.3 and 17.5, respectively. In addition, the particle size ratio of the mean with standard deviation $(\overline{D}_t \pm \sigma_t)/(\overline{D}_m \pm \sigma_m)$ is determined to be between about 20 and 30. The results demonstrate that the fitted curves of measured porosities are consistent with the theoretical packing curves: the porosity of the mixtures is less than the porosities of pure materials. However, the optimal packings of two limit porosities, i.e., minimum and maximum porosities, do not exhibit a distinctive point as derived from the ideal binary mixture shown in Fig. 1. This is probably due to the fact that for mixtures with tire crumbs content less than the optimal packing value, tire particles do not float within the tailings particles matrix without the interference of random tailings packs. For mixtures with tire crumbs content higher than the optimal packing value, tailings particles could not migrate into the pore space between tire particles without frictional resistance that leads to disconnected tire particles. Similar smooth packing trends for mixtures containing construction aggregates of two different sizes have been observed in the literature (Al-Jarallah and Tons 1981, Lade et al. 1998, Jones et al. 2002). In their works, the median particle size ratio is in the range of about 2 to 30. Polito (1999) analyzed the packing for mixtures of 37 sands and 5 non-plastic silts, and concluded that the volumetric mixing ratio of sands at the optimal packing point was within the range of 0.55 to 0.75. In contrast, for the irregular shaped tire crumbs and tailings mixtures, it is found that the optimal packing is located at a lower volumetric mixing ratio of tire crumbs, i.e., in the range of 0.50 to 0.60.

The relationship between the minimum and maximum porosities of the mixtures is shown in Fig. 6. The result reveals that the maximum porosity increases with an increase in the minimum porosity. The data regression equation has the form of (R^2 = 0.85)

$$n_{max} = 0.48\, n_{min} + 0.36 \quad (13)$$

Based on this relation, the packing method used in this study can be employed to prepare mixtures with minimum and maximum porosities. The correlation can also be used to estimate the minimum porosity from the maximum porosity and vice versa, for rubberized geomaterials.

The porosity range, i.e., $n_{max} - n_{min}$ (or the void ratio range, i.e., $e_{max} - e_{min}$) is used as an index property of granular geomaterials that reflects their fabrics (Cubrinovski and Ishihara 2000). Fig. 7 shows the porosity range versus the volumetric mixing ratio of tire crumbs. The values of $n_{max} - n_{min}$ slightly increases with the increasing volumetric mixing ratio of tire crumbs first, then it begins to decrease noticeably with a further increase in the volumetric mixing ratio, finally it decrease steadily. This indicates that a transition region exists, ranging from R_{mV} = 0.55 to 0.75. In this region, both the mine tailings portion and tire crumbs portion in the mixtures govern the porosity of the mixtures, beyond this range, the mixture fabric transits from a rigid (i.e., a mine tailings supported fabric) to a soft (i.e., a tire crumbs supported fabric) granular skeleton. Meanwhile, it is shown that there is little porosity change in packing of pure tire crumbs, which is expected since the vibration has limited effect on densification of lightweight and highly compressible materials.

These observations can provide insight to the optimal mixing design of geomaterials mixed with recycled tire particles, which represent rigid-soft mixtures. Furthermore, the results suggest that factors such as the particle sizes, shapes and gradation may control the packing characteristics of the mixtures. The effect of these features to the thermal behavior of the mixtures will be discussed in the following section.

Thermal Behaviors of Mixtures

The relationships between the thermal conductivity and volumetric mixing ratio of tire crumbs for the densest and loosest random packings are shown in Fig. 8. It is no surprise to see that the thermal conductivities of the mixtures with the densest packing are greater than those with the loosest packing, as the thermal conductivity of solids is higher than that of air. It is of interest to note from Fig. 8 that the trends of thermal conductivity curves at two different packing states are similar. For the densest packing, the thermal conductivity values reduce from 0.248 W/mK for mine tailings to 0.080 W/mK for tire crumbs, while for the loosest packing, the values decrease from 0.140 to 0.073 W/mK. The mixture containing 65.4% of tire crumbs by volume (40% by weight) has a reduction of thermal conductivity of about 50% comparing to the mine tailings without the addition of tire crumbs. More importantly, the thermal conductivities of the two packing states follow a similar trend compared to packing behaviors as presented in Fig. 4. This finding substantiates the fact that the thermal conductivity of granular geomaterials is correlated to the inherent thermal properties of constituents as well as the volumetric fractions of constituents and arrangement of particles in the mixtures.

The relationships between the volumetric heat capacity and volumetric mixing ratio of tire crumbs for the densest and loosest random packings are shown in Fig. 9. The volumetric heat capacity of the densest packing mixtures is larger than that of the loosest packing mixtures. On the other hand, as the volumetric mixing ratio of tire crumbs increases, the volumetric heat capacity initially increases slightly and then dramatically decreases for both packings. It is also noted that the trend of variation of the volumetric heat capacity versus the volumetric mixing ratio of tire crumbs is similar to that of the porosity versus the volumetric mixing ratio of tire crumbs, as indicated in Fig. 5. This embodies that the volumetric heat capacity of the mixtures is more affected by the volumetric fraction of air than by that of solid phases. This is attributable to the fact that the volumetric heat capacity of air is three orders of magnitude lower than that of most solids, including tailings and tire particles.

Fig. 10 shows the relationships between the thermal conductivity and porosity for all experimental data tested in this study, including samples with intermediate packings. The thermal conductivity of mine tailings decreases with increasing porosity and ranges from 0.248 to 0.140 W/mK for porosities between 0.44 and 0.60. Meanwhile, the thermal conductivity of tire crumbs varies from 0.080 to 0.073 W/mK for porosities ranging from 0.63 to 0.68. The measured thermal conductivities of the mixtures of the two materials are located within the upper and lower bounds with respect to the mine tailings and tire crumbs, respectively. This plot also shows that as the weight mixing ratio of tire crumbs increases, the thermal conductivity decreases. Hence, the thermal insulation effect of recycled tire crumbs can be utilized in engineering applications.

The thermal conductivities of dry geomaterials including crushed rocks, gravels, sands, silts and clays, as related to their porosities have been studied by many researchers (Kersten 1949; Gangadhara Rao and Singh 1999; Corte et al. 2009). Fig. 11 shows comparison of the measured values of the thermal conductivity of mine tailings and tire crumbs and those of other materials reported in the literature. The thermal conductivity of mine tailings is within the typical range of sands and clays, whereas the thermal conductivity of tire crumbs is lower than that of typical geomaterials. The plot also explains that the thermal conductivity of geomaterials is sensitive to the fabric as well as the thermal conductivity of their constituents. For instance, the thermal conductivity of crushed rocks is scattered and differs from that of natural gravels despite their similar grain sizes (≈ 20 mm).

Fig. 12 shows the relationships between the volumetric heat capacity and porosity for all experimental data obtained in this study. The volumetric heat capacity of the mixtures decreases with increasing porosity. The volumetric heat capacity of mine tailings ranges from 1.677 to 1.217 MJ/m^{3}K for porosities between 0.44 and 0.60. On the other hand, the thermal conductivity of dry tire crumbs varies from 0.901 to 0.811 MJ/m^{3}K for porosities ranging from 0.63 to 0.68. These two trends are the upper and lower bounds of the mixtures of mine tailings and tire crumbs, respectively. Fig. 12 also demonstrates that the rate of volumetric heat capacity changes against the porosity decreases with increasing weight mixing ratios of tire crumbs in the mixtures.

From Figs. 10-12, one may recognize that the thermal properties of mine tailings and tire crumbs mixtures strongly depend on the packings of the mixtures as represented by porosity. Consequently, the porosity plays a critical role in heat transfer of the dry mixtures, and can be considered to be a secondary factor that captures the primary factors, i.e., the particle sizes, shapes and gradation as well as the particle characteristics of host materials. Especially, given the mechanism of thermal contacts at the particle-scale, the increase in thermal conductivity with decreasing porosity may reflect the improvement of particle contacts in the mixtures.

Statistical Analysis

In the above section, the results of thermal properties and packing tests were interpreted to explore the correlation between thermal and packing behaviors of the mine tailings and crumb tires mixtures. In this section, the results of statistical analysis on the average thermal properties in Table 4 are presented and discussed.

Regression analysis was used for statistical evaluation. The general multiple linear regression model can be formulated in the following equation:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_i X_i + \beta_n X_n + \varepsilon \qquad (14)$$

where β_i is the regression coefficient, X_i is the independent variables, Y is the dependent variable, and ε is a random error term.

In this study, the multiple linear regression analyses were performed in two phases: to build a prediction model for the thermal conductivity, and to develop an analysis chart for the volumetric heat capacity. In the first phase, the multiple linear regression analysis was carried out to establish the relationship of the average thermal conductivity of mine tailings, tire crumbs and their mixtures as related to the volumetric mixing ratio of tire crumbs R_{mV} and porosity n. In the second phase, the volumetric heat capacity values of mine tailings and tire crumbs (i.e., C_m and C_t) were first computed by using multiple linear regression analysis (without accounting for intercept term, β_0) applied to Eq. (4) with other known variables (i.e., C_v , C_a , V_a , V_m and V_t), and then the calculated values are applied to Eq. (5) to produce a volumetric heat capacity diagram of the mixtures as a function of the volumetric mixing ratio of tire crumbs R_{mV} and porosity n.

Regression Model for Thermal Conductivity

A multivariate regression model is developed at a significance level of 5% to relate the thermal conductivity λ, and the volumetric mixing ratio of tire crumbs R_{mV} and porosity n:

$$\lambda = 0.368 - 0.079 R_{mV} - 0.353n \tag{15}$$

Eq. (15) states that the form of the regression model is consistent with the trends of test results observed in Fig. 10. That is, the thermal conductivity decreases with increasing volumetric mixing ratio of tire crumbs and increasing porosity.

The statistical properties from the regression analysis are summarized in Table 5. The coefficient of determination R^2 is 0.908, which indicates a strong correlation between the thermal conductivity and the two variables (i.e., R_{mV} and n). However, a large R^2 value does not necessarily guarantee accurate prediction, and therefore the F - value test is also used to assess the regression model. By definition, the F - value is the ratio of the mean squares of regression (MSR) and mean squares of error (MSE) if the hypothesis of the test is all regression coefficients being zero (Montgomery et al. 2004). When the F - value of the regression model is larger than the critical F - value that is the upper limit of the F ratio, the model is feasible at a given probability and degree of freedom. The F - value is calculated to be 182.5, much greater than the critical F - value at the probability of 95%, i.e., 3.3, suggesting that the regression model is highly significant.

The standard residual of predicted thermal conductivity, defined as $r_s = r / SE$, where r_s = standard residual, r = residuals, and SE = standard error, is shown in Fig. 13. The SE of thermal conductivity regression model is 0.014, and the 95% confidence band is ±2.03. This plot demonstrates that the majority of the standard residuals fall in the 95% confidence bandwidth of 4.05. The standard residuals are evenly distributed with regard to the predicted values of thermal conductivity, indicating the regression model is strongly significant for the estimate of thermal conductivity.

Additionally, even if the regression model is statistically significant in terms of R^2, F - value and standard residuals, implying the model is applicable, it does not guarantee that the model is in any way optimal. It could be, for example, that one variable is dominating the regression equations while another variable in the equation is irreverent. Thus, the significance of the regression coefficients of the variables in the empirical model was examined via Student's t - test, which is designed to evaluate the hypothesis of a particular regression coefficient being zero at an arbitrary probability. The significance of any regression coefficient can be assessed by comparing the t - statistic of the regression coefficient (defined as the ratio of the regression coefficient β_i , and its standard error SE , i.e., $|t - stat| = |\beta_i / SE(\beta_i)|$) and the Student's t distribution. In other words, if the value of t - statistic for any of the regression coefficients is less than the Student's t distribution at the probability of 95%, i.e., 1.69, it can be concluded that the data do not provide convincing evidence that the coefficient is different from zero. The results of Student's t test reveal that the intercept, volumetric mixing ratio of tire crumbs and porosity are significant at the probability of 95% in the regression model, as shown in Table 5. Comparing to the values of t - statistic obtained, the porosity is slightly more significant than the volumetric mixing ratio of tire crumbs.

As a result, the multiple linear regression model to relate the volumetric mixing ratio of tire crumbs R_{mV} and porosity n is highly significant as indicated by a series of statistical analyses. A practical application of the empirical model is to predict the thermal conductivity if the volumetric mixing ratio of tire crumbs and porosity of a mixture are known. Also, it can be applied to estimate conditions to attain a desired thermal conductivity. Although the model was built with limited data, it provides a viable insight to the understanding of the thermal conductivity behaviors of rubberized geomaterials in dry condition.

Analysis Chart for Volumetric Heat Capacity

With known volumetric fractions of constituents (i.e., air, mine tailings and tire crumbs) and volumetric heat capacities of air and mixtures, the volumetric heat capacities of mine tailings and tire crumbs mixtures were determined by using the multiple linear regression analysis applied to Eq. (4). The volumetric heat capacity values of the mine tailings and the tire crumbs are found to be 2.889 and 2.461 MJ/m^{3}K, respectively. The resulting values of statistical properties are coefficient of determination R^2 = 0.999 with standard error SE = 0.033 and F - value = 32,829.6. These volumetric heat capacity values were used to Eq. (5) that correlates the volumetric heat capacity of mixtures C_v, volumetric mixing ratio of tire crumbs R_{mV} , and porosity n . Fig. 14 shows an analysis chart for estimating the volumetric heat capacity of mixtures at known porosity and volumetric mixing ratio of tire crumbs. The curves represent the porosity range of 0.3 - 0.7, as indicated in Fig. 12. The volumetric heat capacity decreases with increasing volumetric mixing ratio of tire crumbs at a given porosity. Meanwhile, the volumetric heat capacity decreases with increasing air fraction in mixtures at a given volumetric mixing ratio of tire crumbs. These trends are consistent with the results shown in Fig. 12. From a practical perspective, the analysis chart may prove useful for reasonable predictions of the volumetric heat capacity from easily available mixture properties, i.e., the volumetric mixing ratio of tire crumbs and porosity only.

Summary and Conclusions

The objective of this study was to investigate the thermal and packing behaviors of mine tailings and tire crumbs mixtures, which has potential applications in utilizing recycled tire particles as lightweight fill materials with enhanced thermal insulation. The study included a detailed literature review on particle packing characteristics of spherical and granular materials, which serves to improve the understanding of the packing of mine tailings and tire crumbs mixtures that associate with their thermal properties. In the experimental program, the thermal and packing properties of dry mixtures of mine tailings and tire crumbs with different mixing ratios were measured to investigate the roles of tire particles inclusion on the thermal and packing behaviors of mineral aggregates, as well as to examine their relationships with the porosity. The following conclusions can be made based on the results of this study:

1. The factors affecting the packing and thermal properties of geomaterials include the particle size, shape and gradation as well as the container wall effect and packing method.
2. The bulk unit weights of the loosest and densest packed mixtures decreased non-linearly with increasing volumetric mixing ratios of tire crumbs in the mixtures, and the variations of their thermal conductivities were similar to the convex-shaped variations of bulk unit weights.
3. The minimum and maximum porosities of the mixtures against the volumetric mixing ratio of tire crumbs showed the smooth concave-shaped variation, not the sharp V-shaped variation derived from the ideal binary mixture. As increased the volumetric mixing ratios of tire crumbs in the mixtures, the volumetric heat capacity values of the mixtures corresponding to the densest and loosest packings initially increased slightly and then decreased considerably, similar to the trend of porosity variation.
4. At the volumetric mixing ratios of tire crumbs of 0.55 to 0.75, the mixtures demonstrated transitional fabrics, i.e., the structure changed from a tailings controlled rigid fabric and a rubber particles controlled soft fabric.
5. The porosity plays a preponderant role in heat transfer of the dry mixtures: both the thermal conductivity and the volumetric heat capacity increased linearly with decreasing porosity.
6. A multiple linear regression model was developed to estimate the thermal conductivity of the mine tailings and tire crumbs mixtures as related to the volumetric mixing ratio of tire crumbs and porosity. A series of statistical analyses revealed that the regression model is highly significant.

7. An analysis chart was established that enables the volumetric heat capacity of the mine tailings and tire crumbs mixtures to be determined at the known porosity and volumetric mixing ratio of tire crumbs in the mixtures.

It is believed that the findings and interpretation methods presented in this study will be beneficial for the understanding of the thermal characteristics of rubberized geomaterials in dry condition.

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Appendix

The statistical measures, i.e., mode D_m, mean $\overline{D}$, standard deviation σ, skewness Sk and kurtosis K, can be used to demonstrate a particle size distribution characteristics, which is described succinctly by Blott and Pye (2001): those quantifying the size with the highest frequency; the average size; the spread (sorting) of the size around the average; the symmetry or preferential spread (skewness) to one side of the average; and the degree of concentration of the particles relative to the average (kurtosis). These measures are commonly calculated geometrically (based on log-normal distribution) using moment method, which are defined as follows:

$$\overline{D} = \exp \sum f \ln D \tag{16}$$

$$\sigma = \exp \sqrt{\sum f (\ln D - \ln \overline{D})^2} \tag{17}$$

$$Sk = \frac{\sum f (\ln D - \ln \overline{D})^3}{\ln \sigma^3} \tag{18}$$

$$K = \frac{\sum f\,(\ln D - \ln \overline{D})^4}{\ln \sigma^4} \tag{19}$$

where f is the fraction of particles between two sieve sizes and D is the average particle size between two sieve sizes.

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Table 1 Densities and thermal properties of basic geomaterial constituents

Material	Particle density ρ (g/cm^3)	Thermal conductivity λ (W/mK)	Volumetric heat capacity C_v (MJ/m^{3}K)
Air	0.00125[a]	0.025 to 0.026[a] (283 K)	1.25×10^{-3} [a]
Water	1[a]	0.57 to 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)	2.01[a]
		3.5[a‡] (298 K)	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 (2005)

[b] Bristow (1998)

Table 2 Index properties of mine tailings and tire crumbs

Properties	Mine tailings	Tire crumbs
Specific gravity, G_s	3.374	1.190
Optimum water content, w_{opt} (%)	13.5	-
Maximum dry unit weight, $\gamma_{d\,\max}$ (kN/m^3)	19.5	-
Effective size, D_{10} (µm)	2.8	237.1
Median size, D_{50} (µm)	25.6	448.1
Coefficient of uniformity, C_u	11.43	2.08
Coefficient of curvature, C_c	1.61	0.96

Table 3 Particle size statistics of mine tailings and tire crumbs

Sample statistics	Mine tailings	Tire crumbs
Mode, D_m (µm)	45.7	425.0
Mean, $\overline{D}$ (µm)	18.5	444.4
Standard deviation, σ (µm)	3.596	1.557
Skewness, Sk (µm)	-0.981	-1.043
Kurtosis, K (µm)	3.469	3.810

Table 4 Summary of packings and thermal properties of the mixtures tested

No.	Weight mixing ratio of tire crumbs R_{mW} (-)	Volumetric mixing ratio of tire crumbs R_{mV} (-)	Bulk unit weight γ_b (kN/m^3)	Porosity n (-)	Thermal conductivity λ (W/mK)	Volumetric heat capacity C_v (MJ/m^{3}K)
1	0	0	13.3	0.60	0.140 (0.003)†	1.217 (0.003)†
2	0	0	14.8	0.55	0.166 (0.002)	1.287 (0.008)
3	0	0	16.2	0.51	0.204 (0.003)	1.452 (0.012)
4	0	0	17.1	0.48	0.226 (0.005)	1.574 (0.014)
5	0	0	18.7	0.44	0.248 (0.002)	1.677 (0.029)
6	0.1	0.240	12.8	0.54	0.138 (0.003)	1.259 (0.014)
7	0.1	0.240	13.9	0.50	0.155 (0.002)	1.312 (0.008)
8	0.1	0.240	15.2	0.46	0.189 (0.003)	1.501 (0.007)
9	0.1	0.240	16.8	0.40	0.218 (0.004)	1.617 (0.026)
10	0.1	0.240	17.7	0.37	0.245 (0.003)	1.728 (0.018)
11	0.2	0.415	11.2	0.54	0.127 (0.005)	1.272 (0.041)
12	0.2	0.415	12.5	0.48	0.146 (0.003)	1.362 (0.017)
13	0.2	0.415	13.4	0.45	0.164 (0.005)	1.447 (0.023)
14	0.2	0.415	14.5	0.40	0.186 (0.009)	1.642 (0.036)
15	0.2	0.415	15.4	0.36	0.220 (0.004)	1.731 (0.010)
16	0.3	0.549	10.2	0.52	0.123 (0.002)	1.255 (0.006)
17	0.3	0.549	10.9	0.49	0.139 (0.005)	1.325 (0.014)
18	0.3	0.549	11.9	0.44	0.166 (0.003)	1.491 (0.021)
19	0.3	0.549	12.6	0.41	0.176 (0.004)	1.542 (0.028)
20	0.3	0.549	13.6	0.36	0.209 (0.003)	1.711 (0.012)
21	0.4	0.654	8.7	0.55	0.114 (0.002)	1.181 (0.008)
22	0.4	0.654	9.4	0.51	0.127 (0.002)	1.278 (0.014)
23	0.4	0.654	9.9	0.48	0.131 (0.002)	1.304 (0.017)
24	0.4	0.654	10.4	0.46	0.145 (0.001)	1.397 (0.005)
25	0.4	0.654	11.1	0.42	0.165 (0.008)	1.532 (0.005)
26	0.5	0.739	7.5	0.56	0.113 (0.002)	1.157 (0.017)
27	0.5	0.739	7.8	0.55	0.118 (0.003)	1.191 (0.021)
28	0.5	0.739	8.3	0.52	0.121 (0.002)	1.207 (0.017)
29	0.5	0.739	8.5	0.51	0.131 (0.002)	1.294 (0.008)
30	0.5	0.739	9.1	0.47	0.138 (0.002)	1.354 (0.008)
31	0.6	0.810	6.8	0.57	0.104 (0.003)	1.131 (0.011)
32	0.6	0.810	7.2	0.54	0.110 (0.003)	1.194 (0.007)
33	0.6	0.810	7.6	0.52	0.117 (0.001)	1.240 (0.010)
34	0.6	0.810	8.0	0.49	0.126 (0.003)	1.307 (0.014)
35	0.8	0.919	5.2	0.62	0.089 (0.000)	0.987 (0.006)
36	0.8	0.919	5.6	0.58	0.097 (0.001)	1.061 (0.005)
37	0.8	0.919	6.0	0.55	0.104 (0.002)	1.124 (0.017)
38	1	1	3.8	0.68	0.073 (0.001)	0.811 (0.010)
39	1	1	4.0	0.66	0.076 (0.002)	0.855 (0.016)
40	1	1	4.3	0.63	0.080 (0.001)	0.901 (0.011)

† Standard deviation

Table 5 Summary of multiple linear regression analysis result

Observations	40		
R - squared	0.908		
Standard error	0.014		
F - value	182.5		
	Coefficients	Standard error	t - statistic
Intercept	0.368	0.015	24.007
R_{mV}	-0.079	0.008	-9.424
n	-0.353	0.033	-10.697

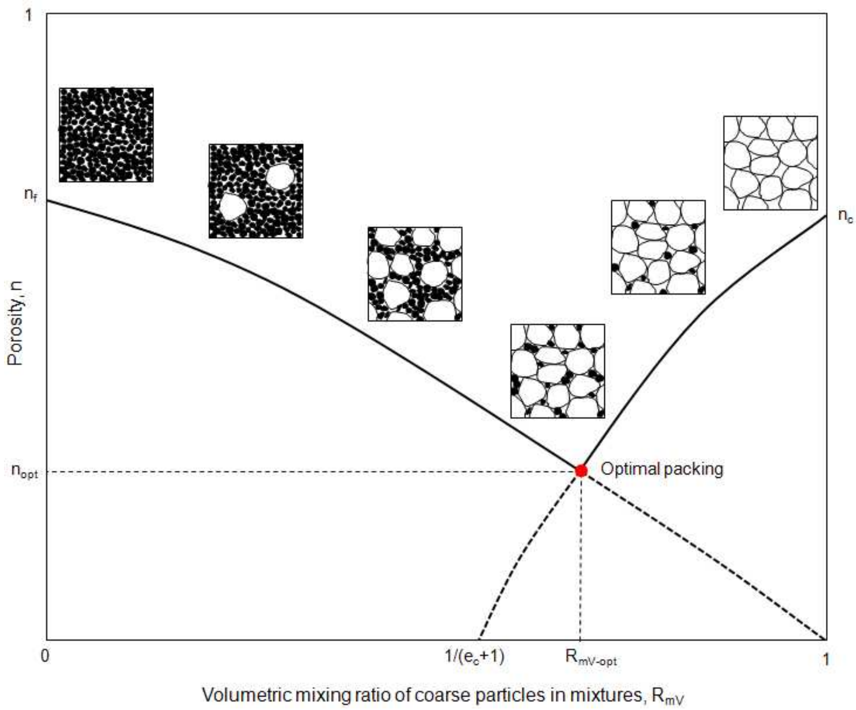
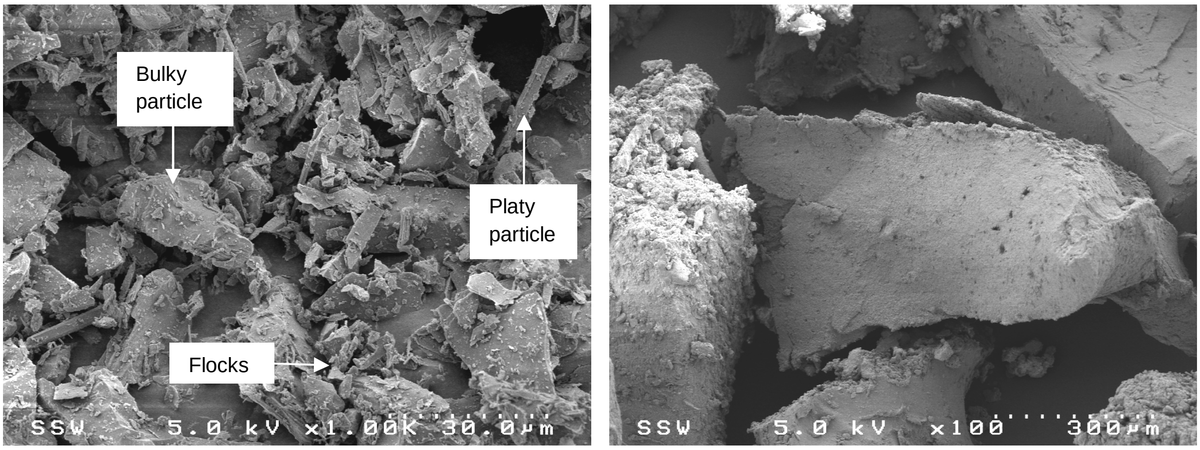
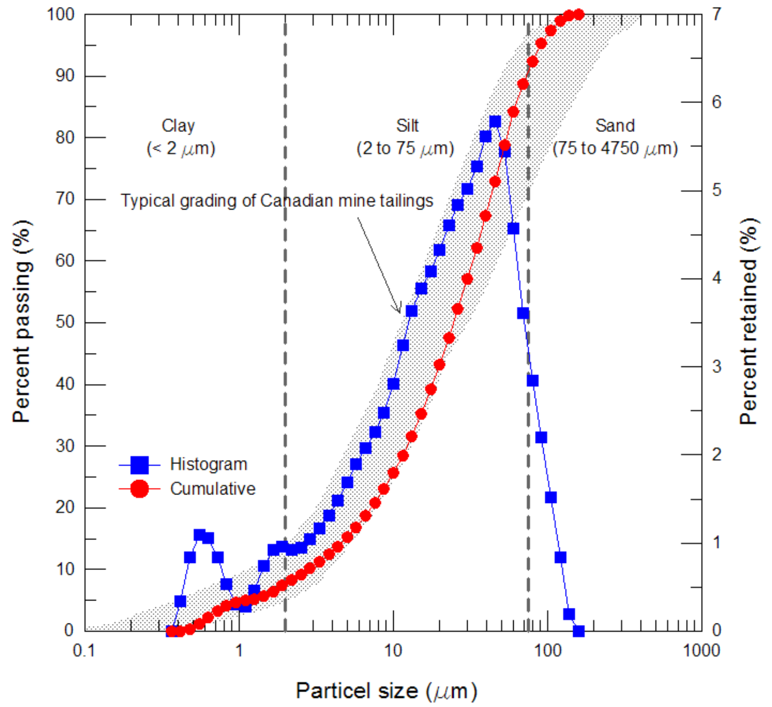


Fig. 1 Porosity in binary packing against volumetric mixing ratio of coarse particles in mixtures (modified from Lade et al. (1998))

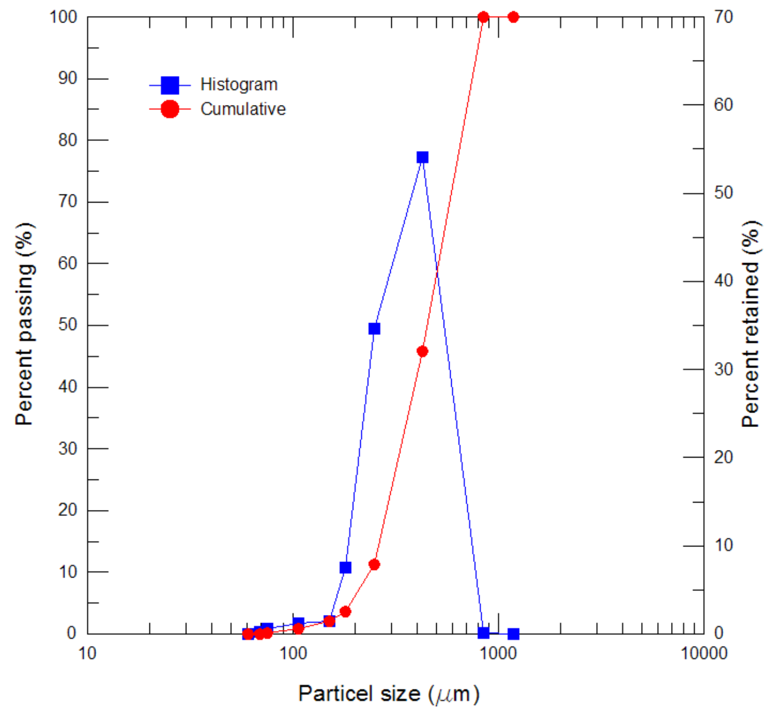


(a) (b)

Fig. 2 SEM images: (a) mine tailings; (b) tire crumbs



(a)



(b)

Fig. 3 Particle size distribution curves: (a) mine tailings; (b) tire crumbs

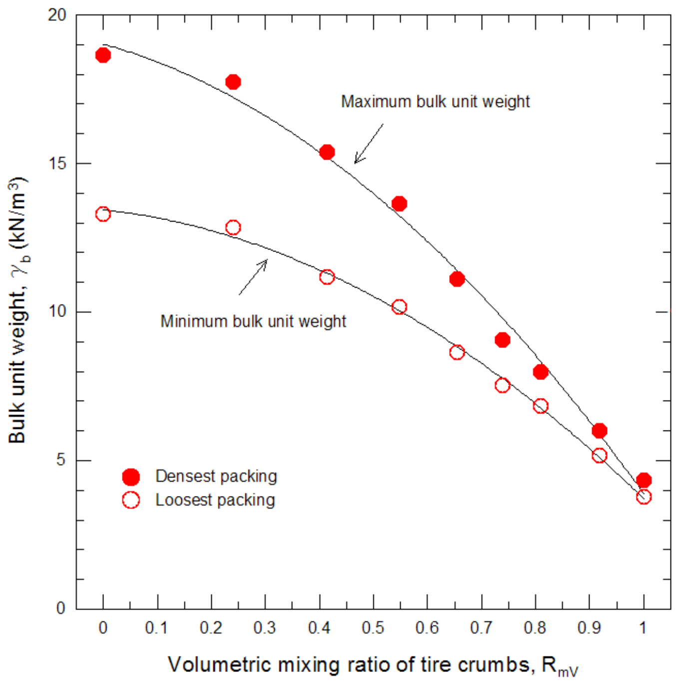


Fig. 4 Variations of minimum and maximum bulk unit weights for mixtures of mine tailings and tire crumbs

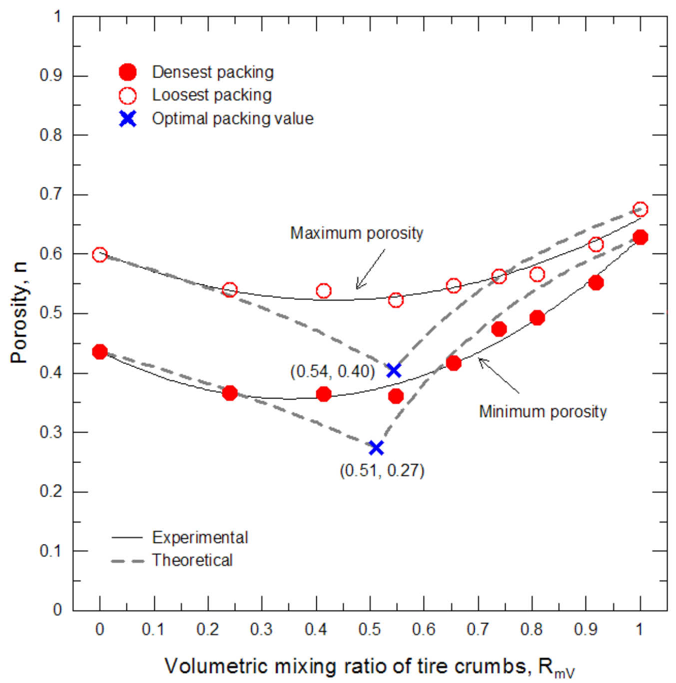


Fig. 5 Variations of minimum and maximum porosities for mixtures of mine tailings and tire crumbs

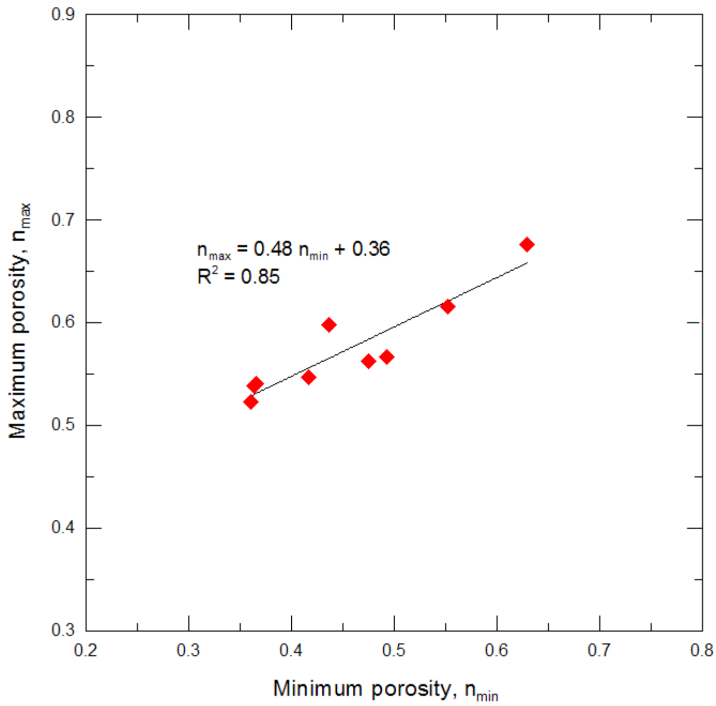


Fig. 6 Correlation between minimum and maximum porosities

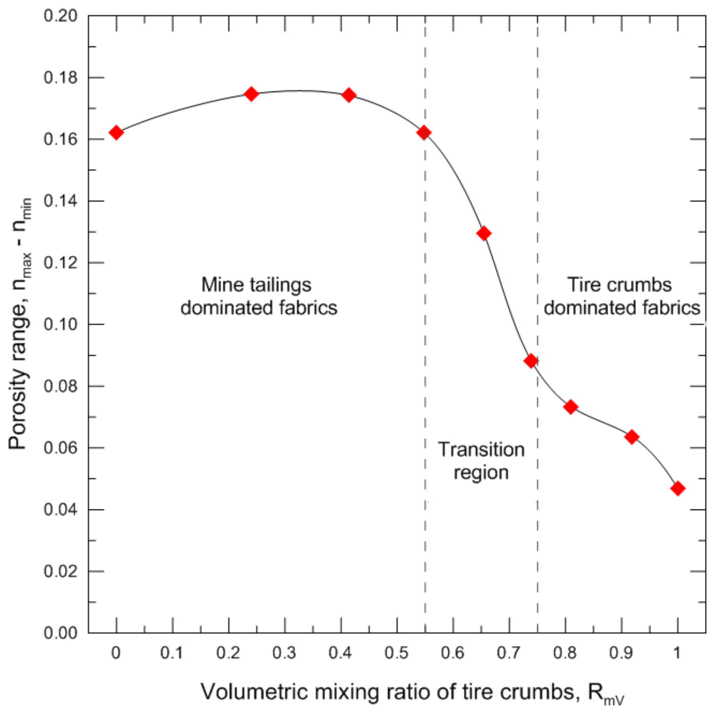


Fig. 7 Change in porosity ranges for mixtures of mine tailings and tire crumbs

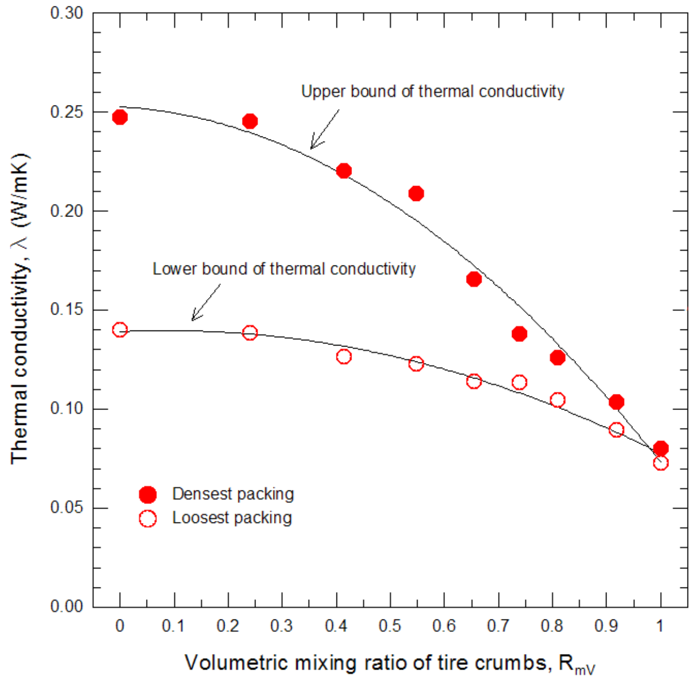


Fig. 8 Relationships between thermal conductivity and volumetric mixing ratio of tire crumbs for loosest and densest packings for mine tailings and tire crumbs mixtures

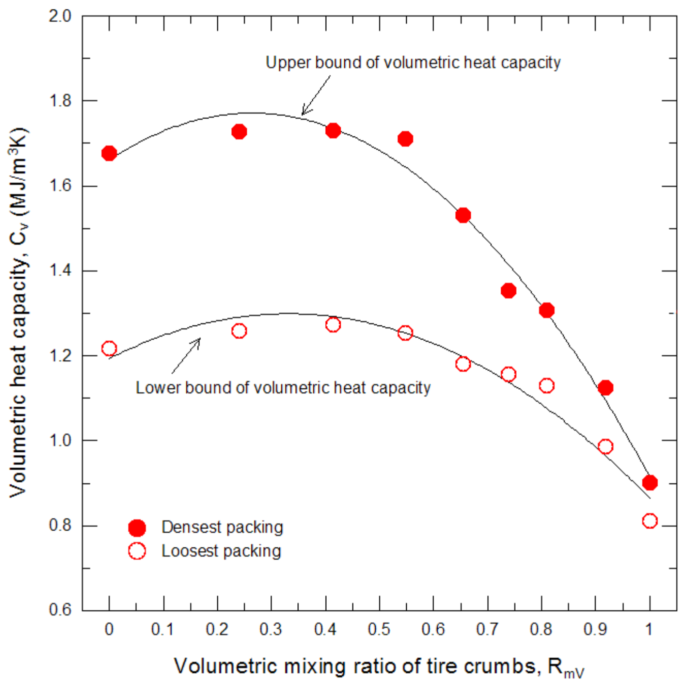


Fig. 9 Relationships between volumetric heat capacity and volumetric mixing ratio of tire crumbs for loosest and densest packings for mine tailings and tire crumbs mixtures

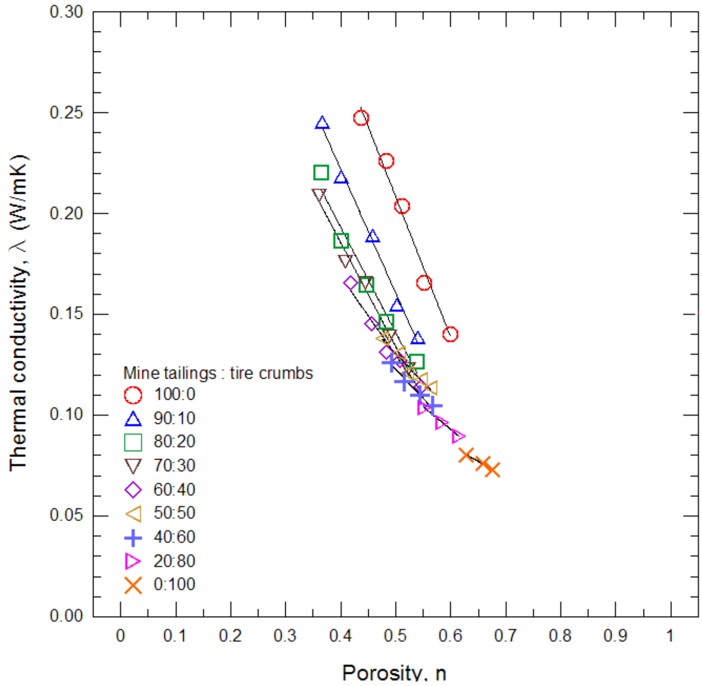


Fig. 10 Effect of weight mixing ratio of mine tailings and tire crumbs mixtures on thermal conductivity

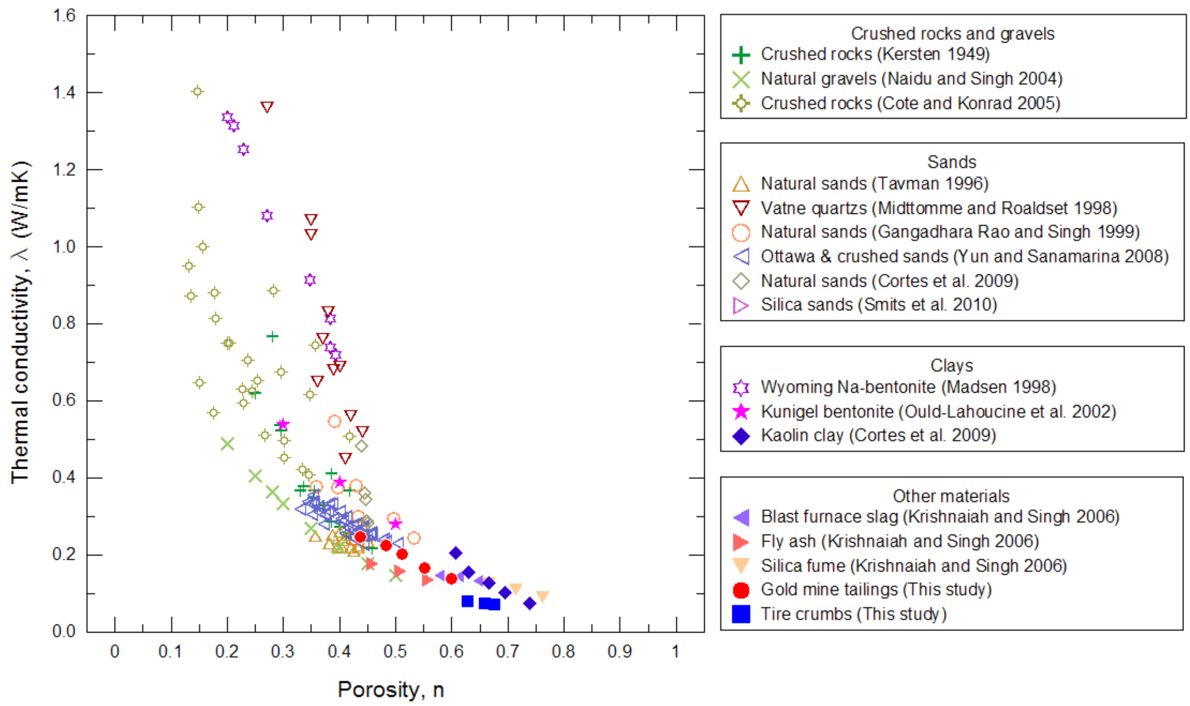


Fig. 11 Thermal conductivity of various dry geomaterials

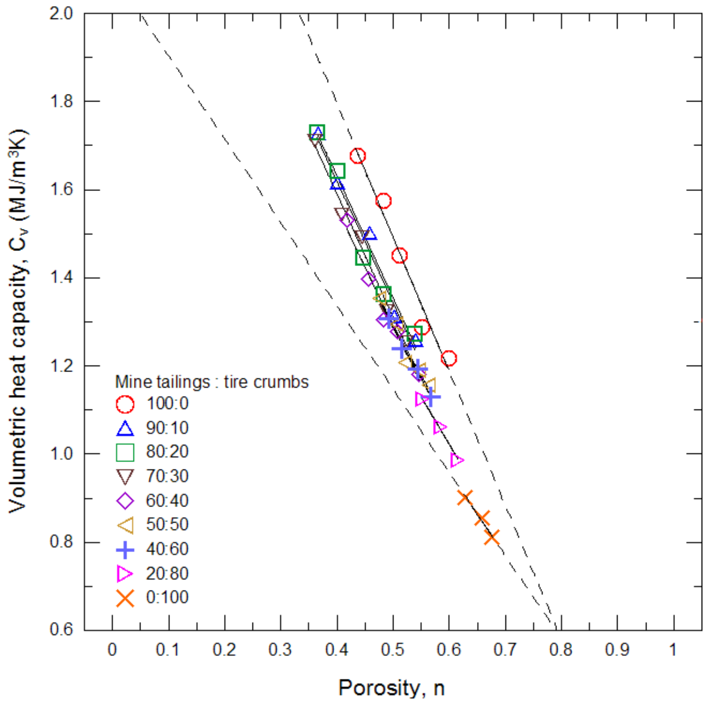


Fig. 12 Effect of weight mixing ratio of mine tailings and tire crumbs mixtures on volumetric heat capacity

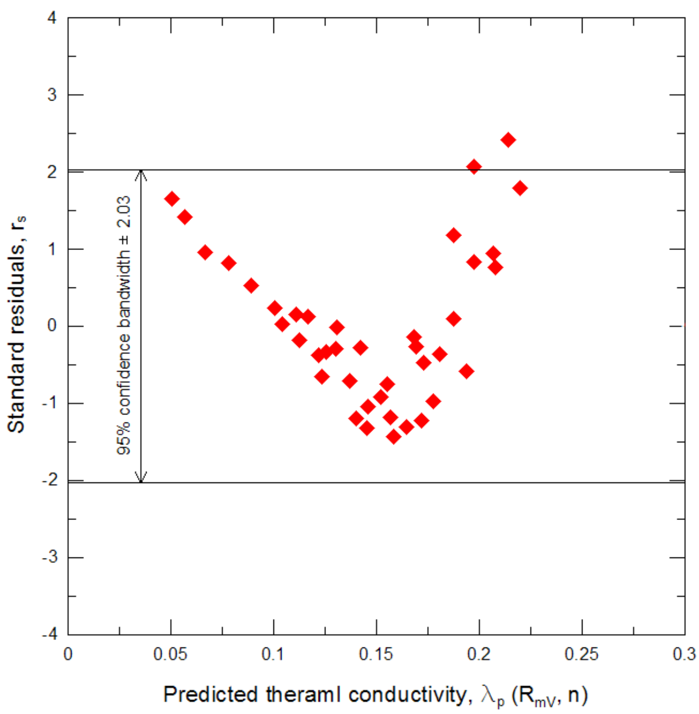


Fig. 13 Standard residuals of a regression model with two variables

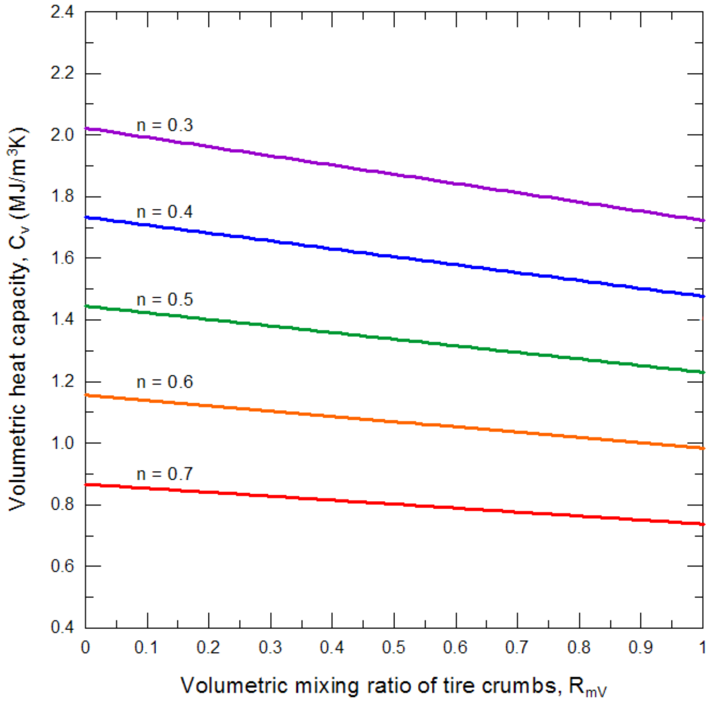


Fig. 14 Change of volumetric heat capacity at different volumetric mixing ratios of tire crumbs and porosities