Transparent fused silica to model natural sand

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ABSTRACT

This paper presents an experimental investigation on geotechnical properties of fused silica. Fused silica, a typical glass calcined by high-temperature, is similar to the amorphous silica used in making transparent soil. However, amorphous silica exhibits a high compressibility and a high secondary consolidation due to its two-pore system similar to that of peat or organic clay. Instead of a two-pore system in amorphous silica, fused silica has only one-pore system similar to that of natural sand and clay. The gain sizes of fused silica used in this study range from 0.1 mm to 2 mm. The geotechnical properties including gradation, compressibility, and both statics and dynamics shear strength of this fused silica are investigated through laboratory testing. The results show that fused silica and natural sand have similar behavior, especially for stress-strain behavior. Fused silica can be used to model natural sand under a low confining pressure condition. An appreciable breakage is noticed in fused silica once the confining stress exceeds 300 kPa. In general, fused silica will provide a better modeling capacity than amorphous silica.

RÉSUMÉ

Ce document présente une recherche expérimentale sur les propriétés géotechniques de la silice fondue. La silice fondue, un verre typique calciné par température, est semblable à la silice amorphe utilisée en faisant le sol transparent. Cependant, la silice amorphe montre une compressibilité élevée et une consolidation secondaire élevée dues à son système de deux-pore semblable à celui de la tourbe ou de l'argile organique. Au lieu d'un système de deux-pore en silice amorphe, la silice fondue a seulement le système d'un-pore semblable à celui du sable et de l'argile normaux. Les tailles de gain de la silice fondue utilisée dans cette gamme d'étude de 0.1 millimètre à 2 millimètres. Les propriétés géotechniques de cette silice fondue comprenant la gradation, compressibilité, et statique et résistance au cisaillement de dynamique sont étudiées par l'essai en laboratoire. Les résultats prouvent que la silice fondue et le sable normal ont le comportement semblable, particulièrement pour le comportement de contrainte-tension. La silice fondue peut être employée pour modeler le sable normal dans une basse condition de emprisonnement de pression. Une rupture appréciable est notée en silice fondue une fois que l'effort de emprisonnement dépasse le kPa 300. La silice généralement fondue fournira une meilleure capacité de modélisation que la silice amorphe.

1 INTRODUCTION

Conventional methods using embedded sensors cannot reveal continuously internal and spatial deformation and flow conditions inside natural soil. In order to avoid these limitations, transparent materials have been used with non-intrusive optical visualization techniques in geotechnical engineering research.

Iskander et al. (1994; 2002; 2003) investigated amorphous silica powder and gel for modeling clay and sand, respectively. Both kinds of amorphous silica have shown the similar properties as those of natural soil. Transparent soils made of amorphous silica have been used by many other researchers in geotechnical model tests. For example, amorphous silica powder has been used to study flow of contaminants into perforated wick drains (Welker 1999) and pile penetration in clays (Gill 1999). Sadek et al. (2003) used amorphous silica gel to study soil deformation beneath a

continuous footing in a small-scale model test and Liu (2003) studied 3-D deformation field inside a layered transparent soil model. However, amorphous silicas exhibit a high compressibility and a high secondary consolidation due to its two-pore system similar to that of peat or organic clay (Liu et al. 2003). Instead of a two-pore system in amorphous silica, fused silica which has only one-pore system similar to that of natural soils is chosen in the present work. Research on similar materials or existing amorphous silica has been investigated by other researchers (Zhao and Ge 2007; Ezzein and Bathurst 2011).

The paper presents a series of laboratory tests carried out on fused silica to systematically investigate geotechnical properties of this new material for modeling sand.

2 GEOTECHNICAL PROPERTIES OF FUSED SILICA

Fused silica is a typical glass calcined by high-temperature that has excellent thermal stability and low thermal conductivity with excellent optical qualities and exceptional transmission over a wide spectral range. More than 99.9% of fused silica is SiO_2 with little CaO and other trace elements. Fused silica is available in a number of grades for different applications. It has high purity and stable chemical properties. Its appearance is colorless.

Fused silica used in this study is angular in shape, manufactured by Jiangsu Kaida Silica Co. LTD in China. Its size ranges from 0.1 mm to 2.0 mm, as shown in Figure 1. The specific gravity is 2.21. Mohs hardness is about 7.0, and PH is about 6.0. The refractive index of fused silica varies from 1.55 to 1.40 through the transmission range 0.16 μm to 3 μm. These features are extremely similar to natural sand, which make fused silica an appropriate material to model natural sand.

Two relative densities were selected for detailed investigation, referred to as loose and dense conditions. Fused silica is classified using the Unified Soil Classification System as SP, poorly graded sand with the uniformity coefficient C_u=2.18 and the coefficient of gradation C_c=0.85.

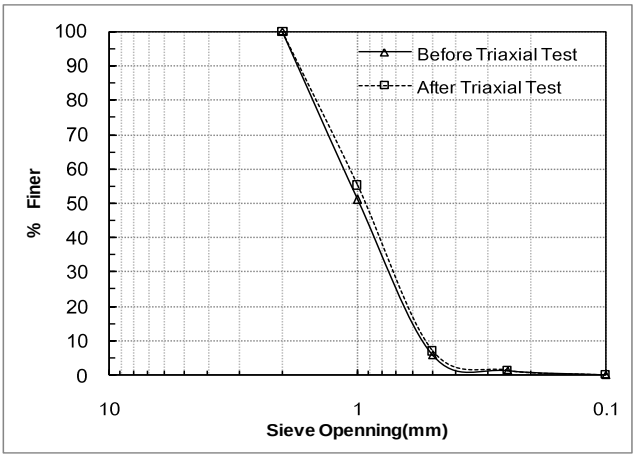

Figure 1. Grain size distribution of tested fused silica

3 GEOTECHNICAL PROPERTIES OF FUSED SILICA

3.1 Static Triaxial Tests

3.1.1 Testing Program and Sample Preparation

Consolidation undrained triaxial compression tests were performed on saturated fused silica under both dense and loose conditions with the relative densities of 70% and 30%, respectively. A strain controlled traxial apparatus was used in this study. For the dense specimens, the samples were compacted in three layers using a hammer falling vertically while the loose specimen was prepared by pulverization without compaction. All samples were 39 mm in diameter and 80 mm in height with saturation degree more than 95%. For each sample, the confining pressure varied from 100 kPa to 400 kPa. All tests were performed at a shearing rate of 0.5 mm/min. Samples of natural sand with the same grain size distribution were also tested under the same conditions.

3.1.2 Static Triaxial Test Result Analyses

Typical stress-strain curves are shown in Figure 2 compared with those stress-strain curves of natural sands with the same gradation condition in Figure 3. Fused silica has higher shearing strength and higher modulus than natural sand. In general, the stress-strain behavior of fused silica is similar to that of natural sand. For fused silica, the deviatoric stress

increases with the increasing confining pressure. It is as expected that the shear strength of the dense fused silica samples is higher than those of loose samples. Under the same confining pressure, the changing process of the deviatoric stress can be divided into two stages apparently; at the beginning the deviatoric stress increases sharply till a peak strength after which it decreases slowly, especially for the dense fused silica sample. That means the dense fused silica sample exhibit typical strain softening behavior, particularly at high confining pressures. The peak strength was reached at a higher strain than normally expected for dense sand, mainly due to smooth surface, nonabsrobency and inner structure of the fused silica. The appreciable breakage of the fused silica particles also is an important factor that should not be ignored; the breakage of grains can be shown in Figure 1 under a confining pressure of 300 kPa for dense specimens. With increasing confining pressure, the differences of the stress-strain behavior become large, especially when the confining pressure exceeds 300kPa.

3.2 Compressibility Tests

Compressibility tests were performed in the oedometer on both dense and loose dry fused silica. The results of those tests are compared with the date from Iskander & Liu (2003) for dry amorphous silica, as shown in Figure 4. Fused silica is a little more compressible than natural sand, but less than amorphous silica. It is as expected that the dense sample is less compressible than the loose sample.

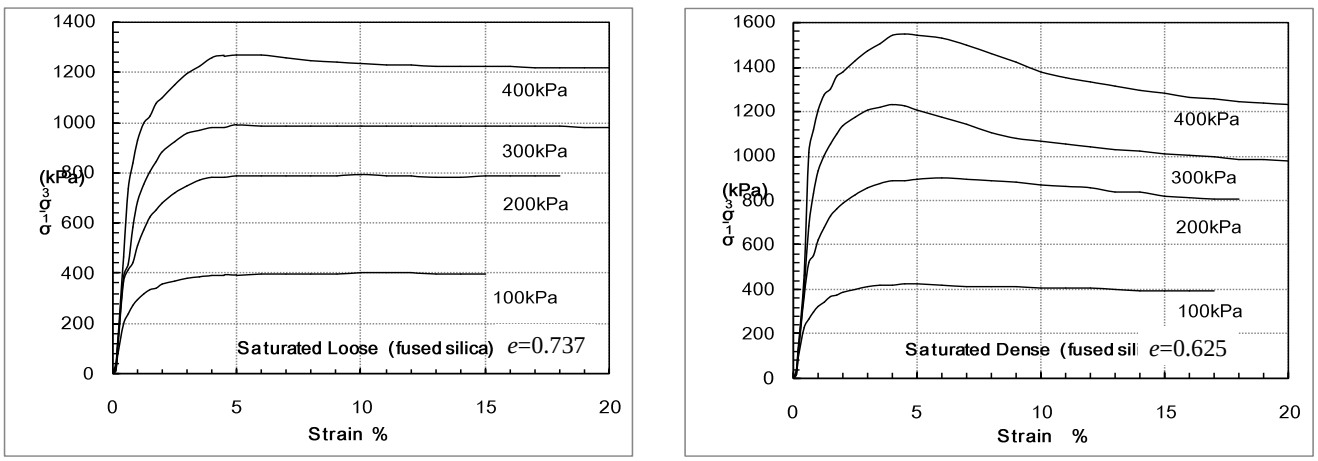

Figure 2. Typical stress-strain curves of fused silica from triaxial compression tests

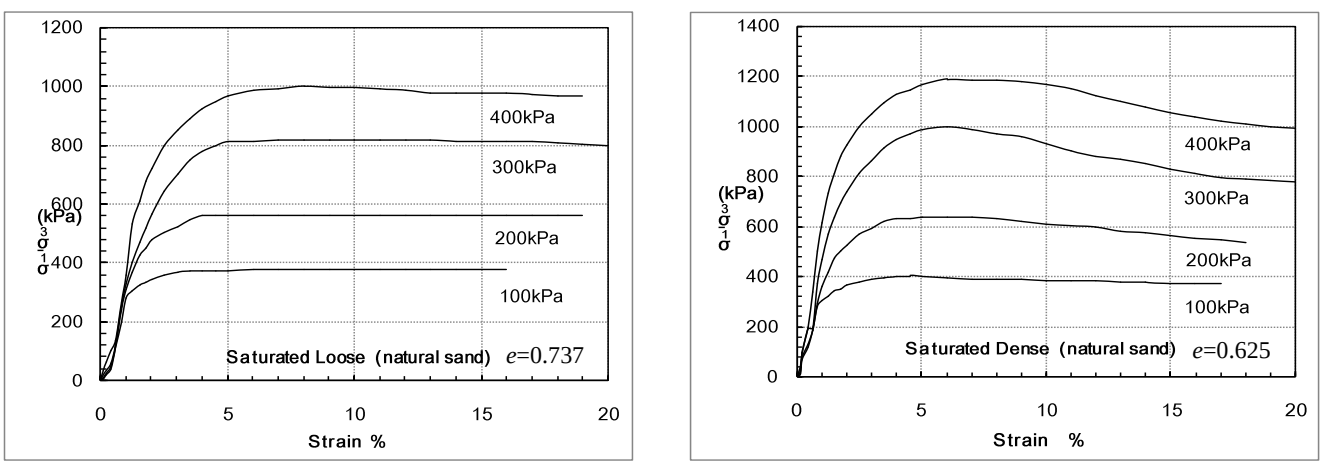

Figure 3. Typical stress-strain curves of natural sand from triaxial compression tests

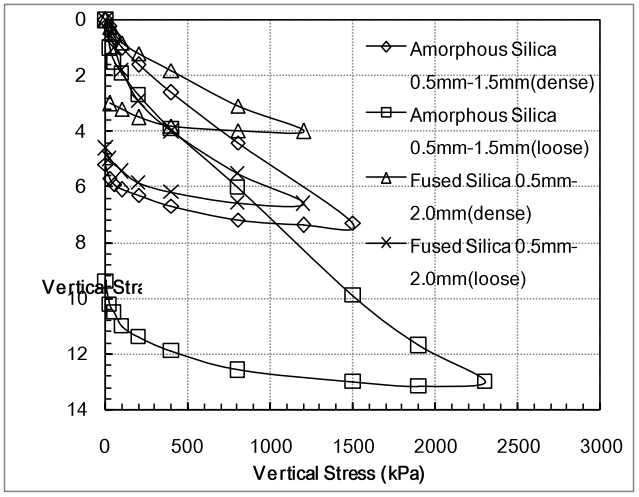

Figure 4. Compressibility of fused silica

Figure 5. Testing apparatus for dynamic triaxial testing

3.3 Dynamic Tests Results

3.3.1 Testing Program and Sample Preparation

A triaxial test apparatus was used in this research, as shown in Fig. 5. The dynamic modules and the damping ratio which are widely used in describing dynamic properties of natural soils are also used for fused silica. These two parameters are influenced by many factors; of which the effective stress level, void ratio and structure of soil are the main influencing factors. The effective stress level and void ratio were selected as the controlling factors in setting up this test program. The selected strain level ranged from 10^{-4} to 10^{0}. Fused silica samples at two different void ratios were selected representing the dense and loose state of fused silica in the current study. For each sample, the confining pressure varied from 50 kPa to 400 kPa. In preparing the dense specimen, the whole sample was evenly divided into five layers. Each layer was compacted by a miniature compactor. For the loose specimen, the whole sample was placed without compaction. The average sample diameter was 100 mm with an average height of 200 mm.

3.3.2 Dynamic Triaxial Test Results

Based on the hysteresis curves at a certain strain level, the damping ratio can be calculated as the ratio between the energy dissipated in one cycle of loading and the maximum strain energy stored during the cycle. The modulus were calculated with backbone curves obtained by the hysteresis circles at certain strain levels.

For both loose and dense samples, the dynamic elastic modulus of fused silica increases with an increase of confining pressure within this dynamic strain range, as shown in Figures 6. For each confining pressure, the dynamic elastic modulus decreases with the increase of the dynamic strain, especially in the range from 10^{-4} to10^{-3} where the dynamic elastic modulus decreases sharply. As expected, the dynamic elastic modulus of those dense samples is bigger than those of loose samples.

The damping ratio increases with decreasing confining pressure, as shown in Fig. 7. Under the same confining pressure, the damping ratio increases with increasing the dynamic strain. The damping ratio of dense specimens is smaller than those of loose specimens under the same conditions. Compared to natural sand, the relatively higher damping ratio are found in fused silica. It is believed that this may be caused mainly by material property, such as hardness, and compressibility and partially by the influence from testing equipments. The dynamic elastic modulus and damping ratio are both independent on the relative density and the confining pressure, as shown in Figs. 8 and 9, when the dynamic elastic modulus E is normalized by E_{max} (the reference elastic modulus defined at a strain magnitude of 10^{-5}) and the dynamic strain ε are normalized by ε_r (the reference strain is defined as σ_f/Emax). These dynamic

properties are similar to those of natural sand. But the E_{max} values of fused silica is higher than those of natural sand, as shown in Fig. 10. The phenomenon coincides with the results of the static triaxial tests. Compressibility and inner structure are the main reasons.

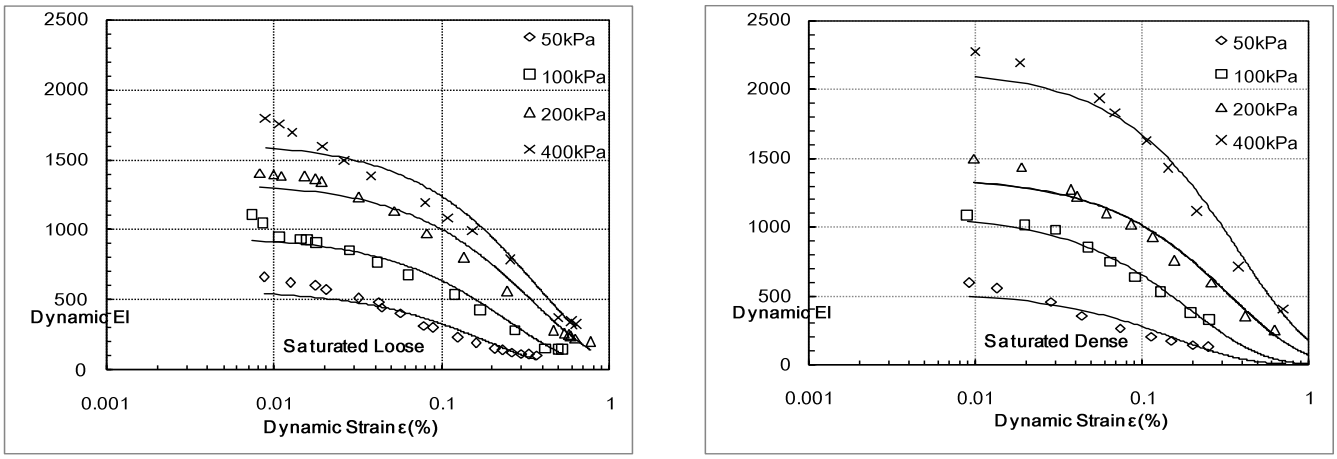

Figure 6. Relationship between dynamic elastic modulus and shear strain for fused silica

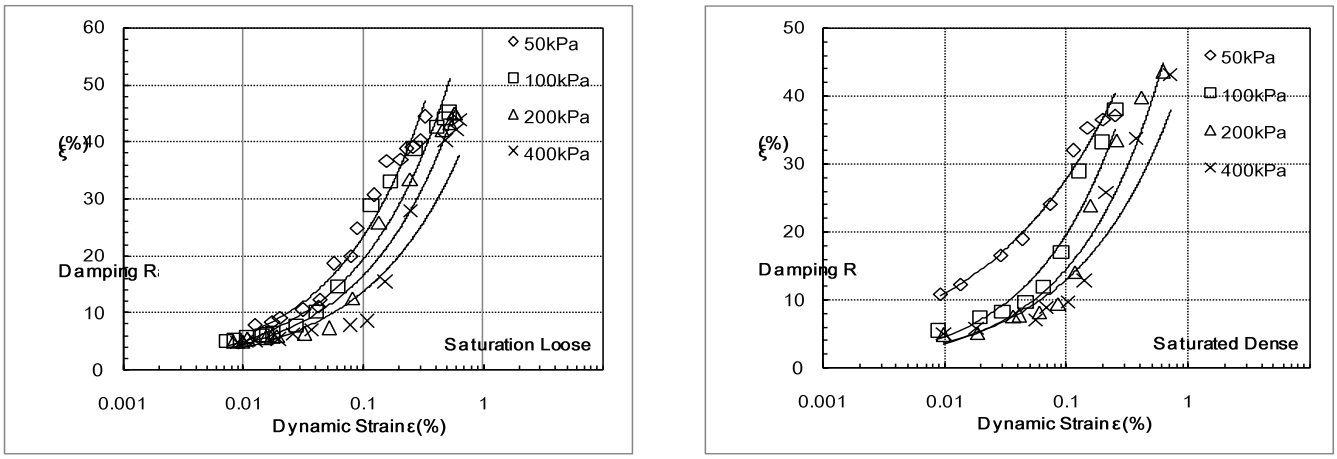

Figure 7. Relationship between damping ratio and shear strain for fused silica

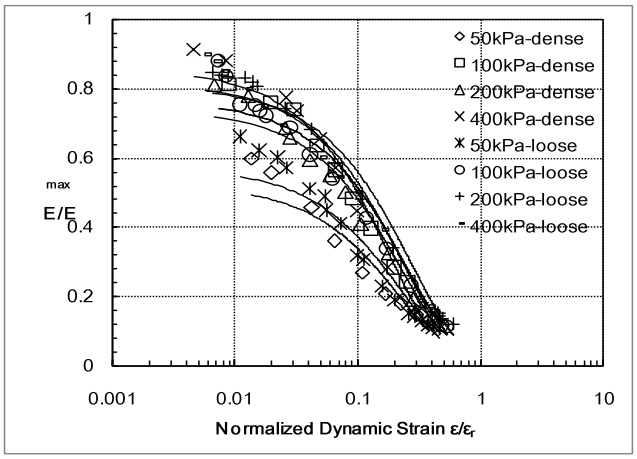

Figure 8. Normalized dynamic shear modulus vs shear strain

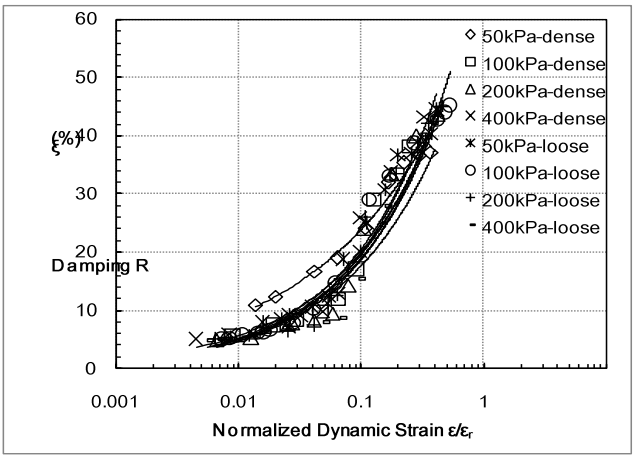

Figure 9. Damping ratio vs normalized shear strain

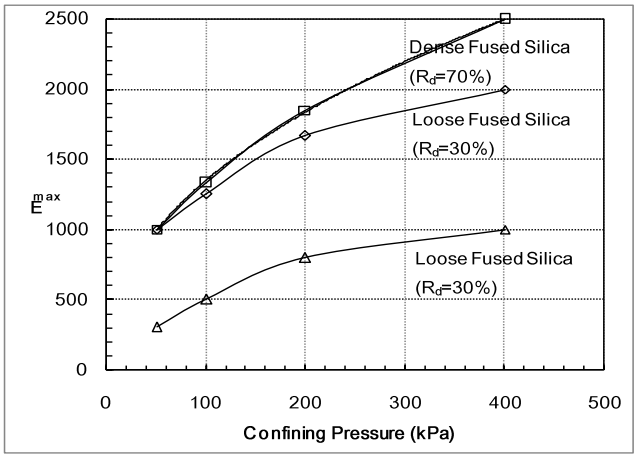

Figure 10. Modulus comparison between fused silica and sand

4 CONCLUSIONS

The geotechnical properties of fused silica are investigated through laboratory testing in this study. Fused silica exhibits physical properties extremely similar to natural sand in terms of strength and dynamic elastic modules and damping ratios. Fused silica is less compressible than amorphous silica and provides a good alternative to make transparent sand. The similar degradation of shear modulus during cyclic shearing also permits the use of fused silica for advanced dynamic problem modelling in geotechnical engineering research.

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