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## Mechanical Properties of Vitrified Soils

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American Society of Civil Engineers

# Fourth Materials Engineering Conference

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November 10 - 14, 1996 / Washington Hilton Hotel, Washington, D.C.

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ASCE's Materials Engineering Division, Fourth Materials Engineering Conference will be held in Washington, DC at the Washington Hilton on November 10-14, 1996. The following are some of the national organizations co-sponsoring this conference: NIST, Federal Highway Administration, U.S. Department of Interior, U.S. Corps of Engineers, Asphalt Institute, AISC, ACI and TRB as well as EMD and AED of ASCE.

The emphasis of the conference will be on creating materials and systems for an entirely new generation of safe and durable constructed facilities, thus enabling the nation to meet the rapidly changing demands of society and industry as we enter the 21st century. The conference will also focus on renewing our aging public works infrastructure through innovations in repair, rehabilitation, and retrofit technologies.

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- ◆ Corrosion Studies
- ◆ Testing and Mechanical Properties
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- ◆ Waterfront and Marine Structures
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- ◆ Field Applications
- ◆ Case Studies
- ◆ Research in Progress and Research Needs

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Ken Berg, Fibergrate Corp, Dallas, TX  
John E. Durrant, Philadelphia Materials Engineering Laboratory

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"Meeting the Challenges of the Twenty-First Century with New Materials": Ed Di Tomas, Turner Corp., New York, NY

"High Performance Metals for Civil and Marine Structures": John W. Fisher, R. Sause, and R.J. Dexter, Lehigh Univ., Bethlehem, PA

"Predicting the Performance of Materials of Construction": Geoffrey Frohnsdorff, NIST, Gaithersburg, MD

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## **Mechanical Properties of Vitrified Soils**

Christopher Y. Tuan<sup>1</sup>, and William C. Dass<sup>2</sup>

### **Abstract**

Recent advances in plasma arc technology have found many civil engineering applications, including in-situ soil vitrification (ISV). The ISV process transforms soils into homogeneous glass-like materials, which possess high compressive and tensile strengths (typically about 10 times those of unreinforced concrete), high leaching resistance, and are unaffected by wet-dry or freeze-thaw cycles. These vitrified earthen materials usually weigh about 2300 to 2500 kg per cubic meter. Potential ISV applications include slope stabilization, groundwater removal, subgrade stabilization, and simulated construction materials.

A 100-kW non-transferred plasma arc torch developed by the Plasma Energy Corporation was used for soil vitrification experiments with operating temperatures at about 4000°C. The soils tested include Piedmont silty sand, kaolin clay, and Tyndall beach sand. 5.1-cm cubes and 5.1-cm diameter cylinders were cut from the vitrified soil samples and subjected to compression tests, split-cylinder tension tests, and split-Hopkinson bar impact tests.

### **Introduction**

The ISV technology was developed by Battelle Memorial Institute's Pacific Northwest Laboratories (PNL) in the mid-80's under sponsorship of the Department of Energy for contaminated soil remediation (Buelte and Carter 1986). The ISV technology developed by PNL uses a system that inserts a square array of four graphite electrodes into a contaminated site. This mechanism allows the electrodes to sink to increasingly greater depths as the molten magma increases in volume until a desired treatment depth is reached. The plasma arc technology was developed over 30 years ago by NASA for the United States space program to simulate re-entry temperatures on heat shields. A plasma is an ionized gas which occurs naturally in

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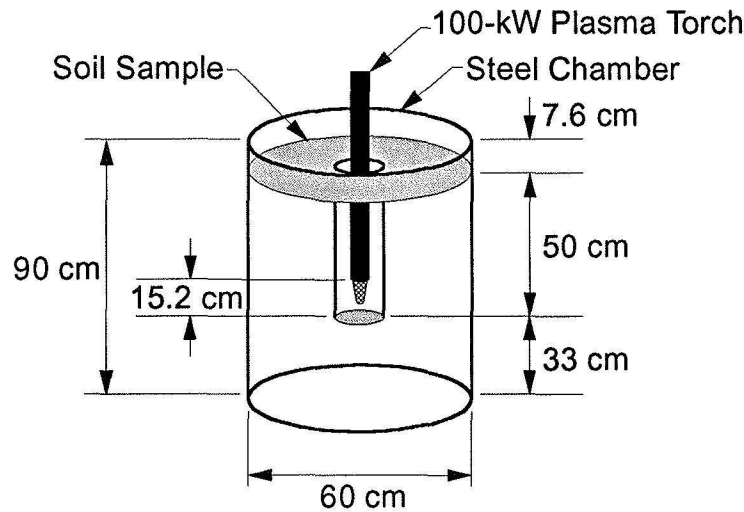
the path of lightning. The ionized particles make plasma an excellent electrical conductor. The heat from a plasma plume melts contaminated solids at very high temperatures, typically in the range of 1600°C to 2000°C for most soils. ISV by plasma arc torch is much more efficient than that by the original 4-electrode configuration. Due to the high heat flux, the magma melt forms in the soil mass within minutes of exposure to the plasma plume. The objective of this study was to explore potential ISV applications to address the U.S. Air Force mission needs for rapid airfield pavement construction. Current applications of the plasma arc torch for thermal soil stabilization are limited to discrete points for substantial penetration, and it is not suitable for covering large surface areas as required for pavement construction or repair work. Proper adaptation of this technology is necessary before the technology can be fielded for the application studied.

### **Soil Vitrification Experiments**

The soil vitrification experiments were conducted at the plasma arc torch facility of Georgia Institute of Technology in Atlanta, Georgia. Both a 100-kW and a 240-kW non-transferred plasma arc torch developed by the Plasma Energy Corporation (Camacho 1988) were used in the experiments with a high-temperature (4000°C~7000°C) plasma plume directed at the target soil. A 60-cm diameter steel chamber was used to contain the test soil. The chamber is 90-cm high and splits in half to allow retrieval of the vitrified soil monolith. The dimensions of the experiment setup are given in Figure 1. For cohesionless soils such as sand, a borehole at the chamber center was cased with a 7.6-cm diameter aluminum stove pipe to protect the plasma torch. The torch was lowered into the borehole casing until the starting position was 15 cm from the borehole base. A 15.2-cm thick layer of kaolin clay was placed at the bottom of the chamber as a filler. The test soil was compacted using 10.2-cm lifts to ensure a homogeneous specimen and to prevent the soil from collapsing into the borehole during the test. The torch was raised 5.1 cm every 10 minutes during the test for approximately a one-hour duration. The total travel of the torch was limited to 25.4 cm. Piedmont silty sand, kaolin clay, and Tyndall AFB beach sand were successfully vitrified into homogeneous monoliths, as shown in Figure 2. Details of these soil vitrification experiments have been reported by Beaver and Mayne (1995).

### **Descriptions of Test Soils**

Piedmont silty sand is commonly found in the Atlanta area. The composition of Piedmont silty sand is approximately 45% quartz, 15% kaolinite, 25% mica minerals, and 15% feldspar (Circeo and Mayne 1993). Kaolin is a very fine white clay whose composition is primarily kaolinite and quartz, with minor iron oxides. The white beach sand from Tyndall Air Force Base is a natural quartz. These soils are primarily composed of silica and alumina oxides, having melting temperatures in the range from 1100°C to 1600°C.



**Figure 1. Soil Vitrification Test Chamber Configuration**



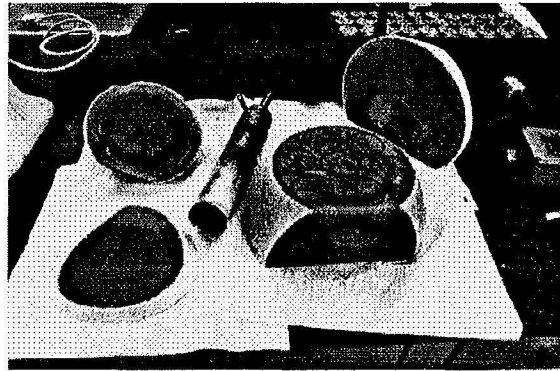
**Figure 2. Vitrified Monoliths of Piedmont Sand and Kaolin Clay**

### **Preparation of Test Specimens**

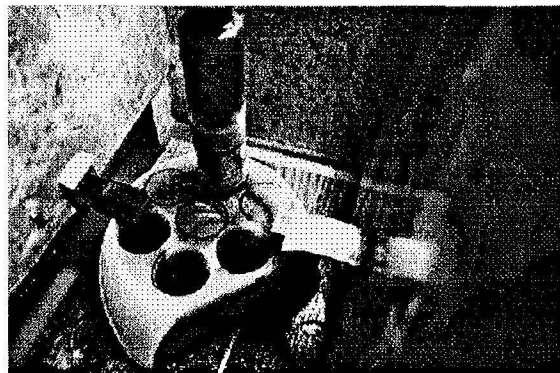
Each monolith was cut and cored with the intent to provide as many test specimens as possible. The 5.1-cm cubes were cut in a *Powermet*<sup>™</sup> abrasive cutter with a circular diamond blade. 10.2-cm long cylinders were cored by a 5.1-cm diameter diamond coring bit with a water swivel for cooling. The coring apparatus was installed in an electric drill press. The drill press was operated at 450 rpm with a feed rate of 0.0058 cm per revolution. Figures 3(a) and 3(b) show the preparation for coring samples from vitrified Tyndall beach sand.

The monoliths obtained from vitrified Piedmont silty sand and kaolin clay had many hairline cracks and a small amount of voids. As a result, coring cylinders from

those blocks was unsuccessful. Furthermore, the Piedmont silty sand samples split or crumbled during attempts to cut 5.1-cm cubes. One probable cause of the hairline cracks is tensile stress relief during cooling. Another possible cause is the boundary effect of the small test chamber that could result in the vapor from the soil moisture being trapped inside the molten magma.



**Figure 3(a). 5.1-cm Diameter Coring Bit and Vitrified Tyndall Sand**



**Figure 3(b). 5.1-cm Diameter, 10.2-cm Long Cores**

### **Instrumentation and Results**

Figure 4 shows some of test specimens with strain gages in place. The 5.1-cm cubes were instrumented with either a 120- $\Omega$  or a 350- $\Omega$ , 3.8-cm long strain gage parallel to the direction of the compression load and wired in a quarter-bridge configuration. The 5.1-cm diameter, 10.2-cm long cylinders were subjected to split-tension tests. The compression and split-tension tests were conducted in either an MTS or a Forney testing machine. In addition to the strain gages, a load cell on the testing machine was used to measure the applied load. Each channel of data was sampled at 50 Hz. The compression and split-tension tests were conducted at a constant loading rate of about 13.35 kN/sec.

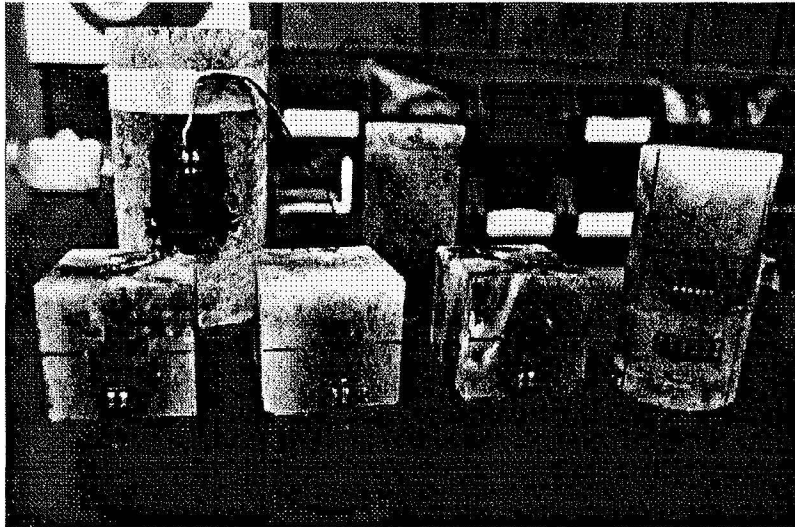
#### **1. Elastic Modulus Measurements**

The elastic wave propagation speed  $c$  in a homogeneous solid is related to the mass density  $\rho$  and elastic modulus  $E$  of the solid as follows:

$$E = \rho c^2 \text{ ----- ( 1 )}$$



Three cylinders of vitrified Tyndall beach sand weighed 444.9 g, 442.7 g, and 442.7g, respectively. A V-meter was used to impinge an ultrasonic pulse on one end of the cylinder. The pulse was received on the other end and the elapsed time for the pulse to propagate through the length of the cylinder was determined. This elapsed time measured for the three specimens was 16.9, 16.6, and 16.8  $\mu$ Sec, respectively. Thus the calculated elastic modulus for vitrified Tyndall sand was 77.8, 80.6, and 78.5 GPa, with an average of 78.9 GPa.



**Figure 4. Strain-gaged Vitrified Soil Test Specimens**

## 2. 5.1-cm Cube Compression Tests

The 5.1-cm cubes cut from vitrified Tyndall beach sand and kaolin clay specimens were subjected to compression tests. Vitrified soils exhibit very brittle material behavior. Test specimens were generally pulverized at failure. Stress-strain curves resulting from these compression tests are compiled in Figure 5. The compressive strengths and averaged elastic moduli of the vitrified soil specimens are summarized in Table 1. Significant scatter exists in the data, and the moduli of vitrified soils obtained from the compression tests are generally less than the 78.9 GPa value obtained from the ultrasonic device. Furthermore, the stiffness and strength parameters obtained from the tests do not correlate with soil type.

## 3. Split-Cylinder Tension Tests

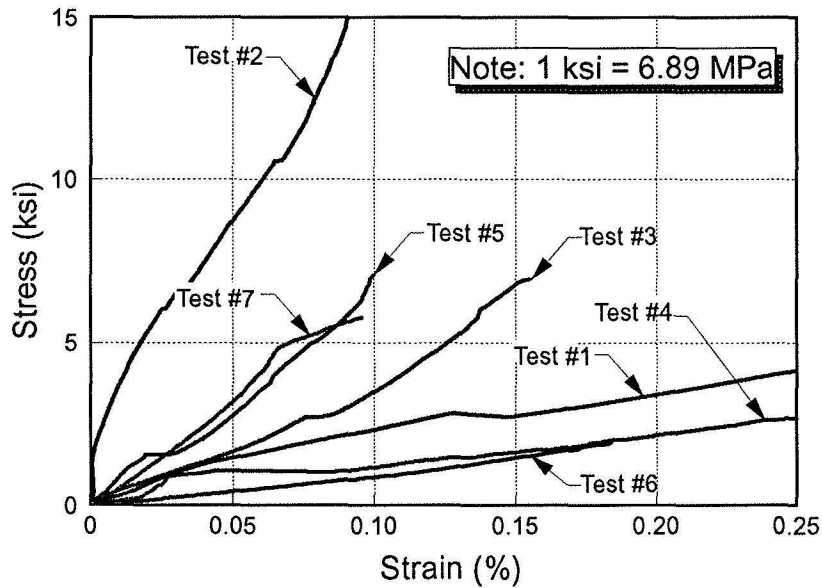
From the theory of elasticity, a cylinder compressed by diametrically opposite forces will develop compressive stress in that diametrical plane with a magnitude equal to

$$\sigma_c = \frac{6 P}{\pi d l} \text{ ----- (2)}$$

and tensile stress perpendicular to that plane with a magnitude equal to

$$\sigma_t = \frac{2 P}{\pi d l} \text{-----} (3)$$

where  $P$  is the total force applied to the cylinder,  $d$  the diameter of the cylinder, and  $l$  the length of the cylinder. A strain gage was installed on one end of the cylinder in its diametrical plane to measure the compressive strain, while another strain gage was installed on the other end of the cylinder perpendicular to the diametrical plane to measure the tensile strain. With this instrumentation, tensile as well as compressive stress-strain relationship can be obtained simultaneously. The computed ultimate stresses along with the measured ultimate strains are summarized in Table 2. Figures 6 and 7 present the compressive and tensile stress-strain curves obtained from the split-cylinder tension tests, respectively.



**Figure 5. Compressive Stress-Strain Curves From 5.1-cm Cubes**

#### 4. Split-Hopkinson Pressure Bar Impact Tests

Thin, circular disks of vitrified soil samples were placed in a split-Hopkinson pressure bar for uniaxial dynamic stress-strain-strain rate measurements. Wasley (1973) provides detailed descriptions of the principle and operating procedures of the split-Hopkinson bar. A thin specimen is sandwiched between two long solid steel rods and is loaded by a single compressive stress pulse of about 100  $\mu$ Sec duration. The pressure bars act to apply the load to the specimen and are instrumented with strain gages to measure the stress pulses incident to and transmitted through the specimen. This arrangement enables determination of averaged stress versus strain in the specimen, with strain rate as a parameter. Figure 8 shows the split-Hopkinson bar test apparatus located at Tyndall Air Force Base, Florida.



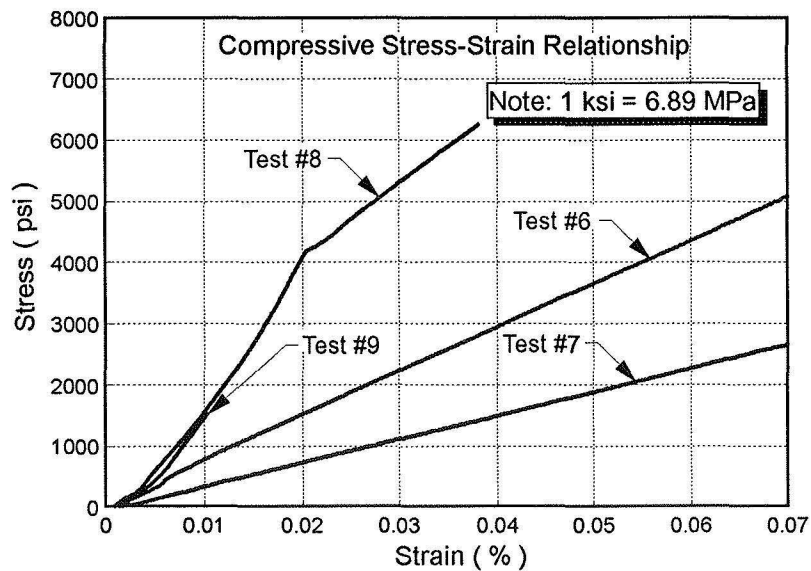
Test No.	Vitrified Soil	Compressive Strength ( MPa )	Ultimate Strain ( % )	Elastic Modulus ( GPa )
1	Tyndall sand	116.87	0.675	12.34
2	kaolin clay	116.41	0.103	100.0
3	Tyndall sand	152.14	0.156	29.52
4	Tyndall sand	19.81	0.278	8.00
5	Tyndall sand	50.88	0.100	50.48
6	kaolin clay	23.34	0.200	8.48
7	kaolin clay	39.87	0.106	47.72

**Table 1. Summary of 5.1-cm Cube Compression Test Data**

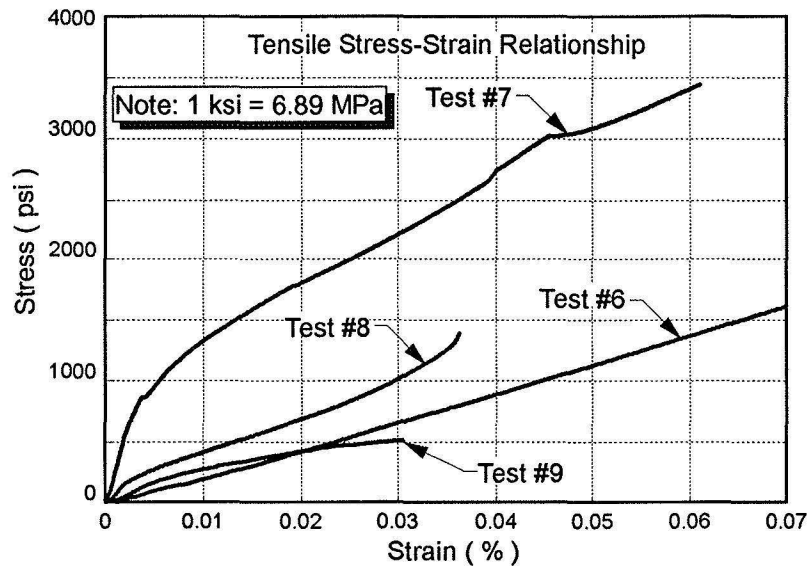
Test No.	Compression at Failure ( kN )	Tensile			Compressive		
		Stress <sup>a</sup> ( MPa )	Strain ( % )	Modulus ( GPa )	Stress <sup>a</sup> ( MPa )	Strain ( % )	Modulus ( GPa )
1	26.45	3.26	---	---	9.79	---	---
2	78.36	9.66	---	---	28.99	---	---
3	128.20	15.81	---	---	47.43	---	---
4	60.74	7.49	---	---	22.48	---	---
5	27.50	3.39	---	---	10.18	---	---
6	256.52	31.63	0.194	53.31	94.91	0.189	52.90
7	201.43	24.84	0.061	106.90	74.52	0.217	30.69
8	116.97	14.43	0.036	83.45	43.28	0.038	84.83
9	32.74	4.04	0.035	59.24	12.12	0.011	125.52

<sup>a</sup> Stress values calculated according to Eqs.(2) and (3).

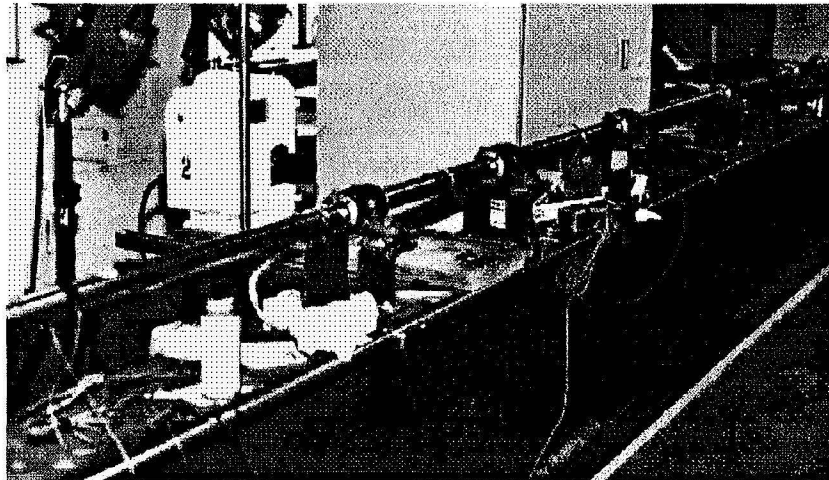
**Table 2. Summary of Split-Cylinder Tension Test Data**



**Figure 6. Split-Cylinder Tension Tests on Vitrified Tyndall Sand**



**Figure 7. Split-Cylinder Tension Tests on Vittrified Tyndall Sand**



**Figure 8. Split-Hopkinson Bar Impact Test**

A 5.1-cm diameter, 2.54-mm thick disk of vittrified Tyndall beach sand was subjected to the split-Hopkinson bar impact test. The incident pressure pulse was 355 MPa and was transmitted 100 percent through the specimen. The specimen was pulverized into fine grains of particles. The strain rate was estimated to be about 67 per second. There was not sufficient data to obtain a dynamic stress-strain relationship. The second test involved a 3.8-cm diameter, 6.35-mm thick disk of vittrified kaolin clay. The peak stress pulse transmitted was about 603 MPa, at which stress the strain rate was approximately 1434 per second. The time-histories of the compressive stress, strain, and strain rate are shown in Figure 9. The dynamic compressive stress-strain curve is shown in Figure 10. The high strain-rate modulus was calculated to be about 44.8 GPa. Vittrified soils are not effective shock absorbing materials, given the very high ratio of transmitted pulse to incident pulse.

The compressive strength of the vitrified soil samples seemed to have been significantly affected by the strain rate. However, the modulus seemed to be independent of the strain rate.

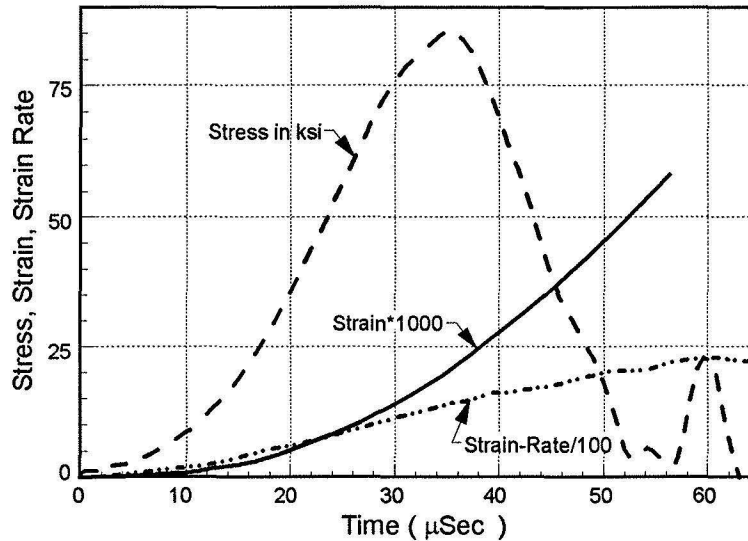


Figure 9. Impact Test Data of Vitrified Kaolin Clay

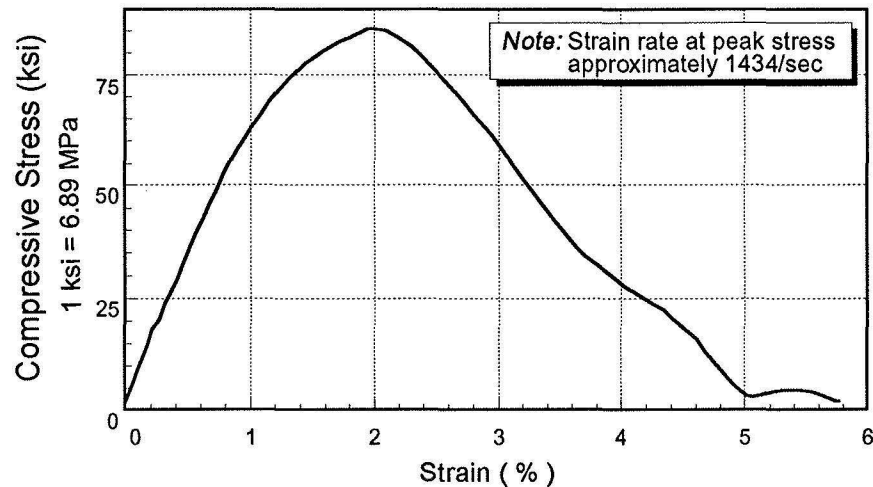


Figure 10. Dynamic Stress-Strain Curve of Vitrified Kaolin Clay

## Conclusions

The in-situ soil vitrification technologies recently developed for hazardous waste remediation have been evaluated for potential applications in airfield runway pavements construction and repair. In-situ soil vitrification by plasma arc torch is much more efficient than that by the original 4-electrode configuration. There is virtually no heat loss at the melt surface and by melting from the bottom up, most of the heat from the melt goes into pre-heating the surrounding soil. Furthermore, plasma arc torches have high thermal efficiency usually in the range between 85 and

93 percent. The risk of having molten magma ejected by vapor bubbles, as occurred in a "top down" vitrification experiment with the 4-electrode feed system, is greatly reduced by the "bottom up" operation of a plasma arc torch. Potential applications related to pavement work include man-made high-strength aggregates, thermal stabilization of subgrade or subbase soil, and groundwater removal. The most critical factor for these applications is the power requirement. Mobile plasma torch systems at 10 to 15 mega-watt (MW) levels have just started to emerge. These systems consist of two trailers and a prime mover. With a 3.5-MW power equipment to process soil at 5 tons per hour, it would take about 30 hours to have enough vitrified material to pour a 23-m (75-ft) wide, 30.5-m (100-ft) long, and 7.6-cm (3-in) thick pavement surface. This pace would not meet Air Force needs to rapidly create or repair airfield pavement in a contingency situation. However, airfield pavements are not required to have the high strength typical of vitrified soil. In fact, the shear strength of common soils increases dramatically with temperature above 200°C and soil plasticity is reduced to zero at about 500°C. Therefore, plasma arc technology may be most cost effective if used for thermal treatment of certain types of soils in a continuous mode of operation. The technology required for this development is still in the conceptual design stage, and many technical issues remain to be resolved.

### **Acknowledgments**

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### **References**

- Beaver, J.R., and Mayne, P.W., "Baseline Geoenvironmental Experiments for In-situ Soil Transformation by Plasma Torch," Presented at the International Symposium on Environmental Technologies: Plasma Systems and Applications, Atlanta, GA, October 8-11, 1995.
- Buelt, J.L., and Carter, J.G., "In Situ Vitrification Large-scale Operational Acceptance Test Analysis," PNL-5828, Pacific Northwest Laboratory, WA, May 1986.
- Camacho, S.L., "Plasma Heating," Chapter 5, Handbook of Applied Thermal Systems, McGraw-Hill, 1988.
- Circeo, L.J., and Mayne, P.W., "In-Situ Thermal Stabilization of Soils Using Plasma Arc Technology," Final Report, submitted to National Science Foundation, Georgia Institute of Technology, Atlanta, GA, March 1993.
- Wasley, R.J., Stress Wave Propagation in Solids, Marcel Dekker, Inc., New York, 1973, pp.215-226.