Evaluation of geotechnical properties of fused quartz for transparent material

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ABSTRACT

Transparent soil surrogates permit nonintrusive three-dimensional deformational measurements in geotechnical model tests. Fused quartz saturated with a matched refractive index oil blend is an appropriate surrogate for natural sands. This paper carried out oedometer tests, consolidated drained (CD) triaxial tests and permeability tests on loose and dense oil-blend-saturated fused quartz. The geotechnical properties of compressibility, strength and permeability of the fused quartz were investigated experimentally and compared to those of natural sands and other transparent soil materials. An optimum transparency was obtained with a volume ratio of #15 white mineral oil and n-dodecane of 10:7.5 at room temperature. The dense fused quartz was less compressible with the coefficient of compressibility ($\alpha_{1-2}$) being 0.192 MPa$^{-1}$. The intrinsic permeability ranged from 18.7 to 31.5 darcys and the differences from the natural sands were ignorable. The peak friction angle ranged between 40.9 and 47.3°, which was within the typical range of sands. The test results show that fused quartz serves as an applicable surrogate in scaled model tests such as tunnel face stability experiments.

Keywords: fused quartz, transparent soils, compressibility coefficient, peak friction angle, intrinsic permeability

1 INTRODUCTION

Visualization of soil internal deformation can enhance the understanding and insight into such geotechnical engineering problems as foundation damage modes and tunnel face collapse mechanisms. The methods of radiography (X-ray), computerized tomography (CT), nuclear magnetic resonance (NMR), photogrammetry and interferometry have been extensively applied to three-dimensional measurements of soil deformation, strain and stress (Bergfelt 1956; Woods et al. 1974; Finno et al. 1997). Other methods of target tracking of embedded lead shots combined with X-ray analysis and embedded earth pressure cells provide spatial deformation and strain information inside the soil mass (Roscoe 1963; Shi et al. 1999). Nevertheless, tracking marks are intrusive, and only a few finite points can be provided. CT and NMR methods are highly costly and limited in the detection depth. Interferometry is sensitive to vibrations and is too complicated to apply in geotechnical engineering (Ng et al. 1996). These issues limit the applications in viewing internal deformations.

Transparent soil surrogates combined with technologies of digital image correlation (DIC) and particle image velocimetry (PIV) have been widely used in geotechnical model tests (Mannheimer et al. 1993; Iskander et al. 2002b). Transparent particle materials, including amorphous silica powders, silica gels, fused quartz and aquabeads, along with matched pore fluids, including mineral oils, paraffinic solvents and calcium bromide solutions, have been used in model tests to represent natural soils, such as clays, peats and sands (Iskander et al. 1994; Iskander et al. 2002a, 2002b). These materials were customized to present macrogeotechnical properties similar to or in the range of those representative of natural soils (Ezzein and Bathurst 2011; Liu and Iskander 2010; Fernandez et al. 2011). Geotechnical properties, including the dynamic responses of transparent materials, have been investigated experimentally in terms of strength, deformation and permeability (Sadik et al. 2002; Cao et al. 2011; Liu et al. 2013; Guzman and Iskander 2013; Kong et al. 2018a, 2018b). The aforementioned investigations prove that transparent materials serve as reasonable surrogates of natural clays and sands on the whole but not for specific types of soils. Additionally, amorphous silica powders and gels are characterized by high compressibility and low Young’s modulus values due to the double porosities of the interaggregate voids and inside-aggregate voids.
Fused quartz is a noncrystalline form of silicon dioxide and has a lower pore fluid porosity than that of amorphous silica gel (Iskander et al. 2015). Studies of the mechanical properties have shown that fused quartz particles saturated with oil blends (Ezzein and Bathurst 2011; Kong et al. 2013, 2014, 2016, 2017) and sucrose (Guzman and Iskander 2013, 2014) are especially applicable for modeling natural angular sands. However, the investigated fused quartz particles are within a certain narrow range of the particle size and are poorly graded or supplied by certain manufacturers. A comprehensive understanding of the properties of fused quartz covering sufficient particle sizes and different material supply resources is necessary prior to its wide application in physical modeling.

The objective of this paper is to present an investigation of the geotechnical properties of loose \((D_r=30\%)\) and dense \((D_r=76\%)\) fused quartz in aspects of strength, deformation and permeability. Conventional oedometer tests, triaxial tests and falling head permeability tests were conducted on oil blend-saturated loose and dense fused quartz. The test results were compared with those of natural sands in a wide range. The modeling capacities of fused quartz materials for use as transparent soil surrogates in scaled tunnel face stability analyses have been evaluated.

### 2 MATERIAL AND SAMPLE PREPARATION

Transparent soils are made by mixing transparent solid materials with matched refractive index pore fluids. The majority of the light sheet passes through the interface, and little of the light sheet is reflected, thus ensuring full light intrusion. The fused quartz surrogate is more suitable than amorphous silica gels (Ezzein and Bathurst 2011; Iskander 2018) and is used in this research. The crystals within the quartz are fused at a temperature of 2000 °C and gather together. The particle material is nonporous, hard and chemically resistant (Ezzein and Bathurst 2011). The particles are angular with sizes ranging from 0.2 to 1.0 mm. The chemical components of the fused quartz materials are summarized in Table 1.

Two pore fluids that are commonly used in transparent soils are oil blends and calcium bromide brines. Calcium bromide is hygroscopic and toxic. The exact concentrations of the solutions are difficult to obtain, thus resulting in mismatched refractive indices. The pore fluid used in this research is a blend of #15 white mineral oil and n-dodecane. The oil blend is chemically stable. The volume ratio or mass ratio can be attained to match the refractive index with that of the fused quartz by mixing two fluids at room temperature.

The temperature was kept at 25 °C during the experiments to eliminate its influence on the refractive indices of the pore fluids (Siemens et al. 2015; Black and Tatari 2015). The refractive index of the fused quartz particles supplied by the manufacturer equals 1.45. The refractive indices of the #15 white mineral oil and n-dodecane are 1.481 and 1.419, respectively, which are measured using an Abbe refractometer. A particular volume ratio (or mass ratio) is necessary to obtain to match the refractive index with that of the fused quartz particles. The #15 white mineral oil and n-dodecane with volume ratios of 10:6, 10:7, 10:7.5, 10:8 and 10:9 were selected and then mixed thoroughly. The mixture was poured into beakers and fused quartz particles were immersed. The whole mixture was stirred with a glass rod to release the entrapped air bubbles inside. The vacuum method was optional. Half an hour was needed for the solid particles and oil blend mixtures to become transparent for visual inspection.

The transparency was first qualitatively evaluated visually. A quantitative method was proposed by Ni et al. (2010). A test paper was made by printing “Transparent soils” with different font sizes ranging from 5 to 36 points. The test paper was placed under the beakers and viewed vertically. The minimum font size that was readable was recorded for each volume ratio solid mixture. The minimum readable font size is 9 points when the volume ratio is 10:7.5. The optimum transparency was obtained with a thickness of 12 cm, both qualitatively and quantitatively.

### Table 1. Chemical components of the fused quartz samples.

| Element | Al  | Ca  | Fe  | K   | Mg  | Na  |
|---------|-----|-----|-----|-----|-----|-----|
| Contents (mg/kg) | 19.06 | 3.01 | 0.83 | 0.21 | 0.24 | 1.08 |

### Table 2. Parameters of compressibility of the fused quartz.

| Type                | \(\alpha_{1-2}\) (MPa\(^{-1}\)) | \(C_c\) (MPa) | \(E_c\) (MPa) | \(E_c\) (MPa) |
|---------------------|-------------------------------|--------------|-------------|--------------|
| Dense fused quartz  | 0.082                         | 20.9         | 115.4       |              |
| Loose fused quartz  | 0.192                         | 9.45         | 42.8        |              |

### 3 RESULTS AND DISCUSSIONS

#### 3.1 Physical properties

The specific gravity of the selected fused quartz is 2.20, which is approximately 83 % of that of natural sands (2.65). The maximum and minimum dry bulk densities were measured as 1.32 g/cm\(^3\) and 1.144 g/cm\(^3\), respectively. The saturated bulk density is 1.624 g/cm\(^3\) for the #15 white mineral oil and n-dodecane blend with a volume ratio of 10:7.5. The dry bulk density is 1.274 g/cm\(^3\). Accordingly, the relative density under natural conditions is 76 % with the void ratio of 0.73. Loose and dense sands with relative densities of 30 % and 76 %, respectively, were chosen for the investigation.

The particle size distribution is shown in Fig. 1. The mean grain size \((D_{50})\), uniformity coefficient and curvature coefficient are 0.39 mm, 1.58 and 0.92, respectively. The fused quartz is poorly graded coarse sand.
3.2 Compressibility

One-dimensional consolidation tests were conducted on specimens of oil blend-saturated loose and dense fused quartz. The typical $e$-$\log p$ curves and $\varepsilon$-$\log p$ curves are shown in Fig. 2. The void ratio of fused quartz decreases nonlinearly before 50 kPa and linearly after 50 kPa with increasing vertical pressure and increases nearly linearly with decreasing vertical pressure. The dense fused quartz is more compressible than the loose fused quartz. The coefficient of compressibility ($\alpha_{1-2}$), compressibility index ($C_c$), and moduli of compressibility ($E_s$) and rebound ($E_c$) are shown in Table 2. The natural fused quartz ($D_r=76\%$) is low compressible.

The compressibility of the fused quartz is compared to those of natural sands (Lambe 1969), silica gel (Iskander et al. 2002a), sucrose-saturated fused quartz (Guzman and Iskander 2013) and mineral oil-saturated fine quartz (Ezzein and Bathurst 2011) in Fig. 3. The observed compression behaviour is consistent with that of angular calcareous sand and stiffer than that of the sucrose-saturated fused quartz. Silica gel aggregate microparticles on the order of 0.02 µm exhibit a high apparent void ratio due to the voids inside the solid aggregations. Fused quartz is noncrystalline quartz and is more favourable than silica gel for simulating sands with respect to the consolidation properties.

3.3 Shear strength

Normally consolidated drained (CD) triaxial tests were carried out on oil blend-saturated loose and dense fused quartz. Consolidation pressures of 50 kPa, 100 kPa, 150 kPa and 200 kPa were selected. Deviatoric stress was applied with a strain rate of 0.5 %/min to allow for full drainage. The stress-strain relations of the fused quartz under shear are shown in Fig. 4 (a) and (b). The peak strength increases with increasing confining pressure from 50 to 200 kPa. The peak pressure appears at high strains, being approximately 9-12 % for the loose samples and experiences a small drop afterwards. The stress increases sharply and reaches a peak pressure at low strains of approximately 3-5 % for the dense samples. Strain softening is more evident for the dense samples than for the loose samples. The residual strength tends to be the same for the loose and dense samples at the same confining pressure. These
observations show that the stress-strain relations of fused quartz agree well with the typical behaviors of natural sands. The typical Mohr-Coulomb peak strength envelopes are presented in Fig. 5 (a) and (b). The peak friction angles are $40.9^\circ$ and $47.3^\circ$, respectively, assuming no cohesion, which are larger than those under direct shear tests. The curvatures of the envelopes decrease as the confining pressure increases. This behavior is especially evident for the dense samples. The curvature begins at approximately 200 kPa, similar to silica gel (Guzman et al. 2014). Similar results are found for natural sands (Lee and Seed 1967).

A summary of the friction angles of transparent glass sand, silica gel and fused quartz under CD triaxial tests is presented in Fig. 6. The friction angles of the samples are larger than those of loose, medium and dense silica gel and glass sand. These findings may be caused by the drainage conditions and the chemical components of both materials. Fused quartz possesses a higher elasticity modulus than silica gel. The friction angles of the samples are generally smaller than that of the fused quartz according to Ivan (2014) but consistent with those of oil blend FQ-1 (Ivan et al. 2014). This discrepancy is attributed to the pore fluid type. Kong et al. (2018b) concluded that fused quartz mixed with an oil blend has the highest similarity to natural sands.

### 3.4 Hydraulic conductivity

Falling head permeability tests were conducted with samples permeated with oil blends. Hydraulic conductivities of $5.5 \times 10^{-3}$ cm/s and $3.3 \times 10^{-3}$ cm/s were measured for fused quartz with 30% and 76% relative densities, respectively, corresponding to intrinsic permeabilities of 31.5 darcys and 18.7 darcys, respectively.

Natural soils with intrinsic permeabilities on this order exhibit hydraulic conductivities to water of $3.4 \times 10^{-2}$ cm/s and $2.1 \times 10^{-2}$ cm/s, which are within the typical range of sands of $1.0 \times 10^{-3}$-$10^{-1}$ cm/s. Similar results have been reported as $1.09 \times 10^{-3}$ and $0.68 \times 10^{-4}$ cm/s for mineral oil-saturated fused quartz by Ezzein and Bathurst (2011), respectively, $(1.3-2.1) \times 10^{-3}$ cm/s for aqueous-saturated loose and dense fused quartz by Guzman et al. (2013, 2014), $2 \times 10^{-5}$-$7 \times 10^{-2}$ cm/s for aquabeads saturated with water (Fernandez et al. 2011) and $(0.242-4.66) \times 10^{-3}$ cm/s, $(1.05-17.5) \times 10^{-3}$ cm/s and $(1.93-73.3) \times 10^{-3}$ cm/s for sucrose-, mineral oil- and calcium bromide brine-saturated fused quartz, respectively, by Kong et al. (2017). Some of the results are summarized in Fig. 7. The measured intrinsic permeability was close to that of saturated fused quartz (Ezzein and Bathurst 2011; Guzman and Iskander 2013; Kong et al. 2017; Guzman et al. 2014). The hydraulic conductivity is related to the pore structure of a soil. Silica gel is a porous interaggregation, while fused quartz is solid.

Transparent soils have established their utility as useful tools for physical modeling over the past 25 years (Iskander 2018). Fused quartz is silicate sand and its chemical components are similar to those of natural sands. The geotechnical properties presented in this investigation show that fused quartz is suitable for representing natural sands and serves as an applicable surrogate in scaled model tests over silica gel.

### 4 CONCLUSIONS

The use of transparent soils and digital image correlation (DIC) permits measurements of the deformation of soils and flows of liquids spatially and nonintrusively. Small-scaled model tests, including pull-out tests of piles, pile penetration tests, soil-foundation interaction tests and tunnel face stability tests have been conducted. A necessary precondition of the tests is that the properties of the transparent soil materials are consistent with those of natural soils.

This paper introduces an oil blend-saturated fused quartz material. The geotechnical properties of compressibility, strength and permeability have been explored experimentally and compared widely with those of the available silica gel, water-saturated and sucrose-saturated fused quartz and natural sands. A perfect transparency was obtained with a thickness of 12 cm. The oil blend-fused quartz is less compressible than untreated quartz. The peak friction angles and hydraulic conductivities agree well with those of natural sands compared with silica gel and sucrose-saturated fused quartz. The measured intrinsic permeability is within the typical range of sands.

The coarseness, relative density and shapes of the solid materials have considerable influence on the geotechnical properties of oil blend-fused quartz. The percent decrease of the coefficient of compressibility due to relative densities was within an order of amplitude. The differences of permeability from the natural sands and silica gels can be ignorable. The strength parameter of friction angles are generally within the typical range from 30 to 45 degrees of natural sands. The geotechnical properties of angular particles combined with other sizes distributions are needed for further investigation.

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Fig. 4. Influence of the confining pressure on the stress-strain response of the fused quartz: (a) Dr=30 % and (b) Dr=76 %.

Fig. 5. Typical Mohr-Coulomb envelope of the fused quartz: (a) Dr=30 % and (b) Dr=76 %.

Fig. 6. Summary of the friction angles under CD triaxial tests (*, oil blend-saturated fine silica gel (0.5-1.5 mm, angular particles); **, ***, **** and ***** , sucrose-saturated, oil blend-saturated, water-saturated fused quartz and glass sand, respectively; Med. dense, Medium density).

Fig. 7. Summary of the intrinsic permeabilities of different transparent soils (*, in this paper).

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