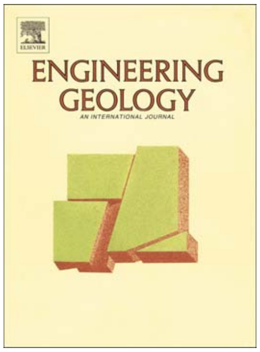

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PII: S0013-7952(13)00187-7
DOI: doi: 10.1016/j.enggeo.2013.06.004
Reference: ENGEO 3617

To appear in: *Engineering Geology*

Received date: 30 December 2012
Revised date: 5 June 2013
Accepted date: 12 June 2013

Please cite this article as: Zihms, S.G., Switzer, C., Irvine, J., Karstunen, M., Effects of high temperature processes on physical properties of silica sand, *Engineering Geology* (2013), doi: 10.1016/j.enggeo.2013.06.004

Effects of high temperature processes on physical properties of silica sand

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High temperature processes may alter soil properties, creating potential risks of subsidence, erosion and other hazards. Soils may be exposed to high temperatures during some aggressive contaminant remediation processes as well as natural events such as fires. Characterising the effects of high temperatures on soil properties is essential to understanding the potential hazards that may arise after exposure. Thermal treatment and smouldering remediation were carried out on silica sand used here as a simple soil. Changes observed in physical properties were associated with the treatment type and exposure temperature. Particle, minimum and maximum densities were independent of heat treatment type and temperature. In contrast, particle size distribution, mineralogy, capillary rise, and hydraulic conductivity were linked to treatment type and exposure temperature with the most substantial changes associated with smouldering remediation. Changes in colour and mass loss with increasing temperature suggest changes within the crystal structure of the silica sand beyond loss of moisture content within the pore space and dehydration of iron deposits from goethite to hematite. Based on these observations, exposure to high temperature processes and the complex geo-chemical reactions during smouldering remediation can have significant effects on soil properties. Monitoring after exposure is advisable to determine the severity of exposure and any mitigation measures that may be necessary.

Keywords: soil engineering properties; high temperature; thermal remediation; smouldering remediation; fire

1. Introduction

Soils can be exposed to elevated temperatures naturally through wild, forest or peat fires or through thermal remediation processes designed to mitigate high concentrations of hazardous organic contaminants. Most research on soil properties and their heat dependency is based on forest fires and therefore concentrates on erosion rates, ground stability and nutrients affected by fire severity. The effects of exposure to temperatures up to 500°C have been studied widely (Are et al., 2009;

Certini, 2005; De Bruyn and Thimus, 1996; Rein, 2009; Rein et al., 2008).`. Literature published on heat treatments of clay evaluates the effects of temperatures up to 1000°C (Tan et al., 2004). Exposures of 200 – 850°C have been observed in soils during wildfires (Certini, 2005; DeBano, 2000; Mataix-Solera and Doerr, 2004; Rein et al., 2008). Moderate (300-400°C) and high (>450°C) temperature processes, such as hot water extraction, thermal desorption, soil heated vapour extraction, incineration or smouldering are widely used to treat contaminated soils (Araruna Jr et al., 2004; Chang and Yen, 2006; Gan et al., 2009; Kronholm et al., 2002; Lee et al., 2008; McGowan et al., 1996; Pironi et al., 2011; Pironi et al., 2009; Switzer et al., 2009; Webb and Phelan, 1997). Previous studies on the effects of non-aqueous phase liquid (NAPL) contamination on soil properties shows a net reduction in soil stability as NAPL content increases (Khamehchiyan et al., 2007). NAPLs displace soil moisture and thus change the interactions between soil particles. Most research on soil remediation techniques focuses on the remediation result and less on the effects the technique has on the soil properties itself. In some cases, the effects on soil properties may be a criterion for selection of the remediation technique (Chang and Yen, 2006; Pironi et al., 2011) or the soil properties may influence the results (Webb and Phelan, 1997). There is little research on the effects of thermal remediation processes on soil physical properties. High temperature remediation displaces soil moisture and removes or destroys NAPL content. In order to establish whether the soil can recover strength and stability after remediation, it is important to establish the changes these remediation processes have on fundamental soil properties.

The maximum temperatures observed in contaminant remediation vary by the process that is used (Table 1). Thermal desorption and soil heated vapour extraction use electric resistant heating either on the soil surface or through steel walls. The current transforms the groundwater and soil water into steam which in turn evaporates any harmful chemicals. The vapours are collected and treated or disposed (Araruna Jr et al., 2004; Chang and Yen, 2006). Hot water extraction uses pre-heated and pressurised water, which is injected into the soil, to extract and react with the targeted chemicals (Kronholm et al., 2002). In practice, maximum temperature is related to the soil conditions, process operating conditions and in some cases, the contaminant that is being treated.

With the exception of smouldering remediation, all of these remediation techniques use heat or heated water to volatilise the contaminant within the soil to enable its extraction. Maximum temperatures for these technologies are typically adjacent to the heat source with more moderate target temperatures of 80-100^{o}C achieved within the wider treatment zone. The contaminant must be collected and treated (Chang and Yen, 2006; Gan et al., 2009; Kronholm et al., 2002; Lee et al., 2008; McGowan et al., 1996; Webb and Phelan, 1997). These processes maintain high temperatures in the soil for weeks to months or longer. In contrast, smouldering remediation uses the contaminant itself as fuel for the combustion reaction (Pironi et al., 2011; Pironi et al., 2009; Switzer et al., 2009). In laboratory studies, the soil particles are exposed to high temperatures on the order of 1000°C for coal tars and 600-800°C for oils for up to 60 minutes. Field scale efforts may result in exposure durations on the order of hours or longer.

Elevated temperatures have been shown to alter the mineralogical composition of soil. These effects have been studied extensively in relation to the effects of wildfires on soil properties. Colour change in soils has been observed after wildfire and after smouldering remediation. In most cases it changes from yellowish brown to reddish brown. This is due to the oxidation of soil iron content from goethite to maghemite or hematite (Goforth et al., 2005; Ketterings and Bigham, 2000). Decomposition of soil particles, especially clay minerals, starts at temperatures above 550°C (Certini, 2005). These temperatures are rarely reported for wild and forest fire, but temperatures up to 1200°C can be achieved during smouldering remediation (Pironi et al., 2009; Switzer et al., 2009).

In previous work, soil stability has been observed to increase with exposure to low and moderate temperatures as cementation of the clay particles occurs (Certini, 2005; Rein et al., 2008). This coincides with a measured increase of sand particle size with increasing temperatures in this range (Terefe et al., 2008). In clay-rich soils, bulk density and compressive strength were observed to increase as temperature was increased above ambient conditions whereas shear strength, liquid limit, and plasticity were observed to decrease (De Bruyn and Thimus, 1996).. As exposure duration increases, clay cracking is observed as moisture is lost. This drying process has two distinct stages: constant evaporation as moisture is lost from the surface followed by decreasing evaporation as the drying front propagates inward (Tang et al, 2010). Cracks form as a result of tensile stresses at the surface and can grow rapidly as moisture depletes.

At temperatures of 500°C or higher, the soil stability has been observed to decrease dramatically. This reduced stability is linked to the loss of organic cements (Certini, 2005). Wild fire temperatures can reach temperatures up to 850°C at the soil-litter interface but temperatures at 0.05m depth are unlikely to exceed 150°C (DeBano, 2000). Therefore, wild fire temperatures do not cover the temperature range encountered by thermal and smouldering remediation processes. It is necessary to understand possible impacts to soil from exposure to the whole temperature range of thermal remediation treatments.

This study aims to characterise the effects of moderate and high temperatures as well as smouldering on physical soil properties to determine the impact any changes will have to the soil and therefore predict possible complications during or after remediation treatment. Silica sand is used as a simple soil with relatively homogenous mineralogy and minimal internal pore structure. These aims are achieved by comparing clean, heat-treated and smouldered silica sands with untreated and oven-dried sands. After each treatment, fundamental properties of the sand are tested and compared to determine the impacts of the treatment conditions.

2. Materials and Methods

Coarse silica sand (Leighton Buzzard 8/16, Sibelco, Sandbach, UK) was used as the base soil for all of the experiments. The sand contains 99% silicon-dioxide, has a mean grain size of 1.34mm and a bulk density of 1.7g/cm^3 (Switzer et al., 2009). All sand was accepted as received and subjected to the same pre-treatment. A programmable muffle furnace (Nabertherm L9/11/SKM, Nabertherm GmbH, Lilienthal, Germany) was used for all heating experiments. The sands evaluated after smouldering remediation were prepared in a 3m^3 experiment involving coal tar mixed with coarse sand. The concentration of this mixture was 31000 ± 14000 mg/kg total extractable petroleum hydrocarbons before treatment and the average concentration after smouldering remediation across the majority of the vessel was 10 ± 4 mg/kg. A 25L sample of the post-treatment material was collected and set aside for characterisation. Kaolin (Whitchem Ltd, UK) was used as an exemplar, non-swelling clay in a limited number of experiments.

2.1 Sample Preparation and Heat Treatment

The silica sand was washed and wet sieved using a 0.63µm sieve to eliminate any loose fines and then air dried for several days. For each test the required amount of samples were placed in a ceramic crucible heated in the muffle furnace, following the heat treatment profiles listed in Table 2. Maximum temperatures of 105, 250, 500, 750, and 1000°C were investigated. Each sample was subjected to a rapid increase in temperature, held at the peak temperature for 1 hour, cooled, and transferred for testing. After the heating period the samples were removed from the muffle furnace and placed in a desiccator to cool. Samples heated to temperatures above 500°C were allowed to cool in the furnace to 200°C before transfer to the desiccator. The necessary pre-treatment meant that all samples were disturbed by handling steps. Therefore, only characteristics unrelated to soil structure were investigated in this study.

2.2 Laboratory Testing

Particle density was measured using the gas-jar method suitable for coarse soils (BS1377-2:1990). A sample of 1000g mass was placed in a 1L gas jar with approximately 500mL of water. The sample was set aside for 4hr and then shaken end-over-end for 30 min. The gas jar was filled with water fully. The average particle density was determined based on the mass of the sand, mass of the water and volume of water displaced by the sand.

Minimum density was measured using 1000g of sand in a 1L glass measuring cylinder with 20mL graduation (BS1377-4:1990). The cylinder was shaken to loosen the sand and inverted four times. The cylinder was then inverted until all of the sand was at rest, returned to the initial position and carefully placed on a flat surface. The volume was recorded at the mean level of the surface to the nearest 10ml. The test was repeated 10 times with the same sample. The minimum density was calculated using the greatest volume reading in the cylinder (BS1377-4:1990).

Maximum density was determined using the vibrating hammer method (BS1377-4:199). Approximately 3000g of sand were placed in a bucket with warm water and thoroughly stirred to remove any air bubbles. The sand was left to cool overnight. A 1L compaction mould was used for all density measurements. The mould was placed in a water tight container on a solid base. Water was poured into the mould to 50mm depth in the mould body and the surrounding container. A portion of the sand-water mixture was carefully added to the mould, approximately filling a third of the mould after compaction. Water was added to the surrounding container to match the water level in the mould. The vibrating hammer used a circular tamper was to compact the sand for at least 2min using a force between 300N and 400N on the sample. This process was repeated for the other 2 layers to fill the mould. The masses of sand and water in the mould were used to determine the maximum density.

Particle size distribution for the sand was determined using a dry sieving method (BS1377-2:1990). Approximately 200g of each sample was placed into the top of set of sieves that included 1.18mm, 600µm, 425µm, 300µm and 212µm sieve sizes. The set of sieves was shaken for 10 min. The mass of sand retained on each sieve was used to determine the particle size distribution. Particle size distribution was carried out in triplicate for each material.

The silica sand pH was tested using 30g of silica sand and 75mL of distilled water in 100mL glass beaker. The mixture was agitated, covered and left overnight at 19°C room temperature. The mixture was agitated again right before the measurement of pH.

A modified falling head test was used to measure infiltration profile and falling head rate. A cylindrical tube (50cm H x 6cm OD) was filled with sand to height of 30cm. Using a funnel and diffuser system, a volume of 170mL of distilled water, which corresponded to a head of water of 60mm, was added to the top of the cylinder and allowed to flow into the sand. Falling head was measured as the time of this 60mm head of water reaching fixed increments on the column as it infiltrated into the sand column. The set-up for this experiment is shown in Figure 1.

Capillary rise was tested using a cylindrical tube (9.3cm H x 2cm OD) with a fine mesh fitted over the bottom. The cylinder was filled with approximately 50g of sand, placed above a reservoir filled with water and slowly lowered until it made contact with the water surface. To ensure a stable set up the tube was held in place with a clamp system. The water was drawn into the sand through capillary forces and the final height was measured once the water level in the tube was observed to remain constant for 2min. Capillary rise measurements were carried out in triplicate for each material.

The mineralogical composition of the silica sands was tested by BRUKER D8 ADVANCE with DAVINCI (2010) powder X-Ray Diffraction (XRD) on crushed samples. Vibrational spectroscopy using Raman measurements were taken on individual silica sand grains. The Raman spectra were measured suing a Renishaw inVia Raman Microscope running from 240 to 2000cm^{-1} argon beam of 514nm, 2400 l mm^{-1} (vis) grating, 10 exposure times, 1 accumulation and 10% power (cross-polar) was used for excitation.

3. Results and Discussion

3.1. Mineralogy

During the heat treatment testing and after smouldering remediation, a colour change of the silica sand was observed (Figure 2). Exposure of this material to high temperatures results in colour change from yellowish brown to reddish brown with increasing temperature for the silica sand grains and a change from yellow to pinkish red for the crushed silica sand. This colour change is associated with the dehydration reaction of goethite with increasing temperatures to form hematite or maghemite.

During the dehydration reaction of goethite, the density of the iron-hydroxide increases from 4.3 mg/m^3 for goethite to 5.2 mg/m^3 for hematite (Wenk and Bulakh, 2004). The sand is comprised primarily of silicon dioxide; iron oxides make up a small fraction of its composition. High temperatures may cause additional changes in mineralogy that may be less likely to be detected by visual examination (Goforth et al., 2005; Pomiès et al., 1998). Similar effects may occur within the silicon dioxide, which becomes unstable with high temperatures and forms silica polymorphs such as trydimite or cristobalite (Hand et al., 1998; Wenk and Bulakh, 2004). Thermal treatments (100-1200°C) on fly ash showed that cristobalite becomes present in the samples and that smaller particles had a more glassy composition due their faster cooling time (Mollah et al., 1999).

Analysis of the silica sands by x-ray diffraction showed that both, iron oxide and quartz minerals are affected by heat treatment and smouldering remediation (Figure 3). Due to the high quartz content, the signal of the iron-oxides is small, but shifts are apparent. Shifts in quartz are apparent in the smouldered samples. For example, the quartz peaks from 2θ = 36 to 46 are very low for the smouldered samples. Glass is amorphous and cannot be excited by XRD analysis. The quartz in the sand grains exposed to smouldering remediation may be losing its crystal structure.

Due to the nature of the excitement in XRD analysis, XRD cannot distinguish between quartz and its polymorphs as they have the same composition with a different structure. The formation of polymorphs was examined by Raman spectroscopy, a technique that allows a more targeted analysis of the grain surfaces (Komorida et al., 2010). After exposure to 1000°C, trydimite and hematite were observed and after smouldering remediation, trydimite, crystobalite, dumortierite, and hematite were observed (Table 3). Trydimite and cristobalite have flatter structures than α-quartz. Mineralogy changes were not observed in Raman measurements at lower temperatures, though small shifts were apparent in x-ray diffraction spectra. Raman analysis on thin sections prepared of sand grains showed no polymorphs, suggesting that the effect remains at the surface.

Use of the Bruker XRD instrument required crushing of the sand grains, effectively diluting any surface changes. Raman spectroscopy was carried out under microscope and limited by the selection of single points for analysis. The extent of changes seems to be increasing with increasing temperature, as expected. More analysis is necessary to fully understand the exposure conditions that trigger these changes to the grain surfaces and how these changes may affect the grain-grain and grain-water interactions, particularly in more complex soils.

3.2. Particle and Bulk Densities

In contrast to mineralogy, elevated temperatures did not seem to affect the particle density or minimum/maximum bulk densities of the silica sand (Table 4). No real relationship was apparent between treatment temperature and density. For the particle density, the values are consistently near 2.65mg/m^3, which is a value that is widely used in geotechnical engineering calculations. The maximum and minimum densities are equally unaffected by heat treatment or smouldering. These observations are not consistent with the literature on wild and forest fire effects on soil properties, which suggests that bulk density would increase with temperature (Are et al., 2009; Certini, 2005). The lack of organic matter may explain the contrast. Organic matter is highly-affected by elevated temperature and thus organic-rich soils may exhibit density changes after exposure. Temperatures in the range of 260 – 370°C are linked with melting and decomposition of organic matter and temperatures in excess of 370°C are linked with complete or near-complete destruction (DeBano, 1981; DeBano, 2000; Robichaud and Hungerford, 2000). The results in this study, which show no significant change in density, suggest that the changes in soil density that are observed after wildfires are associated primarily with effects on organic matter and potentially the smaller silt and clay–sized particles.

3.3. Particle Size Distribution

Particle size analyses suggest that heat treatment has a small but appreciable effect on grain distribution (Table 4). The sieve analyses show that the sample retained on the 1.18mm sieve increases from 94.4%±0.7% for the untreated sample to 95.5%±1.2% for treatment at 250°. After this initial increase, the sample retained on the 1.18mm sieve decreases to 94.0%±0.4% and 93.3%±0.9%, as exposure temperature is increased to 500°C and 1000°C, respectively. Corresponding measurements on sieves <1.18mm show an initial decrease from 5.3%±0.6% to 4.1%±1.2% for the untreated sample to 250°C heat treatment, followed by an increase to 5.6%±0.4% and 6.2%±0.8%, for 500°C and 1000°C, respectively. Figure 4 shows the impact of temperature on the fines fraction <600μm, which increases with increasing temperature. Collection of the sand samples after smouldering remediation involved multiple handling steps, all of which resulted in visually - apparent mobilisation of fines. Thus, these sands were not tested for particle size distribution.

The variation in particle size distribution may be linked to the loss of mass beyond the initial moisture content (Table 4). In the mass loss tests, samples were prepared to 5% moisture content and then treated according to the temperature specified. As temperature increases, mass loss increases, exceeding the initial 5% added moisture for temperatures above 500°C. Although there is a dehydration reaction from goethite to hematite, the fraction of iron oxide relative to the total composition of the sand is too small for this reaction alone to account for the whole additional mass loss. Other mineralogical reactions are likely to contribute to this loss in sample mass. Further investigation is necessary to identify and quantify the mineral changes that are occurring. The changes in particle size distribution can affect larger-scale behaviour of soil such as compaction.

Further fractionation of the sand after heat treatment shows that as temperature increases, fines are recovered across a wider range of size fractions (Table 3). These results show that with increasing temperature the particle size distribution of the sand is extended, which is in accordance with results from thermal desorption tests on sands (Araruna Jr et al., 2004). Based on the same mineralogical composition of fines after the thermal desorption, Araruna Jr. et al (2004) argue that the fines are the product of grains breaking with exposure to higher temperatures. This is a possibility, but not the only explanation that should be considered here. Mobilisation of clay deposits on the sand grains, which would lose their bonds with the sand particles during thermal treatment, may affect the particle size distribution. The potential for clay mobilisation was explored with a set of experiments involving sand-clay mixtures. With moisture, clay was observed to coat the sand grains for temperatures up to 500°C and that this coating is lost for temperatures above 750°C (Figure 5). This supports the theory that the bond between the fines and sand grains is lost and that this causes the extension in particle size distribution. This bond appears to be driven by presence or loss of moisture. It is therefore likely that this effect can occur during thermal and smouldering treatment. At this point, the data are inconclusive to eliminate the potential for breaking of the grains under high temperature, particularly as handling steps release fines into the air as dust, but the clay experiments illustrate the potential that increased fines can result from clay mobilisation.

3.4. Water Dynamics

Water dynamics in the sand was measured with two separate but interrelated tests: falling head and capillary rise. These tests were conducted to show how temperature and smouldering affect interaction of silica sand and water. The falling head test results show that heat treatment has a minimal effect on the sand permeability. For the untreated and heat treated samples, the change in head over time follows approximately the same profile. In contrast, the smouldered sample shows a much steeper profile (Figure 6). Water moves much more rapidly through the smouldered sand. The entire column of water disappears into the sand in 7s and drainage from the column is observed after less than 20s. The delay in the first measurement of head height for the smouldered sand is due to this rapid infiltration. Approximately 50% of the total volume of water infiltrates into the sand as the total volume is delivered to the top of the sand column. In contrast, 17-22% of the total volume of water infiltrates during initial delivery to the other treated and untreated sand columns. In addition, drainage from the smouldered sand is noticeably discoloured with particulates. Channelling is observed in the column and lateral propagation is not evident, though some water is retained in the pore space after infiltration and excavation. These differences in falling head behaviour are not represented in the correlating hydraulic conductivity values, which are on the order of 10^{-4}m/s for all samples (Table 5).

Differences are observed in the capillary rise test when comparing the heat-treated and smouldered sand samples (Table 5). While capillary rise is present in all samples, the capillary rise is lower in the smouldered sample. As the temperature of thermal treatment is increased, the resulting capillary rise after cooling and exposure to the water bath increases as well. Capillary rise is consistent or greater in compacted samples, which may reflect the presence of small clay aggregates in the pore space, which is consistent with the changes observed in particle size distribution. The voids between the grains may have decreased to some extent and therefore caused the capillary forces to increase. In the smouldered sample, the capillary rise in both uncompacted and compacted states is below that observed in all other samples. This difference suggests greater void spaces between the grains, potentially changed contact angles, and less capillary forces, all of which may be influenced by the mobilisation of fines and other potential changes to the grain surfaces.

Heat treatment showed slight influence on the silica sand pH, which remained slightly alkaline between 7.8 and 8.2 (Table 5). The pH of the sand after smouldering remediation had shifted to slightly acidic. This change in pH is likely to be caused by the coal tar contamination present before smouldering and the chemical reactions that take place during smouldering. Decreased pH is associated with decreased cation exchange capacity in the soil, which is, in turn, linked to water holding capacity. Based on the heat treatment results, similar effects are expected in soil treated by smouldering remediation, though the presence of organic matter in the soil and its potential melting or destruction during remediation will affect pH as well. Though soil pH affects grain-water interactions, the changes in infiltration cannot be explained by pH change alone, particularly as saturated hydraulic conductivity is not observed to change as a result of high temperature exposure or smouldering remediation (Table 5). Sand after smouldering has small amounts of chemical residue, typically below detection limits (Switzer et al., 2009). The nature and extent of the residue is unknown, which challenges the decoupling of physical and chemical influences on water infiltration. Although hydraulic conductivity was not observed to be affected by heat treatment or smouldering, the mobilisation of fines was apparent in the effluent water of the tests carried out on 750°C, 1000°C, and smouldered sands.

3.5. Summary and implications of soil changes

High temperature processes impact the dynamic properties of soils. The results outlined above highlight the sometimes contradictory responses to high temperature exposure, particularly water dynamics. The differences in void spaces do not fully explain the differences that are observed in the falling head infiltration profiles. The changes in mineralogy, especially on the grain surfaces in combination with a change in pH suggests a relationship that are visible in all treated samples through colour change do not correlate to the changes observed in dynamic behaviour as the sand is introduced to water. These results suggest that colour change alone cannot be used as an indicator of potential changes in soil behaviour.

Mobilisation of fines is a concern in all cases as a loss in soil mass can result in a loss of soil stability. Heat treatment above 500°C has been shown to weaken and soften sandstones under loading, an effect that is linked to dehydroxylisation of kaolinite (Ranjith et al, 2012). No such effects were observed here, but samples were not subjected to load and all materials were allowed to cool prior to testing. Further testing would be beneficial to explore the effects on soils that are exposed to heat and subjected to loading, particularly in the context of remediation under existing infrastructure. Even though post-remediation soil is affected by reduced water holding capacity and capillary rise, it should still be amenable to stabilisation techniques. The cation exchange reactions of lime stabilisation may be impaired, but other aspects of the remediation process may aid stabilisation. Lime stabilisation has been shown to improve the compressive strength of quartz sand, increased curing time has been shown to enhance this improvement, and elevated temperatures have been shown to enhance curing and ultimate strength achieved (Bell, 1996). Because of their thermal inertia, post-remediation soils are slow to cool. Reductions in lime uptake may be counterbalanced by strategic use of soil stabilisation techniques during the cooling process after remediation, particularly if the installation new infrastructure after remediation is desired. Further work on the combination of aggressive remediation and soil stabilisation processes would be beneficial to determine if integration of these processes could optimise their benefits.

While further study into the links between changes in micro-scale properties and macro-scale behaviour is needed, this work illustrates the importance of understanding the effects of high temperature processes on fundamental soil properties. Further work can explore extended exposure times more reflective of thermal remediation techniques as well more complex soil compositions. This work suggests that the effects of elevated temperatures on soil properties should be considered as part of remediation planning and mitigation measures may be appropriate in the soil during or after exposure.

4. Conclusions

High temperature exposure in the form of thermal treatment and smouldering remediation result in changes to soil properties. Some links between grain-scale characteristics and dynamic behaviour have been established. After exposure of sand to elevated temperatures, particle size distribution increases and a related increase in capillary rise is observed as well. Water infiltration does not seem to be affected by elevated temperature, though this observation may be a function of exposure duration. Sand exposed to smouldering remediation exhibits more rapid water infiltration from the surface. Changes in mineralogy are visible in all treated samples in the form of colour change as goethite is oxidised to hematite. Changes to the quartz crystal structures are observed at an exposure temperature of 1000°C. and maghemite. Colour change alone cannot be used as an indicator of potential changes in soil behaviour. Mass loss increases with increasing temperature and may be related to the mineralogical processes such as the dehydration of iron oxides, mobilisation of fines, and changes in quartz structure. Smouldering treatment has similar effects, perhaps more rapidly due to the higher temperatures achieved. In contrast to these results, thermal and smouldering treatment show minimal effects on silica sand particle and bulk densities. The changes in soil properties may result in altered dynamics between soil aggregates in the field. The effects of high temperature remediation on field soils are anticipated to be more complex as other soil fractions may be more susceptible to heating effects. Further investigation of the effects of high temperature exposure on soil fractions and whole soils, especially from field sites where aggressive remediation processes have been applied, is necessary to fully understand the impact of these processes on soils. After exposure to high temperature or smouldering remediation, soils should remain amenable to improvement with soil amendments. Follow-up investigation and monitoring after exposure is important to understand the extent of impacts and mitigation measures that may be necessary.

Acknowledgements

The authors gratefully acknowledge financial support of the University of Strathclyde in the form of a Faculty Scholarship for Ms Zihms as well the valuable assistance from colleagues at the Universities of Strathclyde, Glasgow, Edinburgh, and Western Ontario as well as SiREM. In particular, we wish to thank Peter Chung for his assistance with the Raman analysis and Ross Blake and Ursula Skordou for their help with some of the physical characterisation tests. Smouldering combustion of liquids is a patented remediation process (PCT Application PCT/GB2006/004591 priority date 10 December 2005 (awarded in the USA as US/8132987) and PCT/US2012/035248 – priority date 29 April 2011).

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Table 1. Possible maximum temperatures of exemplar moderate to high remediation techniques
[1] Maximum temperature is associated with contaminant type and treatment conditions

Table 2. Heat treatment conditions for silica sand
[1] Cooling period varied for each batch so approximate duration is shown.

Table 3. Exemplary mineralogy of points on sand grain surfaces after selected heat treatments

Table 4. Particle density, minimum and maximum bulk density, particle size distribution, and mass loss observed in silica sand after exposure to elevated temperatures or smouldering remediation
[1] Not Determined (ND)

Table 5. Capillary rise height, void ratio, saturated hydraulic conductivity, and pH values for silica sand retained on the 1.18mm sieve

Figure 1. Schematic diagram of the modified falling head test apparatus

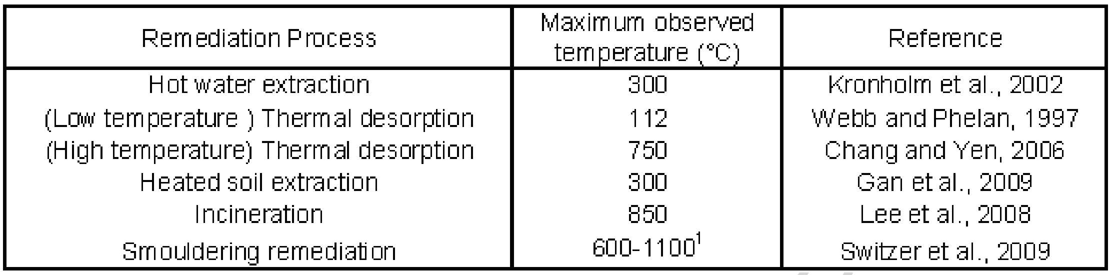
Figure 2. Colour change observed in silica sand grains after heat treatment.

Figure 3. X-ray diffraction spectra for silica sand after thermal and smouldering treatments

Figure 4. Figure 4. Mobilisation of particles smaller than 0.600mm from sand exposed to heat at 250, 500, 750, and 1000°C. Particles between 0.600 and 2.36mm make up 99.7 – 99.9% of the particle size distribution in all cases.

Figure 5. Percentage of sand and sand/clay sample masses retained on the 1.18mm sieve after heat treatment and dry sieving

Figure 6. Head loss (mm) observed over time in untreated sand, heat-treated sand, and sand after contamination with coal tar and smouldering remediation

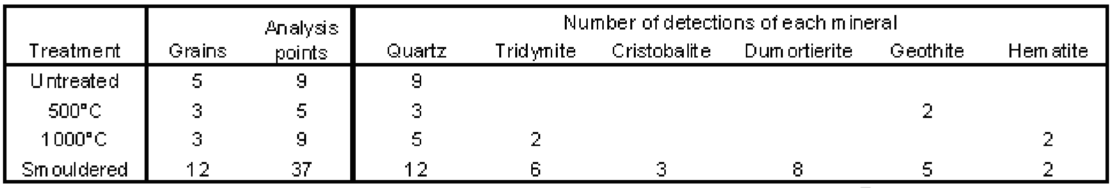


Remediation Process	Maximum observed temperature (°C)	Reference
Hot water extraction	300	Kronholm et al., 2002
(Low temperature) Thermal desorption	112	Webb and Phelan, 1997
(High temperature) Thermal desorption	750	Chang and Yen, 2006
Heated soil extraction	300	Gan et al., 2009
Incineration	850	Lee et al., 2008
Smouldering remediation	600-1100[1]	Switzer et al., 2009

Table 1

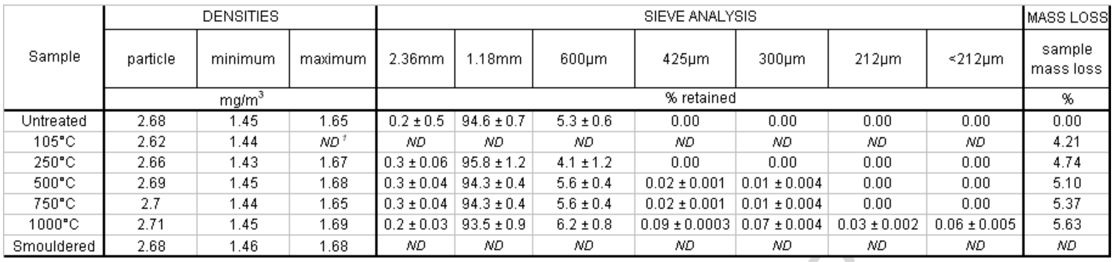
Maximum Exposure Temperature (°C)	Pre-heating duration (min)	Peak temperature exposure duration (min)	Cooling period duration (min)
Untreated	-	-	-
105	30	1440	0
250	30	60	0
500	30	60	~60[1]
750	60	60	~180
1000	60	60	~240

Table 2



Treatment	Grains	Analysis points	Number of detections of each mineral Quartz	Tridymite	Cristobalite	Dumortierite	Geothite	Hematite
Untreated	5	9	9					
500°C	3	5	3				2	
1000°C	3	9	5	2				2
Smouldered	12	37	12	6	3	8	5	2

Table 3



Sample	DENSITIES			SIEVE ANALYSIS							MASS LOSS
	particle	minimum	maximum	2.36mm	1.18mm	600μm	425μm	300μm	212μm	<212μm	sample mass loss
	mg/m^3			% retained							%
Untreated	2.68	1.45	1.65	0.2 ± 0.5	94.6 ± 0.7	5.3 ± 0.6	0.00	0.00	0.00	0.00	0.00
105°C	2.62	1.44	*ND*[1]	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	4.21
250°C	2.66	1.43	1.67	0.3 ± 0.06	95.8 ± 1.2	4.1 ± 1.2	0.00	0.00	0.00	0.00	4.74
500°C	2.69	1.45	1.68	0.3 ± 0.04	94.3 ± 0.4	5.6 ± 0.4	0.02 ± 0.001	0.01 ± 0.004	0.00	0.00	5.10
750°C	2.7	1.44	1.65	0.3 ± 0.04	94.3 ± 0.4	5.6 ± 0.4	0.02 ± 0.001	0.01 ± 0.004	0.00	0.00	5.37
1000°C	2.71	1.45	1.69	0.2 ± 0.03	93.5 ± 0.9	6.2 ± 0.8	0.09 ± 0.0003	0.07 ± 0.004	0.03 ± 0.002	0.06 ± 0.005	5.63
Smouldered	2.68	1.46	1.68	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*

Table 4

Sample	Capillary Rise Height (mm)		void ratio		Hydraulic Conductivity K (m/s)	pH
	uncompacted	compacted	uncompacted	compacted		
Untreated	20.63 ± 4.13	20.63 ± 1.38	0.67	0.63	$9.6 \pm 0.6 \times 10^{-4}$	8.2
105°C	20.63 ± 4.13	20.63 ± 1.38	0.66	0.63	$7.0 \pm 0.5 \times 10^{-4}$	8.1
250°C	22.00 ± 0.00	23.38 ± 2.37	0.67	0.64	$5.2 \pm 0.7 \times 10^{-4}$	8.0
500°C	22.00 ± 2.75	23.38 ± 1.59	0.67	0.68	$5.5 \pm 0.7 \times 10^{-4}$	7.8
750°C	23.38 ± 1.27	23.38 ± 1.59	0.67	0.64	$5.0 \pm 0.6 \times 10^{-4}$	7.9
1000°C	22.63 ± 0.00	26.13 ± 1.38	0.67	0.61	$5.0 \pm 1.0 \times 10^{-4}$	7.8
Smouldered	16.50 ± 3.50	19.25 ± 0.00	0.70	0.63	$7.3 \pm 0.4 \times 10^{-4}$	6.1

Table 5

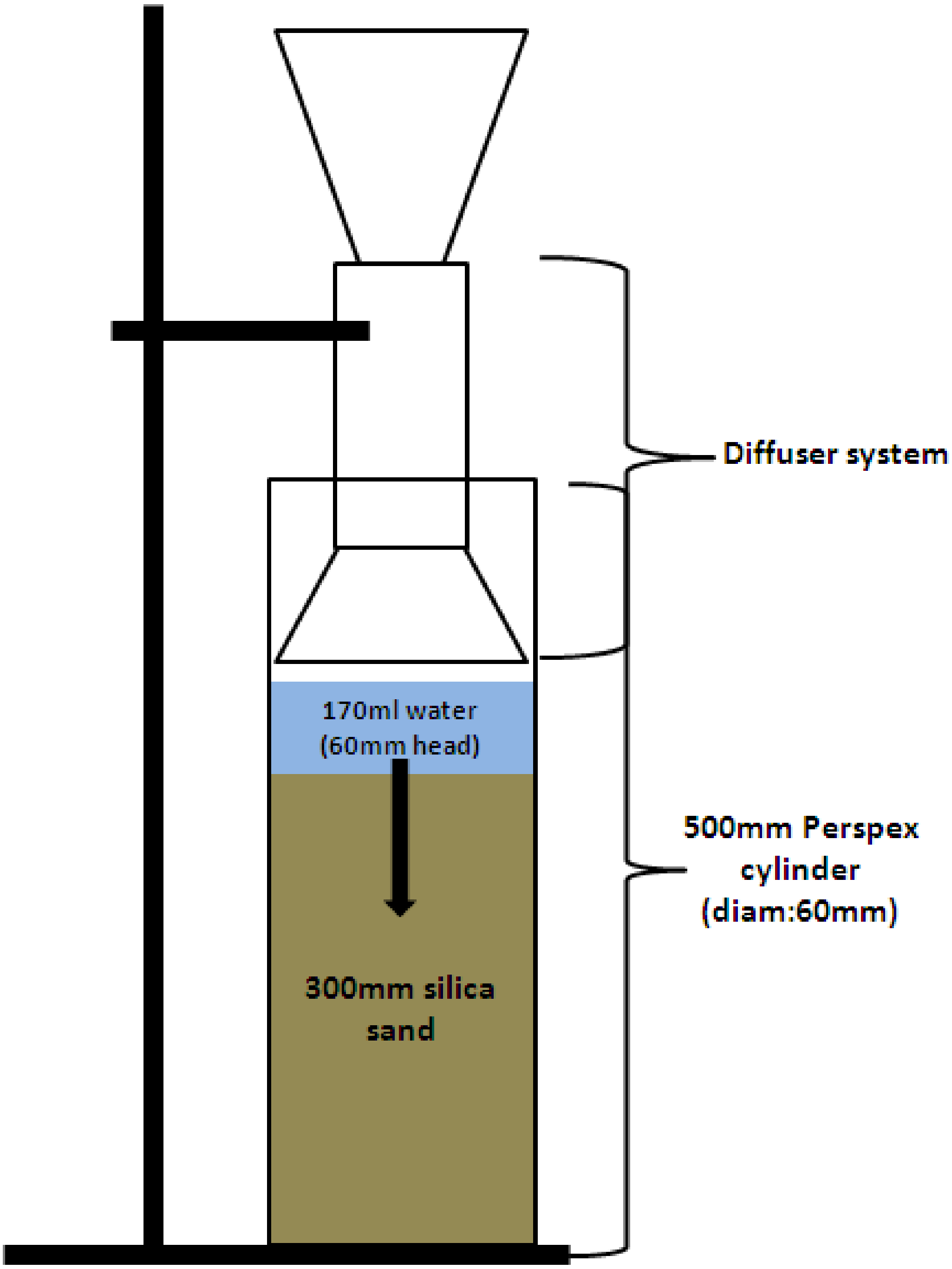

Diffuser system
170ml water
(60mm head)
300mm silica
sand
500mm Perspex
cylinder
(diam:60mm)

Figure 1

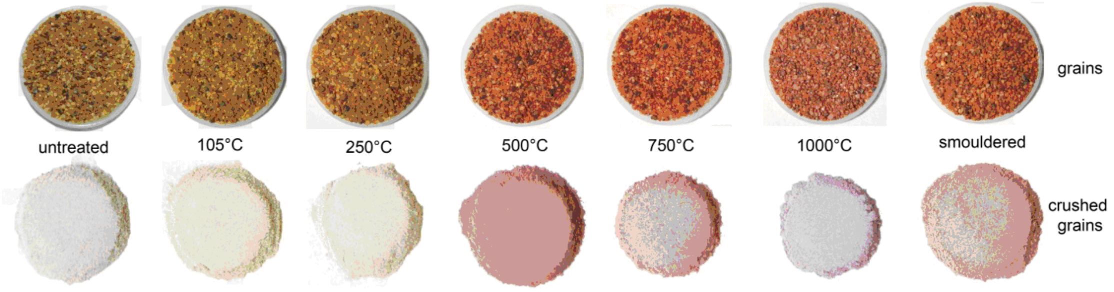

untreated
105°C
250°C
500°C
750°C
1000°C
smouldered
grains
crushed grains

Figure 2

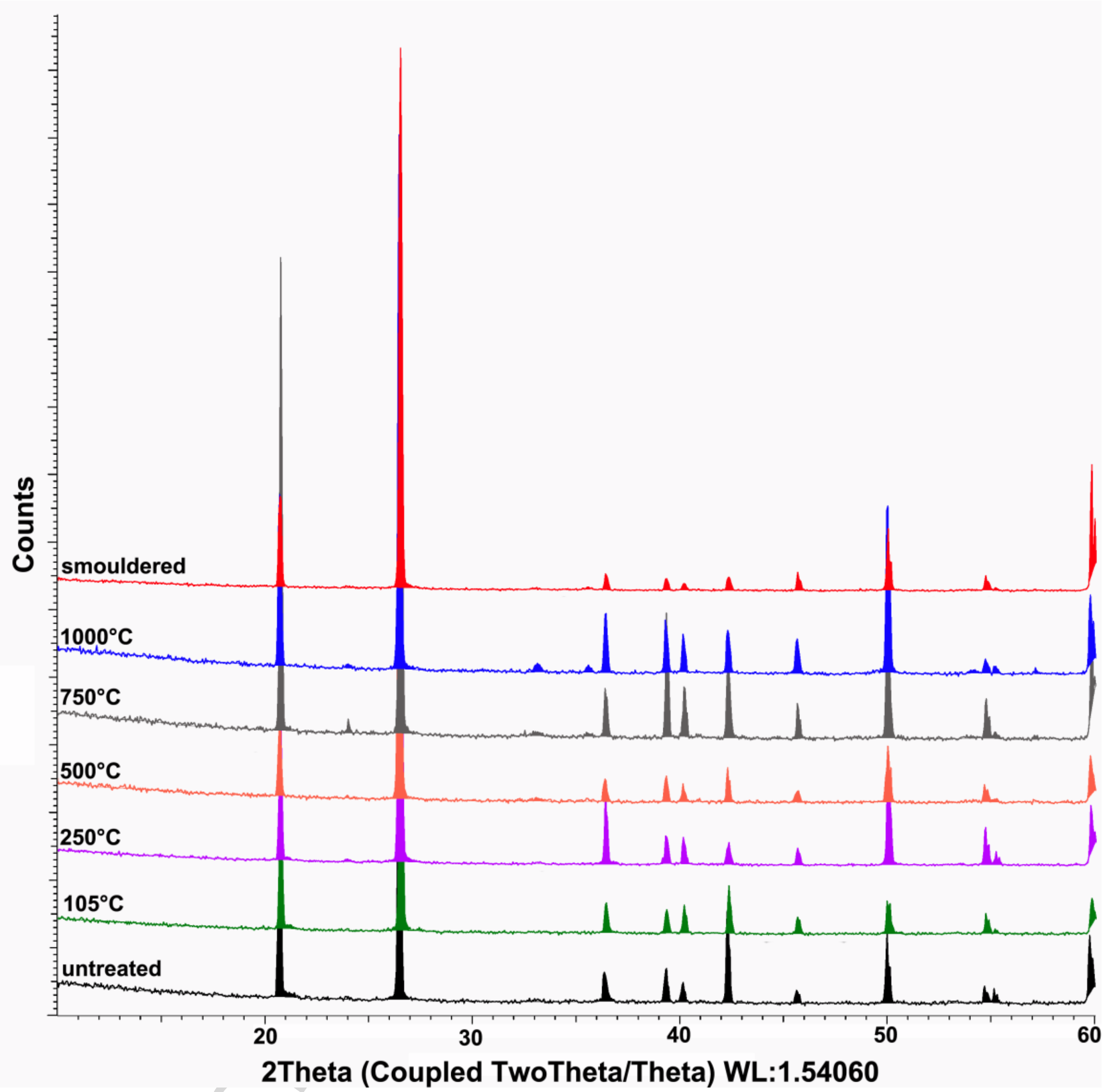

Counts
smouldered
1000°C
750°C
500°C
250°C
105°C
untreated
20
30
40
50
60
2Theta (Coupled TwoTheta/Theta) WL:1.54060

Figure 3

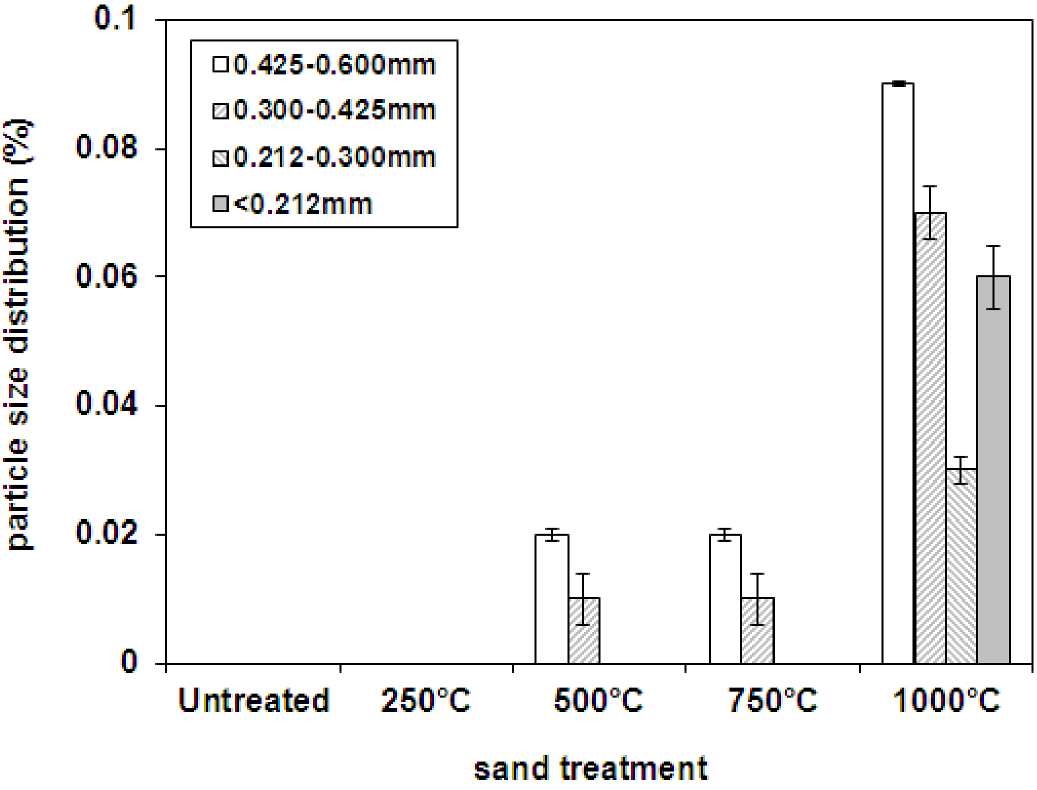

0.1
0.08
0.06
0.04
0.02
0
particle size distribution (%)
0.425-0.600mm
0.300-0.425mm
0.212-0.300mm
<0.212mm
Untreated
250°C
500°C
750°C
1000°C
sand treatment

Figure 4

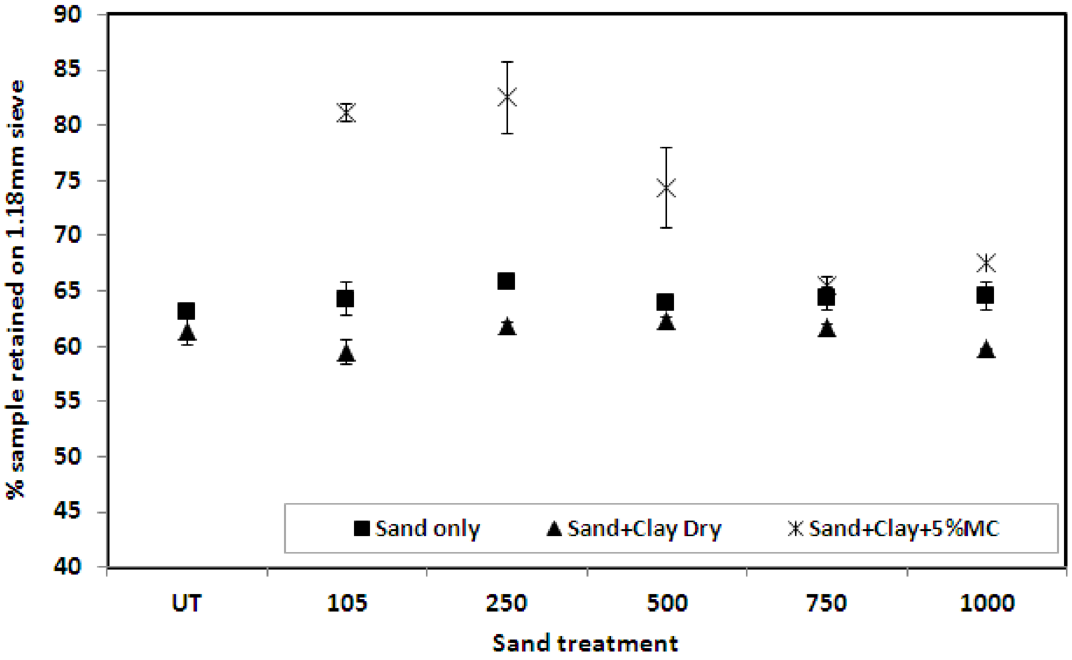

% sample retained on 1.18mm sieve
90
85
80
75
70
65
60
55
50
45
40
■ Sand only
▲ Sand+Clay Dry
⚹ Sand+Clay+5%MC
UT
105
250
500
750
1000
Sand treatment

Figure 5

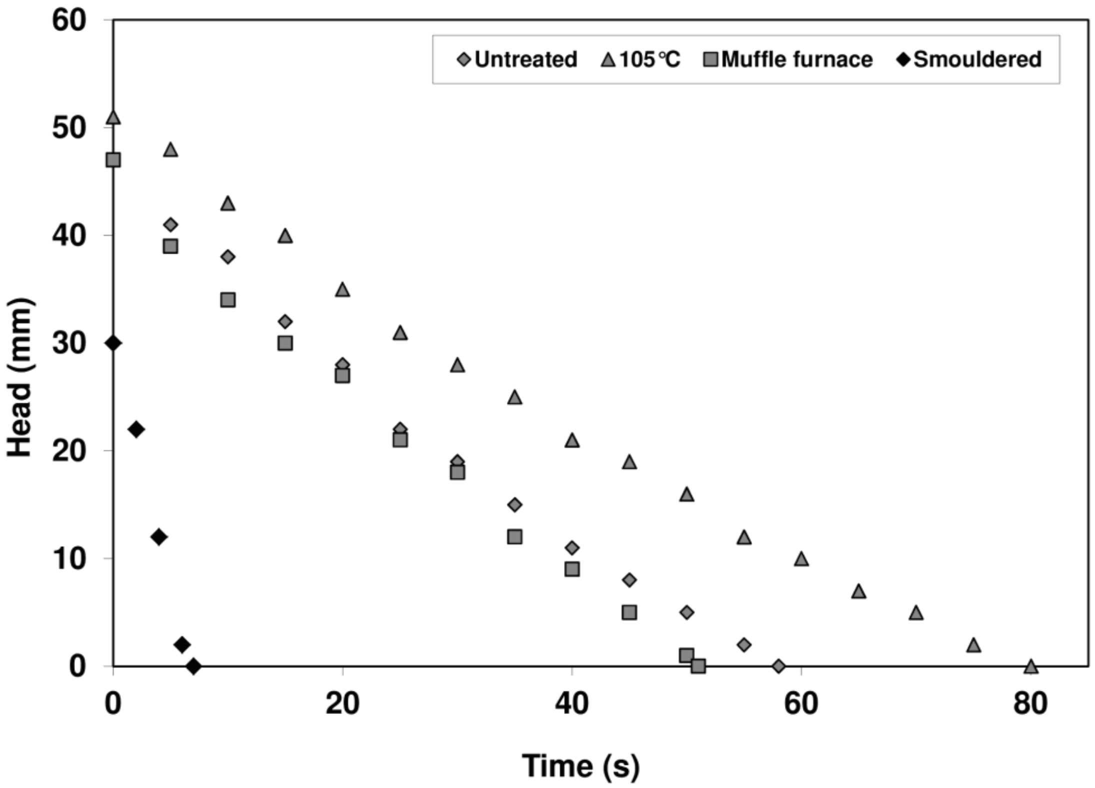

◆Untreated
△105°C
■Muffle furnace
◆Smouldered
Head (mm)
Time (s)
0
10
20
30
40
50
60
0
20
40
60
80

Figure 6

Highlights

- We examine potential changes in soil properties from high temperature remediation.
- Mineralogy, particle size distribution, and permeability are most affected.
- High temperatures change mineralogy at the grain surface and mobilize clay fines.
- Grain-grain and grain-water interactions are affected.
- Density is unaffected, but this may be different in soils with more internal pores.