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Technical Note

Thermal Conductivity of Sand-Tire Shred Mixtures

Yang Xiao, Ph.D., M.ASCE; Bowen Nan; John S. McCartney, Ph.D., P.E., F.ASCE

Abstract: Sand-tire shred mixtures are useful as thermal backfills due to their lower unit weight and thermal conductivity than those of most soils. In this study, a series of thermal conductivity tests on sand-tire shred mixtures and pure sand were performed to investigate the effects of volumetric mixing ratio and tire shred particle size. A volumetric mixing ratio of 40% was found to yield the greatest decrease in thermal conductivity from that of pure sand, with a maximum percent difference of 72%. Using tire shreds with larger relative size ratio was found to result in higher thermal conductivity, and the maximum variation in the thermal conductivity percent difference with the relative size ratio can reach about 20% at a volumetric mixing ratio of 40%. An empirical model proposed to predict of the thermal conductivity of quartz sand-tire shred mixtures could capture trends in the experimental data.

Keywords: thermal conductivity; sand-tire shred mixtures; relative size ratio; volumetric mixing ratio; empirical model

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Introduction

The thermal conductivity of geomaterials is a key parameter in the design of many geotechnical engineering systems, including pavement systems in permafrost (Farouki 1981; Humphrey and Eaton 1995; Bosscher et al. 1997), crude oil pipelines in cold regions (Bai and Niedzwecki 2014), deep radioactive waste repositories (Tang et al. 2008), protection of landfill liners in cold regions (Benson and Olson 1996), geothermal heat exchangers (McCartney et al. 2016; Wang et al. 2016), geothermal energy storage systems (Baser et al. 2018), and energy piles (Loveridge and Powrie 2013). In some of the applications listed above, such as those involving geothermal heat exchangers, geomaterials with higher thermal conductivity are expected to have greater heat transfer efficiency and improved performance. However, in other applications, such as those in buried pipelines in permafrost and energy storage systems, a goal is to retain heat using thermal insulation layers. For example, the importance of backfill thermal conductivity on the performance of buried pipelines has been studied through finite element analyses by Ocłoń et al. (2016).

Rubber is known to be an excellent insulating material, and the potential for reusing the rubber in waste tires in thermal insulation blankets has been studied by Humphrey and Eaton (1995), Benson and Olson (1996), and Bosscher et al. (1997). With the increasing number of vehicles, the number of waste tires has also increased correspondingly, posing challenges for its appropriate disposal or reuse but also making it an abundant geomaterial available worldwide. Reusing waste rubber tires not only reduces toxic gas emissions associated with incineration, but also reduces a widely known breeding environment for pests (Kashani et al. 2017; Noorzad and Raveshi 2017). Scrap rubber tires also have unique engineering properties in addition to their low thermal conductivity, including their light-weight, high frictional resistance and high damping (Zornberg et al. 2004; Ghaaowd et al. 2017; McCartney et al. 2017; Noorzad and Raveshi 2017). Scrap rubber tires have been widely used as a replacement aggregate in many geotechnical applications, such as retaining walls, pavements, and embankments (Humphrey and Eaton 1995; Bosscher et al. 1997; Youwai and Bergado 2003).

Experimental studies on the physical and mechanical properties of tire shred-soil mixtures indicate that the tire shred size and the proportions of tire shreds and soil in a mixture can considerably affect these properties. For example, Zornberg et al. (2004) carried out consolidated drained (CD) triaxial compression tests to investigate the shear strength behavior of sand-tire shred mixtures, and the results illustrated that the shear strength increases with the increasing tire shred content when the content is smaller than 35%. Although rubber has excellent insulating properties, only a few studies have focused on the impacts of the tire shred size and the proportion of tire shred size on the thermal properties of soil-tire shred mixtures. Instead, most studies have focused on the insulating properties of monolithic tire chip layers. For example, Humphrey and Eaton (1995) performed a field trial on tire chip insulation layers and found that they effectively reduce the depth of frost penetration. Benson and Olson (1996) found that tire chips can be used to form an effective insulation layer to protect geomembrane liners in landfills. Lee and Shang (2013) observed that the thermal conductivity of mine tailing-tire shred mixtures is significantly affected by the volumetric proportion of tire shreds, emphasizing the importance of studying this topic further. However, they did not consider the impact of the particle size of the tire shreds. In many of the cases, thermal insulation layers are meant to insulate underlying soil layers from atmospheric temperature fluctuations and are under low applied stresses associated with self-weight.

The objective of this study is to evaluate the combined impacts of tire shred particle size and volumetric fraction on the thermal conductivity of quartz sand-tire shred mixtures. A series of thermal conductivity tests were conducted on a large number of sand-tire shred mixtures prepared in the laboratory to develop a data set suitable for developing and calibrating an empirical model that can be used in the preliminary design of quartz sand-tire shred insulating layers. The dataset presented in this study focuses on quartz sand-tire shred mixtures prepared at the same void ratio and degree of saturation as the impacts of these two variables on the thermal conductivity of sand are well known (Farouki 1981; Brandon and Mitchell 1989), but the impacts of particle size and volumetric fraction on the thermal conductivity of sand mixtures needs further study.

Materials and Test Protocols

Definitions

As mentioned, the two variables investigated in this study are the average size of the tire shred particles and volumetric content of the tire shreds in the sand-tire shred mixtures. To provide normalized quantifications of these variables, two ratios were defined. First, the relative size ratio was used to quantify the relative sizes of the sand particles and tire shred particles with similarly-shaped gradations, which is defined as follows:

$$R_s = \frac{D_{50}^{tire}}{D_{50}^{sand}} \quad \textbf{(1)}$$

where R_s is the relative size ratio, D_{50}^{tire} and D_{50}^{sand} are the mean particle sizes of the tire shreds and sand, respectively. Second, the volumetric mixing ratio, R_{vm} is used to quantify the volumetric content of the tire shreds in the sand-tire shred mixture and is defined as follows:

$$R_{vm} = \frac{V_{ts}}{V_{ts} + V_{ss}} \quad \textbf{(2)}$$

where V_{ts} and V_{ss} are the volumes of the tire shreds and sand solids in the specimen, respectively.

Characteristics of test materials

The sand used in this study is Fujian sand, which is over 96% quartz and is processed to have particles having rounded to sub-rounded shapes. The sand with the specific gravity (G_{ss}) of 2.69 was obtained from the Fujian province of China, and has been studied extensively by Xiao et al. (2017). The gradation of the sand is shown in **Fig. 1(a)**, and its physical properties are summarized in **Table 1**. The tire shreds without steel wires were obtained from Enxiang Building Material Co., Ltd. in Zhejiang province of China. The tire shred particles with angular particle shape are essentially crumb rubber with irregular particle sizes, while the size of the tire pieces are similar or smaller than the sand. The specific gravity (G_{ts}) of the tire shreds was measured in accordance to ASTM C127 (ASTM 2012) with the value of 1.18, which is consistent with the range of 1.13 to 1.36 reported by Bosscher et al. (1997). The gradations of tire shreds were shown in **Fig. 1(b),** and their physical properties are also summarized in **Table 1**.

Thermal conductivity experiments were performed on the sand-tire shred mixtures and pure Fujian sand. The Fujian sand was mixed with tire shreds at different volumetric mixing ratios ranging from 0 to 40% with an increment of 10%. The relative size ratios of the mixtures evaluated in this study were 0.42, 1.0, 2.1, 3.0, and 4.0 for each of the volumetric mixing ratios. The different sand-tire shred mixtures evaluated in the study are summarized in **Table 2**. A designation was given to each mixture based on the relative size ratio and volumetric mixing ratio. For example, the designation R42T20 stands for a mixture with R_s =0.42 and R_{vm} =20%.

Scanning electron micrograph (SEM) images of the sand-tire shred mixtures with the same relative size ratio of 0.42 but different volumetric mixing ratios are shown in **Fig. 2**. **Fig. 2(a)** to **Fig. 2(d)** show that the number of tire shred particles around sand increases dramatically with the increasing volumetric mixing ratio. As a result, as the volumetric mixing ratio increases, the mixture transitions from the sand-matrix mode, where the tire shred particles are floating between sand particles, to the tire shred-matrix mode, where the sand particles are floating between tire shred particles. Similarly, SEM images of sand-tire shred mixtures with a volumetric mixing ratio of 20% but different relative size ratios are shown in **Fig. 3**. **Fig. 3(a)** to **Fig. 3(d)** demonstrate that increasing the relative size ratio results in more contact between the sand particles than between the sand and tire shred particles. Specifically, as the relative size ratio increases, the mixture transfers from the tire shred-matrix mode to the sand-matrix mode.

Experimental Details and Testing Procedure

The thermal conductivity values of the sand-tire shred mixture specimens were measured using the KD2 Pro Thermal Properties Analyzer and a TR-1 thermal needle manufactured by Decagon Devices of Pullman, WA. The probe inserted into specimen consists of a heating element and a temperature-measuring element according to ASTM D5344 (ASTM 2014). The temperature of specimen around the probe rises uniformly from the initial room temperature to a higher value due to the constant energy input applied to the heating element. The increase in temperature of the probe is recorded over a period of time. The thermal conductivity is then determined from the recorded temperature and time using the line source analysis (Farouki 1981; Lee et al. 2017). Compared with steady-state heat transfer methods, the transient method used to perform a thermal needle test may result in more reliable results because only a small temperature gradient during the test does not cause moisture migration in unsaturated soil specimens (Chen 2008). As recommend by the user manual, the TR-1 needle, which has a length (l_{nd}) of 100 mm and a diameter (d_{nd}) of 2.4 mm, is best suited to measuring the thermal conductivity of moist soils. The suitability of this needle to measure the thermal conductivity of sand-tire shred mixtures will be discussed later. The height (H_{sp}) and inner diameter (D_{sp}) of the mold used to form the sand-tire shred specimens in this study are 127 mm and 50 mm, respectively. The specimen preparation procedures and thermal conductivity test procedures are as follows:

Step 1: A single void ratio was evaluated in this study. Specifically, a target void ratio of e_0 =0.9 was evaluated. The sand and tire shreds were mixed with deionized water to prevent the sand and tire shreds from segregating. A target degree of saturation of S_r =12.5% was evaluated in this study. The masses of dry sand (m_{ss}), tire shreds (m_{ts}) and water (m_w) in the specimens were calculated using the following equations:

$$V_s = \frac{1}{1+e_o} V_m \quad \textbf{(3a)}$$

$$m_{ts} = \rho_w G_{ts} V_{ts} = \rho_w G_{ts} V_s R_{vm} \quad \textbf{(3b)}$$

$$m_{ss} = \rho_w G_{ss} V_{ss} = \rho_w G_{ss} V_s (1 - R_{vm}) \quad \textbf{(3c)}$$

$$m_w = \rho_w V_w = \rho_w S_r \frac{e_0}{1+e_0} V_m \quad \textbf{(3d)}$$

where V_m , V_s , V_w are the volumes of the mold, solid (including sand and tire shred solids) and water in the specimen, respectively, and ρ_w (=1.0) is the density of water at 4 ℃.

Step 2: Each specimen was prepared in eight equal lifts having the same mass. The mixture for each lift was poured into the mold, and a layer was formed according to the under-compaction method proposed by Ladd (1978) , wherein the compaction dry density of previous layer is 2% higher than that of the next layer. The moist specimen wrapped with a plastic sheet was cured for at least 12 h at room temperature (25 ± 1℃) to achieve uniform distribution of pore water (Zhang et al. 2015).

Step 3: The thermal needle probe apparatus (Xiao et al. 2018) must be calibrated before testing following recommendations in ASTM D5344 (ASTM 2014). The calibration factor, which is defined as the ratio of the known thermal conductivity of the calibration material to the thermal conductivity of that material measured by this apparatus, was calculated to be 0.95 before testing.

Step 4: The TR-1 needle was inserted along the central axis of the specimen using a guide to ensure verticality. The distance between the center needle and the wall of the mold was 25 mm which was larger than the required value (15 mm) noted in the thermal needle manual, implying that the lateral boundary effects could be ignored. The thermal conductivity of each case (i.e., a mixture with a given combination of relative size ratio and volumetric mixing ratio) list in **Table 2** was measured five times at an interval of 15 minutes to ensure that the thermal needle had returned to ambient conditions at after each measurement. Multiplying the average value of the five measurements by the calibration factor was taken as the thermal conductivity of the specimen, as long as each measurement fell within a ±2% range. All tests were conducted at a controlled room temperature of 25℃ ± 1℃ to avoid the influence of the ambient temperature on the testing process.

The specific surface area, mineralogy, and other physico-chemical aspects of soils may greatly influence the measurements of thermal conductivity of soils. In addition to having different thermal conductivity values, heating of some soil to higher temperatures could change the specific surface area, mineralogy, physic-chemical aspects of some soils (Abuel-Naga et al. 2008; Han et al. 2017). In the current study, the sand and tire shred are assumed to not undergo any changes in these variables during the heating process where the maximum temperature is approximately 35℃.

Experimental Results on Thermal Conductivity

The average thermal conductivity values for each case are summarized in **Table 2** for various volumetric mixing ratios and relative size ratios. For a given relative size ratio, the thermal conductivity of the mixtures tends to decrease with the increasing volumetric mixing ratio. This is mainly attributed to the transition in the modes of the mixtures. Specifically, as the tire shred content increases, the specimen transitions from the sand-matrix mode to the tire shred-matrix mode. The thermal conductivity of quartz (7.7 W/m/K), the predominant mineral in the sand under investigation, is about thirty times greater than that of the individual tire shred particles (0.25 W/m/K). For a given volumetric mixing ratio, the thermal conductivity increases rapidly with the increasing relative size ratio at a comparatively small relative size ratios and then gradually increases with larger relative size ratios. As observed in the evaluation of the SEM images, increasing the tire shred particle size may yield a transition in the mixture mode for the same tire shred content, transforming from the tire shred-matrix mode (i.e., wherein the rubber particles form an insulating layer around the sand particles resulting in a lower thermal conductivity value of the mixture) to the sand-matrix mode (i.e., wherein sand particles encompass the tire shred particles leading to a comparative higher thermal conductivity value of the mixture).

The percent difference ($\Delta\lambda$) in thermal conductivity of the mixtures (λ) with respect to the thermal conductivity of pure sand (λ_0) is as follows:

$$\Delta\lambda=\frac{100(\lambda_0-\lambda)}{\lambda_0} \quad \textbf{(4)}$$

All the $\Delta\lambda$ values for the different mixtures are summarized in **Table 2**. A positive value of $\Delta\lambda$ indicates that the thermal conductivity of the mixture is lower than that of pure sand, indicating that the mixture is a superior insulating material. The value of λ_0 =1.591 used in this study corresponds to pure sand at a degree of saturation of S_r =12.5% and a void ratio of e_0 =0.9. When the volumetric mixing ratio is 40%, the maximum percent difference in the thermal conductivity is approximately 74% for R_s =0.42 and the minimum percent difference in the thermal conductivity is approximately 52% for R_s =4.0, which indicates that the thermal conductivity of the mixture is in relation to the tire shred particle size. Although the thermal insulation effect of small tire shreds is far superior to that of large particles due to their ability to surround the larger soil particles for forming the tire shred-matrix mode, a positive effect of using larger tire shreds is still observed. This is an important observation as large particles are more economical to manufacture from waste tires.

The relationships between $\Delta\lambda$ and R_{vm} are shown in **Fig. 4(a)** for different R_s values. Linear trends between $\Delta\lambda$ and R_{vm} are observed, with different slopes observed for different relative size ratios. Moreover, the lines pass through the coordinate origin. The relationships in **Fig. 4(a)** can be described using the following general equation to express the decrease in thermal conductivity with the addition of the tire shreds:

$$\Delta\lambda=bR_{vm} \quad \textbf{(5)}$$

where b is the slope of the relationship between $\Delta\lambda$ and R_{vm}. **Eq. (5)** fits the data well, as reflected by the coefficient of determination being closed to 1.0. It should be emphasized that the equation can be applied only when the volumetric mixing ratio is less than 40%.

Fig. 4(b) shows the relationship between the slope b and relative size ratio R_s in the double logarithmic coordinate system. A linear relation can be observed between $\ln b$ and $\ln R_s$, which can be expressed by the following power-law relationship:

$$b = \chi R_s^{\xi} \tag{6}$$

where χ (=1.641) and ξ (= -0.184) are empirical fitting parameters to account for the effects of the tire shred particle size.

Based on **Eqs. (4)**, **(5)** and **(6)**, an empirical model of thermal conductivity expressed as a function of the relative size ratio and volumetric mixing ratio can be described as

$$\lambda = \lambda_0 (1 - \frac{\chi R_s^{\xi} R_{vm}}{100}) \tag{7}$$

The surface obtained from **Eq. (7)** along with the thermal conductivity measurements are shown in **Fig. 5**, where an increase in the volumetric mixing ratio at a given relative size ratio leads to a decrease in the thermal conductivity. The predictions in **Eq. (7)** are in good agreement with the test data on the thermal conductivity of the sand-tire shred mixtures (with a maximum error of 0.089 and a coefficient of determination of 0.992).

Discussion and Limitation

Effect of Tire-Shred Paricle Size on Thermal Conductivity

Half-cylindrical specimens were prepared in order to better obersve the sand-tire shred-needle contacts. The half-cylindrical specimen size in **Fig. 6(a)** is the same as the cylindrical specimen in **Fig. 6(b)**. **Figs. 6(c)-(l)** shows images of half-cylindrical specimens of sand-tire shred mixtures

(R_{vm} = 40%) with different relative size ratios. It could be clearly observed that the mixture at the same void ratio transfers from the tire shred-matrix mode to the sand-matrix mode as the relative size ratio increases. The image of the mixture with larger tire-shred particles in **Fig. 6(k)** presents that the number of sand particles is much larger than that of tire shred, even though the volumetric mixing ratio is up to 40%. Therefore, this mixture belongs to the sand-matrix mode. In contrast, the mixture with smaller tire-shred particles in **Fig. 6(c)** shows an obvious tire-shred matrix mode. The thermal conductivity of the tire shred-matrix mode is lower than that of the sand-matrix mode. This means that the thermal conductivity of the mixture at a given volumetric mixing ratio increases with increasing the relative size ratio. This finding is in line with the work by Lee et al. (2015), who observed that the mixtures with large rubber particles have higher thermal conductivity than mixtures with small rubber particles having the same mixing ratio.

Validity of Thermal Conductivity of Sand-Tire Shred Mixture

As observed from the images of the sand-tire shred mixtures with a larger volumetric mixing ratio of 40% in **Fig. 6**, the needle has good contacts with its surrounding sand and tire shred particles even though the tire-shred particle size is 1.7 times larger than the needle probe diameter. This can be explained by the fact that the volume of tire shreds is only 40% of specimen volume. The volume occupied by the sand particles and the number of sand particles are larger than those of the tire shreds, which means the mixture belongs to the sand-matrix mode, as mentioned earlier. Therefore, the needle-probe tests for this mixture are valid from this aspect. Further, the thermal conductivity values for the mixtures with smaller tire-shred particles are valid as the tire-shred and sand particle sizes are smaller than the diameter of the needle probe. The observations of Kömle et al. (2007) also indicate that the measurements for the larger tire shred particle sizes are also valid. Specifically, Kömle et al. (2007) measured the thermal conductivity of gravels having a maximum particle size that was 26.7 times larger than the diameter of the commercial needle probe used in their study (HuksefluxTP02). Kömle et al. (2007) measured the thermal conductivity of the gravel using two other devices (a grid of individual temperature sensors which measures the temperature variations, and a custom-built sequentially working probe for measuring the vertical temperature profile and local thermal diffusivity) and found that the commercial needle probe provided thermal conductivity values that were a good match with those from the other methods and can effectively capture the heat conduction among particles. Consequently, it may be concluded that the needle-probe tests in the current work is also valid as the ratio of the particle size to the needle probe diameter is an order of magnitude smaller than that in the tests by Kömle et al. (2007).

Thermal Conductivity of Sand-Tire Shred Mixture under Loading

The contacts and contact area between particles are expected to increase for increasing applied stress, leading to an increase in the thermal conductivity (Yun and Santamarina 2008). However, the regime in the sand - tire shred mixture under the applied stress becomes more complex, since the sand particles could penetrate into the tire shred particles when the tire shred size is larger than the sand particle size. The contact area between sand and tire shred particles is hard to estimate. It is challenging to analyze the mode and regime of the thermal conductivity under such condition. In addition, the transition of contact modes would be not only affected by the relative size ratio and volumetric mixing ratio but also by stress level. All of these issues are difficult to interpret and are beyond the scope of this **Note**. In the future, we would conduct a large number of experiments on the sand-tire mixtures under loading, and also try to find a reasonable mode for interpreting the transition of contact mode and contact area between sand and tire shred particles. Nonetheless, the results from this study are applicable to the main application of near surface thermal insulating blankets in geotechnical practice which are under low confining stress.

Conclusions

This paper presents a new empirical model to account for the reduction in thermal conductivity of quartz sand through the addition of tire shreds, considering the effects of the volumetric mixing ratio and the relative size ratio. The following major conclusions can be drawn from this study:

(1) For a given relative size ratio, the thermal conductivity of mixtures tends to decrease linearly with the increasing volumetric mixing ratio. For a given volumetric mixing ratio, the thermal conductivity of the sand-tire shred mixture increases rapidly at a small relative size ratio and then increases gradually at a larger relative size ratio.

(2) For a volumetric mixing ratio of 40%, the maximum percent difference in the thermal conductivity is approximately 74% at R_s=0.42 and the minimum percent difference in the thermal conductivity is approximately 52% at R_s=4.0, which indicates that the thermal conductivity of the sand-tire shred mixture is pertaining to the particle size of tire shred. However, from an economic point of view, large particles may be more suitable as a replacement aggregate because of their lower cost.

(3) Two variables (the volumetric mixing ratio and relative size ratio) were used to establish an empirical model for predicting the thermal conductivity of the mixtures. Although this

model is based on the particular void ratio and degree of saturation evaluated in this study, it may be extended to other soil-tire shred mixtures by modifying the parameters to account for these effects using well-known relationships for these variables in the literature. It should also be pointed out that other factors (i.e., particle shape, mineral composition, applied stress, etc.) could affect the thermal conductivity, but they are not considered in this **Note**. This implies that the trends reported herein are representative of quartz sands with rounded to sub-rounded particle shapes.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request (E-mail: hhuxyanson@163.com).

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References

Abuel-Naga, H. M., Bergado, D. T., and Bouazza, A. (2008). "Thermal conductivity evolution of saturated clay under consolidation process." *Int. J. Geomech.*, 8(2), 114-122.

ASTM (2012). "Standard test method for density, relative density (specific gravity), and absorption of coarse aggregate." *C127-12*, West Conshohocken, PA.

ASTM (2014). "Standard test method for determination of thermal conductivity of soil and soft rock by thermal needle probe procedure." *D5334-14*, West Conshohocken, PA.

Bai, Y., and Niedzwecki, J. M. (2014). "Modeling deepwater seabed steady-state thermal fields around buried pipeline including trenching and backfill effects." *Comput. Geotech.*, 61, 221-229.

Baser, T., Dong, Y., Moradi, A. M., Lu, N., Smits, K., Ge, S., Tartakovsky, D., and McCartney, J. S. (2018). "Role of nonequilibrium water vapor diffusion in thermal energy storage systems in the vadose zone." *J. Geotech. Geoenviron. Eng.*, 144(7), 04018038-04018038.

Benson, C. H., and Olson, M. A. (1996). "Temperatures of insulated landfill liner." *Tansportation Research Record*, 1534, 24-31.

Bosscher, P. J., Edil, T. B., and Kuraoka, S. (1997). "Design of highway embankments using tire chips." *J. Geotech. Geoenviron. Eng.*, 123(4), 295-304.

Brandon, T. L., and Mitchell, J. K. (1989). "Factors influencing thermal resistivity of sands." *J. Geotech. Eng.*, 115(12), 1683-1698.

Chen, S. X. (2008). "Thermal conductivity of sands." *Heat Mass. Transfer*, 44, 1241-1246.

Farouki, O. T. (1981). "Thermal properties of soils." *CRREL Monograph 81-1*.

Ghaaowd, I., McCartney, J. S., Thielmann, S. S., Sanders, M. J., and Fox, P. J. (2017). "Shearing behavior of tire-derived aggregate with large particle size. I: Internal and concrete interface direct shear." *J. Geotech. Geoenviron. Eng.*, 143(10), 04017078-04017078.

Han, J., Sun, Q., Xing, H., Zhang, Y., and Sun, H. (2017). "Experimental study on thermophysical properties of clay after high temperature." *Appl. Therm. Eng.*, 111, 847-854.

Humphrey, D. N., and Eaton, R. A. (1995). "Field performance of tire chips as subgrade insulation for rural roads." *6th International Conference on Low-Volume Roads,Transportation Research Board*, 77-86.

Kashani, A., Duc, T., Mendis, P., and Black, J. R. (2017). "A sustainable application of recycled tyre crumbs as insulator in lightweight cellular concrete." *Journal of Cleaner Production*, 149, 925-935.

Kömle, N. I., Bing, H., Feng, W. J., Wawrzaszek, R., Hütter, E. S., He, P., Marczewski, W., Dabrowski, B., Schröer, K., and Spohn, T. (2007). "Thermal conductivity measurements of road construction materials in frozen and unfrozen state." *Acta Geotechnica*, 2(2), 127-138.

Ladd, R. S. (1978). "Preparing test specimens using undercompaction." *Geotech. Test. J.*, 1(1), 16-23.

Lee, C., Suh, H. S., Yoon, B., and Yun, T. S. (2017). "Particle shape effect on thermal conductivity and shear wave velocity in sands." *Acta Geotechnica*, 12(3), 615-625.

Lee, J., Yun, T. S., and Choi, S. U. (2015). "The effect of particle sze on thermal conduction in granular mixtures." *Materials*, 8(7), 3975-3991.

Lee, J. K., and Shang, J. Q. (2013). "Thermal properties of mine tailings and tire crumbs mixtures." *Constr. Build. Mater.*, 48, 636-646.

Loveridge, F., and Powrie, W. (2013). "Pile heat exchangers: thermal behaviour and interactions." *Proceedings of the ICE - Geotechnical Engineering*, 166(GE2), 178-196.

McCartney, J. S., Ghaaowd, I., Fox, P. J., Sanders, M. J., Thielmann, S. S., and Sander, A. C.

(2017). "Shearing behavior of tire-derived aggregate with large particle size. II: Cyclic simple shear." *J. Geotech. Geoenviron. Eng.*, 143(10), 04017079-04017079.

McCartney, J. S., Sánchez, M., and Tomac, I. (2016). "Energy geotechnics: Advances in subsurface energy recovery, storage, exchange, and waste management." *Comput. Geotech.*, 75, 244-256.

Noorzad, R., and Raveshi, M. (2017). "Mechanical behavior of waste tire crumbs–sand mixtures determined by triaxial tests." *Geotech. Geol. Eng.*, 35(4), 1793-1802.

Ocłoń, P., Bittelli, M., Cisek, P., Kroener, E., Pilarczyk, M., Taler, D., Rao, R. V., and Vallati, A. (2016). "The performance analysis of a new thermal backfill material for underground power cable system." *Appl. Therm. Eng.*, 108, 233-250.

Tang, A. M., Cui, Y. J., and Le, T. T. (2008). "A study on the thermal conductivity of compacted bentonites." *Appl. Clay. Sci.*, 41, 181-189.

Wang, Z., Wang, F., Ma, Z., Wang, X., and Wu, X. (2016). "Research of heat and moisture transfer influence on the characteristics of the ground heat pump exchangers in unsaturated soil." *Energ. Buildings.*, 130, 140-149.

Xiao, Y., Liu, H. L., Nan, B. W., and McCartney, J. S. (2018). "Gradation-dependent thermal conductivity of sands." *J. Geotech. Geoenviron. Eng.*, 144(9), 06018010.

Xiao, Y., Xiang, J., Liu, H., and Ma, Q. (2017). "Strength-dilatancy relation of sand containing non-plastic fines." *Geotech. Lett.*, 7(2), 1-7.

Youwai, S., and Bergado, D. T. (2003). "Strength and deformation characteristics of shredded rubber tire-sand mixtures." *Can. Geotech. J.*, 40, 254-264.

Yun, T. S., and Santamarina, J. C. (2008). "Fundamental study of thermal conduction in dry soils."

Granul. Matter, 10, 197-207.

Zhang, N., Yu, X., Pradhan, A., and Puppala, A. J. (2015). "Thermal conductivity of quartz sands by thermo-time domain reflectometry probe and model prediction." *J. Mater. Civil. Eng.*, 27(12), 04015059-04015059.

Zornberg, J. G., Cabral, A. R., and Viratjandr, C. (2004). "Behaviour of tire shred–sand mixtures." *Can. Geotech. J.*, 41(2), 227-241.

Table 1. Physical properties of the experimental materials

Type of material	G_{ss} or G_{ts}	Gradation	D (mm)	D_{50}^{sand} or D_{50}^{tire} (mm)
Fujian sand	2.69	G-S-2	0.8-1.0	0.90
Tire shreds	1.18	G-T-1	0.25-0.5	0.38
		G-T-2	0.8-1.0	0.90
		G-T-3	1.7-2.0	1.85
		G-T-4	2.4-3.0	2.70
		G-T-5	3.2-4.0	3.60

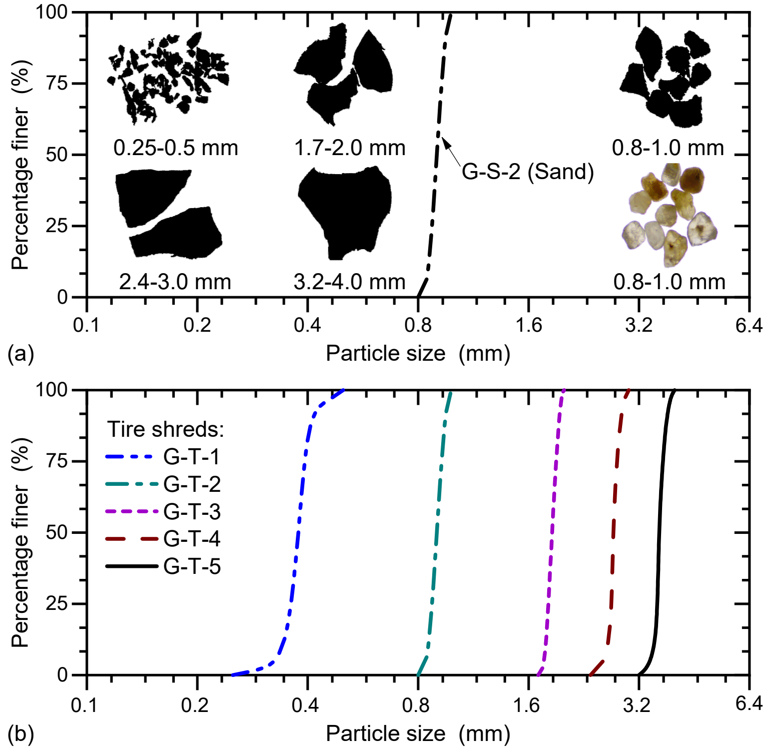
Note: G_{ss} and G_{ts} are the specific gravity of the sand and tire shred, respectively; D is the particle size; D_{50}^{sand} and D_{50}^{tire} are the mean particle size of the sand and tire shred, respectively.

Table 2. Thermal conductivity results for each investigated case

Case	R_s	R_{vm} (%)	λ (W/m/K)	$\Delta\lambda$ (%)
Pure sand	/	/	1.591	0
R42T10	0.42	10	1.209	24.0
R42T20		20	0.890	44.1
R42T30		30	0.639	59.8
R42T40		40	0.412	74.1
R100T10	1.0	10	1.332	16.3
R100T20		20	1.059	33.4
R100T30		30	0.853	46.4
R100T40		40	0.606	61.9
R210T10	2.1	10	1.360	14.5
R210T20		20	1.120	29.6
R210T30		30	0.914	42.6
R210T40		40	0.676	57.5
R300T10	3.0	10	1.384	13.0
R300T20		20	1.162	27.0
R300T30		30	0.942	40.8
R300T40		40	0.720	54.7
R400T10	4.0	10	1.399	12.1
R400T20		20	1.189	25.3
R400T30		30	0.980	38.4
R400T40		40	0.764	52.0

Note: R_s is the ratio of the mean particle size of the tire shred to that of sand; R_{vm} is the ratio of the volume of the tire shred to that of the sand-tire shred mixture. λ is the thermal conductivity; $\Delta\lambda$ is the percent difference in the thermal conductivity of the mixtures with respect to the thermal conductivity of pure sand.

Fig 1 size: Width = One column (i.e., 8.8 cm); DPI = 600

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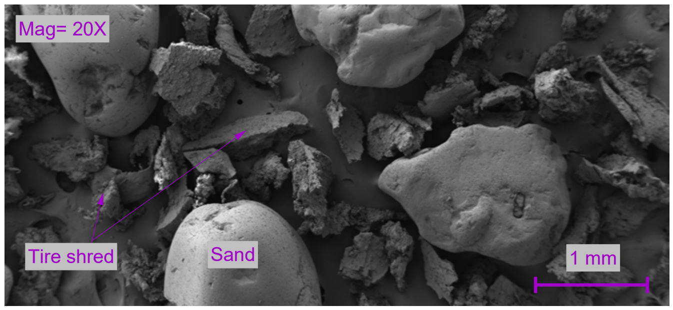
Sand
1 mm

(a)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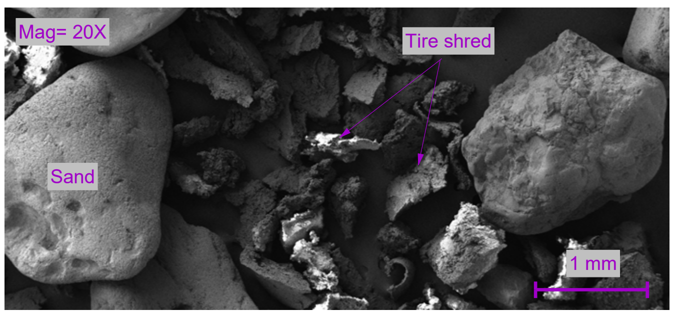
Tire shred
Sand
1 mm

(b)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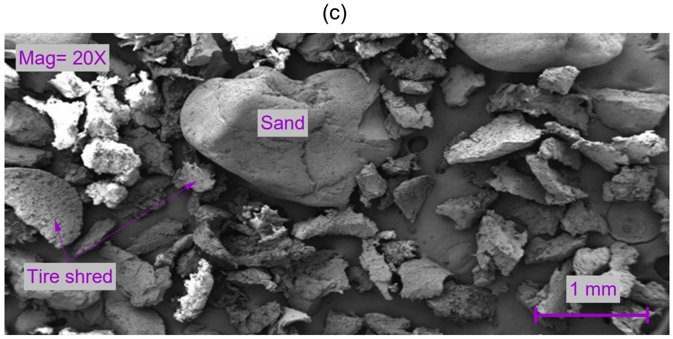
Tire shred
Sand
1 mm

(c)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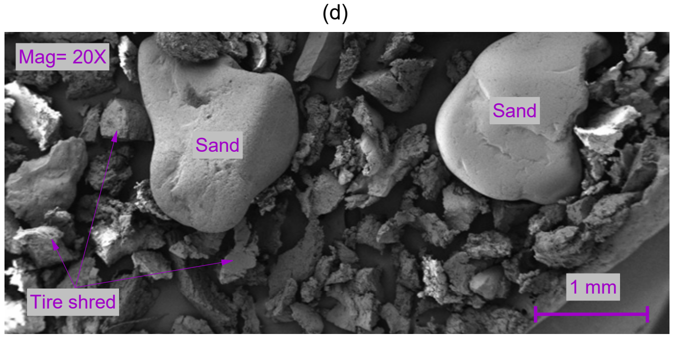
Tire shred
1 mm

(d)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Sand
Tire shred
1 mm

(e)

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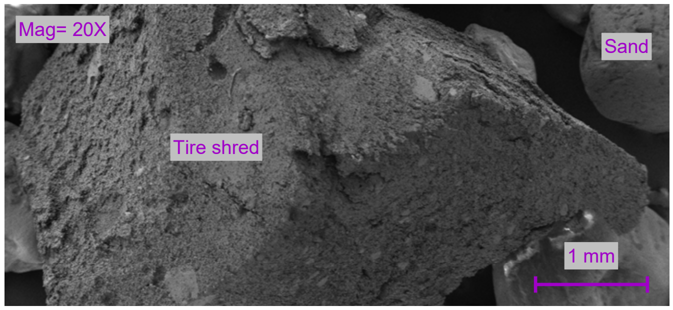

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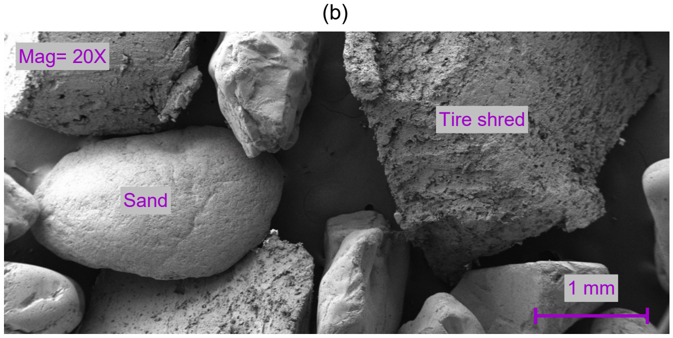

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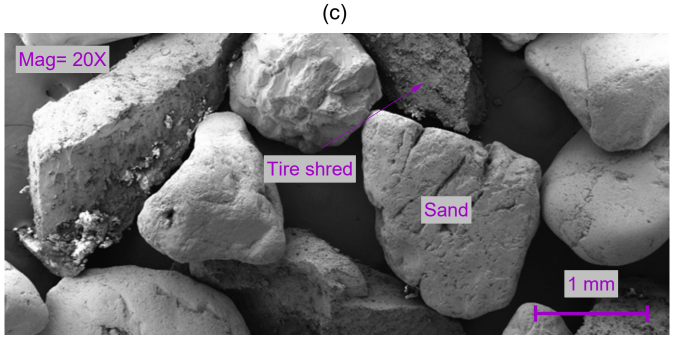

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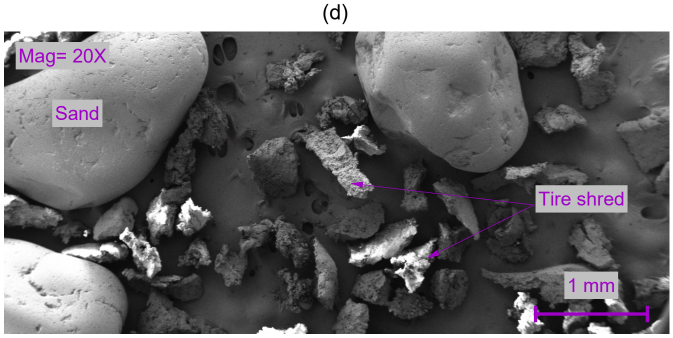

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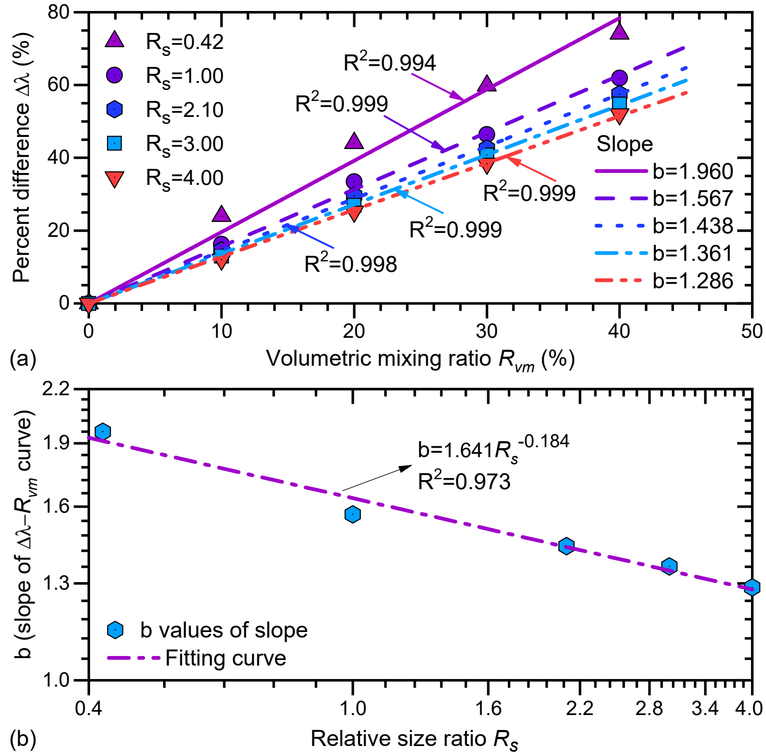

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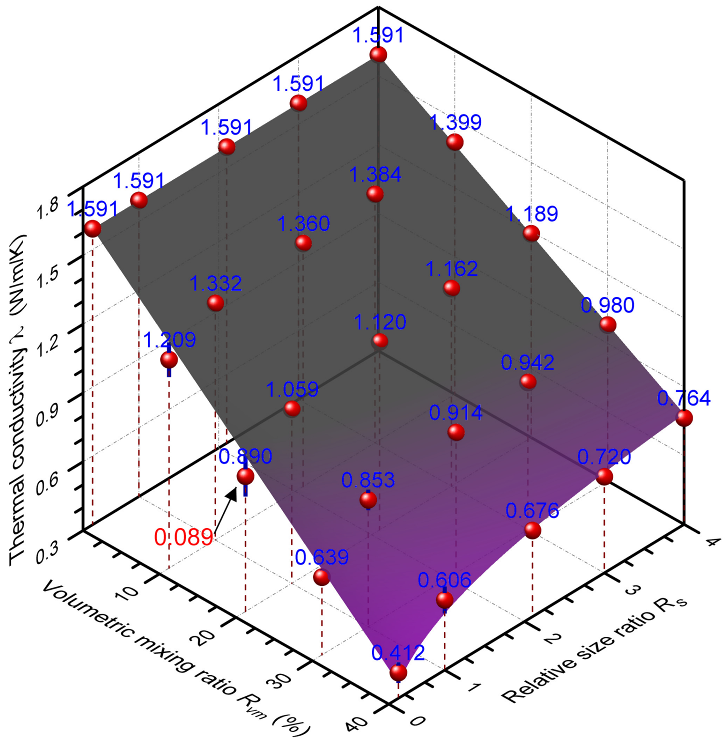

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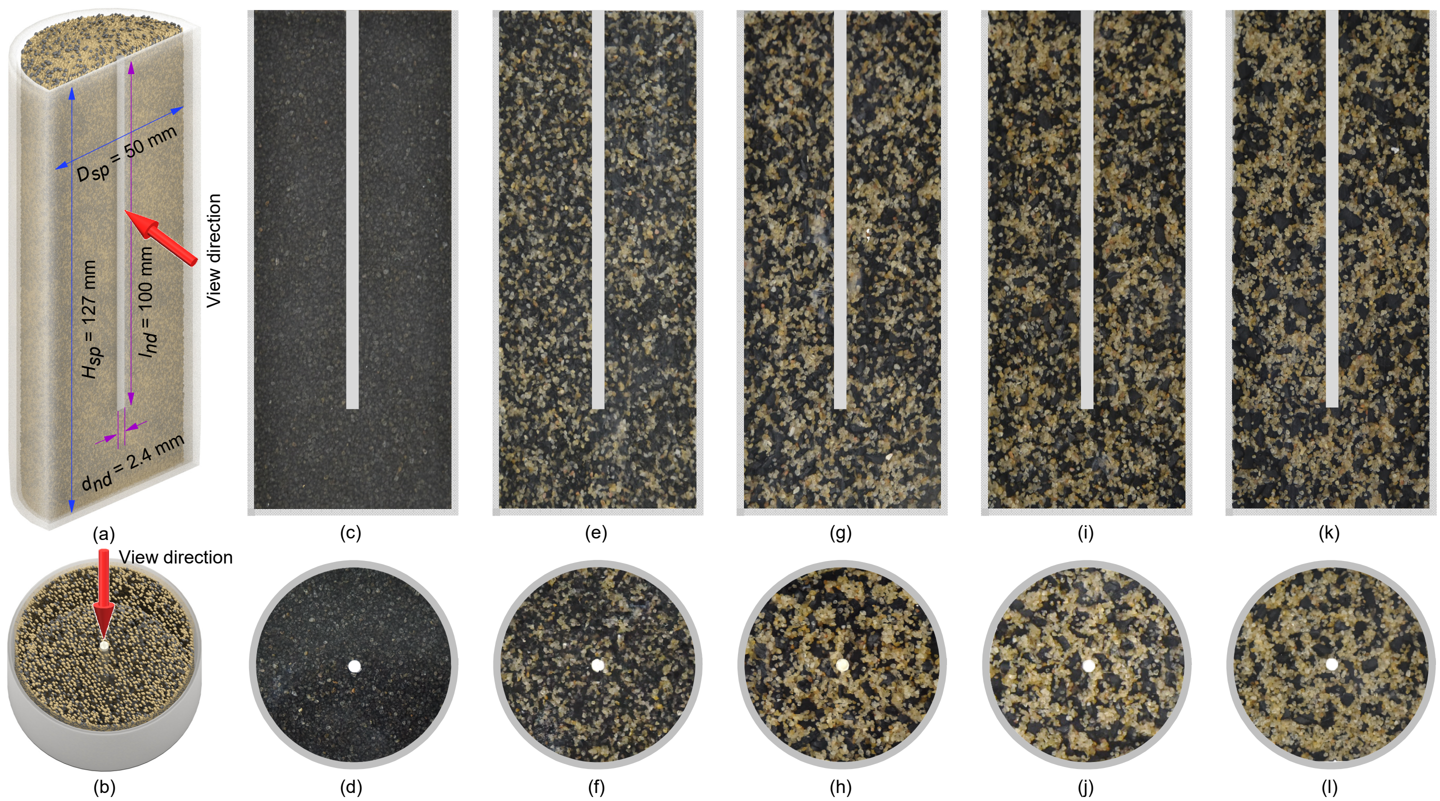

Figure Caption List

Fig. 1. Gradations for the experimental materials: (a) Fujian sand; and (b) tire shreds with different sizes

Fig. 2. Scanning electron micrograph (SEM) images of sand-tire shred mixtures with the same relative size ratio of 0.42: (a) R_{vm} =0%, (b) R_{vm} =10%, (c) R_{vm} =20%, (d) R_{vm} = 30%, and (e) R_{vm} =40%

Fig. 3. Scanning electron micrograph (SEM) images of sand-tire shred mixtures with the same volumetric mixing ratios of 20%: (a) R_s =4.0, (b) R_s =3.0, (c) R_s =2.1, (d) R_s =1.0, and (e) R_s =0.42

Fig. 4. (a) Relationships between the thermal conductivity percent difference and volumetric mixing ratio; and (b) relationship between b (the slope of the $\Delta\lambda \sim \omega$ curve) and R_s (the relative size ratios) in the double-logarithmic space

Fig. 5. Comparisons of the predicted and measured thermal conductivity values for sand-tire shred mixtures with different relative size ratios and volumetric mixing ratios

Fig. 6. (a) Sketch of half-cylindrical specimens; (b) sketch of cylindrical specimens; and images of half-cylindrical and cylindrical specimens of sand-tire shred mixtures (R_{vm} = 40%) with different relative size ratios: (c) and (d) $R_s = 0.42$; (e) and (f) $R_s = 1.0$; (g) and (h) $R_s = 2.1$; (i) and (j) $R_s = 3.0$; and (k) and (l) $R_s = 4.0$. (Note: d_{nd} and l_{nd} are the diameter and length of the thermal needle, respectively; D_{sp} and H_{sp} are the diameter and height of specimen, respectively.)

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<tr><td>Authors</td><td>Yang Xiao; Bowen Nan; John S. McCartney</td></tr>
<tr><td>Decision</td><td>Accept As Is</td></tr>
<tr><th colspan="2">Responses to Jennifer Chapman</th></tr>
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Reviewer #1' Comments	Authors' Responses
Dear Editor, In my perspective, the authors incorporated proper responses to all comments from Reviewer the reviewers in the re-revised technical note. It can be accepted for publication as a Technical Note. I had already submitted my comments with respect to the probe size and the particle size, and the corresponding reliability of the measurements in the previous revisions. In my perspective the measurements can be deemed reliable. Authors may also contact the manufacturer of the instrument for further feedback if conflict continues.	We sincerely appreciate your review of this Technical Note (GTENG-7378R2) and your helps for explaining the reliability of test, i.e., the comment from another reviewer. Thank you so much.
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