EFFECTS OF HEAT SINK COMPOUNDS ON CONTACT RESISTANCE OF POROUS MEDIA

by

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High and low-conductivity heat sink compounds were applied in succession on a thermal probe, which was then used to determine the thermal conductivity and thermal diffusivity of some porous media at room temperature. The experiment was conducted separately under different packing densities and water contents to see the effects of the heat sink compounds on the thermal properties at such conditions. High conductivity grease increased the values of thermal conductivity considerably and thus reduces the contact resistance, with increase in bulk density at air-dry conditions, but had virtually no effects on its thermal diffusivity. It however decreased both the thermal conductivity and thermal diffusivity with water content increment. The thermal properties obtained without thermal grease vary considerably from those with the heat sink compounds as water was being applied. The variation however reduced also considerably towards saturation.

Key words: *thermal conductivity, thermal diffusivity, bulk density, contact resistance, heat sinks, water content*

Introduction

The knowledge of various earth media thermal properties are very important in environmental geophysics and engineering. Soil heat flux is an essential component of the surface energy balance. Dissipation of the energy generated by buried power lines and nuclear waste directly affects the geology of the area. Various experimental methods have been suggested to determine the thermal properties of the earth media [1-5] but due to high thermal contact resistance between the porous material and the probe used have usually yielded unreliable results. The high thermal contact resistance makes the measurement of temperature and heat flux densities in the soil difficult, especially under thermal transitory field conditions where diurnal air and vapour movement caused by wind gusts and thermal gradient exists [6, 7]. The constant underestimation of thermal conductivity in soil has been traced to the presence of thermal contact resistance, the exact magnitude of which, according to [8], is very difficult to estimate especially under field conditions and rather remains, an area of persistent uncertainty.

Recent advancement in probe technology has however led to the recommendation of thermal heat sink compounds to reduce contact resistance errors. In order to minimize

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contact resistance errors [9], a thermal grease with conductivity greater than 4 W/mK is usually applied. Thermal contact resistance in saturated media was found to be inexistent [10, 11] and in air-dry condition was found to increase with particle size when no heat sinks compound was applied [12]. The situation, however, is still very unclear between air-dry and saturated conditions, thus prompting the need for this research work. The objectives therefore were to study the enhancements or otherwise of heat sink compounds on the reduction of thermal contact resistance errors between air-dry and saturated conditions and also to investigate its behaviour with bulk density variations.

Theory

The thermal conductivity was measured using, the KD2 probe (Decagon Devices Inc., Pullman, Wash., USA) with a diameter of 0.9 mm. It can be treated as an infinitely long heat source in an isotropic and homogenous medium under a uniform initial temperature. In such a condition, the governing equation according to [13] is:

$$\frac{\partial T}{\partial t} \quad \alpha \quad \frac{\partial^2 T}{\partial r^2} \quad \frac{1}{r}\frac{\partial T}{\partial r} \tag{1}$$

where T [°C], is temperature, t [s] is time , α [mm^2/s] is thermal diffusivity and r [m] is radial distance. Linearly regressing ΔT on ln(t) yields a slope that, after rearranging, gives thermal conductivity as:

$$\lambda \quad \frac{q}{4\pi m} \tag{2}$$

where q is known from the power supplied to the heater and m is the slope of the graph. The thermal diffusivity can also be obtained from eq. (1). The intersection of the regression line with the t-axis ($\Delta T = 0$) gives:

$$\ln(t_0) \quad \lambda \quad \ln \frac{r^2}{4\alpha} \tag{3}$$

From calculated t_0 (the interception of ΔT *vs*. ln (t)) and finite r, eq. (3) gives thermal diffusivity.

Thermal contact resistance is the resistance to heat transfer at an interface due to poor physical contact between adjoining objects of different shapes or roughness. It depends strongly on the amount of air in contact with the probe, [14, 15].

The resistance per unit length $\Gamma_{1,0}$ between the probe and the surrounding is equal to the sum of the contact resistance per unit length Γ_1 and the internal heat resistance $W_{1\ i}$ between the probe and the wall of the cylinder according to the equation [16] below:

$$\Gamma_{1,0} \quad \Gamma_1 \quad W_{1\,i} \tag{4}$$

and also from [10] the contact resistance can also be expressed as:

$$\Gamma \quad 2\pi \nu \Gamma_1 \tag{5}$$

where ν is the outside radius of the tube.

Materials and methods

Two experiments were run: the first, to see the enhancements or otherwise of the heat sink compounds on the thermal conductivity and thermal diffusivity values, and the second, to investigate the effects of heat sink compounds on thermal conductivity and thermal diffusivity using different bulk densities.

The sand used in experiments was a commercial grade quartz sand composed of 20.5, 68.9, 10.2, and 0.4%, *i. e.* coarse, medium, fine, and very fine sand, respectively. The stone dust was a ground granite from a nearby quarry and it is composed of 90, 4.8, and 5.2% sand, clay, and silt, respectively, while the clay used was composed of 47.6, 38.8, and 15.6% sand, clay, and silt, respectively. Glass beads and quartz sand were 1 mm in diameter while stone dust and clay were 2 mm in diameter. The particle size and sand fractionation analysis were according to ASTM standard (ASTM D422-63) [17].

Experiment 1

A cylindrical container (12.0 cm deep and 10.2 cm wide) was used to pack each of the air-dried samples of the porous material under investigation and the packing was done in such a way that the bulk densities of all the samples were in the same range. This was done to reduce to its barest minimum the effects of bulk density. The amount of 100 ml of water was slowly added to each sample until higher saturation, paying attention to keep the dry-basis bulk density. The experiment which was carried out at the room temperature, employed two heat sink compounds of high and low thermal conductivities *i. e.* arctic silver grease (ASG) with λ = 8 W/mK and white grease (WG) with $\lambda \approx$ 1 W/mK. Both ASG and WG were high-temperature (–50 to 130 °C) thermally conductive compounds with a high stability when applied on the probe. A layer of WG was initially thinly applied on the probe and measurement was made twice in each cylinder (at two different locations). WG was then wiped off with alcohol and a thin layer of ASG was then applied. Measurements were performed twice in each container again at two different locations. The design resulted in 6 measurements of thermal conductivity and thermal diffusivity for each porous material, and at each water level. All the measurements were performed at the constant room temperature in order to eliminate the influence of temperature.

Experiment 2

In the second experiment, the packing was done three times for each sample, *i. e*. for low, medium, and high bulk densities. The packing was done using of an iron rod with a flat base, almost having the diameter of the cylinder. The same measuring procedure for the thermal properties as used above was also applied, resulting in 6 measurements of thermal conductivity and thermal diffusivity for each porous medium, and for each density packing.

Results and discussion

λ and α were measured with and without the heat sink compounds (HSC) *i. e*. WG and ASG, for all the porous media under different water and packing conditions as given in tabs. 1-4. The relative difference in the measured values of λ_2 and λ_1, λ_3 and λ_1, α_2 and α_1, and α_3 and α_1 for glass beads, sand, stone dust, and clay were also presented in tabs. 1-4. λ_1, λ_2 and λ_3, however, represent the average values of λ without any grease, with WG and with ASG, respectively, while α_1, α_2, and α_3 are the average values of the thermal diffusivity without any grease, with WG and ASG, respectively. The thermal conductivities and diffusivities for different packing densities are given in figs. 1 and 2 while figs. 3 and 4 compare the effects of HSC on λ and α for different water contents.

Effects of HSC on thermal conductivity/water content

The heat sink application on the probe decreased the values of the thermal conductivity in glass beads under moist condition. This implies that thermal conductivity without grease application is reliable at moist condition, thus leaving no need for heat sink compounds application on the probe at such conditions. This was clearly observed in their negative relative differences from tab. 3. WG application caused the greatest decrease, but the average values of λ obtained with and without the heat sink compounds however increased with water. The variation in the values of λ_1, λ_2, and λ_3 under moist conditions was more pronounced than air-dry conditions, with highest variation reached at 300 ml probably due to the fact that the combined effects of water and grease could have trapped some air in the pore spaces thus reducing the density of the heat flow rows. There was, however, a general increase of thermal conductivity with water content and a gradual reduction in the variation, and thus a gradual assumption of uniform values towards saturation condition owing to the fact that the thermal contact resistance problem is almost non-existent at high saturation condition.

In the experimentation with the quartz sand, λ values without thermal grease application were higher, and also varied widely as against those with grease, especially the WG. The variation under 300 ml was again more significant and thereafter, a gradual reduction in the variation goes towards higher saturation. The same trend was observed in the experimentation with the stone dust, with thermal conductivity with and without the ASG almost assuming same values at 100 and 200 ml. There was still a very wide varia-

Table 1. Thermal conductivity and diffusivity of glass beads with and without thermal grease on the probe

Glass beads					
θ [ml]	λ_1 [W/mK]	λ_2 [W/mK]	λ_3 [WmK]	Difference $\lambda_2 - \lambda_1$ [%]	Difference $\lambda_3 - \lambda_1$ [%]
100	0.405	0.300	0.445	–25.9	9.8
200	0.590	0.325	0.335	–44.9	–43.2
300	0.655	0.255	0.380	–61.1	4.2
400	0.715	0.725	0.715	1.4	0.0
θ [ml]	α_1 [mm^2/s]	α_2 [mm^2/s]	α_3 [mm^2/s]	Difference $\alpha_2 - \alpha_1$ [%]	Difference $\alpha_3 - \alpha_1$ [%]
100	0.130	0.115	0.150	–11.5	15.4
200	0.135	0.130	0.115	–3.7	–14.8
300	0.130	0.110	0.125	–15.4	–3.8
400	0.140	0.145	0.145	3.6	3.6
ρ [Mg/m^3]	λ_1 [W/mK]	λ_2 [W/mK]	λ_3 [W/mK]	Difference $\lambda_2 - \lambda_1$ [%]	Difference $\lambda_3 - \lambda_1$ [%]
1.550	0.155	0.155	0.150	0.0	–3.2
1.563	0.155	0.145	0.155	–6.5	0.0
1.599	0.150	0.155	0.160	3.3	6.7
ρ [Mg/m^3]	α_1 [mm^2/s]	α_2 [mm^2/s]	α_3 [mm^2/s]	Difference $\alpha_2 - \alpha_1$ [%]	Difference $\alpha_3 - \alpha_1$ [%]
1.550	0.095	0.090	0.100	–5.3	5.3
1.563	0.090	0.100	0.100	11.1	11.1
1.599	0.090	0.095	0.100	5.6	11.1

tion in the values of λ_1, λ_2, and λ_3 at 300 ml and a gradual reduction in the variation towards the saturation. The situation was remarkably different in the experimentation with clay with very low values obtained for thermal conductivity with and without thermal grease at all water levels, only with the exception of λ_3 at 100 ml which was relatively very high.

Effects of HSC on thermal diffusivity/water content

Thermal diffusivity values with and without heat sink compounds had minimal variations even as water level was increased in the glass beads. The situation was completely different in the experimentation with the quartz sand, with very wide variations of thermal diffusivity values with and without the thermal grease application. Application of 300 ml further increased the variation, with a gradual reduction in the variation towards higher saturation. The values of α_1 were, however, much greater than α_2 and α_3.

Table 2. Thermal conductivity and diffusivity of quartz sand with and without thermal grease on the probe

Quartz sand					
θ [ml]	λ_1 [W/mK]	λ_2 [W/mK]	λ_3 [W/mK]	Difference $\lambda_2-\lambda_1$ [%]	Difference $\lambda_3-\lambda_1$ [%]
100	2.605	1.070	1.830	–58.9	–29.8
200	2.400	0.950	1.850	–60.4	–22.9
300	2.260	0.705	0.385	–68.8	–83.0
400	2.215	2.075	2.025	–6.3	–8.6
θ [ml]	α_1 [mm^2/s]	α_2 [mm^2/s]	α_3 [mm^2/s]	Difference $\alpha_2-\alpha_1$ [%]	Difference $\alpha_3-\alpha_1$ [%]
100	0.855	0.595	0.770	–30.4	–9.9
200	0.820	0.600	0.370	–26.8	–54.9
300	0.845	0.405	0.215	–52.1	–74.6
400	0.860	0.825	0.870	–4.1	–9.3
ρ [Mg/m^3]	λ_1 [W/mK]	λ_2 [W/mK]	λ_3 [W/mK]	Difference $\lambda_2-\lambda_1$ [%]	Difference $\lambda_3-\lambda_1$ [%]
1.667	0.235	0.235	0.280	0.0	19.1
1.739	0.220	0.230	0.240	11.6	14.0
1.817	0.210	0.225	0.255	7.1	21.4
ρ [Mg/m^3]	α_1 [mm^2/s]	α_2 [mm^2/s]	α_3 [mm^2/s]	Difference $\alpha_2-\alpha_1$ [%]	Difference $\alpha_3-\alpha_1$ [%]
1.667	0.100	0.100	0.100	0	0
1.739	0.100	0.100	0.100	0	0
1.817	0.100	0.100	0.100	0	0

The same trend was observed in stone dust, which belongs to the same sand family as the quartz sand. The values of α_2 were, however, lower than those of α_3, except the case of quartz sand. The values of α with and without the thermal grease were very low and almost constant at the various water levels with the exception of 300 ml and 400 ml.

Effects of HSC on thermal conductivity/bulk density

In the experiment with glass beads, the values of thermal conductivity were low with the application of both ASG and WG at low densities as could be clearly seen from their negative relative differences from tab. 1. This trend was however reversed significantly at high densities with the application of HSC causing an increase in the average values of thermal conductivity and thus decreasing the contact resistance errors, especially when the ASG applied.

The situation was slightly different in the experimentation with quartz sand, as could be observed in fig. 1. Even though, both the ASG and WG increased the values of

Table 3. Thermal conductivity and diffusivity of stone dust with and without thermal grease on the probe

Stone dust					
θ [ml]	λ_1 [W/mK]	λ_2 [W/mK]	λ_3 [W/mK]	Difference $\lambda_2 - \lambda_1$ [%]	Difference $\lambda_3 - \lambda_1$ [%]
100	0.500	0.410	0.500	–18.0	0.0
200	0.905	0.345	0.555	–61.9	–106.1
300	0.990	0.270	0.520	–72.7	47.5
400	1.010	1.050	1.050	4.0	4.0
θ [ml]	α_1 [mm^2/s]	α_2 [mm^2/s]	α_3 [mm^2/s]	Difference $\alpha_2 - \alpha_1$ [%]	Difference $\alpha_3 - \alpha_1$ [%]
100	0.250	0.175	0.190	–14.6	–7.3
200	0.265	0.145	0.250	–45.3	–5.7
300	0.345	0.120	0.230	–22.5	–33.3
400	0.330	0.325	0.285	–1.5	–13.6
ρ [Mg/m^3]	λ_1 [W/mK]	λ_2 [W/mK]	λ_3 [W/mK]	Difference $\lambda_2 - \lambda_1$ [%]	Difference $\lambda_3 - \lambda_1$ [%]
1.435	0.125	0.125	0.130	0.0	4.0
1.488	0.135	0.135	0.160	0.0	18.5
1.612	0.150	0.155	0.155	3.3	3.3
ρ [Mg/m^3]	α_1 [mm^2/s]	α_2 [mm^2/s]	α_3 [mm^2/s]	Difference $\alpha_2 - \alpha_1$ [%]	Difference $\alpha_3 - \alpha_1$ [%]
1.435	0.095	0.100	0.100	5.3	5.3
1.488	0.090	0.090	0.090	0.0	0.0
1.612	0.090	0.090	0.090	0.0	0.0

thermal conductivity, yet λ_1, λ_2, and λ_3 were largely constant despite increase in the bulk densities. The effect of thermal grease application was not also very significant as neither the ASG nor the WG translated to significant changes in values of λ. Application of ASG in stone dust experiment, as could be clearly seen from fig. 1, increased the values of the thermal conductivity, especially when the bulk density increased from 1.435 to 1.488 Mg/m^3. However, at high densities, λ_1, λ_2, and λ_3 were almost assuming the same values.

In the experimentation with clay, the difference in the values of thermal conductivity with and without the WG, and with and without the ASG was very minimal at low densities. However at high densities, application of ASG and WG on the thermal probe increased the values of thermal conductivity with ASG having a more pronounced increase.

Effects of HSC on thermal diffusivity/bulk density

In the glass beads experiment, while the thermal diffusivity obtained with ASG application on the probe was constant despite an increase in the values of bulk density,

Table 4. Thermal conductivity and diffusivity of clay with and without thermal grease on the probe

Clay					
θ [ml]	λ_1 [W/mK]	λ_2 [W/mK]	λ_3 [W/mK]	Difference $\lambda_2 - \lambda_1$ [%]	Difference $\lambda_3 - \lambda_1$ [%]
100	0.000	0.000	0.245	0.0	0.0
200	0.005	0.005	0.005	0.0	0.0
300	0.005	0.005	0.005	0.0	0.0
400	0.010	0.010	0.005	0.0	–50.0
θ [ml]	α_1 [mm^2/s]	α_2 [mm^2/s]	α_3 [mm^2/s]	Difference $\alpha_2 - \alpha_1$ [%]	Difference $\alpha_3 - \alpha_1$ [%]
100	0.185	0.160	0.115	–13.5	–37.8
200	0.155	0.140	0.135	–9.7	–12.9
300	0.075	0.175	0.075	133.3	0.0
400	0.000	0.000	0.435	0.0	0.0
ρ [Mg/m^3]	λ_1 [W/mK]	λ_2 [W/mK]	λ_3 [W/mK]	Difference $\lambda_2 - \lambda_1$ [%]	Difference $\lambda_3 - \lambda_1$ [%]
1.296	0.120	0.145	0.135	20.8	12.5
1.379	0.130	0.140	0.165	7.7	26.9
1.463	0.160	0.185	0.210	15.6	31.3
ρ [Mg/m^3]	α_1 [mm^2/s]	α_2 [mm^2/s]	α_3 [mm^2/s]	Difference $\alpha_2 - \alpha_1$ [%]	Difference $\alpha_3 - \alpha_1$ [%]
1.296	0.100	0.090	0.090	–5.0	0.0
1.379	0.100	0.095	0.095	–5.0	–5.0
1.463	0.095	0.100	0.100	–5.3	5.3

the variation on the other hand in the values of the thermal diffusivity with and without the WG application was not particularly due to any definite trend of bulk density. The value of α_3 was, however, much higher than α_1 and α_2, which implies a more pronounced effect of ASG on the probe to increase the values of thermal diffusivity. The situation was similar in the experimentation with quartz sand where neither an increase in the bulk density nor the application of the thermal heat compounds had any definite impact on thermal diffusivity (fig. 2). The values of α_1, α_2, and α_3 maintained uniform values throughout the experimentation with quartz sand despite an increase in the bulk densities.

Stone dust experimentation had a similar trend as the quartz sand. Bulk densities and heat sink compounds application had virtually no effect on the values of thermal diffusivity. This could be expected since both quartz sand and stone dust were more of sands in their content analysis. The effect of bulk density on the behaviour of thermal diffusivity under the application of thermal grease in the experimentation with clay was similar to that of its thermal conductivity. However heat sink compounds decreased the values of α, but at high densities, the situation became significantly different with the

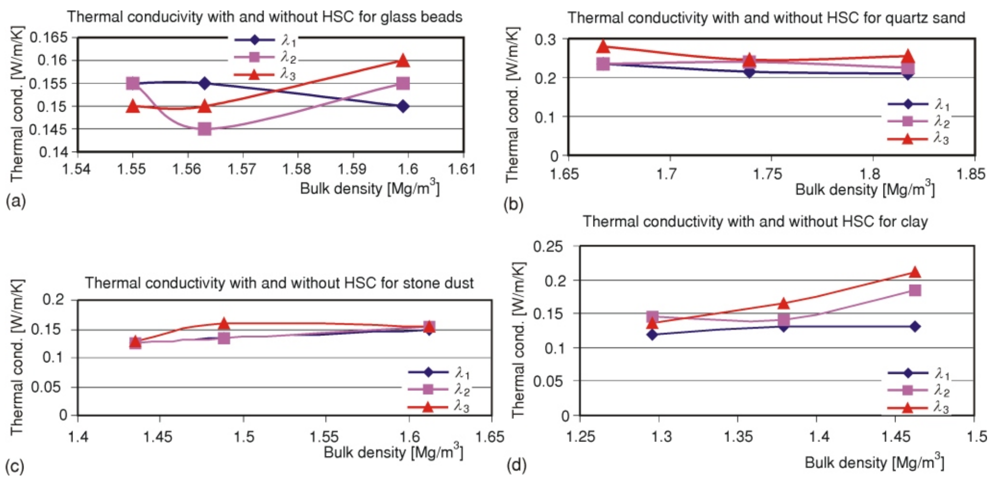

Figure 1. Thermal Conductivity with and without HSC at different packing densities

heat sink compounds, especially when the ASG increased the values of the thermal diffusivity (fig. 2).

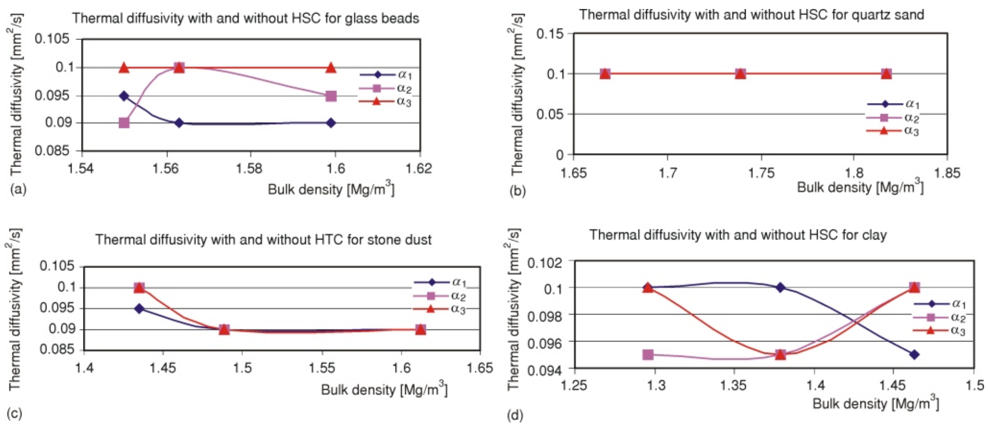

Figure 2. Thermal Diffusivities with and without HSC at different packing densities

Conclusions

In this work, effects of heat sink compounds on thermal conductivity and diffusivity probes have been investigated in porous media. High-conductivity heat sink

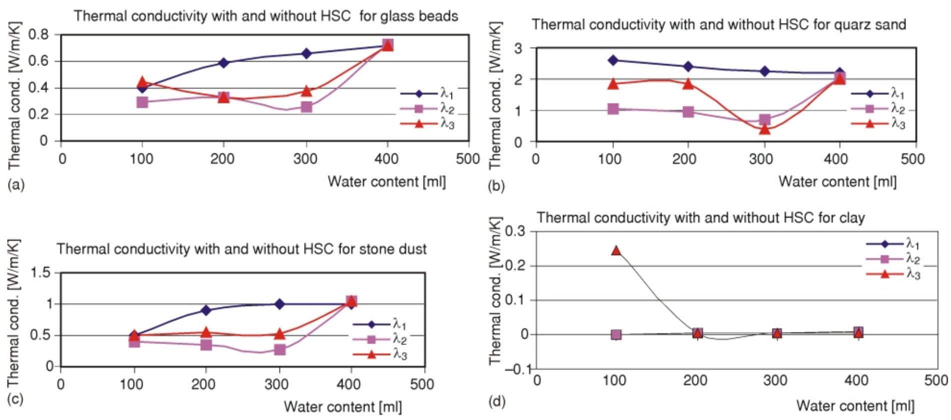

Figure 3. Thermal conductivity with and without HSC at different water contents

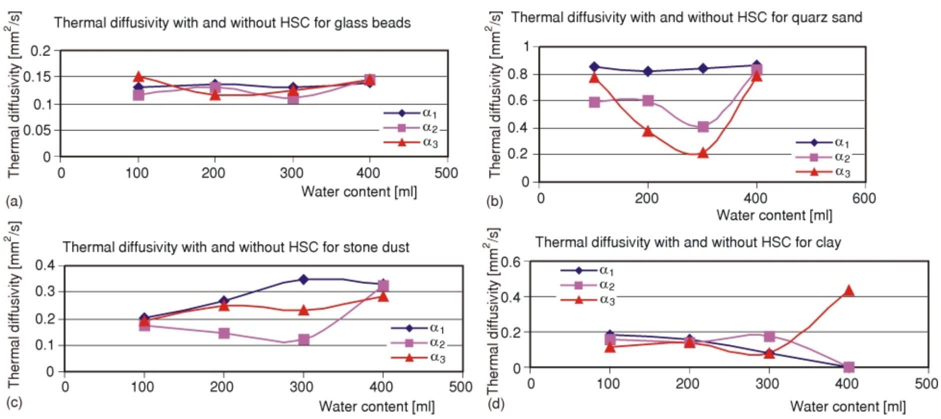

Figure 4. Thermal diffusivity with and without HSC at different water contents

compounds increased the thermal conductivity of porous materials at air-dry conditions with increase in bulk density, and thus reduced the contact resistance errors. Increase in bulk density reduced the differences in the values of λ_1, λ_2 and λ_3 as opposed to increase in water content.

High-conductivity heat sink compounds decreased thermal conductivity, with increase in water contents. On the other hand, neither the bulk density increment nor the application of the heat sink compounds had any considerable effect on the values of thermal diffusivity. The application of 300 ml of water caused significantly the variations of the values of λ_1, λ_2, and λ_3. Further increase in water content however reduced the variations gradually towards saturation, in all the porous media with the exception of clay.

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