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Experimental assessment of the heal-ability of a polymer bonded sand

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HIGHLIGHTS

- Heat injection post-failure in a polymer bonded sand results in partial recovery in strength and stiffness.
- The magnitude of strength recovery under direct shear depends on the normal stress.
- Strength recovery decreases with the number of healing cycles whereas stiffness recovery remains constant.

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ABSTRACT

In-situ healing of cemented materials, as opposed to decommissioning, can extend the service life of civil infrastructure. Heat induced polymer bonding of coarse-grained soils is a novel cementation technique whereby heat is injected into a mixture of ground thermoplastic polymer and soil. The polymer melts into menisci located at particle contacts, and solidifies upon cooling, rendering the soil cemented. The ability of post-failure heat injection to reestablish broken bonds, and hence heal the cemented soil, is evaluated herein via experiments. Results show that heat injection post-failure results in small-strain stiffness recovery of up to 50%. Such recovery is independent on the number of healing cycles (H_N); yet, the unconfined compression strength of remoulded specimens decreases with H_N, suggesting the degradation of the polymer's strength with heating cycles. Direct shear test results reveal that the strength recovery for specimens healed in place, i.e., inside the shear box, is up to ≈30%, independent of H_N, and controlled by the structure of the healed shear band, which is dependent on the normal stress sustained during heat injection.

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1. Introduction

Failure in construction materials is often the result of progressive deterioration in material properties under service loads. Microscopic cracks and defects form and propagate over time, crippling civil infrastructure and triggering decommission and reconstruction. Material healing during service could extend service life and economically reduce the risks associated with catastrophic failures. Thus, material healing has been an active area of research for the last two decades. Concrete, the most widely used construction material in the USA, possesses some natural autogenous healing properties [1]. Autogenous healing is attributed to ongoing hydration of cement particles in 'young' concrete [2,3], and dissolution and carbonation of calcium hydroxide at a later age [3,4]. However, autogenous concrete healing is limited to small cracks (<200 μm) and it is difficult to control [5–7]. Enhanced autogenous healing efforts aim at exploiting concrete's natural ability to re-fill cracks with cementitious products by controlling: (1) crack width [8–10], (2) water supply [11,12] and (3) hydration and crystallization [13–15].

Unlike concrete, lightly cemented sands do not exhibit an interconnected cementitious matrix. Cementitious products concentrate at inter-particle contacts and have significantly higher specific surface area. Therefore, there are significantly less unhydrated cement particles and relatively minor strains can result in complete dislocation of cemented contacts. Manmade lightly cemented soils are therefore, generally sacrificial. They are designed to degrade over time without maintenance until removal and reconstruction are required. However, in certain applications, failure of lightly cemented soils can cause premature failure of more important structural components. In the case of cement stabilized pavement subgrades and bases, for instance, failure of the lightly cemented components can cause premature failure of the surface layer (concrete or asphalt). In the absence of in-service

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healing alternatives, the only option for corrective action is decommissioning and reconstruction.

Heat induced polymer bonding of soils is a novel soil improvement technique whereby heat is injected into a mixture of ground thermoplastic polymer and soil [16,17]. The polymer melts and flows, coating the mineral surfaces. Upon cooling the polymer solidifies and renders the soil cemented. Polymer bonded sands (PBS) have been shown to attain compressive strengths similar to those of lightly cemented sand (i.e., similar binder contents), at a fraction of the embedded energy [16]. Considering that thirty-three million tons of plastic waste are generated every year in the United States of which less than 10% is recycled [18], recycled PBS could offer an economically feasible, environmentally friendly alternative to mineral cements. Not only does the heat induced bonding preclude the use of water (space exploration and construction [19]), but also provides an opportunity for in-service healing. Because the polymer can be re-softened by heating, it is expected that heat injection post-failure can 'heal' the material by re-bonding the grains and thus reestablish strength and stiffness. This paper explores the ability of polymer bonded silica sand to heal as a result of heat injection post failure.

2. Materials

Tests specimens were created using a uniformly graded coarse-grained silica sand composed of rounded grains with mean particle size of 1 mm. The binding agent used was virgin polyethylene (V-PE) with a maximum particle size of 0.52 mm and an average particle size of 0.3 mm (see Fig. 1); thus, $d_{sand}/d_{V\text{-}PE} \approx 3.3$. Round and uniform soil grains were selected to minimize grain shape and gradation effects on strength behavior, and to promote homogeneity in the quality and distribution of contact bonds. Relevant material properties of the two materials are presented in Table 1.

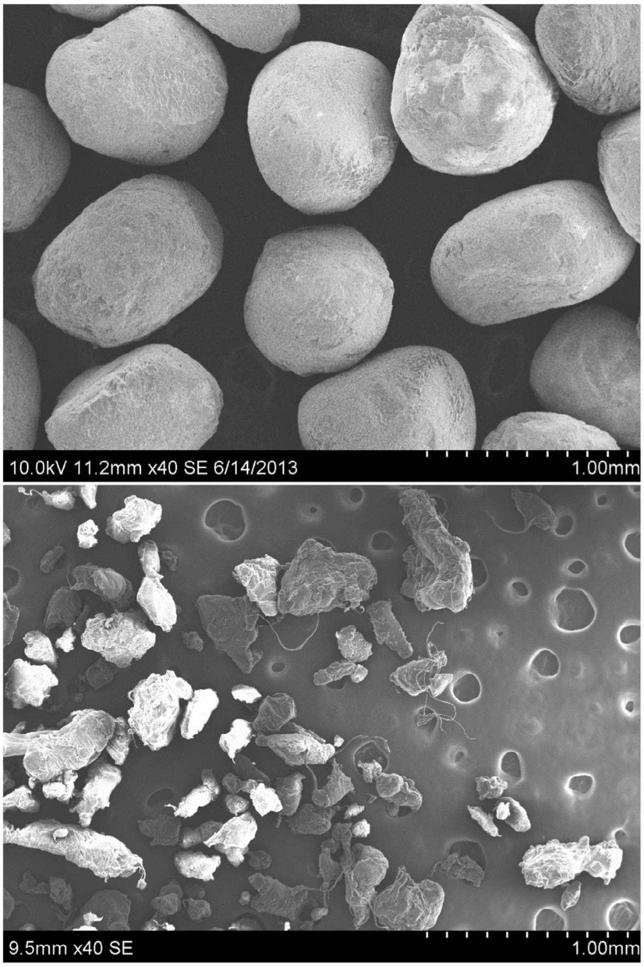

Fig. 1. Uniformly graded round silica sand (top) and angular V-PE particles (bottom); sizeratio = $d_{sand}/d_{V\text{-}PE} \approx 3.3$.

3. Specimen preparation

Cylindrical polymer bonded sand (PBS) specimens were prepared for small-strain stiffness and unconfined compression (UC) tests. Each specimen was prepared by mixing 200 g of sand, 4 g of polymer, i.e., 2% polymer by mass of sand, and 10 g of water, i.e., 5% water by mass of sand. The water hinders segregation and facilitates the transport of polymer fines directly to inter-particle contacts via receding menisci during mixing and latter during heat treatment. The mixture is then placed in three independently tamped layers into a custom cylinder mold 50.8 mm in diameter (Fig. 2-a) lined internally with aluminum foil, so as to allow easy removal of the specimen post bonding. A steel piston is then placed on the specimen to enable placement of a spring that upon compression subjects the specimen to a seating stress of ~10 kPa. The spring loaded specimen is placed inside a programmable oven for heat treatment. Specimens were heated for two hours to 140 °C. Such treatments were determined after preliminary trials conducted to establish thorough bonding, as evidenced by repeatability in preliminary UC tests. The preparation of specimens used for direct shear testing follows the same steps described above, except that specimens where cast inside of a rectangular steel mold with cross section dimensions of 90 mm × 38.1 mm (Fig. 2-b). Examples of prepared test specimens are presented in Fig. 3.

4. Testing

Elastic wave testing was conducted to examine the heal-ability of PBS with regards to small strain stiffness. Tests were performed by placing a pair of Panametrics ×1020 piezoelectric transducers on opposite sides of each cylindrical PBS specimen. A small amount of vacuum grease was used to improve the coupling between the transducers and the specimen. An Agilent DSOX 2004A digital oscilloscope was used to (1) send 60 5-volt peak-to-peak pulses per second to the source transducer (which in turn deforms to send a p-wave through the specimen), and to (2) gather and stack the signals produced by the receiver transducer. Knowledge of the specimen length L and the time difference between the signals sent and received by the corresponding transducers Δt enables the calculation of the p-wave velocity $v_p = L/\Delta t$. The small-strain constrained modulus is computed with knowledge of the mass density as $M = \rho v_p^2$.

UC tests were performed on the same cylindrical specimens tested for small-strain stiffness, using an MTS 810 servo hydraulic load frame, and following ASTM D2166 [26]. Specimens were loaded at a rate of 0.2% strain per minute. Following the first UC test, each specimen was broken down into a granular material by carefully abrading the sides of the broken specimen with a metal spatula. The resulting material was used to cast a new remoulded, "healed" specimen following the same steps used for the initial

Table 1
Physical properties of materials used for testing [20–25].

Parameter	V-PE	Sand
Melting Temperature (°C)	112 ~ 135	1550
Glass Transition Temperature (°C)	−110 ~ −80	–
Young's Modulus (GPa)	0.4 ~ 1.3	73
Tensile Strength (MPa)	21 ~ 35	1000
Specific Gravity	0.945	2.6
Melt Flow Index (g/10 min)	1.872	–

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