CHAPTER 8 – CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

EMI ground conductivity instruments when integrated with GPS provide a fast, efficient and cost-effective means for providing continuous mapping of the spatial distribution of the bulk conductivity of the roadbase over long distances. The new Geonics EM31-3 provides a more efficient means of collecting EMI data by reducing the number of data collection passes required along each profile, thus greatly reducing the field effort.

Currently, the available EMI modeling software, as with the earlier phases of this study, is still not easily capable of processing EMI data from this type of EMI survey. With the Emigma software, the primary limitation was in the preprocessing of the data prior to the inversion process. The preprocessing steps included sorting, positioning, and combining the data sets for each profile. Once the data was in the proper sorted and data subsets format, the inversion process proceeded more efficiently.

Through a comparison of the soil lab data from the 20 soil borings from Dulce, a weak correlation is shown to exist between LL and soil conductivity. Similar trends and prediction line fits are evident not only in the plot of Interval Conductance (1 to 1.5 m (3.28 to 4.92 ft)) vs. LL, but also in the plot of bulk conductivity (2 m (6.56 ft) coil separation, vertical dipole) vs. LL and in the plot of bulk conductivity (3.66 m (12 ft) coil separation, vertical dipole) vs. LL. An even weaker correlation is shown between soil conductivity and PI; however, this appears to be primarily related to the effect of LL. Bulk soil conductivity appears to be insensitive to moisture content and the samples clay percent at this site.

In general, the use of this EMI method will provide FHWA with two major advantages: 1) a geotechnical investigation could possibly be tailored to sample specific areas defined by either interval conductance or bulk conductivity; and 2) a potential reduction in the cost of soil borings and laboratory tests could be realized by providing a direct approximation of LL and PI values across long stretches of roadway. As noted in the Pavement and Subgrade Investigation Report 02-02 [(7)], "*From milepost 45 to 50, the pavement distresses were significantly more severe than from milepost 55 to 50. Although this trend is not supported from the soil classification data, it is supported when evaluating the PI data of the soil*." This statement suggests that soil boring alone is not enough to evaluate the subgrade at this site, and that laboratory analysis of soil samples is necessary to accurately identify problem areas. EMI surveys could provide an efficient means to map the spatial distribution (laterally and vertically) of soil conductivity. The conductivity data collected at this site shows the overall trend stated in the quoted statement above with overall relatively high conductivity values from MP 45 to 50 and overall relatively low conductivity values from MP 55 to 50. In addition, the data can be used to provide a prediction of the approximate LL and PI values along this entire length of roadway with much greater data density and spatial resolution than using soil boring data alone.

This project has been in part a demonstration of various EMI instruments and deployment of the new Geonics EM31-3 study. Although using EMI soil conductivity meters to map the spatial distribution of apparent ground conductivity is common, applying multiple instrument configurations to produce 2-D vertical profiles over large areas is rarely attempted. In addition, the integration of the interpreted EMI data in P & P drawings has been an iterative process between CFLHD and Blackhawk personnel in order to determine the most appropriate information to overlay on the P & P and the best way to display these data.

Large amount of time and effort have been expended in order to accomplish the program objectives and to derive an appropriate processing scheme to best meet the objectives. Through the efforts of all phases of this study, most of the difficulties have been overcome and future work could precede in a much more time- and cost-effective manner.

The deployment of the new Geonics EM31-3 instruments has provided several advantages over the other EMI (EM38 and EM31) instruments used during the Phase I and Phase II investigations:

- Three EM31 receiver coils separated at three different coil spacings all recorded simultaneously.
- Digital data acquisition with faster sampling rates allow for a faster rate of data collection.
- Capability to log both GPS and EMI data on the same data logger.

Table 12 presents a summary of the correlation of coefficients comparing Atterberg Limits of soils with conductive properties. As shown in the table, none of the attributes correlate strongly. The highest correlation was for the LL at the 0.9 to 1.5 m (3 and 5 ft) grab sample depth. This probably was due to the wide range of LL measured from the samples. The lower correlation for the 1.5 to 3.0 m (5 to 9.8 ft) grab sample depth and Natchez are due to the consistent LL values with no variation.

Based on the results obtained from this study, and the correlation coefficient shown in Table 12, the following conclusions can be made:

- Soil conductivity information derived through EMI methods can provide valuable information for the evaluation of road base materials in the design and redesign process.
- Soil conductivity information can be used to guide the soil-boring program by targeting the most likely locations with potential swelling clay problems.
- The weak correlation between bulk conductivity and LL can provide a first pass approximation of the predicted LL values along the entire length of the roadway surveyed.
- The correlation between bulk conductivity and Casagrande Plasticity Classification may be used as a quick evaluation tool for predicting Casagrande soil type along the entire length of roadway surveyed.

Overall, the EMI method is a fast, efficient, and cost effective geophysical tool for mapping spatial variations in soil conductivity beneath roadways with non-metal reinforced pavement types. A strong correlation between soil conductivity and the Atterberg Limits of Soils were not established, however, a qualitative evaluation of areas with increased potential for high plasticity clay content can be estimated from the EMI data. The EMI method can be used to focus the drilling programs during project site investigations, road rehabilitation, and construction. The EMI method may provide significant cost savings by reducing construction cost overruns.

Table 12. Correlation of Coefficients Summary

Attribute	Location	R^2		
		1 - 1.5 m Interval Conductance	**2 m Bulk Conductivity**	**3.66 m Bulk Conductivity**
% 200 Sieve	Dulce, 0.9 - 1.5 m	0.0026	0.0034	0.0091
	Dulce, 1.5 - 3.0 m	0.0210	0.0019	0.0003
	Natchez	*1	*2	*2
Liquid Limit	Dulce, 0.9 - 1.5 m	0.4127	0.4270	0.4133
	Dulce, 1.5 - 3.0 m	0.0169	0.0057	0.1476
	Natchez	*1	0.0667	0.0334
Plastic Limit	Dulce, 0.9 - 1.5 m	0.0161	0.0083	0.0036
	Dulce, 1.5 - 3.0 m	0.0016	0.0377	0.0806
	Natchez	*1	0.0009	0.002
Plasticity Index	Dulce, 0.9 - 1.5 m	0.3228	0.2968	0.2579
	Dulce, 1.5 - 3.0 m	0.0188	0.0885	0.1005
	Natchez	*1	0.0923	0.0942
% Moisture	Dulce, 0.9 - 1.5 m	0.0695	0.0975	0.1126
	Dulce, 1.5 - 3.0 m	0.0044	0.0601	0.0509
	Natchez	*1	0.041	0.0058
Liquidity Index	Dulce, 0.9 - 1.5 m	0.1045	0.0844	0.0611
	Dulce, 1.5 - 3.0 m	0.0477	0.0139	0.0139
	Natchez	*1	0.0307	0.0021
*1 - Interval conductance values were not calculated for the Natchez data.				
*2 - Lab did not test % 200 Sieve.				

8.2 RECOMMENDATIONS

Recommendations for future work include the following:

- The EM31-3 should be used in vertical dipole mode with only a single pass down each lane of the roadway to produce three different plan maps, each with a different effective depth of investigation.
- Although a good correlation with Atterberg Limits of Soils has not been shown, a reasonable qualitative correlation between high soil conductivity and areas with buckling or problematic roadbase appears to exist. This would make the EMI method a useful reconnaissance tool for mapping bulk soil conductivity prior to the soil-boring program.
- Inversion of the EMI data to produce vertical interval conductance profiles, while extremely time intensive using the currently available EM inversion software, appears to

provide only a small benefit over plan mapping alone. In particular, with the new EM31-3 instrument, the data from the three separate coil separations, recorded simultaneously, can be plotted side-by-side as three separate plan maps, each with a different effective depth of investigation. Inversion of the EMI data is unnecessary as it currently provides little additional benefit, yet greatly increases the time and cost required to process the data using currently available commercial EMI inversion software.

- EMI surveys should be conducted at suitable sites prior to the soil-boring program, such that the results of the EMI survey can be used to identify potential problem areas that can then be investigated through soil borings and other geotechnical investigations. This will significantly reduce the risk of missing a potential problem area when compared to conventional random soil boring programs alone.
- The EMI method should be utilized as a tool to complement the drilling program during preliminary site investigations, and for road rehabilitation design and construction highway projects, when the presence of clay in the road subgrade is of concern.
- Making a direct correlation between measured conductivity and Atterberg Limits of Soils properties data has proven difficult at this time. Furthermore, the development of empirical relationships between the geo-electric and soil properties are complex, site-specific and not readily quantified into individual soil properties.
- Various methods, such as laboratory testing, computational modeling, and limited geophysical techniques are currently being used for soil investigations. This study has demonstrated that a combination of these methods can provide better information to understand the soil behavior. Although finding a direct correlation between EMI results and laboratory geotechnical classification has proven difficult, EMI surveys should be implemented in geotechnical engineering projects independently of the current classification methods. Further developments in geophysical testing may produce a new classification scheme that can compliment current geotechnical classification practice. EMI methods can be used for investigating in-situ soil behavior rather than depending on the laboratory classification only.

8.3 ELECTROMAGNETIC INDUCTION BENEFITS

The EMI method is a fast, efficient, and cost effective geophysical tool for mapping spatial variations in soil conductivity beneath roadways with non-metal reinforced pavement types. While a direct correlation between soil conductivity and Atterberg Limits of Soils measurements may not be possible, a qualitative evaluation of potential problems areas can be determined from the EMI data.

- The EMI method will complement and focus soil sampling programs during preliminary site investigations, and for road rehabilitation design and construction projects.
- The EMI method will create significant cost savings by reducing construction cost overruns.

CERTIFICATION AND DISCLAIMER

All geophysical data analysis, interpretations, conclusions, and recommendations in this document have been prepared under the supervision of and reviewed by Blackhawk senior geophysicists.

This geophysical investigation was conducted using sound scientific principles and state-of-the-art technology. A high degree of professionalism was maintained during all aspects of the project from the field investigation and data acquisition, through data processing, interpretation, and reporting. The results and interpretations were limited by the data obtained in the field and from the client. All original field data files, field notes, observations, and other pertinent information are maintained in the project files at Blackhawk's Golden office, and are available to the client for a minimum of five years.

A geophysicist's certification of interpreted geophysical conditions comprises a declaration of his/her professional judgment. It does not constitute a warranty or guarantee, expressed or implied, nor does it relieve any other party of its responsibility to abide by contract documents, applicable codes, standards, regulations, or ordinances.

In order to ensure the highest quality geophysical data, a multi-layer approach to Quality Assurance and Quality Control (QA/QC) was implemented. Before shipping equipment to job sites, rigorous tests were conducted to ensure all equipment is functioning properly.

Quality control is obtained in the field by highly trained geophysicists. Survey parameters and acquisition procedures are agreed to by at least two geophysicists, who are then responsible for conducting the surveys. When time allows, survey data is recorded a second time, either in the same or opposite directions, to ensure repeatability. Data were then compared during the data processing and interpretation steps. Data are also returned to the home office for analysis by senior geophysicists within the QA/QC department.

During data processing and interpretation, the geophysicists discuss results and interpretations with the internal QA/QC department on a daily basis. Ideas and alternate techniques are discussed and implemented to provide clients with the most accurate data possible.

The processing geophysicists generally handle report writing. Draft reports are generated and circulated within the QA/QC department as well as given to at least one additional senior geophysicist. These different layers of the QA/QC approach ensure that a high-quality product is produced for each and every client.