*Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds)*

# High temperature ground improvement

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ABSTRACT: High-temperature ground improvement is becoming more widely used for various geotechnical applications. However, examples of the application of ground heating to tunnelling are limited. This study aims to assess the applicability of high-temperature ground improvement to tunnelling by reporting the variation in Unconfined Compressive Strength (UCS) and other geotechnical properties of clay and sand after heating to high temperatures. Laboratory experiments were conducted to assess the engineering properties of clay and sand specimens heated in a furnace at temperatures ranging from room temperature (~25°C) to 1200°C. The results show that a high temperature of 1200°C considerably affects the UCS and point load strength index of the clay and sand specimens, mainly mixed clay and sand specimens with ratios of 3:1 and 1:1 sand to clay. A higher clay content results in increased depth and frequency of surface fracturing within the specimens resulting in reduced material strength. The highest value of UCS obtained from the experiments is 1.9 MPa by heating a 25% clay 75% sand specimen to 1200°C until it becomes vitrified. Generally, high temperatures (~1200°C) result in an increase in the UCS strength index of soft clayey, sandy soils.

## 1 INTRODUCTION

Tunnels in soft ground sometimes require pre-support and reinforcement during excavation. If the tunnel heading is unsupported, failures and collapses within the excavation may occur (Paraskevopoulou et al., 2022). Current soft ground tunnel support and reinforcement methods include advance pipe umbrella, grouted pipe spiles, driven spiles, face bolt reinforcement, temporary invert and full-face grouting reinforcement (Wang et al., 2019). Failures in tunnels are a health and safety risk that lead to project delays, increases in project costs due to remediation and, in extreme cases, can lead to severe injury or death. This study aims to assess the applicability of high-temperature ground improvement to tunnelling to enable a self-supporting framework around the tunnel during excavation. Heat is applied to the soft soil surrounding the excavation to strengthen it and provide support and reinforcement to the tunnel during excavation. High-temperature treatment of soil to influence its mechanical behaviour is becoming more widely used as a method of ground improvement for various geotechnical applications such as high-level radioactive waste (HLW) disposal; contaminated land remediation (Oma, 2019); geothermal energy systems; heat storage (Laloui, 2001); petroleum drilling, injection and production; underground coal gasification and volcano flank stability (Ranjith, et al., 2012). The advantage of this method is that it could speed up the excavation process and

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require less tunnel reinforcements, therefore reducing costs, as the tunnel support system will be mainly composed of the surrounding rock medium.

## 2 BACKGROUND

### 2.1 *Definitions*

From an engineering perspective, soil can be defined as an unconsolidated aggregation of sediment or solid particles produced by the physical and chemical disintegration, or weathering, of rocks. Soil is composed of a mixture of minerals, organic matter, water and air (Afrin, 2017). Ground improvement, in geotechnical engineering, can be defined as using physical, chemical or mechanical means to improve poor ground conditions (Moseley & Kirsch, 2004). Ground improvement methods aim to improve the geotechnical engineering properties of the soil mass, with the common objectives of improving the bearing capacity of the soil, increasing density, controlling settlements and permeability, mitigating liquefaction and improving slope stability (Schaefer et al., 2012).

### 2.2 *Ground improvement and high-temperature heating*

Ground improvement techniques have developed considerably in the past 50 years and are now used regularly in many geotechnical engineering projects (Schaefer et al., 2012). They are often used to improve the stability of soft or loose soils by increasing the cohesion and/or reducing the permeability of the soil; or they are used to control deformations, such as settlements, heave or distortions, once a structure is built on top of the soil, or once an excavation or tunnel is bored into it. Ground improvement techniques can be grouped into eight broad categories: vibration, adding load, structural reinforcement, structural fill, admixtures, grouting, thermal stabilisation and vegetation (Mitchell & Jardine, 2002). Thermal stabilisation is one category of ground improvement which involves heating or cooling soil to alter its geotechnical properties, resulting in stabilising and strengthening the soil mass. It includes both ground freezing and ground heating. If the improvement of the ground is only needed temporarily, ground freezing may be suitable; however, if the improvement is needed permanently, then ground heating may be used (Schaefer et al., 2012). Heating soil to 100°C causes the pore water in the soil to evaporate while the soil dries out (Mitchell & Jardine, 2002). On the other hand, heating the soil from 600°C to 1000°C will result in irreversible changes (Mitchell & Jardine, 2002), such as a decrease in compressibility, an increase in cohesion and an increase in the internal angle of friction and elastic modulus of the soil (Sharma et al., 2022). Ground heating is predominantly used in Russia and Eastern Europe and mainly to treat loess - a fine-grained, friable wind-blown soil (Mitchell & Jardine, 2002). The temperature to which the soil is heated ranges from 200°C – 1000°C, with the minimum treatment temperatures for different applications given as guidance in Table 1.

Table 1. Minimum treatment temperatures for different ground heating applications (modified from Mitchell, 1982).

| Purpose of heating | Minimum treatment temperature (°C) |
|---|---|
| Reduction of lateral pressure | 300-500 |
| Elimination of collapse properties (loess) | 350-400 |
| Control frost heave | 500 |
| Massive column construction below frost depth | 600 |
| Manufacture of building materials | 900-1000 |

### 2.3 *Effects of high-temperature in engineering properties of soils*

Most high-temperature treatment studies focus on the remediation of contaminated soils rather than the effects of high temperatures on the geotechnical properties of the soil. This section discusses the effect of high temperatures (20-1000°C) on the geotechnical properties of sand and clay.

#### 2.3.1 *Sand*

Ranjith et al. (2012) studied the effects of high temperature (<1000°C) on silica sand and suggested that there is a positive correlation between the mechanical properties of sand and temperature, whereby unconfined compressive strength and Young's modulus increases with increasing temperature up to a maximum temperature of 500°C. However, beyond 500°C, the stability of the sand decreased dramatically. This behaviour can be explained by the progressive dihydroxylation of the kaolinite within the sand, causing weakening and softening as the temperature increased. Rao et al. (2007) reported the effects of high temperature on the mechanical properties of sandstone and concluded that the evaporation of pore water within the rock due to increasing temperature resulted in an improvement in the mechanical properties of the sandstone. Additionally, Rao et al. (2017) found that uniaxial tensile strength, uniaxial compressive strength, elastic modulus and fracture toughness were linearly increased with temperature up to 250°C. Once the temperature went beyond 250°C, the same properties decreased.

#### 2.3.2 *Clay*

Laloui & Cekerevac (2003) investigated the thermo-mechanical behaviour of two different clays (MC clay and Boom clay), up to a maximum temperature of 90°C, using laboratory testing (using a thermo-mechanical triaxial cell) and numerical modelling. They focused on the effect of various temperatures (22°C, 60°C and 90°C) on pre-consolidation pressure, void ratio and strain of the clay samples, and they suggested that the behaviour of clays was strongly affected by temperature as a consequence of its influence on free and adsorbed water. They concluded that quantitatively the modification of the mechanical behaviour of clay was correlated with a continuous variation in geotechnical properties (strength, stiffness) with an increase in temperature and qualitatively represented the transition to more ductile behaviour. Marques & Leroueil (2005) substantiated the findings of Laloui & Cekerevac (2003) with a study on the effects of heat on the hydraulic conductivity and settlement behaviour of clay up to temperatures of 60°C. Marques & Leroueil (2005) demonstrated that when the clay was heated to 60°C, the hydraulic conductivity was increased by a factor of 2.8, resulting in an increase of the consolidation rate by the same factor. Mon et al. (2013) challenged the effect of high temperature on clay's permeability and hydraulic conductivity, specifically kaolin clay. They suggested that the effects of temperature on the macroscopic pore structure, which governs pore water permeability, were less significant within the temperature range studied (5 °C to 40°C).

Sun et al. (2016) confirmed that a series of changes occur in the clay mineral kaolinite at temperatures between 400-600°C and considered it to be the primary cause of the modification of physical and mechanical properties in clay at high temperatures. Geng & Sun (2018) and Han et al. (2017) investigated the effects of high temperature (<900°C) on the thermo-physical properties of clay. They concluded that clay undergoes a series of changes during high-temperature treatment. Once the critical heating temperature value was reached, some carbonate minerals such as calcium carbonate, dolomite and magnesite were decomposed, which decreased the Young's modulus, tensile strength and compressive strength (Sun et al., 2016).

### 2.4 *Scientific knowledge gap*

Prior research generally agrees that high temperature significantly affects the mechanical properties of different soils. However, little research has been conducted to show the effects of extremely high temperatures (above 900°C). Prior studies have also failed to evaluate the effect of high temperatures on the mechanical properties of silt. Additionally, although the effects of ground heating have been investigated, its application to tunnelling has not. This project aims to evaluate the effects of extremely high temperature (up to 1000°C) on the mechanical properties of clay, silt and sand, with the further aim of investigating the application of ground heating to tunnelling.

## 3 METHODOLOGY

In this section, the methodology is discussed, along with the process of refining the data collection method. This is followed by an overview of the materials tested as part of this study, including soil descriptions and the specimen preparation process. The experimental methods for X-ray diffraction, consistency description, high-temperature treatment, colour description and strength measurement are also specified. More specifically, the methodology followed herein involves hand-mixed, extruded specimens of clay and sand.

### 3.1 *Description of materials tested and sample preparation*

The experimental sand was sampled from a borehole drilled in Birnam during the ground investigation for the A9 Dualling: Tay Crossing to Ballinluig project (Table 2.a). The experimental clay was sampled from a borehole drilled during the ground investigation for the Northumberland Line project between Ashington and central Newcastle (Table 2.b). The clay and sand samples were provided by Soil Engineering Geoservices Limited. It should be noted that sample EG03 was dry sieved to obtain grain sizes of 63 μm – 500 μm which were used in this experiment, the remaining material was discarded.

Table 2. Description of geomaterials tested: a. Sand; and, b. Clay.

| Sample material | a. Sand | b. Clay |
|---|---|---|
| Sample name | EG03 | EG04 |
| Project number | TE8258 | TE8311 |
| Project name | A9 Birnam | Northumberland Line |
| Location | Unknown | Unknown |
| Sampling origin | Borehole | Borehole |
| Borehole number | BTT4007 | NL/ASH/TP/D4 |
| Depth from (m) | 3.80 – 4.50 m | 2.20 – 2.70 m |
| Date sample retrieved | 04/03/2020 | 23/11/2020 |
| Sample class | Class 5 | Class 5 |

The soil descriptions were based on visual and manual identification in accordance with BS EN ISO 14688-1:2018, BS EN ISO 14688-2:2004+A1:2013 and BS 5930-2015+A1:2020. The samples were stored in clear polythene bags tied with rope, in the RMEGG laboratory at the University of Leeds at room temperature (~25°C) and out of direct sunlight.

To meet the required ISRM standard of specimen dimensions for UCS testing (ISRM, 1979), where test specimens shall be right circular cylinders with a height-to-diameter ratio of 2.5-3.0, specimens for UCS testing were prepared using a cylindrical mould 50 mm in diameter and c. 150 mm in length. The sand (EG03) was fully dried for 24 hours in an oven at 105°C before specimen preparation. The clay (EG04) was used with its natural moisture content. The specimens were mixed by hand with varying percentages of clay and sand. Each mix contained enough material to prepare three UCS specimens (weighing approximately 600 g each). Once mixed, the material was compressed by hand into a cylindrical mould using a wooden tamping rod and a weighted cylinder. The specimens were removed from the moulds using a sample extruder and weighed in grams to 1 d.p. using an SMS laboratory balance. The diameter and length of the specimens was measured in mm to 1 d.p. using Mitutoyo 150mm Vernier Calipers. The specimens were tightly wrapped in plastic film and placed into a sealed plastic bag to prevent moisture loss and were stored at an ambient temperature of ~ 25°C. A total of 24 UCS specimens and 30 point load specimens were prepared for the experiment. Figure 1 illustrates the sampling preparation process in six steps used in this study.

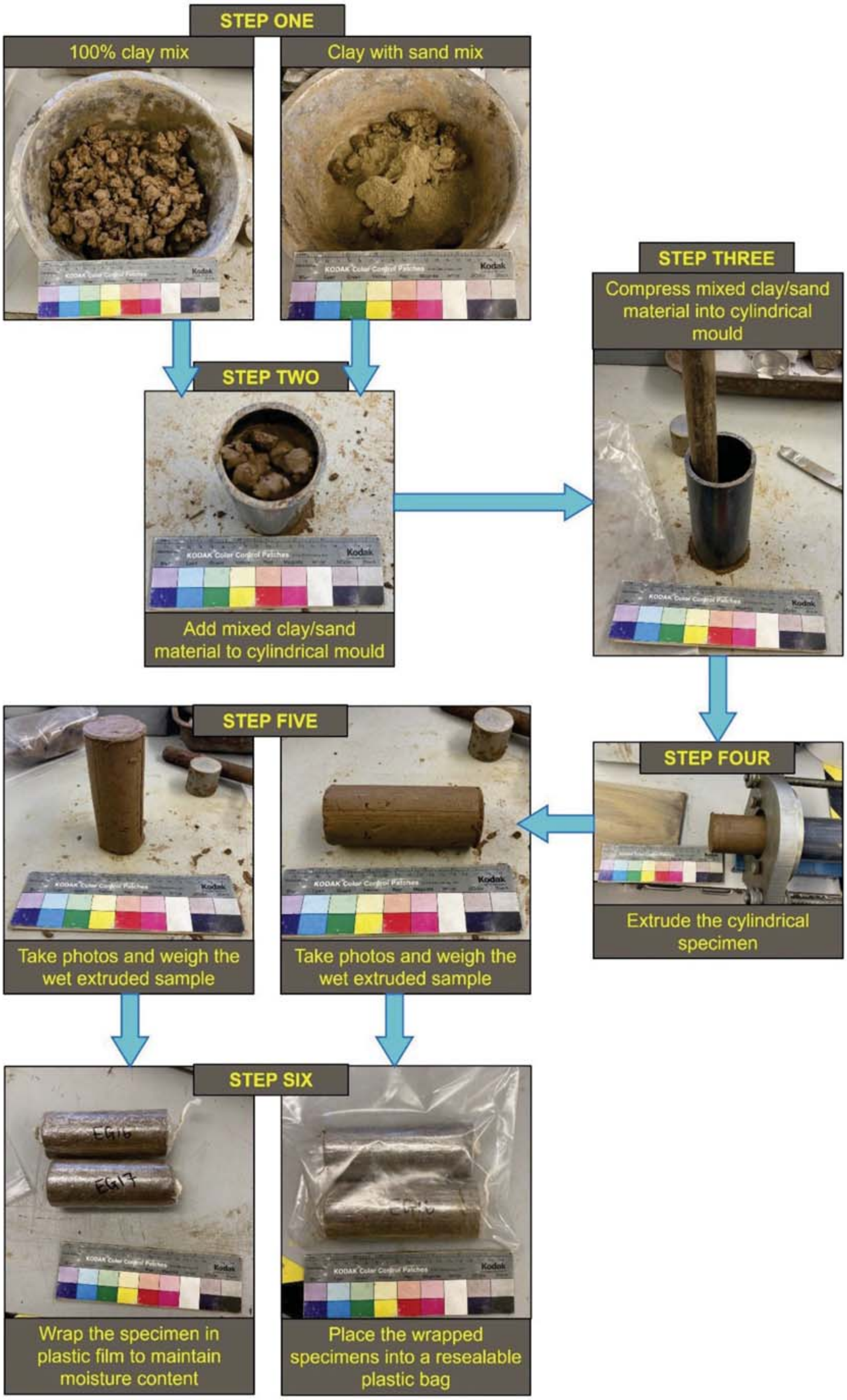

Figure 1. Flowchart of the sample preparation process used in this study.

### 3.2 *Testing procedure*

The laboratory component of the study involved heating clay and sand specimens to various temperatures (200°C, 400°C, 600°C, 800°C, 1000°C and 1200°C), shown in Figure 2, followed by UCS testing. The maximum temperature value considered (1200°C) exceeded that of current literature which focused on maximum temperatures between 950-1000°C. As the temperature approached 1200°C, the soil material surpassed the elastic rock deformation stage and started to become vitrified, which was likely to have a significant effect on the strength of the material. More specifically, the specimens were heated to their target temperature in a Carbolite ashing furnace and were heat treated from room temperature (~20-21°C) with a heating rate of 10°C/min to minimise thermal shock and stress fracturing. The specimens were held at the target temperature for 2 hours to ensure the heat was uniformly distributed throughout the specimen. The specimens were then allowed to cool completely within the furnace to ambient room temperature (~20°C) before being removed from the furnace. Finally, the specimens were stored at room temperature (~25°C) before being UCS tested.

X-ray diffraction (XRD), consistency description and colour description were performed prior to UCS testing. The natural water content of the samples was measured before mixing, and the quantity of water added during mixing was recorded to calculate the moisture content of each clay/sand specimen before heating. Approximately 2 g of samples were dried in an oven at 105°C for 24 hours, before being ground to a fine homogeneous powder suitable for XRD analysis with an agate pestle and mortar. The sample powder was pressed into a stainless steel holder and placed into a Bruker D8 X-ray Diffractometer for quantitative phase analysis. The Bruker D8 XRD uses a Cu Kα source and has a scanning range of 2-150. Furthermore, the consistency of the specimens was described before heating based on the manual tests shown in Figure 2, according to BS EN ISO 14688-1:2018.

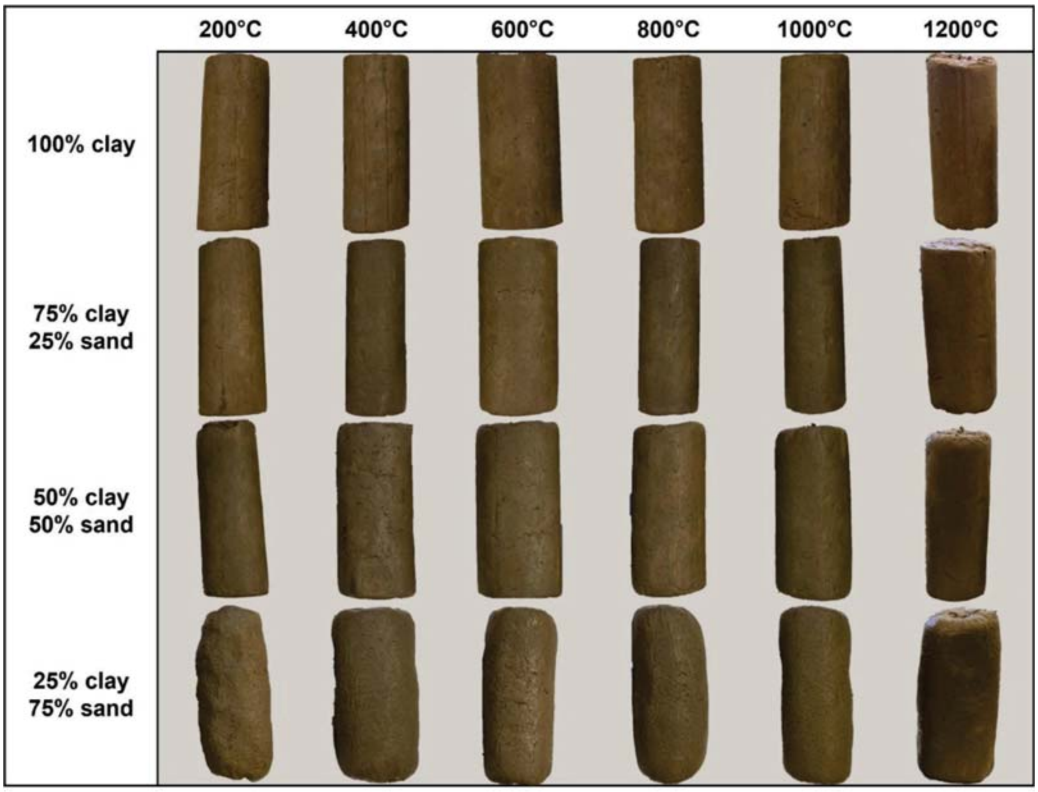

Figure 2. UCS specimens and their clay-sand contents before testing at respective temperatures.

The specimens' strength after heating was then derived by performing UCS tests according to ISRM guidelines (ISRM, 1985).

## 4 RESULTS & DISCUSSION

Figure 3 shows the specimens after being heated at high temperatures. The ends of the specimens were cut using a rock cutting device to ensure the specimens were right circular cylinders. The ends of the specimens were ground using a face grinder to ensure the end surfaces were perfectly planar and perpendicular to the long axis of the cylindrical specimen. The UCS equipment used had a weak soft rock 250 kN load frame as the specimens were not expected to exceed 250 kN.

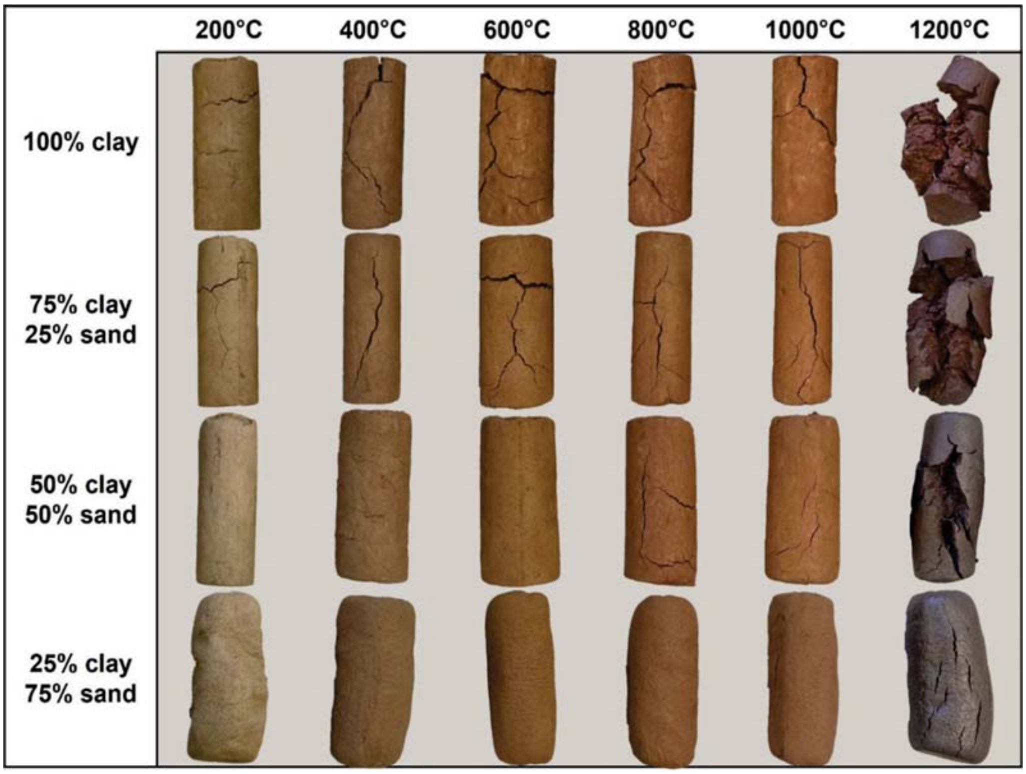

Figure 3. UCS specimen and their clay-sand content variations before testing at respective temperatures.

Table 3 shows the UCS test results, with the highest strength of 1933 kPa (1.9 MPa). According to the ISRM standard terminology for UCS, this is considered very low strength (ISRM, 1979). The three specimens with the highest value of UCS (EG31, EG33 and EG27) were heated to temperatures in the range of 800-1000°C. The specimens with the lowest values for UCS were heated to lower temperatures between 200-400°C, confirming that high temperatures improve the UCS of the soil.

Table 3. Summary of UCS test results, firing temperature and description of specimen.

| Specimen number | % clay | % sand | Firing Temperature (°C) | UCS (kPa) | UCS (MPa) | ISRM Term |
|---|---|---|---|---|---|---|
| EG29 | 50 | 50 | 200 | 220 | 0.2 | Very low strength |
| EG32 | 50 | 50 | 400 | 256 | 0.3 | Very low strength |
| EG26 | 75 | 25 | 400 | 259 | 0.3 | Very low strength |
| EG30 | 50 | 50 | 600 | 419 | 0.4 | Very low strength |
| EG23 | 75 | 25 | 200 | 808 | 0.8 | Very low strength |
| EG17 | 100 | 0 | 200 | 954 | 1.0 | Very low strength |
| EG31 | 50 | 50 | 1000 | 1378 | 1.4 | Very low strength |
| EG33 | 50 | 50 | 800 | 1539 | 1.5 | Very low strength |
| EG27 | 75 | 25 | 800 | 1933 | 1.9 | Very low strength |

## 5 CONCLUDING REMARKS

High-temperature ground improvement could be used to improve the strength of very weak, soft soils during tunnelling by applying heat to the soil surrounding the tunnel excavation through boreholes drilled perpendicular to and ahead of the tunnel face. The soil immediately surrounding the borehole would become hardened and would form an arch of higher-strength rock to support and reinforce the tunnel crown and the walls during excavation. This arch would also reduce the gravitational stresses acting on the soil within the tunnel face. This research aimed to assess the applicability of high temperature ground improvement to tunnelling. Based on the quantitative and qualitative analysis of the effect of high temperature on the strength and other geotechnical properties of clay and sand, it can be concluded that high temperatures (>800°C) cause an increase in the UCS and point load strength index of low strength clayey sandy soils. The results indicate that very high temperatures (>1000°C) cause an increase in the UCS of soft clayey sandy soils.

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