# Suction measurements by a fixed-matrix porous ceramic disc sensor

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ABSTRACT: This paper presents suction measurements of unsaturated geomaterials using a fixed-matrix porous ceramic disc water potential sensor. Suction measurements were carried out on a cement kiln dust and a sand at several water contents. The investigation showed that very high suctions up to about 100 MPa and very low suctions down to about 10 kPa can be measured using the water potential sensor. The suction equilibrium time for the materials studied was found to vary between a few hours to several days depending upon the magnitude of suction and type of materials. The measured suctions of the materials were compared with the total suction measurements by a chilled-mirror dew-point potentiameter. Differences between the test results from the two measurement devices were noted, particularly at high degree of saturation of the materials studied.

## 1 INTRODUCTION

Several devices are available currently to measure suction in unsaturated soils (Fredlund et al. 2012). Null-type axis-translation apparatus, tensiometers, and high suction probe are conventionally used for measuring matric suction. The matric suction of soils can also be measured indirectly by using the electrical conductivity sensor, the thermal conductivity sensor, and from the contact filter paper test. Measurement of soil suction at low water contents are usually carried out using devices that resort to the vapour phase equilibrium process (Leong et al. 2003). The total suction of soils can be measured by using psychrometers, relative humidity sensors, chilled-mirror dew-point potentiameter, and from the non-contact filter paper tests (Fredlund et al. 2012).

Various factors influence the selection of suction measurement devices that measure either matric or total suction (Tripathy et al. 2016), such as the suction equilibrium time, suction measurement range and accuracy, operating temperature, and resolution of the device. In situ measurement of suction is usually carried out by tensiometers that can measure suction up to about 100 kPa. Therefore, devices that facilitate measuring a large range of suction with reasonable accuracy and time are beneficial.

This paper presents suction measurements of unsaturated geomaterials with a capacitance-type water potential sensor that uses fixed-matrix porous ceramic discs. The measured suctions from the sensor were compared with the test results from a chilled-mirror dew-point potentiameter.

## 2 FIXED-MATRIX POROUS CERAMIC DISCS WATER POTENTIAL SENSOR

The water potential sensor (MPS-6) used in this study was from Decagon Devices Inc, Pullman, WA (METER Group 2017). The sensor currently known as TEROS 21 (Figure 1), uses two fixed-matrix porous ceramic discs (dielectrics) separated by a printed electric circuit board to form a capacitor.

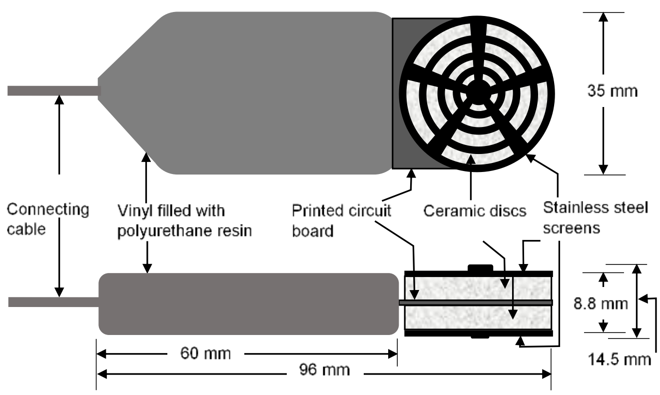


Figure 1. Details of the fixed-matrix porous ceramic disc sensor (from Tripathy et al. 2016).

The charging time of the capacitor is affected by the water content of the ceramic discs. When the sensor is brought in contact with a soil, the water content of the ceramic disc assembly changes. The suction of the soil and the ceramic discs tend to become equal with elapsed time. The sensor measures the water content of the ceramic discs. The water content of the ceramic discs is translated into matric suction based on a predetermined relationship between water content and matric suction of the fixed-matrix ceramic discs (Figure 2). At equilibrium, the suction of the ceramic disc and the soil are equal. The sensor can be connected to a data acquisition system to monitor and record the measured suction. The water retention characteristic of the fixed-matrix porous ceramic discs (Figure 2) is established based on the mercury intrusion porosimetry data (METER Group 2017). A thermistor is located underneath the sensor overmold (resin) that enables monitoring of temperature.

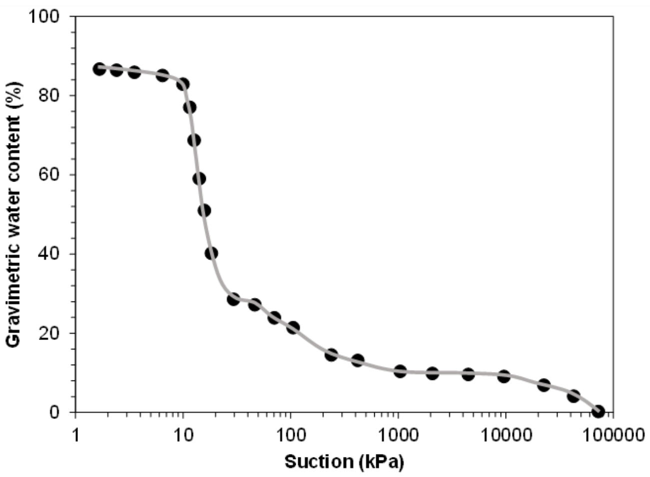


Figure 2. Water retention curve of the fixed-matrix porous ceramic discs in MPS6 sensors.

According to the manufacturer's specifications, the suction measurement range of the sensor is from 9 to 100,000 kPa with a resolution of 0.1 kPa. The lower suction limit of the sensor (i.e., 9 kPa) corresponds to the air entry value of the largest pores in the ceramic discs. The operating temperature of the sensor is between 0 and 60 °C. The accuracy of the sensor is ±(10 % of reading +2 kPa) for a suction range of 9–100 kPa. At high suctions, the accuracy of the sensor depends upon the water retention characteristic of the ceramic disc (Figure 2).

Tripathy et al. (2016) have reported suctions of MX80 bentonite and Speswhite kaolin measured by MPS-6 sensors. The study has shown that very high suctions up to about 10,000 kPa and very low suctions down to about 10 kPa can be measured using the sensor. The suction equilibrium time for the soils studied was found to vary between a couple of hours to several days depending upon the magnitude of suction and initial state of the sensor (i.e., wet or dry). The agreements between the test results from the sensor and the chilled-mirror dew-point potentiometer were found to be very good for Speswhite kaolin. Tripathy et al. (2017) stated that the moisture exchange between a dry sensor and a sample of MX80 bentonite caused shrinkage of the bentonite surrounding the sensor, whereas the exchange of moisture between a wet sensor and a dry bentonite samples created a low permeable zone. In both cases, a longer suction equilibrium time was noted.

The total suctions of soils can be measured by the chilled-mirror dew-point potentiameter. Following the works reported by Leong et al. (2003), the device has been used by several researchers to measure total suction of a variety of soils and polyethylene glycol solutions (Tripathy and Rees 2013). The current model of the potentiameter (WP4C) from Decagon devices Inc, Pullman, WA (METER Group 2017) possesses a suction range of 0.1 to 300 MPa. The accuracy of the potentiometer is ±0.05 MPa for a suction range of 0 to 5 MPa and 1% for a range of suction of 5 to 300 MPa. Suction measurements using the device can be made within a selectable temperature range of 5 to 40 °C.

## 3 MATERIALS AND METHODS

### 3.1 *Materials used*

Suction measurements were carried out on a cement kiln dust and a quartz sand. The cement kiln dust is a by-product material of the cement manufacturing process. Studies in the past have explored the suitability of this waste material in various civil engineering applications (Baghdadi et al. 1995). The cement kiln dust used in this investigation was supplied by a local cement company. The quartz sand was procured from an aggregate industry. The properties of the materials used are shown in Table 1.

Table 1. Properties of materials used.

| Properties | Cement kiln dust | Sand |
|---|---|---|
| Specific gravity | 2.72 | 2.65 |
| *Grain size distribution* | | |
| Sand (coarse, medium, fine) (%) | - | 1.4, 56.8, 41.3 |
| Silt-size (%) | 71 | 0.5 |
| Clay-size (%) | 29 | - |
| Coefficient of uniformity (-) | - | 2.17 |
| Coefficient of curvature (-) | | 1.16 |
| *Atterberg limits* | | |
| Liquid limit (%) | 41 | NP |
| Plasticity index (%) | 14 | NP |

The dominant minerals present in the cement kiln dust and sand were calcite and quartz, respectively. The quartz sand contained 0.5% of fine-size particles. The cement kiln dust contained $Ca^{2+}$ as the main cation with varying percentages of other cations, such as $K^{+}$, $Na^{+}$ and $Mg^{2+}$. The presence of ions in porous media is expected to generate osmotic suction, the magnitude of which may vary depending upon the amount of water present in the material.

The fixed-matrix porous ceramic disc water potential sensor is expected to measure matric suction provided that the ion concentration of the pore water in the material which is in contact with the sensor is equal that in the ceramic discs. Since the sand used in this study would not develop appreciable osmotic suction, both the chilled-mirror dew-point potentiamter and the fixed-matrix porous ceramic disc sensor were expected to provide similar results. Differences in the test results from the two devices for the cement kiln dust were anticipated and due to the osmotic suction of the material.

### 3.2 *Specimen preparation and testing details*

Predetermined quantities of deionised water were added to the materials for preparing homogenous mixtures at several selected water contents. The mixtures were then placed in sealed plastic bags and kept in airtight containers for 24 hours for moisture equilibrium to take place.

For suction measurements with fixed-matrix porous ceramic disc sensors, specimens of the cement kiln dust and sand were prepared in cylindrical plastic containers (volume of specimen container = 150 $cm^3$). A layer of the moist material was first laid at the base of a specimen container. A sensor was positioned at the centre of the base layer and the remaining amount of the material was packed surrounding the sensor. A tamping rod was used for compacting the mixture. The dry density of specimens of cement kiln dust was found to vary between 0.91 to 1.35 $Mg/m^3$. A better control of the dry density was achieved for the sand specimens. In this case, the dry density of the specimens was about 1.3 $Mg/m^3$. At the end of compaction process the sensor overmold (resin) remained half-buried within the specimens. Molten wax was used to cover the surface of the specimen for minimizing evaporation of water from the specimens. The specimen containers along with the sensors were placed in a thermocol box. The cables of the sensors were connected to a data acquisition system. The tests were terminated after more than about 4 days. After reaching the equilibrium condition (indicated by a steady suction value), the materials surrounding the ceramic discs were taken for measuring the final water contents.

The initial state of the fixed-matrix porous ceramic disc sensors prior to measuring suctions can be either wet or dry. The sensors can be submerged in water to attain a wet condition in which case the suction usually reads about 9 kPa. The sensors can be air-dried to read higher suctions of various magnitudes. The suction of a dry sensor may vary depending upon the duration of exposure to the ambient conditions. In this study, air dried sensors were used for measuring suction of the materials.

Suction measurements using the chilled-mirror dew-point potentiameter were carried out on statically compacted specimens of the materials. The dry density of specimens of cement kiln dust was found to vary between 0.74 and 1.41 $Mg/m^3$. For the sand, a majority of the specimens were compacted at two targeted dry densities, such as 1.30 and 1.50 $Mg/m^3$.

The chilled-mirror dew-point potentiameter tests on the sand were carried out in two series of tests. In one case unwashed sand was used, whereas in the other the sand was washed with water using a 0.063 mm sieve to remove the fine fractions. The prepared specimens were half-filled the sample cups. A thermal equilibration plate was used for temperature conditioning of the specimens prior to the tests. The measurements of suction using the device was carried out at a set temperature of 25 °C. The water contents of the specimens were measured after completion of the tests.

## 4 TEST RESULTS AND DISCUSSION

### 4.1 *Fixed-matrix porous ceramic disc water potential sensor test results*

Figures 3 and 4 show the elapsed time versus measured suction plots for cement kiln dust and sand specimens. For the specimens with higher water contents, the measured suctions decreased with an elapsed time prior to attaining an equilibrium, whereas for the specimens with low water contents, the measured suctions decreased, increased and further decreased before attaining an equilibrium.

The suction equilibrium time for the specimens with higher water contents was found to vary between 5 to less than about 24 h, whereas much higher equilibrium times were noted for specimens with low water contents (Figure 4), particularly for the sand specimens. A longer equilibrium time in case of the sand specimens is attributed to a lack of continuity of water phase between the specimens and the sensors.

Figure 5 shows the water content versus suction plots for the cement kiln dust and sand. It can be seen that the sensor was capable of making distinction between suctions of different materials. The lowest suction measured by the sensor was about 9 kPa, whereas the highest measured suction was about 100 MPa. The shapes of the water content – suction plots were found to be different which is expected due to the differences in the mineralogy, grain size, chemical properties, and pore size distribution of the geomaterials used.

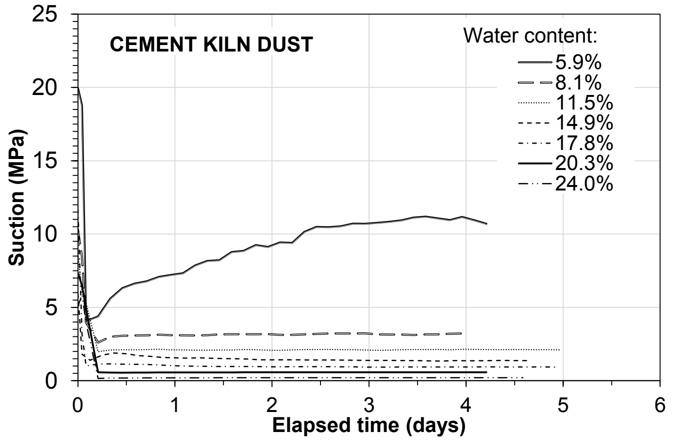


Figure 3. Measured suctions with elapsed time for cement kiln dust specimens using fixed-matrix ceramic disc water potential sensor.

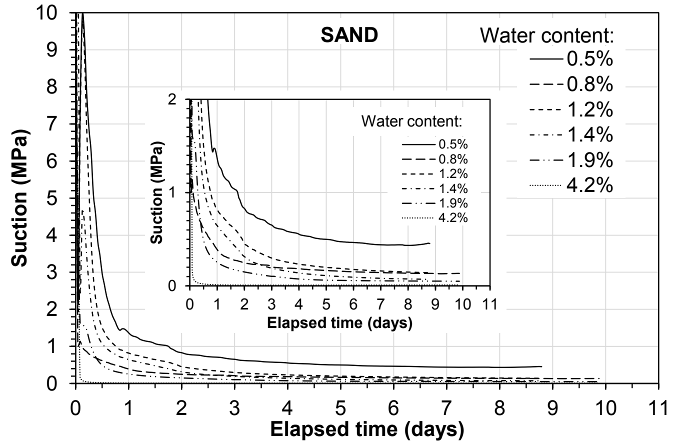


Figure 4. Measured suctions with elapsed time for sand specimens using fixed-matrix ceramic disc water potential sensor.

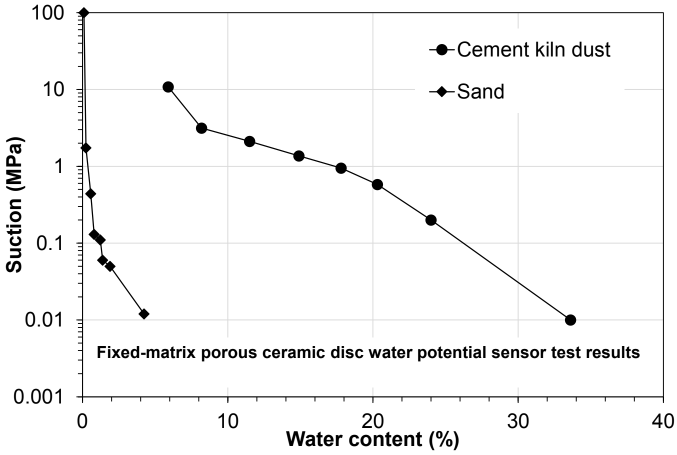


Figure 5. Suctions of the geomaterials measured by the fixed-matrix porous ceramic disc water potential sensor.

## 4.2 *Chilled-mirror dew-point potentiameter test results*

Figure 6 shows the suction measurement times required in the chilled-mirror dew-point potentiameter device for the specimens of cement kiln dust and sand. It can be noted that the measurement time increased dramatically as the water content of materials decreased. In general, the suction measurement time was less than about 15 minutes for most of the specimens of the cement kiln dust. The suction measurement time varied between 15 to about 65 minutes in case of the sand specimens.

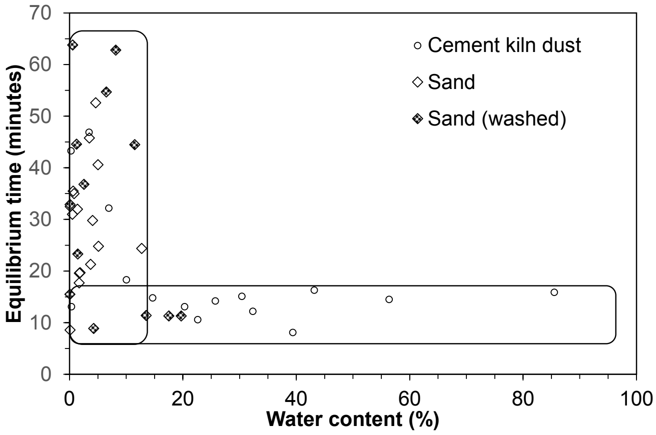


Figure 6. Suction measurement time in chilled-mirror dew-point potentiameter.

Figure 7 shows the total suctions measured by the chilled-mirror dew-point potentiameter for the specimens of cement kiln dust and sand. The test results for both unwashed and washed sand specimens at various water contents are shown in Fig. 7. The highest measured suction was about 200 MPa, whereas the lowest measured suction was about 10 kPa for the range of water content and type of materials considered in this study. Due to the limitation of the device to measure smaller values of suction, the measured suctions less than about 100 kPa may not be considered reliable. The washed sand specimens showed smaller magnitudes suction as compared to the unwashed sand specimens. At any water content, suction of the cement kiln dust was far greater than that of the sand.

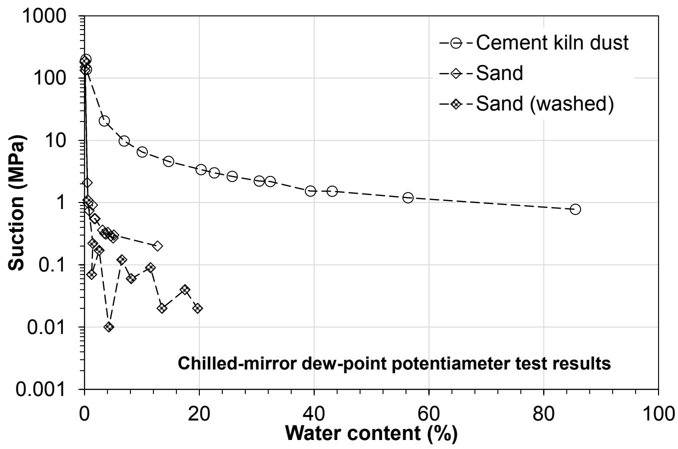


Figure 7. Total suctions of the geomaterials measured by the chilled-mirror dew-point potentiameter device.

## 4.3 *Comparisons of fixed-matrix porous ceramic disc sensor and chilled-mirror dew-point potentiameter test results*

Figures 8 and 9 show the water content versus suction plots based on the fixed-matrix porous ceramic disc water potential sensor and chilled-mirror dew-point potentiameter tests for cement kiln dust and sand, respectively. For the cement kiln dust (Figure 8), the total suction results from the chilled-mirror dew-point tests remained above that of the test results from the fixed-matrix porous ceramic disc sensor, particularly for the specimens with water content greater than about 5%. For the sand (Figure 9), suctions of unwashed sand clearly remained above that of the measured suctions from the fixed-matrix porous ceramic disc sensor. The agreements between the test results from both devices for the washed sand specimens was better at higher suctions. The differences in the suction results from both devices cannot be solely attributed to the osmotic suction. It is because differences in the test results from the two devices were also noted in case of the washed sand specimens that had insignificant osmotic suction. Considerations of the accuracies of the measuring devices did not eliminate the differences between suctions measured by the two devices.

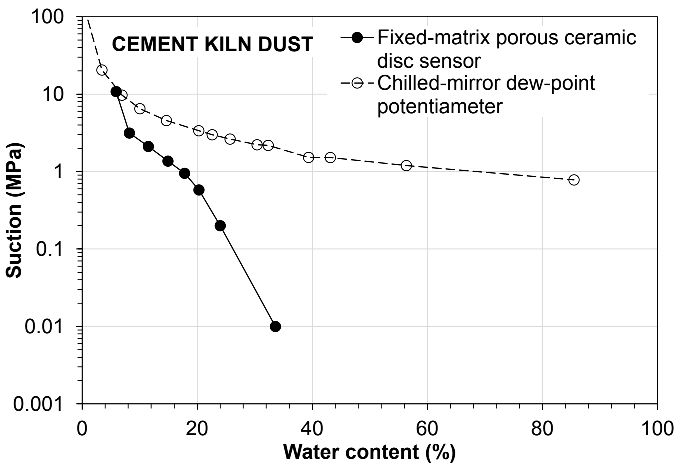


Figure 8. Comparison of water content – suction plots for cement kiln dust.

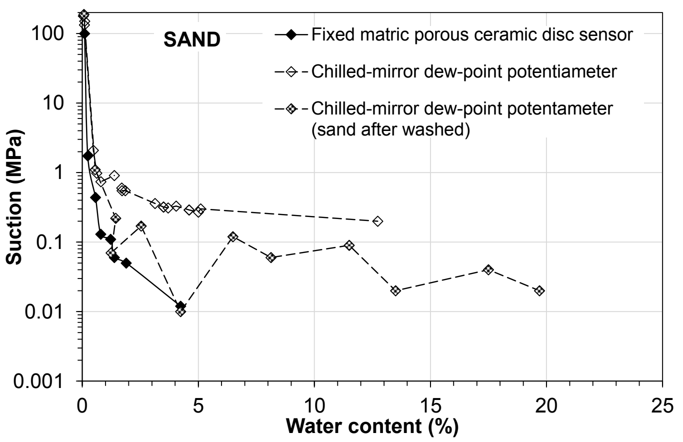


Figure 9. Comparison of water content – suction plots for sand.

Lins et al. (2004) and Tripathy et al. (2017) have reported the impact of initial compaction dry density on the suction – degree of saturation relationships of a sand and highly plastic clays, respectively. These studies have shown that a specimen with a lower initial dry density or a higher initial void ratio tends to exhibit a lower water content at given suction and a lower air entry value as compared to a specimen of the same material but with a higher dry density.

Figures 10 and 11 show the initial compaction conditions (water content and dry density) of the cement kiln dust and sand specimens. It can be seen that the chosen initial compaction conditions of the specimens for the cement kiln dust that were tested using the fixed-matrix porous ceramic disc sensors were such that the dry density increased with an increase in the water content. The dry density of the specimens for the tests with chilled-mirror dew-point potentiameter slightly increased and then decreased. Except for a few specimens, the dry density remained nearly constant at two different values (about 1.5 $Mg/m^3$ and 1.3 $Mg/m^3$) for the specimens of sand that were tested using the chilled-mirror dew-point potentiameter. The specimens of sand were tested at a near constant dry density of 1.3 $Mg/m^3$ using the fixed-matrix porous ceramic disc sensor.

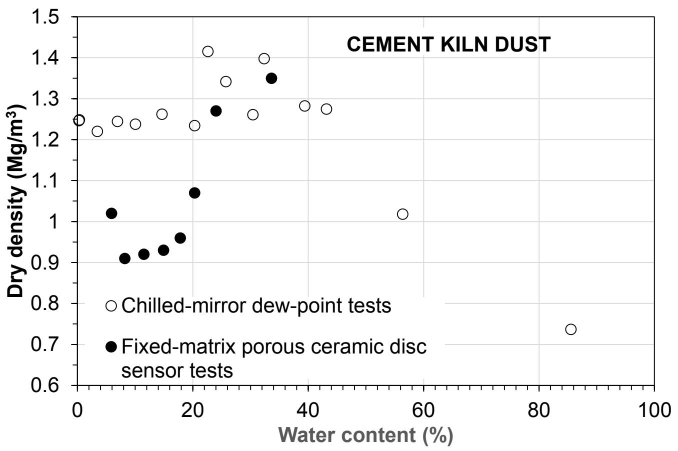


Figure 10. Chosen compaction conditions of the cement kiln dust specimens.

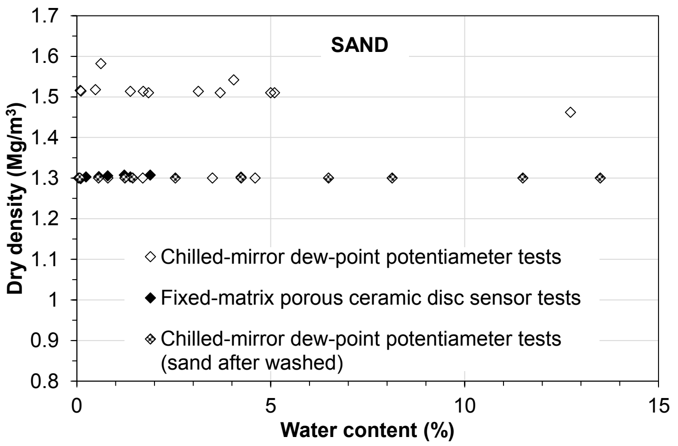


Figure 11. Chosen compaction conditions of the sand specimens.

Figures 12 and 13 show the suction – degree of saturation results of the two materials studied. For the cement kiln dust, the suction results correspond to a variable density of the material (Figures 10 and 12). For the sand, the results can be considered under two different dry densities (1.3 and 1.5 $Mg/m^3$) (Figures 11 and 13). The values of maximum degree of saturation for the cement kiln dust and sand were about 100% and 50%, respectively.

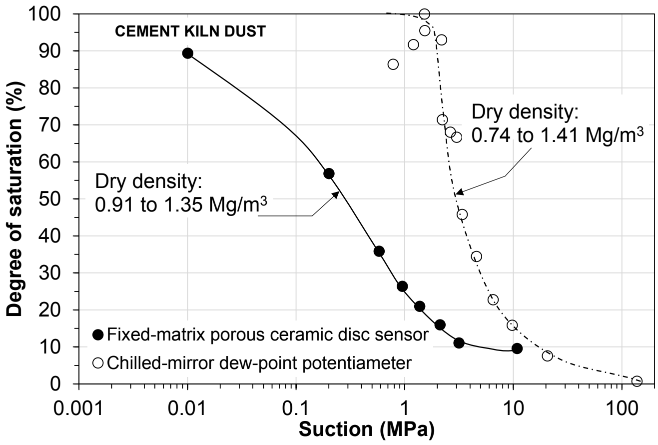


Figure 12. Suction – degree of saturation test results of the cement kiln dust used in this study.

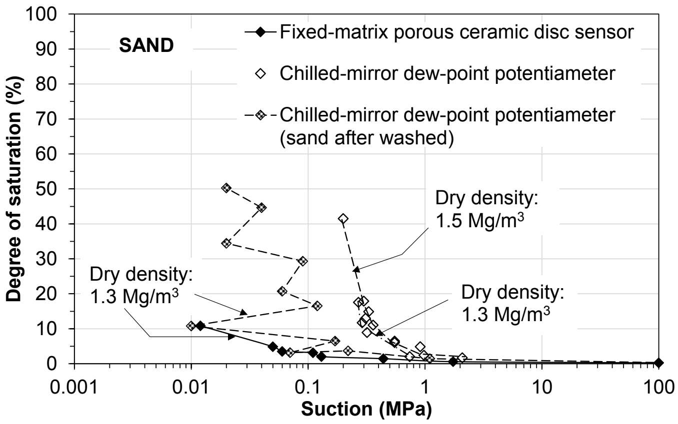


Figure 13. Suction – degree of saturation test results of the sand used in this study.

It can be seen in Figure 12 that differences between the test results from the two devices remained distinct for the cement kiln dust for a range of degree of saturation of 10 to 100%. For the sand (Figure 13), the suctions measured by the two devices were similar up to a suction of about 1.0 MPa; however, distinct differences were noted as the degree of saturation was greater than about 5%, particularly for the unwashed sand in which case the differences in suctions measured by the two devices were also noted for the specimens with the same dry density of 1.3 $Mg/m^3$. The test results indicated that the differences in suctions measured by the two devices may not be considered solely due to the compaction dry density effect. The agreements between the results from the two devices were better for the washed sand specimens.

The test results showed that a lack of good contact between the fixed-matrix porous ceramic disc sensors and the tested materials (as shown in this study by a longer suction equilibrium time), initial compaction dry density, fine fractions, accuracy of the sensor, and osmotic suction (specifically for the cement kiln dust) were some of the factors contributed to the differences between the test results from the two devices. The measured suctions by the sensors at higher water contents or higher degree of saturations of the materials were found to be generally lower than that measured by the chilled-mirror dew-point potentiameter.

## 5 CONCLUSIONS

Suction measurements were carried out on two materials (a cement kiln dust and a quartz sand) using a fixed-matrix porous ceramic disc water potential sensor. The test results were compared with the suctions measured using a chilled-mirror dew-point potentiameter. The ability of the water potential sensor to measure very high suctions up to 100 MPa clearly suggests its potential use in the field. Differences in the test results from the two devices were attributed to the combined influence of hydraulic contact issue, initial compaction dry density and osmotic suction.

## 6 ACKNOWLEDGEMENTS

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