7.0 SUMMARY AND CONCLUSIONS

There are numerous examples from the literature in which the penetration resistance of sands increases with time. These increases, called aging effects, have been measured in hydraulically placed fills and freshly densified deposits, with some of the largest increases following the use of ground modification techniques such as vibrocompaction, dynamic compaction, and blast densification. A validated hypothesis for what causes these time-dependent increases in penetration resistance is not available. The objective of this research was to gain an understanding of the possible mechanisms responsible for aging effects in sands. A detailed literature review was performed, which included examples of aging effects from field and laboratory studies and hypotheses that have been proposed to explain these phenomena.

From the literature review, the following was learned regarding time-dependent property increases in sands:

- The increases in penetration resistance following ground modification and in hydraulically placed fills can be significant. In some cases, there is a 100% increase or more in penetration resistance within days or weeks.
- In addition to the cases where penetration resistance was observed to increase with time, there are also a few examples (reported) where no increases occurred.
- There is a lack of information regarding the influence of variables such as groundwater chemistry, temperature, sand mineralogy and structure, and spatial variation of soil properties on the aging process.
- There are very few examples of laboratory studies on time-dependent increases in cone penetration resistance.

A number of hypotheses have been proposed to explain what causes these time-dependent property changes. These are generally categorized as being mechanical or
chemical in nature. Mechanical mechanisms are thought to occur during secondary compression and include macro-interlocking of sand particles, micro-interlocking of surface roughness, and internal stress arching. Chemical mechanisms generally focus on the dissolution and precipitation of silica or other soluble material like carbonate minerals. Some tests have been performed to support the different hypotheses, but to date there is no unambiguous evidence that proves that the mechanisms are mechanical, chemical, some combination of the two, or something completely different.

To contribute to the current knowledge of aging effects in sands, a laboratory testing program was designed to study the influence of different variables on the presence and magnitude of aging effects. Three different sands were tested in rigid wall cells and buckets. Samples were aged under different effective stresses, densities, temperatures, and pore fluids. In every rigid wall cell, three independent measurements were made to monitor property changes during the aging process: small strain shear modulus using bender elements, electrical conductivity, and mini-cone penetration resistance. A total of 22 tests in rigid wall cells were performed with periods of aging ranging from 30 to 118 days. The significant findings from the experimental study are as follows:

- Increases in the small strain shear modulus of sand in rigid wall cells were measured with time. It was found that the sand type and pore fluid composition greatly influenced the magnitude of the small strain shear modulus increase. The effect of density was also significant. Temperature had very little effect on the increases in small strain shear modulus with time.

- Electrical conductivity measurements were very useful in monitoring the dissolution and precipitation of minerals in solution. In most of the tests, there was continual dissolution of minerals with time. In two tests, there was a decrease in the electrical conductivity with time, which suggested that some precipitation occurred.

- An assessment of changes in fabric or anisotropy using conductivity measurements was inconclusive. Either the formation factor and anisotropy index
were not sensitive enough to measure significant changes in fabric, or no significant changes occurred.

- Mineralogical studies and chemical analyses showed that in at least two of the tests in rigid wall cells, conditions were right for precipitation of carbonates and silica. This data was consistent with the electrical conductivity measurements; however, scanning electron micrographs showed no visible evidence of precipitation.

- The time dependent changes in the small strain shear modulus, electrical conductivity, and chemistry of the samples did not translate into a measurable increase in mini-cone penetration resistance. No increases in penetration resistance were observed in any of the tests.

This last finding is significant. Despite observing changes in the small-strain shear modulus and chemistry of the samples under a variety of sand types, densities, pore fluids and temperatures, these changes did not translate into increases in cone penetration resistance.

The results of the laboratory testing program suggest that small scale laboratory experiments do not capture the mechanism(s) which are responsible for time-dependent increases in penetration resistance in the field. This finding contradicts the results of two laboratory studies presented in the literature. Differences in the laboratory testing programs may account for the contradictory results. These include differences in boundary conditions, energy imparted to the soil, sample preparation, and type of penetration test that was performed.

A parametric study was performed to investigate whether reasonable changes in soil properties, such as stiffness and stress conditions, could account for observed time-dependent increases in penetration resistance in the field. This study was performed using cavity expansion theory. It was found that reasonable changes in soil stiffness and
stress state could not account for the measured increases in penetration resistance in the field using cavity expansion theory.

From the results of the laboratory testing program and the parametric study, it appears that controlled laboratory tests and currently available analytical techniques have missed the phenomenon that causes aging effects in sand. This suggests that some condition in natural deposits is not replicated in small scale laboratory testing and analytical methods. Possible conditions that may be different in the field include heterogeneity of the deposit, energy imparted by ground improvement, and biological activity.

A qualitative assessment of cone penetration records was performed using case histories where aging effects were recorded. Following ground modification, there is a general trend of an increase in heterogeneity of sand deposits (as indicated by the cone penetration records) that accompanies increases in cone penetration resistance. The changing level of heterogeneity may be an indication of stress redistribution, or internal stress arching, within the sand deposit; this may be an important factor in aging effects in sands.

7.1 Recommendations for Future Work

The results of the current research suggest that small-scale laboratory studies may not be appropriate for determining the mechanisms responsible for increases in penetration resistance in the field. It is recommended that a detailed field study be performed to investigate this phenomenon. A common problem with existing case studies is that aging is rarely the main focus of the study. As a result, potentially significant details, such as information about groundwater chemistry, sand mineralogy, sand structure, spatial variation of soil properties, and heterogeneity of the deposit are often overlooked.

Research is also needed to study aspects of the aging phenomena that were not covered in great detail in this study. These aspects include the following:

- The effect of different types and amount of energy imparted to the soil
• Biological activity in the ground
• Magnitudes and changes in heterogeneity of the soil deposit

To perform a detailed field study on the time-dependent increases in penetration resistance, the following guidelines could be used.

• Choose a relatively uniform deposit of loose, saturated sand with little fines content. This would avoid some of the difficulties encountered by researchers who performed aging studies in dense sands, or in sands overlain by cohesive layers of soil.
• Perform one or more types of ground improvement to directly compare the effect of different types and amounts of energy imparted to the soil on increases in penetration resistance.
• Provide a control section where no ground improvement is performed.
• Measure sleeve friction as well as tip resistance.
• Perform more than one penetration test at each time. An organized layout of test locations, such as the one used by Dowding and Hryciw (1986) and shown in Figure 6.1, should be made.
• Characterize the sand mineralogy, sand structure, and chemistry of the groundwater. These tests may provide insight into the role of sand type and pore fluid composition on aging effects.
• Characterize the spatial variation of the penetration resistance to separate time-dependent changes in properties from the natural variability of soil properties.
• Assess the biological activity in the ground.
• Monitor changes in heterogeneity with time, as measured by the cone penetration test, to provide insight into time-dependent stress redistributions and internal stress arching.
It is important to increase the number of field studies of aging effects in sands, both for cases in which increases in penetration resistance occur and cases in which no aging effects are observed. However, it is equally important that the case studies are detailed enough to improve the understanding of the phenomenon. Reported case histories should adequately characterize the site, level and amount of ground modification, and aging effects using the above guidelines.

There are clear, practical advantages to understanding more about these time dependent phenomena in sands. If the factors which influence the presence and magnitude of aging effects can be quantified, these effects could be incorporated into practice to make ground modification techniques a more economical alternative for improving sandy soils. Such an understanding would be of relevance to geotechnical engineers in general and of great interest to the ground modification community.