In-situ plasma vitrification of geomaterials

Vitrification *in-situ* par plasma des materiaux

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ABSTRACT: Nontransferred arc plasma technology is an especially powerful thermal means of ground improvement that is capable of melting all soil and rock types by direct application of high temperatures between 4000°C to 7000°C. The process uses a plasma torch placed downhole for in-situ ground modification and subsurface remediation. Laboratory simulations have successfully melted different soil and rock types and a field demonstration has been completed in clayey sands. Materials characterization has included pre- and post-measures of the original soils and created artificial rock types, including determinations of changes in porosity, mass density, shear wave velocity (resonant column for soils and ultrasonics for rocks), uniaxial and triaxial compressive strengths, and stiffness. In addition, geologic and chemical studies were conducted on the original and transformed geomaterials.

RÉSUMÉ: La technologie "Nontransferred arc plasma" est un moyen thermique, particulierement puissant, d'amélioration du sol capable de fondre tous types de sols et de roches par l'application directe de hautes températures entre 4000°C à 7000°C. Le procédé utilise un torche a plasma placée pour in situ modification de sol et preparation du sous-sol. Des simulations au laboratoire ont montrees, avec succès, la fonte de différents types de sol. Un essai sur terrain a ete effectuee avec des profils de sols en sable de clayey. La caractérisation des matériaux a utilise des pre et des post-mesures du sol original et a cree des types de roches artificielles. Parmi ces mesures, celles de changements de porosite, de densité de masse, de vitesse de propagation d'ondes de cisaillement (la colonne résonnante pour les sols et les ultrasons pour les roches), de forces compressives uniaxiales et triaxiales, et de solidite. De plus, des études geologiques et chimiques ont été faites sur les geo-materiaux originaux et transformés.

1 INTRODUCTION

Thermal soil treatment has been used to enhance soil stiffness and strength for construction purposes. Historically, thermal ground improvement was inhibited due to limitations of the energy sources in providing sufficiently high temperatures at reasonable costs. This paper discusses a new approach utilizing nontransferred plasma technology for the in-situ vitrification of soils and contaminants.

Traditional thermal treatment methods include the use of a mobile wood furnace, forcing heated air in tunnels, burning fuel in boreholes, and using embedded electrodes. One of the hurdles facing these processes is the fact that soil is mainly composed of silica and alumina oxides that have melting temperatures of 1100°C to 1600°C. Accordingly, it was not possible until recently to melt soils using traditional heating methods (Mayne 1994). Therefore with the introduction of new technologies, soil melting became feasible. On cooling, the melt turns into an artificial igneous mass. This process was named vitrification, which is derived from the two Latin words: vitrum meaning "glass" and facere which means, "to make."

In-situ vitrification (ISV) uses electrical energy for the in situ melting of contaminated soils via four electrodes placed in a square pattern. An electric current is allowed to pass between diagonally opposing electrodes. This process creates Joule heat resulting in the melting of the surrounding soil. The treatment yields an inert glassy material (Langerman 1991), yet a drawback of ISV is the high cost due to the high electric power consumption.

In the early nineties, the use of nontransferred plasma arc technology was introduced as a means for ground improvement and remediation in the field of geotechnical engineering (Celes and Mayne, 2000). Laboratory and full-scale tests were conducted using different types of soils and rocks. This paper provides an overview of this novel technology known as in-situ plasma vitrification (ISPV).

2 PLASMA VITRIFICATION

2.1 *Plasma*

Plasma is highly ionized gas existing at very high temperatures varying from 4000°C to 12,000°C. The creation of plasma is based on the conversion of electric energy to heating energy. The natural form of plasma is lightning. The arc created by the plasma torch reaches temperatures as high as 7000°C, tapering to 4000°C at the tip. Since tungsten has a melting temperature of 2450°C that is the highest among common elements, all earthly materials would either melt or volatize at the temperatures reached using the plasma torch (Mayne et al. 2000).

2.2 *Nontransferred Plasma Arc Equipment*

Traditionally, thermal treatment of contaminated soils takes place in arc melters used for waste minimization. This process results in the transformation of contaminants into unleachable amorphous product (Paik and Nguyen 1995). Plasma causes the contaminants to decompose to their elementary chemical constituents getting rid of the by-products created by more traditional combustion furnaces (Sears et al. 1990). In these applications, the transferred arc plasma torch is utilized. The nontransferred plasma arc torch, shown in Figure 1, has the advantage of not requiring an external electrode.
Plasma torches vary in size from 100-kW to 10-MW and for both transferred and nontransferred arc torches, an electric current is used to ionize a gas. For the tests conducted herein, the

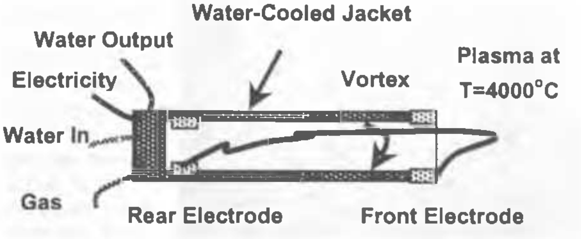

Figure 1. Internal Configuration of a Nontransferred Arc Plasma Torch

gas was air from a compressor. The nontransferred arc can direct the torch at specific targets (Camacho 1988).

2.3 *Overview*

Several laboratory-scale simulations were conducted on different types of soils and rocks to transform them into igneous masses. A pool of molten matter is created within five minutes of exposure to the plasma torch. The melt is allowed to cool down for several days before the igneous body is exhumed for examination and testing. The end product depends on various factors including the original material type and the cooling rate. Both 100-kW and 200-kW torches were used for the laboratory tests while 500-kW and 1-MW torches were employed for field testing. A picture of the 1-MW torch is shown in Figure 2.

Different tests were used to evaluate the changes in engineering, chemical, and geologic properties of the igneous masses compared to the original soil. Tests included void ratio, porosity, density, wave velocities, stiffness, and strength. In addition, x-ray diffraction tests were conducted on the tested soil as well as the vitrified product (Beaver and Mayne 1995). Petrographic studies were conducted on the amorphous rock formed by the vitrification of kaolin (Celes and Mayne 2000).

2.4 *Laboratory Tests*

Tests were conducted in cylindrical steel chambers with diameters of 0.6, 0.9 and 1.2 m and all 0.9 m in height. Experiments used different geomaterials including sands, clayey sand, silt, clay, kaolin, weathered mudstone and shale. Soils were mixed at various moisture contents varying from 4 to 50%. The soils were compacted in 10 cm to 20 cm lifts when placed in the chamber. In some tests, temperature variations were recorded using K-type thermocouples operating in the range of up to 1400°C. Thermocouples were placed at fixed heights and depths within the soil deposit. Temperature readings were recorded every time five minutes throughout the test duration. After cooling, the chamber was opened and the igneous mass exhumed. Laboratory tests were then conducted on the vitrified masses to determine the change in properties due to vitrification. Figure 3 shows a cross section through a column created by plasma vitrification.

Figure 2. Preparation of the 1-MW Nontransferred Arc Torch

Figure 3. Cross Section of a Vitrified Column Cut by Diamond Saw.

2.5 *Field Demonstration*

A field demonstration of nontransferred plasma vitrification was conducted at the Savannah River Site in South Carolina. A 1-MW torch was used at this site. The field demonstration was characterized by using higher energy levels (870 kWh and 1740 kWh compared to a maximum of 1100 kWh in laboratory scale chamber tests). This increase in energy input in the field was due to using a more powerful torch and running the test for a longer duration. Three columns of the igneous product were created at this site. Two of the columns were created side by side forming one mass while the third formed a single column. Several pre- and post-vitrification tests were conducted to detect the location and size of the igneous bodies (Mayne et al. 2000). These tests included measuring the shear wave velocities of natural and vitrified soil using the crosshole test. Shear wave velocities offer a basic measurement of the stiffness of solids making this test applicable to both rocks and soils. The material stiffness is based on shear wave velocity values:

$$G_0 = G_{max} = \rho \cdot V_s^2 \tag{1}$$

where G_{max} = small-strain shear modulus; ρ = total mass density and V_s = shear wave propagation velocity.

Before vitrification, an initial set of geophysical tests was conducted using four boreholes. A mechanical hammer was lowered in the first borehole while receiver geophones were placed in the other three. Tests were conducted at 0.3 m-depths. Travel time between the source and receiver was measured at each depth. The shear wave velocity of the natural soil varied between 106 and 180 m/sec. One month after vitrification, another set of tests was conducted using boreholes on both sides of the single and double vitrified columns. The shear wave velocities increased by approximately 50% and 100% for the single and double columns respectively. Figures 4a and 4b show the crosshole test setup and results, respectively, and show the velocities are a combined soil-column determination.

After conducting the crosshole tests, the vitrified columns were extracted to obtain the mass and size of the igneous bodies. The diameters of the vitrified columns ranged between 0.9 and 1.2 m. Material characterization tests were conducted on the igneous masses to evaluate the improvement in material properties due to vitrification. A comparison of the vitrified mass created in the field relative to that created in the laboratory is discussed later in the paper.

3 GEOLOGIC TESTS

3.1 *Mineral Identification*

Minerals could be identified using different methods ranging from visual inspection to x-ray diffraction, infrared studies and thermal analysis. The method used in this investigation was x-ray diffraction that showed the main mineral of vitrified processed kaolin to be mullite. However, the main mineral of vitrified natural kaolin was not completely identified. Therefore, a Becke line test was conducted on the small samples less than 0.5 mm in diameter and proved that the main mineral in the vitrified natural kaolin sample to be mullite (Celes and Mayne 2000).

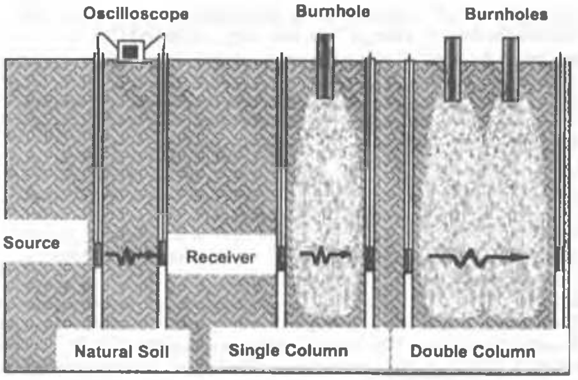

Figure 4a. Pre- and Post-Vitrification Crosshole Setups in Aiken, SC.

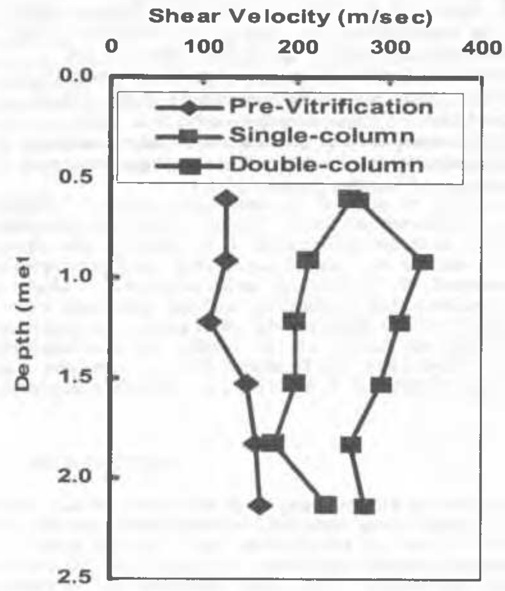

Figure 4b. Pre- and Post-Vitrification Crosshole Results in SC.

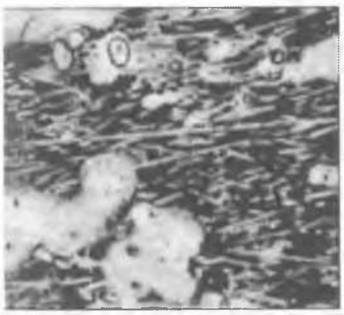

Figure 5. Petrographic Slide of Vitrified Kaolin at 10-times Magnification (Celes 1999)

3.2 *Petrographic Studies*

Petrography is the classification of rocks using geologic procedures. Thin rock sections are prepared and examined using a microscope. The rock samples were epoxy impregnated to enable mounting the specimens on the microscope slides without losing the original rock structure. After mineral identification, point counting was used in determining the percentages of the different rock constituents. The point counting is conducted on 30 μm thick sections using a polarizing microscope. Three major components were found in each slide: black glass, mullite ($3Al_2O_3.2SiO_2$) and pores. Naturally mullite is only found on the Isle of Mull off the Scottish coast (Grofcsik 1961). Figure 5 shows a petrographic image of vitrified kaolin.

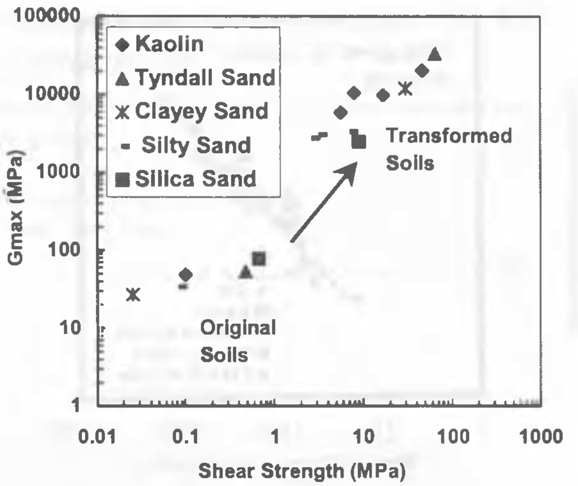

Figure 6. Comparison of Compressive Strength and Stiffness of Original Soils Versus Vitrified Rock Product

4 MATERIALS CHARACTERIZATION

Laboratory tests were conducted on both the natural and vitrified materials to measure the changes in porosity, void ratio, density, stiffness, and strength. For tests conducted on soils, the initial void ratios ranged between 0.6 and 0.9 compared to 0.02 to 0.2 after vitrification. The unit weights varied from 14 to 16.5 kN/m^3 for the natural geomaterials. The unit weights of the transformed product ranged from 22 to 26 kN/m^3. The small-strain shear modulus was determined for both soils and transformed product. Resonant column tests were used to test the soils according to ASTM D 4015 using effective stresses ranging between 0 to 700 kPa (Beaver 1996). Ultrasonic testing was used to determine the rock modulus (ASTM D 2845). For strength of soils, triaxial and direct shear tests were conducted. For the vitrified product, uniaxial compression tests were conducted on cores and cubes. Figure 6 shows the drastic improvement in soil strength and shear modulus. An increase of about two orders of magnitude is noticed in both the stiffness and shear strength of the vitrified product compared to the original soils.

5 RELATIONSHIP BEWTEEN VITRIFED MASS AND ENERGY CONSUMPTION

The vitrified mass was found to increase with energy. During the plasma tests, electric power is measured with time. Knowing the test duration, the electric energy consumption is calculated as the product of the average electric power times the test duration. Figure 7 shows the variation in the vitrified mass with energy consumption. An empirical correlation was found between the vitrified mass and the amount of energy consumption. This correlation is shown in equation 2 shown below:

$$IM = 0.78\ E^{0.76} \quad (2)$$

where IM = igneous mass in kg and E = energy consumption in kWh (power times duration).

This equation is based on a set of laboratory scale simulations using both 100 and 200-kW torches. The test running times generally varied between 50 to 70 minutes, although a few tests were up to 5 hours long.

A set of three tests was conducted in the field using the 1-MW torch (Mayne, et al., 2000). The vitrified masses created in the field were found to be higher compared to those predicted using equation 2, which is based on laboratory test results. Figure 8 shows a comparison between the actual and estimated igneous masses for laboratory and field tests. The ratio of the actual versus predicted masses ranged between 2 and 2.9. This difference can be attributed to higher heat loss from laboratory chambers (3-d) compared to the field (1-d). More field tests should be conducted in order to better correlate the vitrified mass to energy consumed in the field.

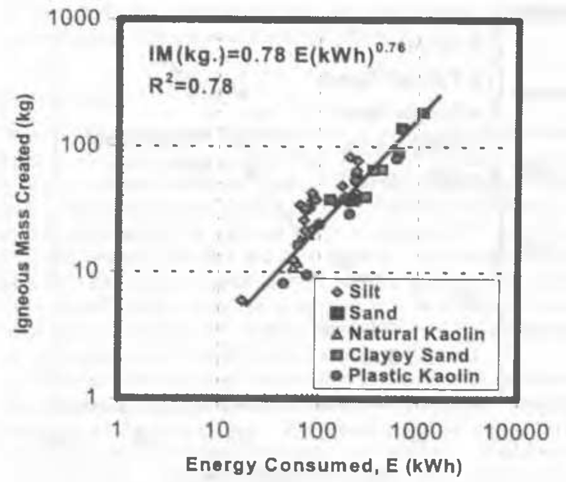

Figure 7. Igneous Mass versus Energy Consumption Relationship (based on laboratory chamber tests)

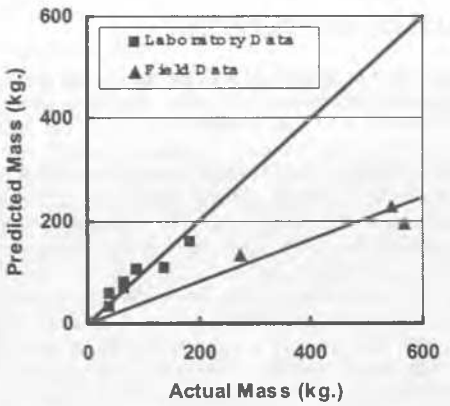

Figure 8. Comparison of Actual and Estimated Igneous Masses From Laboratory and Field Tests (using equation 2).

Different factors affect the efficiency of the melting process. Among these factors is the torch withdrawal rate. It was noticed that if the rate of withdrawal is too slow, the torch gets into the melt causing the lifetime of the electrodes to become shorter. On the other hand, if the withdrawal rate is too fast, the heat does not propagate well into the soil thus creating a smaller vitrified zone. Another factor is the effect of varying the borehole to torch diameter ratio. Some ongoing experiments are being conducted to investigate the effects of these factors.

6 CONCLUSIONS

Nontransferred arc plasma technology has shown to be a viable method for the in-situ remediation of soil and weathered rocks. The high temperatures created by the plasma torch cause melting of soils that cools to form an igneous rock-like material. Laboratory and field tests show a drastic change in properties of the transformed mass compared to the original geomaterial.

7 ACKNOWLEDGMENTS

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