Measurement of the Effective Thermal Conductivities of Molding Sands at High Temperatures

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(Received February 14, 1996)

It is well known that the effective thermal conductivity of bonded molding sands depends on the volume fraction, thermal conductivity and arrangement of the components e.g., sand particles, bonding medium and air. The arrangement of components is known to be affected by particle size distribution, average size and shape. In this study, an experimental system using the line-heat-source method was designed and effective thermal conductivities of molding sands at temperatures up to 750℃ were measured. The effects of binder content, initial moisture content, dry density and temperature were also investigated for four selected sand types : silica, olivine, zircon and chromite sands. The effect of dry density on the effective thermal conductivity of bentonite-bonded molding sands turned out to be more significant than the effect of either binder content or initial moisture content. The minimum effective thermal conductivity for bentonite bonded silica sand occurred at about 500℃. The effective thermal conductivity of silica sands bonded with western bentonite was found to be higher than that of silica sands bonded with southern bentonite up to 750℃.

Key Words : Effective Thermal Conductivity, Molding Sands, Bentonite Binder, High Temperature

1. Introduction

The experimental data on the effective thermal conductivity of molding sands are important to understand the heat transfer phenomena in the casting system. Numerous experiments have been performed to investigate the effects of many practical parameters. The earliest investigation of the thermal properties of molding sands was carried out by Briggs and Gezelius (1933). Six-inch -diameter steel spheres were cast in molds made from a number of different materials, and the temperature rise at various distances from the metal/mold interface was measured. Atterton (1953) investigated the influences of several parameters on the effective thermal conductivity of bonded sand molds. The effective thermal conductivity is found to be the apparent thermal conductivity in the multi-phase material. Thus, it may vary with the characteristics of each components. The steady state method used by Niven (1905) was applied to determine the thermal conductivity of mold materials over the temperature range of 20 to 1600℃.

Kubo et al. (1982) developed a heat transfer model modified from Kunii's theory for a packed bed. An equation was suggested for the prediction of the effective thermal conductivity of sand molds at temperatures below 600℃. The predictions show good agreement with measured thermal conductivities of dry molding sands bonded with western bentonite and of resin-bonded molding sands. In 1983, Kubo et al. (1983) measured the thermal properties of dry and green molds of silica, olivine, zircon and chromite sands by the pouring method. The effective thermal conductivity as a function of temperature was obtained from the pouring method using a param-

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eter optimization technique.

Hartley, Babcock and Berry (1981) measured the thermal conductivities of bentonite-bonded silica, zircon, olivine and chromite sands using the thermal probe method. They found that an optimum binder content and an optimum initial moisture content exist for dry, bonded sands. Hartley and Patterson (1983) investigateed the effects of temperature, initial moisture content, and binder content on the effective thermal conductivity of bentonite-bonded silica and zircon sand molds. From the measurements at temperatures up to 750℃, they presented normalized functions to account for the effects of temperature, initial moisture contents, and binder content.

In this study, the effective thermal conductivities of unbonded and bonded molding sands at temperatures up to 750℃ were measured using the probe method and the hot-wire method. Sand types selected are silica, olivine, zircon and chromite. Both western and southern bentonite were considered. The effect of sand particle characteristics such as particle size and shape was examined for unbonded sand. The effects of dry density or volume fraction of sand particles, binder content, initial moisture content and temperature were investigated.

2. Measurement System for Probe Method

2.1 Thermal conductivity probe

The thermal conductivity probe designed for this study is similar to the laboratory probe constructed by Steinmanis (1982). The probe consists of a thermocouple wire, a heater wire, a ceramic insulator and a stainless steel tube. The length-to-diameter ratio of the probe was 58. Probe temperatures up to 750℃ were measured with 30 AWG chromel-alumel thermocouple wire. Nichrome-V (Ni 80% - Cr 20% alloy) was chosen for the heater element. The thermocouple wire and the heater wire were inserted through the holes of the ceramic insulator and the insulator was protected by a type 304 stainless steel tube having an outer diameter of 2.41 mm. The length of the probe was about 15.2 cm, and the probe was inserted into the specimen to a depth of about 14 cm.

2.2 Measurement system

The basic measurement system for the probe method is composed of a thermal conductivity probe, a regulated DC power supply, a furnace, and a probe temperature and electric power measurement system as shown in Fig. 1.

The heater element in the probe was heated at a constant rate of electric current provided by the direct current power supply. The transient temperature response of the probe was recorded using a temperature measuring system. The current in the heater element as well as the applied voltage were measured with digital multimeters.

For high temperature measurements in the box furnace, both ends of the specimen were insulated with a ceramic fiber blancket. In addition, the specimens were enclosed in a protective cylinder formed by a copper sheet having a thickness of 0.53 mm. The protective cylinder helped to ensure even heat distribution in the axial and circumferential directions while to restrict heat flows in the radial direction. Thus, the axial and radial temperature differences in the specimen caused by uneven heating within the furnace prior to the thermal conductivity measurement were minimized.

2.3 Experimental apparatus

A 4 kVA box furnace was used to maintain a uniform temperature field within the test specimen at the chosen test temperatures. The temperature within the furnace was controlled by an on

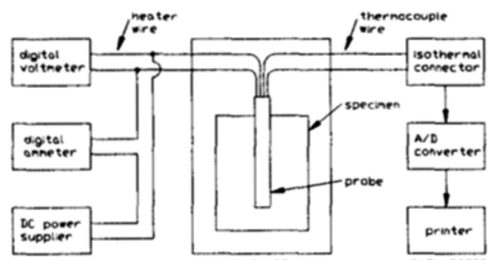

Fig. 1 Schematic diagram of measurement system

Table 1 Average size and density of sand particles

Sand Type	Median diameter (microns)	AFS grain fineness number	Measured particle density (g/cm^3)
Ottawa	431	41.32	2.65
Fine silica	147	73.88	2.65
Masonry	587	30.94	2.65
Zircon	144	103.08	4.56
Olivine #180	118	135.95	3.22
Olivine #70	297	56.87	3.22
Chromite	477	40.77	4.45

-off temperature controller. Furnace temperatures up to 1030℃ could be achieved. The furnace cavity measured about 12.5 cm by 13.5 cm by 38 cm. Electric current to the probe was provided by a regulated direct current power supply.

2.4 Characteristics of sand particles

The particle size distribution of the sands were determined using ASTM standard sieves and a portable sieve shaker. The average or median particle size of sand particles can be determined in many ways. The method chosen in this study is to define the median particle size as the fifty percent value of diameter obtained from a plot of particle size versus cumulative weight percent. Also, the particle densities of sand particles were measured in this study. The average particle size and the density measured are listed in Table 1.

2.5 Sample preparation

For bonded sand samples, 1800 grams of dry sand were used. Then, the binder weight and the water weight were determined. After the sand and the binder were mixed together, water was added to the mixture by spraying. Handmixing was used throughout the process. After mixing, the sample was kept in an air-tight enclosure for at least 24 hours to ensure that the moisture was distributed uniformly throughout the specimen.

A special compacting tool was designed for compaction of the sample. Before sample compaction began, the probe was inserted through the hole in the center of the bottom plate of the compacting tool and was fixed in place. The sample was compacted in layers, each of which had a height of 1.02 cm. A total of 15 layers was used. The weighed mixture for each layer was poured into the sample container and distributed carefully to obtain a uniform thickness. Next, spacers were positioned in the compacting tool so that the mixture was compacted to a layer thickness of 1.02 cm. This procedure was repeated until the sample container was filled with the bonded-sand mixture. Then, the sample was dried in an oven for about 24 hours at a temperature of 110 to 125℃. The initial moisture content was determined by measuring the decrease in the weight of specimen after dried.

2.6 Experimental procedure

After the mixture of sand and clay was dried, the sample temperature was measured by the thermocouple in the probe. Steady state conditions were assumed to exist when the temperature variation of the probe was less than 0.05℃ during a 30-minute interval. The temperature was monitered at 30-second intervals for 20 minutes. The DC power supply was adjusted to provide constant heat generation in the heating wire of the probe. The current and the voltage were measured by a digital ammeter and a digital voltmeter, respectively. The power supplied to the probe was selected such that the temperature rise would be less than 20℃ over the duration of a test.

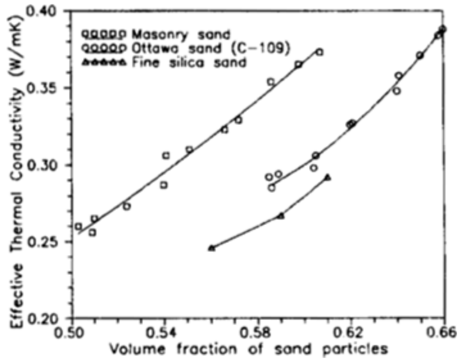

Fig. 2 Measured effective thermal conductivities of dry, unbonded silica sands

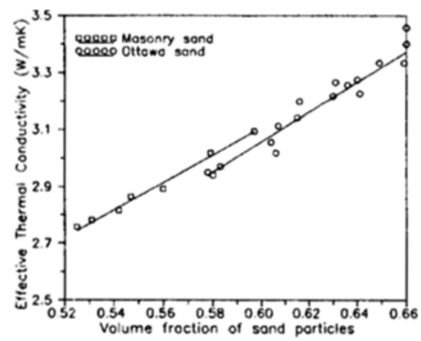

Fig. 3 Measured effective thermal conductivities of unbonded silica sands saturated with water

3. Experimental Results

For unbonded sands at room temperature, the parameters examined in this study are the volume fraction of sand particles, the thermal conductivity of the saturating fluid, the sand particle shape, the average particle size, and the sand type. For bonded molding sands at room temperature, the effect of the dry density, the binder type and content, and the initial moisture content were examined. The effect of temperature on the effective thermal conductivity of molding sands was also investigated from high temperature thermal conductivity measurements.

3.1 Unbonded sands

Four sand types have been selected : silica, olivine, zircon and chromite sands. The effective thermal conductivities of unbonded Ottawa sand were measured, and the effect of the volume fraction of sand particles was examined. The measured results are shown in Fig. 2.

The effective thermal conductivity of the dry, unbonded Ottawa silica sand increases as the volume fraction of sand particles is increased. This means that, as the volume fraction of sand particles increases, the distance between the sand particles is reduced. Also, the number of contact points per sand particles is increased. The effective thermal conductivity of dry, unbonded fine silica sand was measured to examine the effect of sand particle size. The results were compared with those for other silica sands in Fig. 2. This figure shows that the effective thermal conductivity of fine silica sand is lower by about 7 percent than that of Ottawa sand. One of the most important geometrical paramenters is the particle shape. Ottawa sand has a round shape while Masonry sand has a relatively angular shape. The measured results for Masonry sand are also shown in Fig. 2. Even though the range of volume fraction of sand particles is different for the two sands, the effective thermal conductivity of the dry, unbonded Masonry sand is about 20% higher than that of Ottawa sand at the same volume fraction of sand particles.

The effective thermal conductivities of the unbonded Ottawa sand and Masonry sand saturated with water were also measured and the results are shown in Fig. 3.

The difference between measured thermal conductivities of the two sands is about 5%. The thermal conductance between the sand particles is probably greater for the angular shaped particles because a greater compaction force must be applied to obtain the same volume fraction of sand particles. The influence of the increased conductance between the sand particles due to increased angularity is very pronounced for the dry, unbonded sands, but it is much reduced for the sands saturated with water because the thermal conductivity of water is much greater than

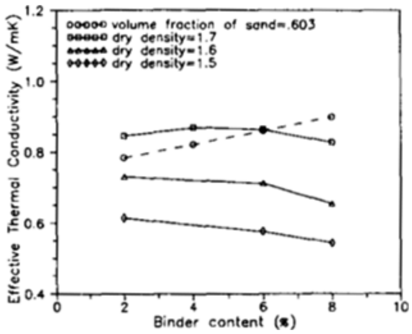

Fig. 4 Effect of binder content for Ottawa sand bonded with western bentonite

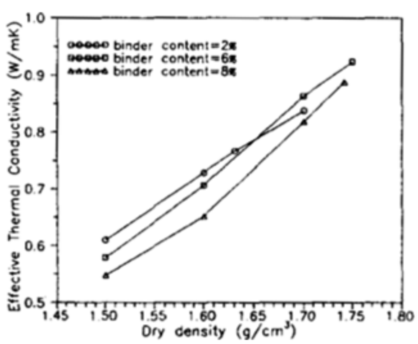

Fig. 5 Effect of dry density for Ottawa sand bonded with western bentonite

that of air.

3.2 Bonded molding sands

The effective thermal conductivity of dry, bonded molding sands depends upon the binder type and content, initial moisture content, dry density and temperature. Ottawa sand was selected because the thermal conductivity of the particle is known. Two different binder types were selected: western bentonite and southern bentonite. Western bentonite, also called Black-hills bentonite, swells upon wetting while southern bentonite, called Dixie Bond, is a non-swelling clay.

For room temperature measurements, the binder content was varied from 2 to 8 % by dry weight, the initial moisture content ranged from 3 to 6 % by weight, and the dry density ranged from 1.5 to 1.75 g/cm3.

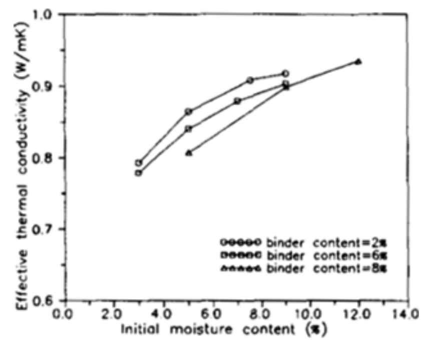

Fig. 6 Effect of initial moisture content for Ottawa sand bonded with western bentonite

The effect of binder content and volume fraction of sand particles on the effective thermal conductivity of Ottawa sand bonded with western bentonite is shown in Fig. 4.

The initial moisture content was maintained at 5%. Figure 4 show that, for a dry density of 1.7 g/cm^3, the effective thermal conductivity increases slowly up to a binder content equal to about 4% and decreases thereafter. The difference between the thermal conductivity curves for constant dry density and for constant volume fraction of sand particles indicates the effect of the replacement of sand particles by the bentonite binder.

The effective thermal conductivity of bonded molding sands increases rapidly and almostly linearly with increasing dry density as shown in Fig. 5.

The increase in the thermal conductivity with increasing dry density is attributed primarily to the resulting increase in volume fraction of sand particles. The contact area between sand particles also increases as the volume fraction of sand particles increases and the conduction through the interstitial binder film is increased. The effect of the dry density on the effective thermal conductivity is more pronounced than the effect of the binder content.

The effect of the initial moisture content is shown in Fig. 6 for a constant dry density.

The dry density of bonded Ottawa sand was 1.7g/cm^3. The effective thermal conductivity

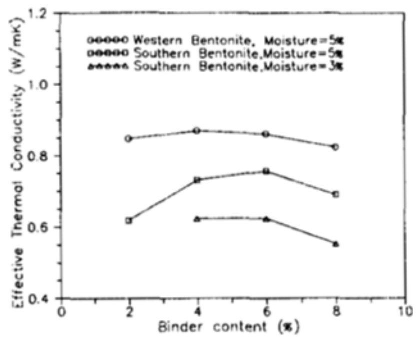

Fig. 7 Effect of binder content for bonded Ottawa sand

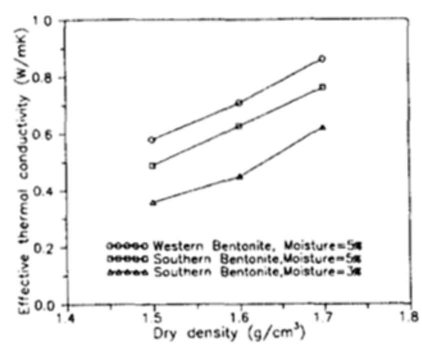

Fig. 8 Effect of dry density for bonded Ottawa sand

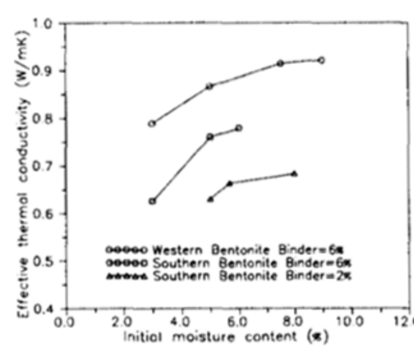

Fig. 9 Effect of initial moisture content for bonded Ottawa sand

increases most rapidly at low initial moisture contents, and the rate of increase is reduced at high initial moisture contents. As the moisture content is increased, the mixture of bentonite and water, called the total binder content, has greater plasticity and behaves more like a liquid binder. Thus, as the total clay content is increased, the fraction of bentonite clay which coalesces at the contact points between sand particles probably increases rapidly at low moisture content until a complete meniscus structure is formed at the sand particle contact points. Further increase in the moisture content only fills the pore spaces and the effect is probably small.

To investigate the effect of the binder type, the effective thermal conductivity of Ottawa sand bonded with southern bentonite was also measured and the measured results are shown in Fig. 7.

The dry density was maintained constant at 1.7 g/cm^3. The effective thermal conductivity of Ottawa sand bonded with western bentonite is greater than that of Ottawa sand bonded with southern bentonite. The effect of binder content is more pronounced for southern bentonite. The difference between the thermal conductivities of the sands bonded with these bentonite clays can be explained with the swelling characteristics of water and bentonite mixture. A mixture of western bentonite and water has greater plasticity and behaves more like a liquid binder. Therefore, more of the clay mixture will coalesce at contact points between sand particles and the contact area between sand particles is increased when western bentonite is used.

Figure 8 shows the variation of the effective thermal conductivity of bonded Ottawa sand with dry density. The binder content was maintained to be 6% by weight. The effective thermal conductivity of the sand bonded with southern bentonite increases fairly linearly with increasing dry density. A similar trend is observed for Ottawa sand bonded with western bentonite.

In Fig. 9, the variation with initial moisture content of the effective thermal conductivity of Ottawa sand bonded with western and southern bentonite is shown. The dry density was 1.7g/cm^3. This figure shows that the effective thermal conductivity of Ottawa sand bonded with southern bentonite increases with increasing initial moisture content. The effect of initial moisture content is greater for specimens having a higher binder content. The variations for both bentonite types are similar.

3.3 High temperature measurements

The effective thermal conductivities of dry, unbonded Ottawa sand, Olivine #70 sand and zircon sand were measured at temperatures up to 800℃ using the thermal conductivity probe method. The measured results are shown in Fig. 10.

The volume fractions of sand particles of Ottawa, olivine and zircon sands were maintained constant at 0.665, 0.597 and 0.682, respectively. The effective thermal conductivities increase with temperature because the thermal conductivity of air increases with temperature even though the thermal conductivity of sand particles may decrease (Godbee, 1963). This may indicate that the contribution of conduction heat transfer through the contact points between sand particles is greater for the unbonded sands. In addition, the radiation contribution may be significant at high temperatures above about 500℃. Figure 9 also shows that the effective thermal conductivity of Ottawa sand increase remarkably at a temperature of 600℃. This may be due to the rapid increase in the thermal expansion coefficient of silica sand particles within the rigid steel sample container.

The effective thermal conductivity of Ottawa sand bonded with bentonite clays was measured at temperatures up to 750℃ using the probe method and the hot-wire method. Each value measured by two different methods is shown in Fig. 11.

The dry density, binder content and initial moisture content were 1.7 g/cm^3, 6% and 5%, respectively. This figure shows that the values obtained by the two methods are in good agreement at or below 600℃. However, the values measured at 750℃ by the thermal conductivity probe method are scattered. The effective thermal conductivity of bonded Ottawa sand was found to decrease as temperature increased up to about 500℃. Thereafter it increased as temperature increased. This trend is the same as that reported in the literature by other investigators and is explained by Atterton (1953). The thermal conductivity of air increases with increasing temperature. But, at low temperatures below 500℃, the effective thermal conductivity decreases with increasing temperature because the thermal conductivity of silica sand particles decreases with temperature. This trend is quite different from that of unbonded sands. This may indicate that the effect of thermal conductivity of sand particles is greater for the bonded sands. At temperatures above 500℃, radiation heat transfer can become significant. Thus the effective thermal conductivity may increase rapidly because the radiant thermal conductivity of air in the pore spaces and of the sand grains are supposedly proportional to the cube of the absolute temperature. This figure also indicates that the effective thermal conductivity of Ottawa sand bonded with western bentonite is higher than that of Ottawa sand bonded with southern bentonite. The variations with tempera-

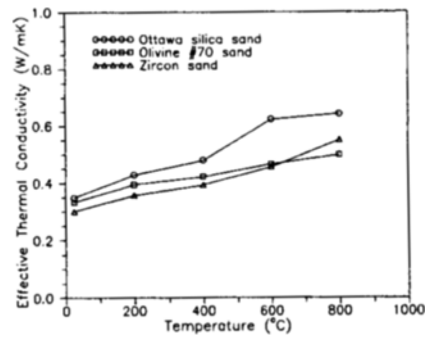

Fig. 10 Measured effective thermal conductivity of dry, unbonded sands at high temperatures

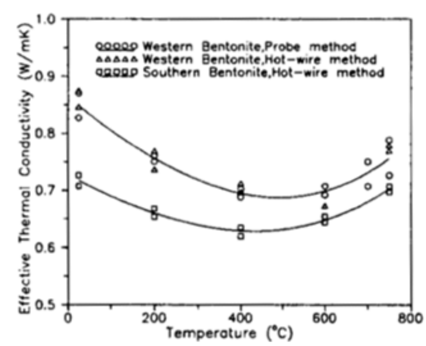

Fig. 11 Measured effective thermal conductivity of bonded Ottawa sand at high temperatures

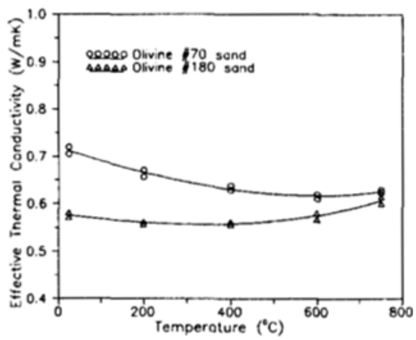

Fig. 12 Measured effective thermal conductivity of olivine sands bonded with western bentonite at high temperatures

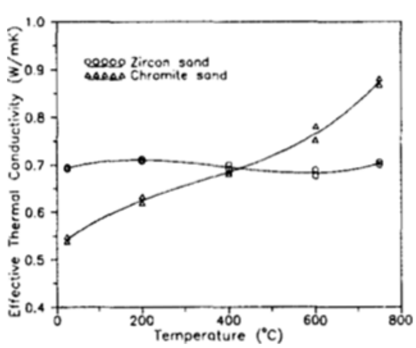

Fig. 13 Measured effective thermal conductivities of zircon and chromite sands bonded with western bentonite at high temperatures

ture of these two effective thermal conductivities are similar, but the effect of temperature is more significant for the sand bonded with western bentonite.

Figure 11 also shows the repeatability of the measurement methods at high temperatures. The repeatability of the thermal conductivity probe method on the same specimen is better than 1.0 percent at room temperature. However, data of the probe method is more scattered at high temperatures than those of hot-wire method. Thus the repeatability of the hot-wire measurements is better than that of the probe method, being better than about 5 percent.

The effective thermal conductivities of olivine sands bonded with western bentonite are shown in Fig. 12.

For olivine #70 sand, the dry density, binder content and initial moisture content were 1.9 g/cm^3, 6% and 5%, respectively. And for olivine #180 sand, the dry density, binder content and initial moisture content were 1.9 g/cm^3, 6% and 6%, respectively. For bonded olivine #180 and olivine #70 sands, the effective thermal conductivity decreases with temperature at low temperatures and then increases slightly again. The thermal conductivity of the olivine sand particles decreases with increasing temperature (Touloukian et al, 1970). The measurement shows that the effective thermal conductivity of the bonded olivine #180 sand is greater than that of the olivine #70 sand. This may be because the compaction force needs to be greater for the finer sand. Thus, the conduction through the binder film between sand particles is enhanced and the effect of binder content becomes more pronounced. However, for coarse sands, the effect of radiation may be more significant. Thus, the temperature at which the minimum effective thermal conductivity occurs will be shifted to a lower temperature for the coarser sands.

The effective thermal conductivity of zircon and chromite sands bonded with western bentonite was measured at temperatures up to 750℃, and the measured values are shown in Fig. 13.

For zircon sand, the dry density, binder content and initial moisture content were 2.8 g/cm^3 and 6% and 5%, respectively. The effective thermal conductivity of bonded zircon sand varies with temperature in a peculiar way. This can be explained by the effect of temperature on the conduction and radiation heat transfer through zircon molding sands. For pure zircon sand, the thermal conductivity increases slightly with temperature near room temperature (Touloukian et al, 1970). Thus, the effective thermal conductivity increases slightly with temperature up to about 200℃. At temperatures above 200℃, the effective thermal conductivity may decrease with temperature because of a decrease in the thermal conductivity of zircon sand particles. However, above 600℃, radiation becomes significant and the effective thermal conductivity of the bonded zircon sand increases.

For chromite sand, the dry density, binder content and initial moisture content, binder content, initial moisture content were 2.8 g/cm^3 and 4% and 4% respectively. The effective thermal conductivity of bonded chromite sand increases rapidly with increasing temperature, and the rate of increase is slightly higher at temperatures above 600℃. No data on the thermal conductivity of the chromite sand particle is available in the literlature, but Fig. 13 indicates that the particle thermal conductivity of the chromite sands probably increases with increasing temperature.

4. Conclusions

The following conclusions are drawn from the results of these investigations:

(1) For unbonded sands, the effective thermal conductivity increases with increasing volume fraction of sand particles. Also, the effect of the thermal conductivity of the saturated fluid is more pronounced when the ratio of the thermal conductivity of sand particles to that of the saturated fluid is increased.

(2) Western bentonite is more effective as a thermal binder than southern bentonite.

(3) The effect of dry density on the effective thermal conductivity of bentonite-bonded molding sands is more significant than the effect of either binder content or initial moisture content.

(4) The effective thermal conductivity of the unbonded sands tested in this study increases with temperature because of increase in the thermal conductivity of air.

(5) For bentonite-bonded silica sands, the effective thermal conductivity decreases with increasing temperature in the temperatures range below about 500℃. However, it increases above 500℃ because the thermal conductivity of air increases and the contribution of radiation becomes significant.

(6) Up to 750℃, the effective thermal conductivity of silica sand bonded with western bentonite is higher than that of silica sand bonded with southern bentonite, but the temperature dependence of the effective thermal conductivity of both is similar.

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