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ABSTRACT: The thermal conductivity of compacted mine tailings and tire crumbs mixtures is studied as affected by the water content, mixing ratio of tailings and tire crumbs, compactive effort and size of tire crumbs. The results show a clear correlation between the thermal conductivity and bulk density of the mixtures. Furthermore, the anisotropic thermal conductivity of the compacted mixtures is investigated and the results reveal that the effect is more pronounced when the mixtures have lower water contents. The experimental data are processed via analysis of variance (ANOVA) and the results indicate that the factors included in the simulation are statistically significant. A multiple linear regression model is proposed to relate the thermal conductivity with the mixture composition and compaction conditions. The interpretation methods developed in this study can be extended to enhance the understanding to the thermal characteristics of compacted geomaterials in engineering applications.

KEYWORDS: Thermal conductivity; Compaction; Anisotropy; Statistics; Mine tailings; Tires; Recycling

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Introduction

Geomaterials mostly consist of mineral solids, water and air at various proportions. The study on heat transfer through geomaterials is important in geoengineering applications such as oil and gas pipelines, high-power electric cables, radioactive waste disposal facilities, ground heat exchangers, etc. Thermal transport takes place through conduction, convection and radiation, in which conduction is most predominant in granular materials and is quantified by the thermal conductivity.

The thermal conductivity of a geomaterial is strongly dependent on the volumetric fractions of its constituents. The thermal conductivities of basic geomaterial constituents vary across several orders of magnitude, for example, mineral solids (order of 10 W/mK), water (order of 1 W/mK) and air (order of 0.01 W/mK). Numerous studies have been reported on the thermal conductivity of geomaterials as influenced by the properties associated to their constituents, i.e., dry density, water content, degree of saturation, water vapors and ices, water flow, electrolyte type and concentration, and mineralogical compositions (Horai 1971; Steiner and Komle 1991; Abu-Hamdeh and Reeder 2000; Tarnawski et al. 2000; Bachmann et al. 2001; Ochsner et al. 2001; Yun et al. 2011). Moreover, the structure of geomaterials has a significant impact on their thermal conductivity. The term of structure refers to the combined effects of fabric (the geometrical configuration of solid particles of all size ranges, shapes and surface roughness) and bonding (the inter-particulate forces that hold particle together, including cementation, electrostatic, electromagnetic and other forces) (Mitchell and Soga 2005). Woodsinde and Messmer (1961) pointed out that the cementation of particles is an effective process to increase the thermal conductivity of geomaterials. Narsilio et al. (2010) found that the improved extent/quality of contacts between inter-particles leads to better thermal conduction.

Reusing solid wastes in civil engineering applications can be beneficial to reduce greenhouse gas emissions. The solid wastes that have potential to be recycled for use as construction materials include scrap tires and mine tailings. Waste rubber tires exhibits low density, high durability, good thermal insulation, high energy absorption as well as relatively low cost. The scrap tires are grinded to particles of various sizes for practical purposes. According to ASTM D 6270-08, granulated rubber is defined as particulate rubber composed of mainly non-spherical particles, normally less than 12 mm in size, that is commonly known as tire crumbs (Edincliler et al. 2010). On the other hand, tailings from mining activities are ground rock particles from which valuable metals and minerals are extracted. Mine tailings are conventionally disposed on site and often used as fill material where natural soils are not available or abundant, provided that the generation of acid mine drainage (AMD) is prohibited. In combination, tire particles and mine tailings may be utilized in construction as fills. Lee and Shang (under review) examined the thermal characteristics of dry mixtures of low reactivity mine tailings and tire crumbs, suggesting their potential beneficial use as lightweight fill materials with enhanced thermal insulation. A prediction model for the thermal conductivity and an analysis chart for estimating the volumetric heat capacity for mine tailings and tire crumbs mixtures in dry state are presented by the same authors.

This paper is the continuation of the work by Lee and Shang (under review), in which thermal conductivity measurements were performed on wet mixtures of mine tailings and tire crumbs. Forty specimens were compacted under various water contents, mixing ratios, compactive efforts and tire crumbs sizes in the laboratory. Experimental results were presented to illustrate the general relations of thermal conductivity with the influencing factors. The thermal conductivity anisotropy of the compacted mixtures is also observed. Statistical data

analysis was conducted to identify the significance of these influencing factors. A stepwise multiple linear regression analysis was also carried out to establish an empirical model for predicting the thermal conductivity of the compacted mine tailings and tire crumbs mixtures.

Experimental Design

To study the thermal conductivity characteristics of compacted mixtures of mine tailings and tire crumbs, an experimental program was designed and performed. The materials, specimen preparation, and devices and methodology are described in this section.

Materials

In this study, mine tailings and tire crumbs are the host materials used to produce the mixtures. Distilled water with the temperature of about 20 °C was used in compaction of the mixtures. The physical properties of the mine tailings and tire crumbs are summarized in Table 1, whereas Fig. 1 shows the particle size distributions.

The dry mine tailings were recovered from the Musselwhite mine located in northern Ontario, Canada. The specific gravity of mine tailings is 3.37, which is greater than that of most soils. The Atterberg limit tests on tailings particles finer than 75 μm indicated that the mine tailings are non-plastic. The tailings comprise a wide range of particle sizes (0.42 to 138 μm), which is in the typical grading range of Canadian hard rock tailings (Bussiere 2007). The detailed mineralogical properties of the tailings tested in this study have been reported by Wang et al. (2006). According to their results, the mine tailings contain relatively low percentage of sulphide minerals (i.e., 3% pyrrhotite by mass), comparing to that of other sulphide-containing mine tailings published in the literature (e.g., 80% pyrrhotite: Amaratunga 1995, 54% pyrite: Ouellet et al. 2006), hence the tailings exhibits relatively low reactivity.

The tire crumbs of two particle sizes were supplied by a tire recycling facility located in Ontario. Both tire crumbs contain no steel wires. The small tire crumbs contain a small amount of fiber dust. The specific gravities of small and large tire crumbs are measured as 1.19 and 1.16, respectively, which are comparable to those of tire derived aggregates reported in ASTM D 6270-08. The particle sizes of small tire crumbs vary from 0.069 to 1.18 mm with the median particle size of 0.46 mm, whereas the particle sizes for large tire crumbs range from 0.25 to 4.75 mm with the median particle size of 2.1 mm. Based on the coefficients of uniformity and curvature (C_u and C_c), both tire crumbs can be characterized as poorly graded materials.

Specimen Preparation

The mixing ratio of tire crumbs in the mixtures, R_m, is based on the dry mass of solids and defined as

$$R_m = \frac{m_{TC}}{m_{MT} + m_{TC}} \tag{1}$$

where m_{TC} is the mass of tire crumbs and m_{MT} is the mass of mine tailings. Initially, six dry mixtures of mine tailings and tire crumbs were prepared: five with the mixing ratios of 0.0, 0.1, 0.2, 0.3 and 0.4 for small tire crumbs, and one with 0.2 for large tire crumbs. Each mixture was thoroughly mixed in a mechanical mixer.

After the preparation of a dry mixture, a predetermined mass of the mixture was mixed with distilled water of known mass to obtain the desired gravimetric water content. For each mixture, five molding water contents of 5 to 25% with an increment of 5% were used. After mixing with water, the mixture was compacted into a cylindrical mold of volume 943.7 cm^3 (101.6 mm diameter and 116.4 mm height) in accordance with the standard Proctor compaction procedures

of ASTM D 698-07. In the case of mixtures with small tire crumbs with a mixing ratio of 0.2, two specimens were also prepared with the modified Proctor in ASTM D 1577-09 and reduced Proctor suggested by Daniel and Benson (1990). The reduced Proctor procedure is identical to the standard Proctor procedure but the number of blows per layer is reduced from 25 to 15. These compactive efforts were designed to simulate the compaction states generally encountered in the field. To minimize the variability in the compactive effort applied to each mixture, an automatic compaction equipment was utilized. Following compaction, the excess mixture was trimmed off from the mold, then the mass of the specimen in the mold was measured to determine the bulk density and dry density.

In this study, 40 specimens were tested and their identifications are presented in Table 2, with the mnemonic abbreviation noted below the table. For example, TC0.2-SP-S-W15 represents a specimen with the 0.2 mixing ratio of small tire crumbs and 15% water content, compacted under standard Proctor energy.

Devices and Methodology

All thermal conductivity measurements were made using a KD2 Pro thermal property analyzer. It consists of a handhold controller and a sensor. The sensor has two-parallel stainless-steel probes of 1.3 mm diameter and 30 mm length at a spacing 6 mm, which is inserted into subject medium. One of probes contains a heating element to generate a heat pulse into the medium between the probes and the other contains a thermocouple to measure the heat transported from the medium. The thermal conductivity of the medium is automatically determined from the temperature evolution with time based on the transient line heat source theory reported by Kluitenberg et al. (1995). This device reproduces thermal properties of reference materials with

±5% accuracy within the temperature range of - 50 °C to 150 °C and a single measurement approximately takes 2 minutes.

For the thermal conductivity measurement, the compacted mixture of mine tailings and tire crumbs was extruded from the mold using a hydraulic jack. Figure 2 shows a uniformly compacted specimen with the mixing ratio of small tire crumbs of 0.2 and the water contents of 15%, i.e., specimen TC0.2-SP-S-W15. In order to explore the anisotropy of the thermal conductivity, the direction of measurement direction on the specimen was controlled: 1) the thermal conductivity along the principal axis of the cylinder (representing the horizontal thermal conductivity) was measured by inserting the sensor perpendicular to the orientation of compaction; 2) the thermal conductivity perpendicular to the principal axis of the cylinder (representing the vertical thermal conductivity) was measured by inserting the sensor parallel to the orientation of compaction. At top and bottom layers of the compacted specimen, respectively, two sets of horizontal and vertical thermal conductivities were tested with eight readings taken in each specimen. The thermal conductivity measurements were carried out at the room temperature of 20 ± 0.5°C.

Methods of Data Analysis

Based on the results of thermal conductivity measurement on compacted mine tailings and tire crumbs mixtures, statistical analyses were performed as follows: 1) the mean, median and standard deviation of four readings corresponding to the "horizontal" and "vertical" thermal conductivities (λ_h and λ_v) were calculated; 2) the same statistical estimates of eight readings from all horizontal and vertical thermal conductivities measured from each specimen were

computed and represented as the "overall" thermal conductivity λ. The summary of the thermal conductivity measurement and statistical data is presented in Table 2.

To observe the trends of thermal conductivity against the effects of the influencing factors (i.e., water content, mixing ratio, compactive effort and tire crumbs size) of the compacted mixtures, the means of horizontal, vertical and overall thermal conductivities and their standard deviations were plotted with respect to the influencing factors. Analysis of variance (ANOVA) was then carried out to assess, in quantitative terms, the relative contributions of the influencing factors on the thermal conductivity of compacted mixtures. Stepwise multiple linear regression analysis was also employed to predict the thermal conductivity of the compacted mixtures. These statistical analyses were conducted by using 320 raw data (= 40 specimens × 8 test points).

Results and Discussion

Compaction Characteristics

Figure 3 shows the changes in maximum dry density, $\rho_{d\max}$, and optimum water content, w_{opt}, with the mixing ratio of small tire crumbs. The maximum dry density ranges from 1.99 to 1.23 g/cm³, while the optimum water content varies from 12.7 to 17.3%. The maximum dry density decreases with the increase in the mixing ratio of tire crumbs. This is due to the reduced specific gravity of the mixtures with higher fraction of tire crumbs. On the other hand, the optimum water content slightly decreases first, then increases with increasing mixing ratio of tire crumbs. This can be interpreted as that with the increase of tire crumbs, more water is required to re-orientate solid particles during compaction. Similar compaction behavior was reported for mixtures of soils and tire particles in the literature (Cetin et al. 2006; Christ and Park 2010). Moreover, the significant increase of optimum water content is observed in the mixing ratios of tire crumbs R_m

> 0.3. In this case, the compacted mixtures transit from a rigid mine tailings dominated fabric to a soft tire crumbs dominated fabric, based on the packing mechanism on a binary mixture of particles of different sizes (Lade et al. 1998).

Thermal Conductivity Characteristics

Figures 4-6 show the bulk density, ρ_b, and thermal conductivity, λ, of the compacted specimens of mine tailings and tire crumbs mixture versus the water content, as related to the mixing ratio of tire crumbs, compactive effort and tire crumbs size, respectively.

Figure 4 illustrates the variations of bulk density and thermal conductivity for the compacted mixtures with different mixing ratios of small tire crumbs. The bulk density of the specimens decreases with increasing mixing ratio of tire crumbs for a given water content. For example, the bulk densities are 2.28, 2.02, 1.81, 1.61 and 1.41 g/cm^3, respectively, when the mixing ratio of tire crumbs are 0, 0.1, 0.2, 0.3 and 0.4 at a water content of 15%. The bulk density decreases by 38% when the mixing ratio of tire crumbs is increased from 0 to 0.4 at a water content of 15%. Furthermore, at a given water content, the thermal conductivity of the specimens decreases with increasing mixing ratio of tire crumbs. For instance, the thermal conductivities are 1.610, 1.195, 0.925, 0.742 and 0.543 W/mK, respectively, when the mixing ratio of tire crumbs are 0, 0.1, 0.2, 0.3 and 0.4 at a water content of 15%. The thermal conductivity decreases by 66% when the mixing ratio of tire crumbs is increased from 0 to 0.4 at a water content of 15%. The reduction of both the bulk density and thermal conductivity is mainly due to the low density and low thermal conductivity of tire rubber particles. However, it should be noted that the air content of the specimens increases with increasing mixing ratio of tire crumbs, which adds to the decrease in bulk density and thermal conductivity to a minor

extent. This is attributed to the fact that the angular shape and rough surface of rubber particles that are produced through the mill process have a tendency to entrap air. It is inferred from these results that recycled tire crumbs have potential applications as lightweight fill materials with improved thermal insulation.

Figure 5 highlights the effect of compactive effort on the bulk density and thermal conductivity of compacted mixtures of small tire crumbs with the mixing ratio of 0.2. The highest values of bulk density and thermal conductivity of the specimens are attained at the modified Proctor, followed by the standard Proctor and the reduced Proctor. As seen in Fig. 5, at a constant water content of 15%, specimens with bulk densities of 1.83, 1.81 and 1.70 g/cm^3 corresponding to modified, standard and reduced Proctors have thermal conductivities of 0.957, 0.925 and 0.807 W/mK, respectively. The increase in the thermal conductivity with the increase of compactive effort is probably because the higher compactive effort induces better contact between neighboring solid particles for heat transfer.

Figure 6 compares the bulk densities and thermal conductivities of the compacted mixtures with the same mixing ratio of tire crumbs but different tire crumbs sizes. As shown in Figs. 6(a) and 6(b), the specimens with small tire crumbs have the lower bulk density and thermal conductivity than those mixed with large tire crumbs. Quantitatively, the bulk densities of the specimens with small tire crumbs are 2 to 6% less than those of large tire crumbs and the thermal conductivities are 3 to 12% lower. The differences in both the bulk density and thermal conductivity of the specimens with different tire crumbs size are highly related to the air content in their matrix since air has much lower density/thermal conductivity than water and solids: the increase in the air content with decreasing tire crumbs size leads to lower bulk density and

thermal conductivity. It is confirmed in Fig. 6(c), in which the volumetric air content θ_a (the volumetric ratio of air to the total volume of a compacted mixture) is determined by

$$\theta_a = 1 - w\rho_d - \frac{\rho_d}{G_s} \tag{2}$$

where w is the water content, ρ_d is the dry density of the mixture and G_s is the specific gravity of the mixture. As seen in Fig. 6, the volumetric air content of specimens with small tire crumbs is more than that of specimens with large tire crumbs under all water contents. This is likely due to the fact that small tire crumbs exhibits higher specific surface that results in higher air-entrainment in their rough surface than large tire crumbs. Given the conduction mechanism at the microscale, the decrease in the air content with decreasing tire crumbs size attenuates the thermal bridge between solid particles and contributes to the decrease in heat conduction.

In general, it is observed in Figs. 4-6 that the changes of bulk density and thermal conductivity with the water content display a similar trend: at a given compactive effort, the bulk density and thermal conductivity increase with increasing water content, until the maximum bulk density and maximum thermal conductivity are reached. Then, both the bulk density and thermal conductivity slightly decrease with further increase in the water content. This trend can be explained as follows: as water is added to a mine tailings and tire crumbs mixture, it replaces the air, provoking increased bulk density as well as forms a thin film around the tailings solids and rubber particles, acting as a thermal bridge for heat transfer; as the water content increases, the pore air is replaced by water and solids, causing significant increases in the bulk density and thermal conductivity; however, beyond a certain water content, the water takes up the space that would have been occupied by the solids with little change of air volume near saturation, resulting in slight reduction of bulk density and thermal conductivity (see Fig. 6). It is also found that a

maximum thermal conductivity tends to occur at the optimal water content corresponding to the maximum bulk density, indicating the closest arrangement of solid particles. Similar observations were obtained for fine-grained soils by Salomone and Kovacs (1983, 1984) who used the term "critical water content" that is correlated to the optimum water content. Thus, it can be demonstrated that the influence of water content on the thermal conductivity of the compacted mine tailings and tire crumbs mixtures is more prominent when the water content is less than the critical water content. On the other hand, the impact is minor when the water content is higher than the critical water content. The critical water content is dependent on the mixing ratio of tire crumbs, compactive effort and tire crumbs size, which is essentially associated to the gradation, size, shape, surface roughness of the materials. Meanwhile, it is worth noting that the thermal conductivity difference that is attributable to varying water contents leads to the difference in microstructures formed during compaction. For instance, Delage et al. (1996) investigated the impacts of water content change on the fabric of compacted soils and pointed out that compaction on the dry side induces aggregate-dominated fabric whereas the wet side causes matrix-dominated fabric without apparent aggregates.

Figure 7 shows the thermal conductivity, λ, versus bulk density, ρ_b, of all specimens. The thermal conductivity increases with increasing bulk density with a linear correlation ($R^2 = 0.93$). Therefore, one may recognize that the bulk density is a key property in heat transfer of compacted geomaterials.

Anisotropy of Thermal Conductivity

Compacted geomaterials may form anisotropic fabrics attributed to the pore structure and particle orientation. The fabric anisotropy often induces the anisotropy of engineering properties

(Mitchell and Soga 2005). In particular, the anisotropy of thermal conductivity of compacted geomaterials may be significant in hear transfer.

The horizontal thermal conductivity, λ_h, versus vertical thermal conductivity, λ_v, for all specimens are plotted in Fig. 8(a). The thermal conductivity of the compacted mine tailings and tire crumbs mixtures shows to be slightly anisotropic: the horizontal thermal conductivities are higher than the vertical thermal conductivities with a difference less than 15%. The anisotropy ratio η of thermal conductivity can be expressed as

$$\eta = \frac{\lambda_h}{\lambda_v} \tag{3}$$

The linear regression of data in Fig. 8(a) yields an anisotropy ratio of 1.05 (R^2 = 0.99). The anisotropy may, in part, be due to the pore orientation as well as mineral and rubber bedding. Meanwhile, the role of water content in the thermal conductivity anisotropy of the compacted mine tailings and small tire crumbs mixture is illustrated in Figs. 8(b) and 8(c). The anisotropy impact is more evident at lower water contents, regardless of the mixing ratio of tire crumbs, compactive effort and tire crumbs size. In general, there is no significant effect of the mixing ratio of tire crumbs on the thermal conductivity anisotropy. Anisotropy is also independent of the compactive effort and tire crumbs sizes considered in this study. This observation on the influence of water content to the thermal conductivity anisotropy of the compacted mixtures is consistent with the understanding of the microstructure of compacted geomaterials, discussed previously.

Statistical Analyses

The experimental results on compacted mixtures of mine tailings and tire crumbs have been presented in Figs. 4-6 to demonstrate the correlations of the thermal conductivity as related to the compositional and compaction factors. In this section, the statistical significance of these data is analyzed. An ANOVA study was conducted by the general linear modeling procedure of a statistical analysis software (SAS). Statistical significance was established when the calculated F values exceeded the critical F values for a significance level of 5% (Montgomery et al. 2004). The calculated F values, defined as the ratio of the between-samples sum of squares to the error sum of squares, estimate the random error. The critical F value is the upper limit of the F ratio and can be found in statistical references. The p value is the tail probability for a given distribution, which will be less than 0.05 whenever the calculated F value is greater than the critical F value, which is an indicator of the statistical significance in relation to the contribution of a given variable.

A four-factor ANOVA was carried out with the thermal conductivities measured on compacted mine tailings and tire crumbs mixtures, which included four variables: water content (A); mixing ratio of tire crumbs (B); compactive effort (C); and tire crumbs size (D); and their two way interactions with the water content (AB, AC and AD). The results of the ANOVA analysis are summarized in Table 3. It is shown that at a 95% confidence level, all factors affect the thermal conductivity significantly, and the mixing ratio of tire crumbs has the most significant influence. The significance of the four factors on the thermal conductivity of the compacted mixtures is identified in the following order: the mixing ratio of tire crumbs, water content, whereas the tire crumbs size and compactive effort show the similar significance level. On the other hand, the two way interactions between the water content and other two factors, the mixing ratio of tire crumbs and compactive effort, are statistically significant; while the

interaction of water content and tire crumbs size is not significant statistically to the variations of the thermal conductivity.

A stepwise multiple linear regression analysis was utilized to develop an empirical model to capture the impact of the influencing factors on the thermal conductivity of the compacted mine tailings and tire crumbs mixtures. Since the compactive effort is not a quantitative variable, a multisource regression model that includes class independent variables as well as quantitative independent variables was established. The development of the multisource regression model in geoengineering applications were reported in the literature (Benson and Trast 1995; Nazzal et al. 2007). In stepwise regression procedures, the regression model was optimized by repeating the procedures that add or delete an independent variable after checking its correlation with the dependent variables until the selection of an additional independent variable did not increase the coefficient of determination (R-squared) by a 5% level of significance (Brook and Arnold 1985). The significance of the variables in a regression model can be evaluated by comparing the calculated t value, defined as the ratio of the regression coefficient β_i and its standard error SE, and the student's t distribution. In other word, if the absolute value of calculated t value is less than the student's t distribution at a designed significance level, the variable is not affected significantly to the regression model.

According to the stepwise regression analysis, it is found that the following equation best fits the data:

$$\lambda = 0.989 + 0.021w - 2.177R_m + 0.053CE \tag{4}$$

in which w is the water content, R_m is the mixing ratio of tire crumbs. CE is the integer class index representing compactive effort (compactive effort index): the $CE = 1$ is designated to the

energy level of the modified Proctor compaction; the $CE = 0$ is designated to the energy level of the standard Proctor compaction; and the $CE = -1$ is designated to the energy level of the reduced Proctor compaction. The tire crumbs size did not give any additional information with statistical significance. One of possible reasons for this is that the data set is limited to only two. The values of regression coefficient of the variables suggest that increasing water content and compactive effort leads to the increase in the thermal conductivity whereas increasing mixing ratio of tire crumbs results in the decrease in the thermal conductivity. This is consistent with the trends observed in Figs. 4-6.

Table 4 presents the results of regression analysis on Eq 4 under a confidence level of 95%. The coefficient of determination and standard error of the regression model are 0.867 and 0.113, respectively, indicating Eq 4 fits the measured data very well. Figure 9 shows that the predicted thermal conductivity λ_p, using the proposed model yields good agreement with the measured thermal conductivity λ_m. The overall F value is 688.6, much greater than the F value at the probability of 95% = 2.633. This indicates that the regression equation (Eq 4) with four variables is statistically significant. Moreover, all absolute t values in Table 4 are greater than the t value = 1.968 at the probability of 95%, implying that the water content, mixing ratio of tire crumbs, compactive effort index and intercept are contributed significantly to the regression model. Comparing to the t values obtained, the effect of the mixing ratio of tire crumbs to the observed trend is greater than those other influencing factors, which is consistent with the results from the four factor ANOVA test. Consequently, the regression equation relating to the water content w, mixing ratio of tire crumbs R_m and compactive effort index CE is highly significant at 95% confidence limits as indicated by statistical analyses. The results provide a insight to the thermal

conductivity of the compacted mine tailings and tire crumbs mixtures as affected by the water content, mixing ratio of tire crumbs, compactive effort and tire crumbs size.

Conclusions

Mine tailings and tire crumbs are recycled solid wastes, and their mixtures can be beneficially used as lightweight fill materials with improved thermal insulation for geoengineering applications. Results of thermal conductivity tests performed on compacted mixtures of mine tailings and tire crumbs are presented, and analyzed to identify the effect of water content, mixing ratio of tire crumbs, compactive effort and tire crumbs size on the thermal conductivity. The anisotropy of thermal conductivity was observed on compacted mixtures. The following is the main conclusion of this study.

The thermal conductivity of the compacted mine tailings and tire crumbs mixtures depends on the water content, mixing ratio of tire crumbs, compactive effort and tire crumbs size. The thermal conductivity is sensitive to the water content when it is lower than a critical water content, while it is almost independent of the water content after the critical water content is exceeded. The thermal conductivity decreases with increasing the mixing ratio of tire crumbs. A higher compactive effort leads to a higher thermal conductivity, and the compacted mixtures with small tire crumbs have lower thermal conductivity than those with large tire crumbs. Linear relationship is established between the thermal conductivity and bulk density for all specimens tested.

There is a clear indication of thermal conductivity anisotropy of the compacted mixtures: the horizontal thermal conductivities are higher than the vertical thermal conductivities with a difference less than 15%. The anisotropy ratio of the thermal conductivity is estimated to be 1.05.

The thermal conductivity anisotropy is dependent on the water content: as the water content increases, the thermal conductivity anisotropy reduces. In contrast, the mixing ratio of tire crumbs, compactive effort and tire crumbs size show little influence on the thermal conductivity anisotropy.

The ANOVA results indicates that the thermal conductivity of the compacted mixtures are significantly affected by the water content, mixing ratio of mine tailings and tire crumbs, compactive effort and size of tire crumbs at a confidence level of 95%. The stepwise multiple linear regression analysis showed that the thermal conductivity of the compacted mixtures can be predicted using a general model consisting of the mixture composition as quantitative variable and compaction condition as an index variable.

The findings and interpretation methods presented in this study will be helpful for comprehending the thermal conductivity behaviors of compacted rubberized geomaterials.

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Nomenclature

C_c coefficient of curvature

C_u coefficient of uniformity

CE compactive effort index

D_{10}	effective size of particles (μm)
D_{50}	median size of particles (μm)
G_s	specific gravity
m_{MT}	mass of mine tailings (g)
m_{TC}	mass of tire crumbs (g)
R_m	mixing ratio of tire crumbs in a mixture
w	water content (%)
w_{opt}	optimum water content (%)
η	anisotropy ratio of thermal conductivity
θ_a	volumetric air content (m^3/ m^3)
λ	thermal conductivity (W/mK)
λ_h	horizontal thermal conductivity (W/mK)
λ_m	measured thermal conductivity (W/mK)
λ_p	predicted thermal conductivity (W/mK)
λ_v	vertical thermal conductivity (W/mK)
ρ_b	bulk density (g/cm^3)
ρ_d	dry density (g/cm^3)

TABLE 1-*Physical properties of mine tailings and tire crumbs.*

Properties	Mine tailings	Tire crumbs	
		Small size	Large size
Specific gravity, G_s	3.37	1.19	1.16
Effective size, D_{10} (mm)	0.0028	0.24	1.0
Median size, D_{50} (mm)	0.0256	0.46	2.1
Coefficient of uniformity, C_u	11.4	2.08	2.20
Coefficient of curvature, C_c	1.6	0.96	0.89

TABLE 2-*Summary of horizontal, vertical and overall thermal conductivities of compacted mixtures tested.*

Specimen ID	$\lambda_h{}^*$			$\lambda_v{}^*$			λ^{**}		
	Median (W/mK)	Mean (W/mK)	SD (W/mK)	Median (W/mK)	Mean (W/mK)	SD (W/mK)	Media (W/mK)	Mean (W/mK)	SD (W/mK)
TC0.0-SP-S-W5	1.011	1.017	0.059	0.869	0.869	0.055	0.943	0.943	0.095
TC0.0-SP-S-W10	1.303	1.302	0.007	1.179	1.180	0.008	1.243	1.241	0.066
TC0.0-SP-S-W15	1.635	1.638	0.015	1.579	1.582	0.011	1.611	1.610	0.032
TC0.0-SP-S-W20	1.604	1.600	0.018	1.557	1.558	0.004	1.570	1.579	0.026
TC0.0-SP-S-W25	1.593	1.599	0.033	1.606	1.604	0.011	1.600	1.601	0.023
TC0.1-SP-S-W5	0.731	0.733	0.066	0.645	0.645	0.059	0.687	0.689	0.075
TC0.1-SP-S-W10	1.151	1.147	0.062	1.073	1.074	0.049	1.109	1.111	0.065
TC0.1-SP-S-W15	1.216	1.219	0.013	1.169	1.170	0.013	1.197	1.195	0.029
TC0.1-SP-S-W20	1.202	1.211	0.018	1.174	1.176	0.007	1.190	1.194	0.024
TC0.1-SP-S-W25	1.232	1.243	0.030	1.220	1.219	0.003	1.222	1.231	0.024
TC0.2-SP-S-W5	0.593	0.587	0.051	0.511	0.509	0.052	0.554	0.548	0.063
TC0.2-SP-S-W10	0.784	0.786	0.049	0.724	0.723	0.042	0.749	0.755	0.054
TC0.2-SP-S-W15	0.943	0.940	0.013	0.911	0.910	0.017	0.925	0.925	0.021
TC0.2-SP-S-W20	0.947	0.945	0.023	0.907	0.904	0.028	0.928	0.925	0.035
TC0.2-SP-S-W25	0.933	0.933	0.020	0.927	0.926	0.029	0.933	0.930	0.023
TC0.3-SP-S-W5	0.442	0.443	0.050	0.401	0.400	0.047	0.417	0.422	0.051
TC0.3-SP-S-W10	0.610	0.612	0.029	0.559	0.560	0.027	0.584	0.586	0.038
TC0.3-SP-S-W15	0.748	0.746	0.023	0.737	0.738	0.026	0.744	0.742	0.023
TC0.3-SP-S-W20	0.766	0.766	0.030	0.742	0.744	0.012	0.756	0.755	0.016
TC0.3-SP-S-W25	0.805	0.802	0.008	0.792	0.790	0.006	0.795	0.796	0.009

Note: TC = tire crumbs; SP = standard Proctor; MP = modified Proctor; RP = reduced Proctor; S = small tire crumbs; L = large tire crumbs; W = water content; SD = standard deviation; the numbers that follow the TC and W indicate the mixing ratio of tire crumbs (g/g) and water content (%) in the compacted specimen, respectively; an asterisk indicates the statistical estimates of four measurements of the specimen and a double asterisk indicates the statistical estimates of eight measurements of the specimen.

TABLE 2-*Summary of horizontal, vertical and overall thermal conductivities of compacted mixtures tested (continued).*

Specimen ID	$\lambda_h{}^*$			$\lambda_v{}^*$			$\lambda{}^{**}$		
	Median (W/mK)	Mean (W/mK)	SD (W/mK)	Median (W/mK)	Mean (W/mK)	SD (W/mK)	Median (W/mK)	Mean (W/mK)	SD (W/mK)
TC0.4-SP-S-W5	0.361	0.361	0.026	0.316	0.317	0.026	0.339	0.339	0.034
TC0.4-SP-S-W10	0.457	0.462	0.027	0.418	0.420	0.032	0.444	0.441	0.035
TC0.4-SP-S-W15	0.559	0.558	0.057	0.527	0.527	0.048	0.538	0.543	0.051
TC0.4-SP-S-W20	0.620	0.619	0.012	0.592	0.591	0.017	0.604	0.605	0.022
TC0.4-SP-S-W25	0.681	0.681	0.004	0.645	0.647	0.008	0.668	0.664	0.019
TC0.2-MP-S-W5	0.644	0.642	0.079	0.556	0.555	0.078	0.602	0.599	0.086
TC0.2-MP-S-W10	0.898	0.897	0.113	0.832	0.832	0.084	0.853	0.865	0.098
TC0.2-MP-S-W15	0.983	0.981	0.008	0.933	0.932	0.005	0.954	0.957	0.027
TC0.2-MP-S-W20	0.970	0.973	0.045	0.932	0.942	0.040	0.957	0.957	0.043
TC0.2-MP-S-W25	0.965	0.965	0.007	0.925	0.927	0.007	0.947	0.946	0.021
TC0.2-RP-S-W5	0.485	0.491	0.058	0.417	0.415	0.055	0.450	0.453	0.066
TC0.2-RP-S-W10	0.679	0.681	0.047	0.634	0.639	0.042	0.656	0.666	0.047
TC0.2-RP-S-W15	0.830	0.832	0.061	0.783	0.782	0.066	0.812	0.807	0.065
TC0.2-RP-S-W20	0.955	0.950	0.012	0.944	0.933	0.015	0.945	0.941	0.015
TC0.2-RP-S-W25	0.945	0.945	0.012	0.925	0.927	0.016	0.935	0.936	0.016
TC0.2-SP-L-W5	0.663	0.666	0.027	0.581	0.578	0.028	0.623	0.622	0.053
TC0.2-SP-L-W10	0.863	0.864	0.005	0.796	0.795	0.008	0.832	0.830	0.037
TC0.2-SP-L-W15	0.969	0.976	0.016	0.937	0.938	0.020	0.964	0.957	0.026
TC0.2-SP-L-W20	1.040	1.052	0.049	1.025	1.025	0.056	1.040	1.039	0.051
TC0.2-SP-L-W25	1.045	1.041	0.037	1.011	1.006	0.032	1.027	1.024	0.037

Note: TC = tire crumbs; SP = standard Proctor; MP = modified Proctor; RP = reduced Proctor; S = small tire crumbs; L = large tire crumbs; W = water content; SD = standard deviation; the numbers that follow the TC and W indicate the mixing ratio of tire crumbs (g/g) and water content (%) in the compacted specimen, respectively; an asterisk indicates the statistical estimates of four measurements of the specimen and a double asterisk indicates the statistical estimates of eight measurements of the specimen.

TABLE 3-*Results of ANOVA for response variable.*

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	$F_{calculated}$	$F_{critical}$	p - value
Water content (A)	4	0.827	0.270	94.618	2.401	< 0.0001
Mixing ratio (B)	4	19.553	4.888	2236.871	2.401	< 0.0001
Compactive effort (C)	2	0.221	0.111	50.618	3.025	< 0.0001
Tire crumbs size (D)	1	0.121	0.121	55.219	3.872	< 0.0001
A×B	16	0.781	0.049	22.346	1.676	< 0.0001
A×C	8	0.139	0.017	7.948	1.969	< 0.0001
A×D	4	0.015	0.004	1.704	2.401	0.149

TABLE 4-*Results of stepwise multiple linear regression analysis.*

Observations	320		
R squared	0.867		
Standard error	0.113		
Overall F - statistic	688.6		
Variables	Coefficients	Standard error	t - statistic
Intercept	0.989	0.019	53.017
w (%)	0.021	0.001	23.843
R_m (-)	-2.177	0.057	-38.471
CE (-)	0.053	0.013	4.151
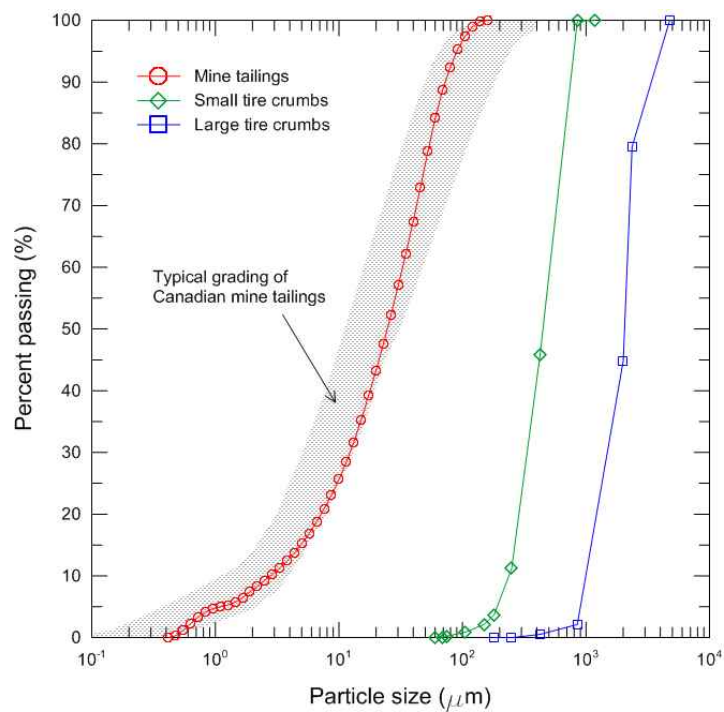
FIG. 1-*Particle size distributions of test materials.*

FIG. 2-*A compacted specimen of mine tailings and small tire crumbs mixtures with the mixing ratio of tire crumbs of 0.2 and the water content of 15% (i.e., TC0.2-SP-S-W15).*
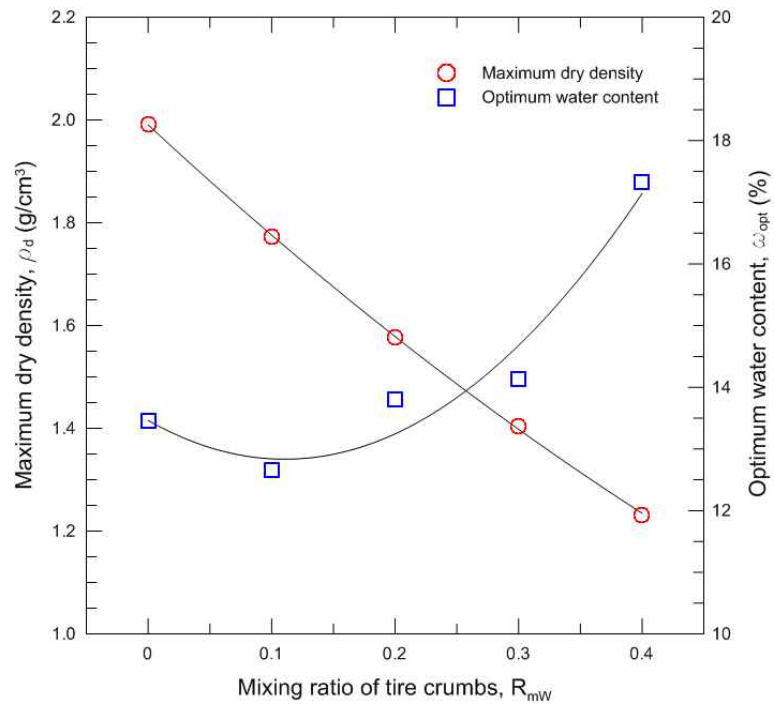
FIG. 3-*Variations of maximum dry density and optimum water content with mixing ratio of tire crumbs.*
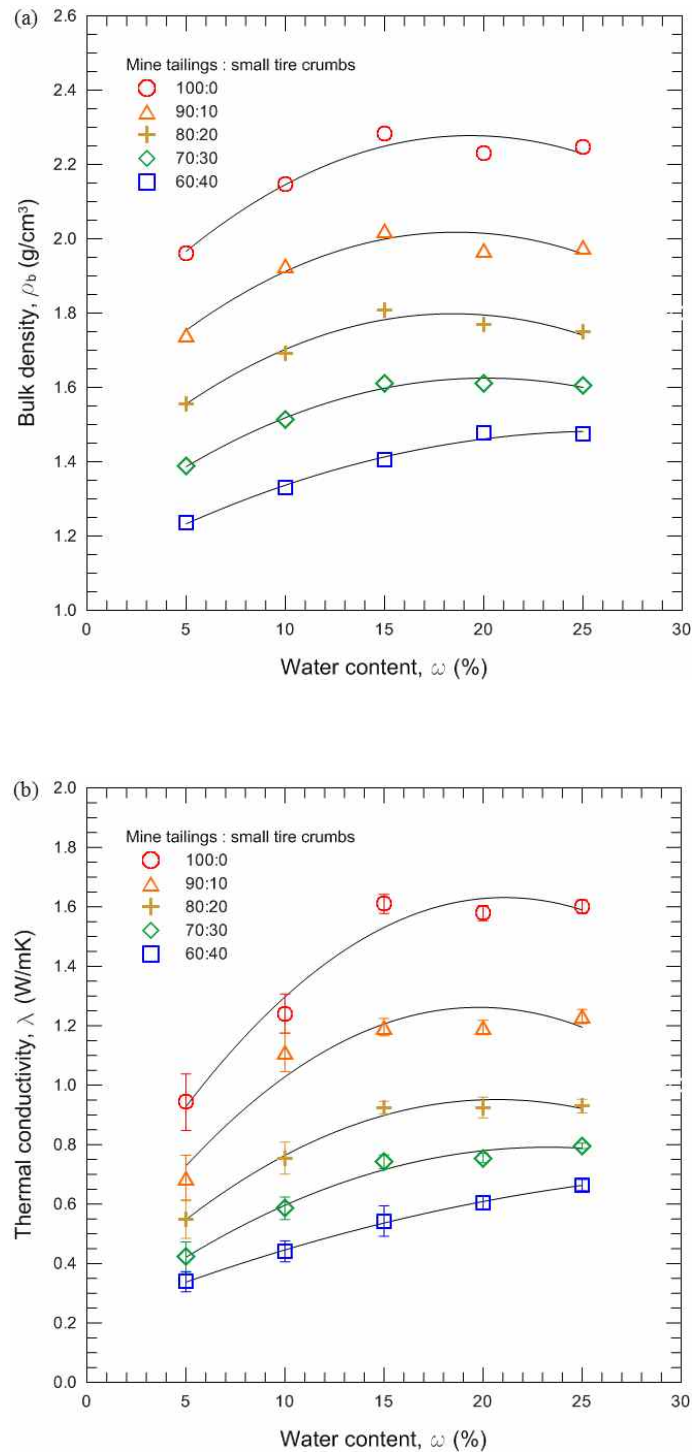
FIG. 4-*Variations of bulk density and thermal conductivity with water content for compacted mine tailings and small tire crumbs mixtures with different mixing ratios of tire crumbs.*
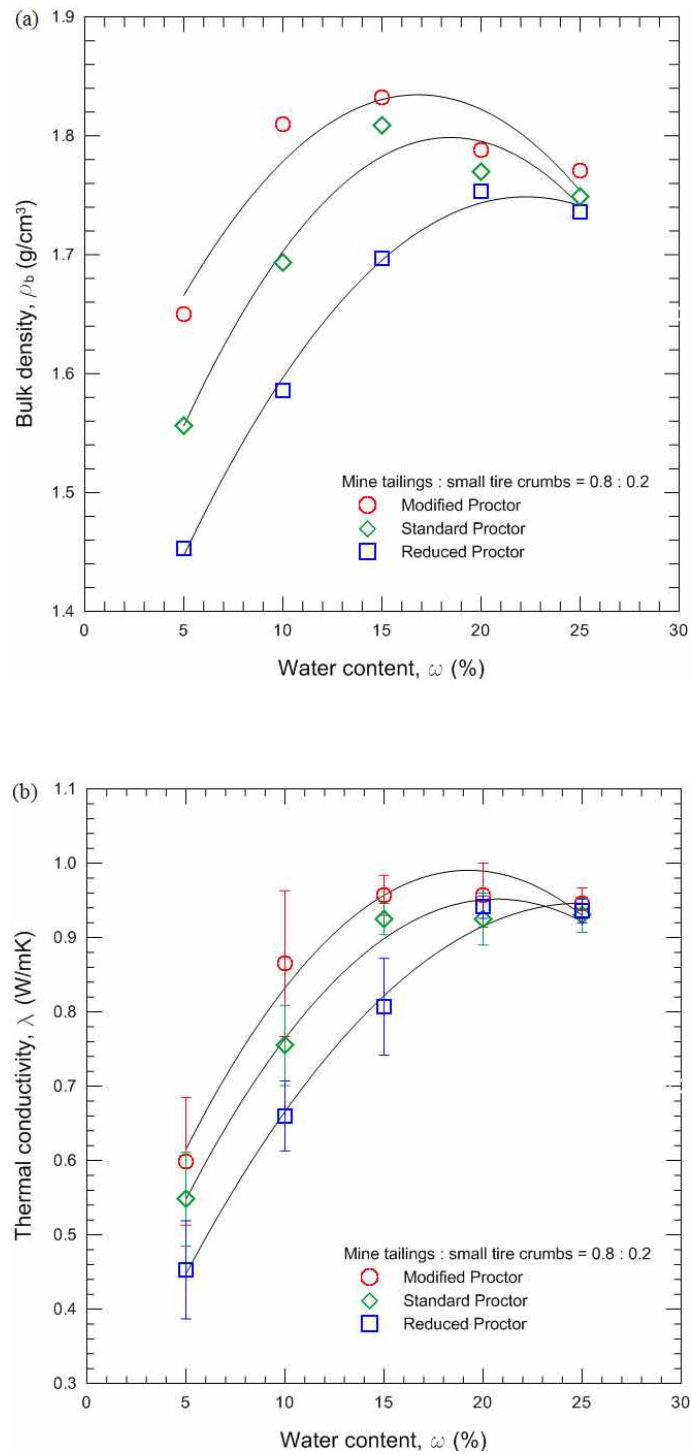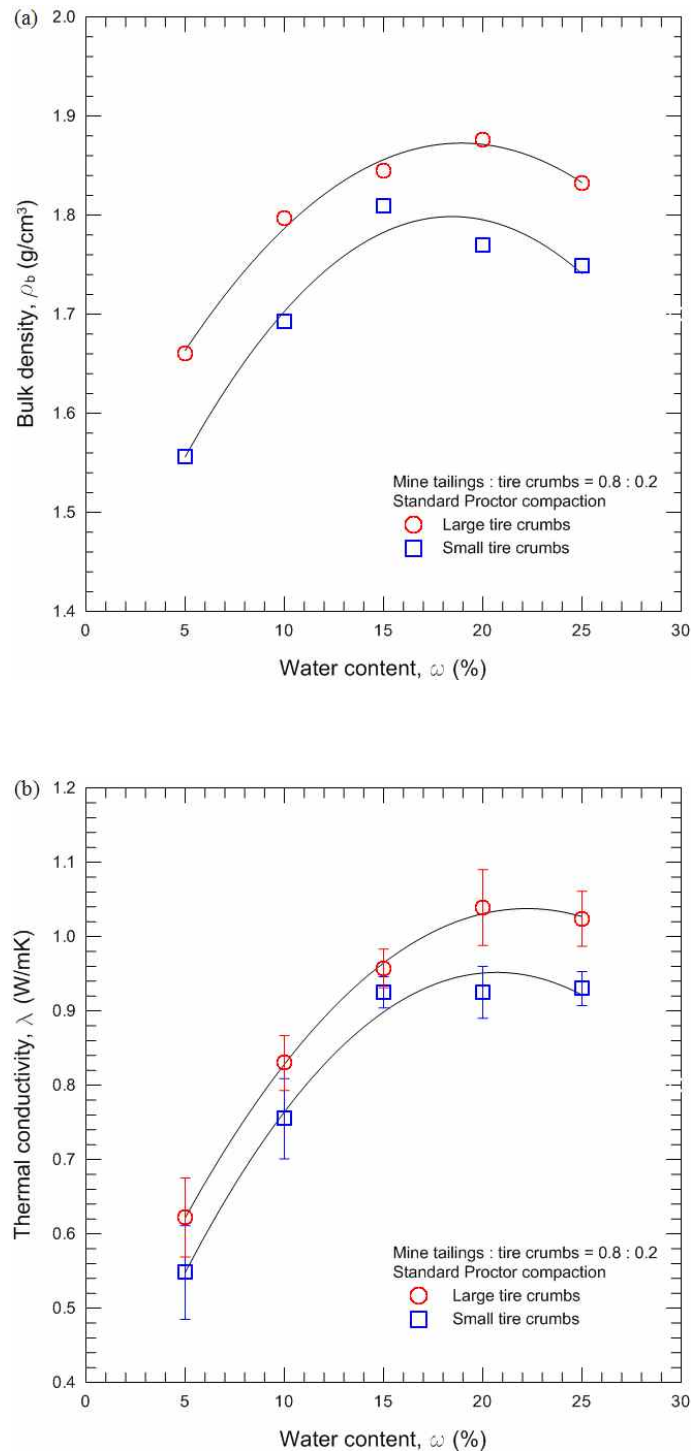
FIG. 5-*Variations of bulk density and thermal conductivity with water content for compacted mine tailings and small tire crumbs mixtures with different compactive efforts.*

FIG. 6-*Variations of (a) bulk density, (b) thermal conductivity, and (c) volumetric air content with water content for compacted mixtures with different tire crumbs sizes.*
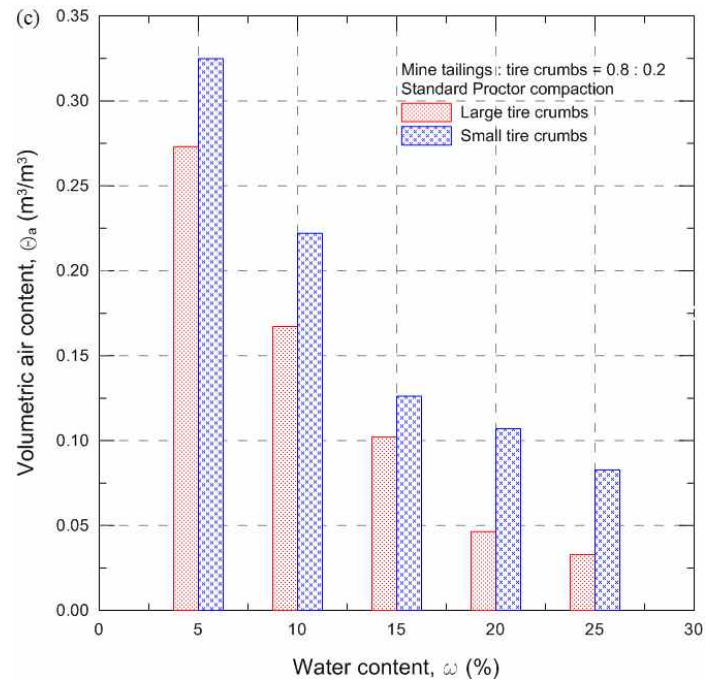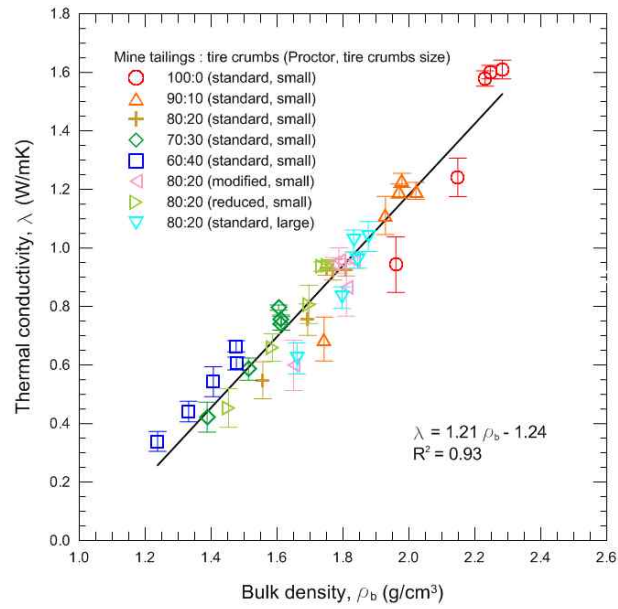
FIG. 6-*Variations of (a) bulk density, (b) thermal conductivity, and (c) volumetric air content with water content for compacted mixtures with different tire crumbs sizes (continued).*

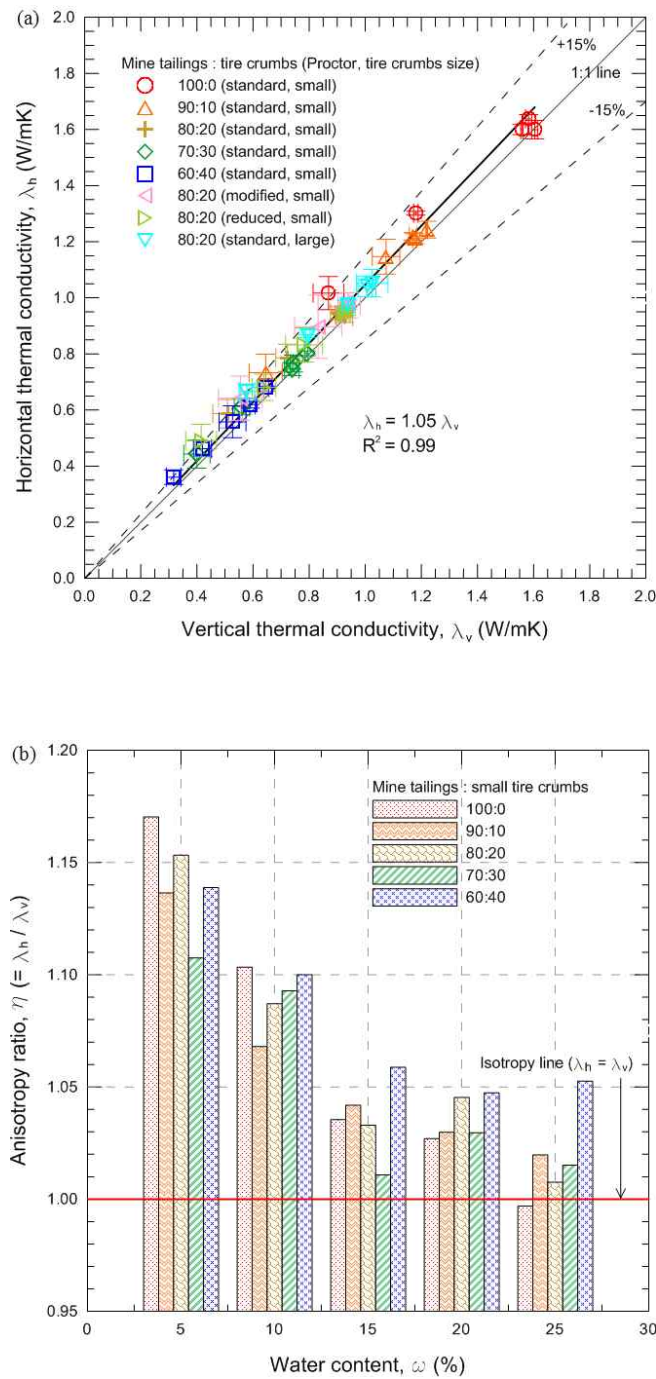FIG. 7-*Relationship between thermal conductivity and bulk density for all compacted mixtures.*

FIG. 8-*Anisotropy of thermal conductivity for compacted mine tailings and tire crumbs mixtures: (a) horizontal versus vertical thermal conductivity; (b) effects of water content and mixing ratio of tire crumbs on anisotropy ratio; (c) effects of water content, compactive effort and tire crumbs size on anisotropy ratio.*
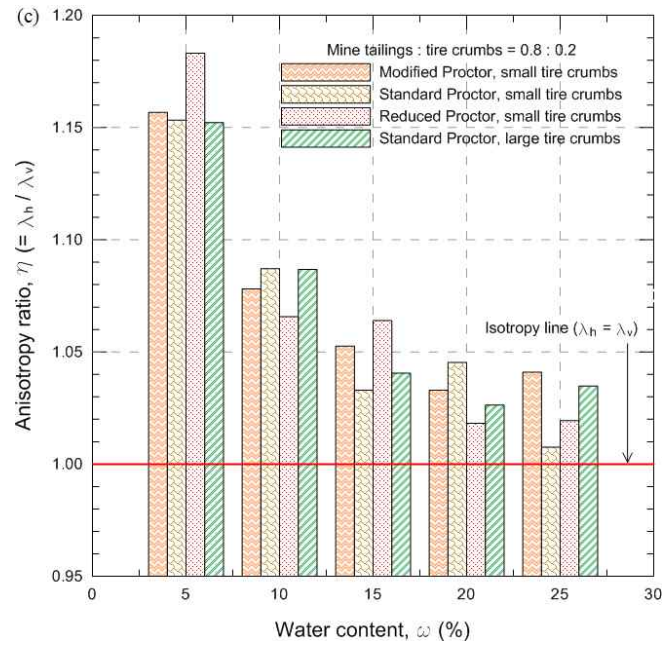
FIG. 8-*Anisotropy of thermal conductivity for compacted mine tailings and tire crumbs mixtures: (a) horizontal versus vertical thermal conductivity; (b) effects of water content and mixing ratio of tire crumbs on anisotropy ratio; (c) effects of water content, compactive effort and tire crumbs size on anisotropy ratio (continued).*
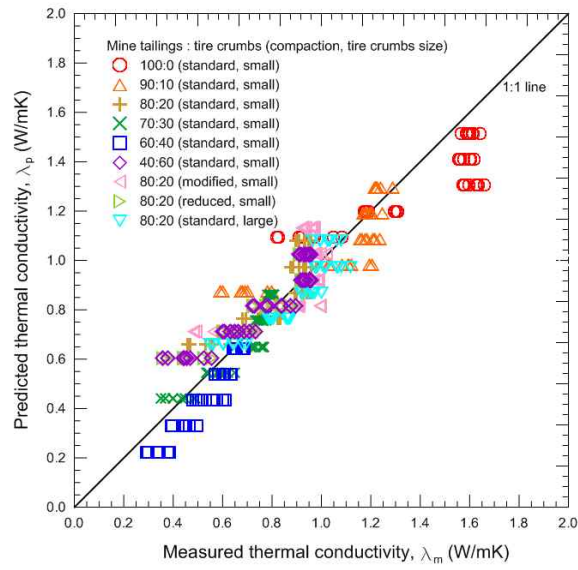
FIG. 9-*Predicted thermal conductivity of compacted mine tailings and tire crumbs mixtures using the statistical model versus actual data.*