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Effects of high temperatures on soil properties: Lessons to share from smouldering remediation experience

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Abstract

Aggressive, high-temperature contaminant remediation processes such as smouldering remediation are growing in popularity as technical knowledge of their capabilities becomes more widespread. Smouldering remediation is most aggressive of these processes and exposes soils to temperatures across the range of 500-1000 °C for hours to days, displacing water and destroying in excess of 99.9% of contaminant mass. The high temperatures and aggressive chemical reactions result in significant changes to the soil properties, particularly at the particle surface. Shifts in soil geochemistry, mineralogy, and structure are observed. Micro computed tomography shows that grain surfaces become significantly smoother after remediation. The changes are more extensive than initial mineralogy testing had suggested. Increased smoothness affects grain-grain and grain-water interactions and may explain some of the dynamic changes in infiltration, permeability, cohesiveness, and strength that have been observed in soils after smouldering remediation. Understanding these effects is essential to link micro-scale changes to macro-scale behaviour and develop a holistic approach to contaminated soil remediation and reuse. Important analogies can be drawn to the effects of fires on soil properties.

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1 INTRODUCTION

Smouldering remediation is a recently-developed, beneficial application of combustion to address soils and other porous materials that are heavily contaminated with hazardous organic liquids (Pironi et al., 2011; Pironi et al., 2009; Switzer et al., 2009). Smouldering remediation subjects soils to temperatures of 500-1000 °C for periods of minutes, hours, or days depending on operational scale and can remove 99.9% of contaminant from the soil (Switzer et al., 2009). These temperatures exceed the range of study in previous literature and are expected to have significant effects on soil properties. Characterising the effects is essential as part of a holistic approach to remediation and reuse of contaminated soils.

On a visual level, the effects of smouldering remediation are similar to the effects of wildfires on soil properties (Figure 1). Characteristic reddening is observed in iron-rich materials after exposure to high temperatures (Goforth et al., 2005; Ketterings and Bigham, 2000). Soils exposed to temperatures in the range of 200-250 °C during wildfires may develop water repellency as soil organic matter melts into soil pores; repellency tends to disappear above exposure temperatures of 250 °C (DeBano, 2000). Soils contaminated heavily with organic liquids have some inherent water repellency, which disappears as the contaminant is destroyed by remediation. Typically for smouldering processes, heat losses and oxidiser flux are the most influential parameters (Ohlemiller, 1985); these are the dominant factors affecting the initiation and outcome of smouldering remediation.

Using coarse quartz sand as a simple soil with relatively homogenous composition and minimal internal pore structure, significant shifts in mineralogy were observed with exposure to high temperatures and particularly smouldering remediation (Zihms et al., 2013). Shifts from α-quartz to tridymite were observed above 750 °C. After smouldering remediation, changes to the grain surface were more apparent with more detections of cristobalite and trydimite as well as a strong decrease of α-quartz. The hypothesis of the work presented here is that the extreme temperatures encountered during the smouldering remediation process result in a net smoothing of the grain surfaces. This hypothesis was tested systematically through the application of micro computed tomography (Micro CT).


Figure 1. Smouldering remediation of coal tar in made ground. This is the top view into the excavation of a horizontal air injection experiment. The sharp transitions from remediated material in the centre to material that was unaffected by the process are evident, particularly on the left-hand side.

2 METHODS

The smouldering remediation process was developed with commercially-available coal tar (10/15 EVT, Koppers, Scunthorpe Works, UK) and coarse sand (Leighton Buzzard 8/16 sand, Sibelco, UK) as an idealized base case and extended to other contaminant and soil types (Pironi et al., 2011; Switzer et al., 2009). This work returns to the base case of coal tar in sand to explore changes to grain surfaces.

A large-scale experiment was conducted in a 3m^3 chain-lift style dumpster (bottom footprint of 1.68m x 1.97m). Igniters and four air injection devices were placed at the bottom of the experimental vessel and covered with coarse sand. The vessel was filled with coal tar and sand mixtures prepared in batches that combined 75kg of sand with approximately 5L of coal tar. A total of 5t of sand at a concentration of 31000mg/kg total extractable petroleum hydrocarbons was used in this experiment (SiREM, 2010). The coal tar and sand mixture was covered in an additional layer of clean sand to absorb expanding liquids. Clusters of thermocouples were embedded throughout the vessel to track smouldering progress. Smouldering was initiated by preheating to a pre-determined temperature near the igniters and then injecting air at a rate of 2800L/min through the air diffusers. Once the smouldering front was well-developed, the igniters were turned off. Air supply continued until the smouldering process finished.

A sample of sand was set aside for analysis before contamination or remediation. A 10L sample of post-remediation sand was collected from the middle of the experimental vessel. Changes to the sand surface were determined by scanning and generating three-dimensional representations of grain structure with micro computed tomography (Scanco Medical AG, Brüttisellen, Switzerland).

3 RESULTS AND DISCUSSION

During the smouldering remediation process, sand grains were exposed temperatures above 500 °C for a period of approximately 7 hours and reached peak temperatures of 900-1000 °C during the early part of this exposure period. This estimation is based on thermocouple profiles throughout the experimental vessel. The total duration of the experiment was approximately 30 hours including preheating and operation. Contaminant coal tar mass was reduced from 31000mg/kg to 10mg/kg total extractable petroleum hydrocarbons across 5t of cleaned material (SiREM, 2010). The mean propagation velocity of the smouldering front was $3.4 \pm 0.6 \times 10^{-5}$m/s (16 measurements), which is consistent with other observations of smouldering remediation (Pironi et al., 2011; Pironi et al., 2009; Switzer et al., 2009) and smouldering phenomena elsewhere (Rein, 2009).

Micro CT scans of sand grains before and after remediation show clear differences. Figure 2 shows two exemplar Micro CT reconstructions of sand grains with remediation images inset. The surface topography of the post-remediation grain seems significantly smoother than the pre-remediation grain. The images in Figure 2 represent two different grains. While this image shows only two grains, this result was repeatable for more than 100 grains of each sample. The main limitation of this technique is the sample size, which is limited to a few grams of material. It is not possible to track individual grains through the remediation process; however, the reconstructions provide significant support to hypothesis of grain smoothing.

These observations are consistent with previous observations of α-quartz transformations to tridymite and crystobalite (Zihms et al., 2013), which are flatter crystal structures, and may imply some degree of glassification of the grain surface as well. These surface changes have important implications on grain-grain and grain-water interactions, which influence the dynamic behaviour of soils. Differences have been observed in infiltration, permeability, cohesiveness, and shear strength of soils after remediation. Quartz sand is relatively resilient to heat compared to other soil fractions. Initial experiments on kaolin, a non-swelling clay, show that the Atterberg plastic and liquid limits increase significantly at 750 °C and cannot be measured at 1000 °C (Zihms et al., 2013). A combination of de-hydroxylation, aggregation, and sintering is suspected. Effects on silt and other clays may emerge at lower temperatures with more severity. Similar changes may be possible during exposure to fires, though the exposure dynamics may be quite different.

4 CONCLUSIONS

Micro CT images have shown that high temperature smouldering remediation transforms soil surface mineralogy and smoothes grain surfaces. These changes may explain changes that have been observed in dynamic soil grain-grain and grain-water interactions. In quartz sand and kaolin, the most significant effects are observed above 750 °C. Structural changes are anticipated in other soil fractions, particularly swelling clays and silts, at much lower temperatures.

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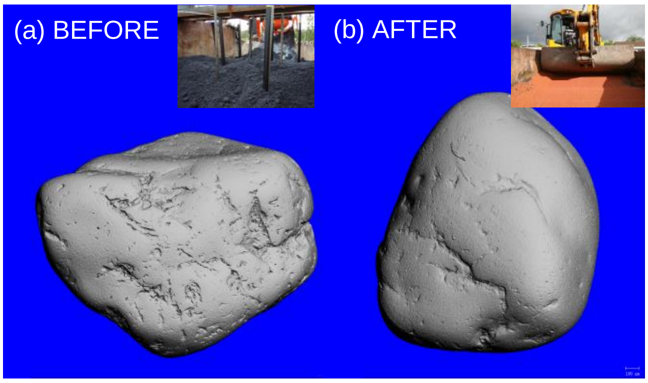

Figure 2. Micro CT surface reconstructions of exemplar sand grains (a) before and (b) after smouldering remediation. Images of the large-scale experiment before and after remediation are inset.

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