Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-427

Use of GPR to Detect Cement Content in Soil Cement Subgrade Soils

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ABSTRACT: Achieving uniform cement stabilization in cement treated subgrade (soil cement) is critical to the long-term performance of the road pavement. However, field inconsistencies such as poor mixing and non-uniform moisture often result in uneven cement distribution, leading to structural deficiencies. Traditional methods of estimating cement content are destructive, labor intensive, costly and time consuming. This study introduces a non-destructive methodology that integrates laboratory and field measurements to estimate cement content using dielectric constant and electrical conductivity. Soil cement mixtures were prepared with 4 varying cement contents (0%, 3%, 6%, and 9%) and 3 varying moisture contents (4%, 8%, 12%) in the laboratory. Dielectric constant and electrical conductivity measurements were obtained using a percometer device over a 7-day curing period to capture hydration effects. For the field evaluation, GPR scans were conducted along an stabilized road base section using a 2 GHz antenna. Electrical conductivity was calculated from the results of the GPR's dielectric constant using an empirical calibration model. In summary, the study demonstrates that dielectric constant and electrical conductivity measurements can be effectively used to estimate cement content in cement-treated subgrade without destructive sampling. The combined laboratory–field approach enables rapid, non-invasive assessment of cement content variations, potentially improving quality control and long-term pavement performance.

KEYWORDS: Ground Penetrating radar, dielectric constant, electrical conductivity, cement content.

1 INTRODUCTION

Cement stabilization is a widely adopted technique in road construction to enhance the strength and durability of base and subgrade layers. The primary types of cement stabilization methods include soil cement, cement modified soil and full depth reclamation (FDR) with cement (1), (2) (3). Full Depth Reclamation (FDR) is a sustainable pavement rehabilitation technique that recycles existing asphalt and base materials to form a new, stabilized base layer, offering a cost-effective and environmentally responsible alternative to traditional reconstruction methods (4) (5).

Field observations frequently reveal variability in cement content due to factors such as inconsistent pulverization depth, non-uniform moisture content, inadequate mixing, or operational limitations of reclaimer machines (6) (7). While overstabilization can lead to brittleness and cracking, under-stabilization compromises structural performance (8). Guidelines from (9) and the Portland Cement Association recommend cement content based on soil classification, range from 3–5% for coarse soils (A-1-a) to 10–16% for fine-grained soils (A-7), achieving this accurately in the field remains a challenge (10) Traditional methods for evaluating cement content in road base stabilization pose significant limitations due to their labor-intensive nature, high cost, and the permanent damage it causes to the pavement structure. These drawbacks hinder their practicality for continuous quality control, especially when spatial variability of cement content is a concern.

Transportation agencies have increasingly turned to the use of non-destructive testing (NDT) methods to improve quality assurance while minimizing destruction of pavement. Among these methods, Ground Penetrating Radar (GPR) has gained prominence due to its rapid data acquisition, cost-effectiveness, and ability to perform continuous profiling at traffic speeds. GPR systems transmit high-frequency electromagnetic waves into pavement layers and analyze the reflected signals to infer material properties, layer thickness, and subsurface conditions such as voids, moisture, and delamination (11) (12). Various GPR system configurations such as air-coupled or ground-coupled antennas along with pulse, stepped-frequency, and synthetic aperture modes, offer tailored performance in terms of depth penetration and resolution (13).

Dielectric constant and electrical conductivity are fundamental electromagnetic properties that offer valuable insights into the composition, moisture state, and hydration behavior of cement-stabilized materials. The dielectric constant (ε_r), which quantifies a material's capacity to store electrical energy relative to vacuum permittivity (ε_0), is influenced by the presence of free water i.e higher water-to-cement ratios typically yield elevated dielectric constant (ε_r) values. Similarly, electrical conductivity reflects the availability of free ions in the pore structure and declines over time as hydration products restrict ionic mobility. These parameters are sensitive to variations in moist cement, cement hydration, and ionic concentration within pore fluids, making them suitable for tracking binder content and curing progression. (14) (15) (16) Despite this potential, most studies to date either focus on laboratory based dielectric probing or employ ground penetrating radar (GPR) primarily for thickness estimation, without utilizing conductivity related metrics for binder quantification (15) (17). Empirical studies have shown that both dielectric constant and conductivity exhibit pronounced changes during early curing which is highest in the first 7 days due to abundant free water and ionic species, then stabilizing as hydration progresses. (14)

A laboratory study by (18) demonstrated that both dielectric constant and electrical conductivity declined with carbonation and strength loss in cement mortars. Using an open ended coaxial probe across 0.2 – 2.0 GHz frequencies, the researchers established strong correlations between electromagnetic properties, compressive strength, and hydration levels. Complementing this, (19) proposed a semi-empirical model linking dielectric response to soil paste conductivity, accounting for moisture and surface interactions.

Early foundational work by (20) explored the relationship between electromagnetic properties and pore fluid characteristics, showing that moisture and ionic concentration are primary drivers of electric behavior in fine grained soils. More recently, (21) introduced a mechanistic empirical model relating to dielectric response to cement on concentrations and evaporable water in stabilized soils. The study combined dielectric and conductivity testing with ASTM based suction and moisture density procedures and proposed a theoretical formulation for electrical conductivity derived from GPR signal polarization. Despite these conceptual advancements, field implementation remains limited due to the absence of calibration standards and robust contour mapping techniques.

Field applications of dielectric – conductivity methods also highlight the complexities introduced by non-ideal conditions. For instance, (17) observed erratic GPR responses in early-stage cement treated soil layers caused by moisture induced scattering and poor layer definition, underscoring the need for dielectric calibration and moisture compensation. Hybrid approaches, such as that proposed by (22) bridged laboratory and field data by integrating GPR with percometer measurements. Their soil cement study demonstrated the feasibility of estimating cement content through predictive modeling of hydration rates, dielectric constant and conductivity. However, their method relied on percometer field-based conductivity measurements rather than conductivity derived from the GPR signal itself.

Despite these advancements, there is still no comprehensive framework that integrates laboratory derived dielectric properties with GPR based field measurements for spatially estimating cement content in soil cement applications. Major challenges include the lack of model validation under variable field conditions, absence of standardized calibration procedures between laboratory and field data, and underutilization of GPR signal attenuation for estimating conductivity. Moreover, current methods fall short in converting electromagnetic data into spatially resolved cement content maps for effective field quality control.

This study addresses these gaps by developing a field calibrating a dielectric – conductivity model that integrates 2 GHz GPR scan data with laboratory percometer measurements.

2 METHODOLOGY

2.1 *Background*

This study employed an integrated laboratory and field-based approach to estimate cement content in cement stabilized subgrade soils using dielectric constant and electrical conductivity. The methodology consists of three major phases: sample preparation and laboratory testing, field data collection using Ground Penetrating radar (GPR), and data analysis. In the laboratory phase, soil-cement mixtures were prepared with 4 varying cement contents and 3 varying moisture contents. Dielectric constant and electrical conductivity measurements were obtained using a percometer over a 7-day curing period to capture hydration effects. For the field evaluation, GPR scans were conducted along the stabilized sections using a 2 GHz antenna. Dielectric profiles were extracted and converted to electrical conductivity using an empirical calibration model. Then, the final phase involved interpolating field derived electromagnetic readings with laboratory parameters to estimate the cement content.

2.2 *Field Data Collection using the Ground Penetrating Radar (GPR)*

Field data acquisition was conducted using Ground Penetrating radar (GPR) to evaluate the electromagnetic properties of the soil cement layer. The scan was carried out for 2 or more days starting from the day of stabilization before the roadway was paved. A 2 GHz horn antenna system was employed to perform scans along the road section. The data collection followed standard GPR protocols for subsurface evaluation of bound layers, ensuring optimal antenna-ground coupling and minimal signal noise (23). The GPR system was connected to a survey wheel and GPS for synchronized spatial referencing. Post-processing of the radargrams was conducted using Radan 7 Software which facilitated the extraction of critical signal parameters including two-way travel time (TWT), reflection amplitudes, and signal attenuation (24)

The field Ground Penetrating radar was conducted over a 3-day period. For this work, the 8 inches stabilized soil layer was considered. The results as shown in Figure 1 revealed progressive changes in subsurface electromagnetic properties, indicating evolving moisture conditions and cement hydration within the base layer. On day 1, the dielectric constant profile exhibited high variability along the scanned distance, with numerous peaks suggestive of zones with elevated moisture content and active hydration. By day 2, the dielectric values remained high but demonstrated more pronounced fluctuation and localized increases, reflecting continued hydration reactions and uneven moisture redistribution within the layer. By day 3, a noticeable stabilization and flattening of the dielectric constant response was observed, with values consistently lower and exhibiting reduced spatial variability.

The calculated electrical conductivity results as shown in Figure 2 exhibit a generally high and consistent profile, indicating elevated ionic activity and presence of moisture within the stabilized base layer. Initial sections of the scan show notable fluctuations and intermittent drops. As the scan progresses, conductivity stabilizes, reflecting a more uniform distribution of moisture and cementitious ions as hydration advances. The results of the estimated cement content are shown in Figure 3. The percentage cement content profile showed a general consistent range between 4.5 and 5.5%.

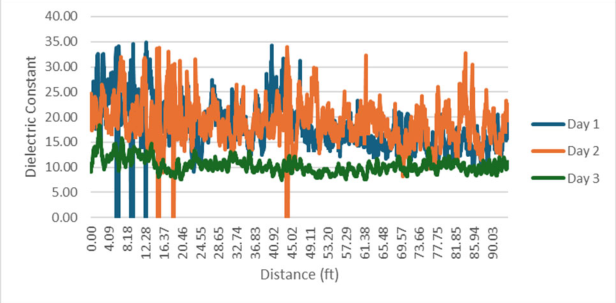

Figure 1. GPR dielectric Constant result for Test Site

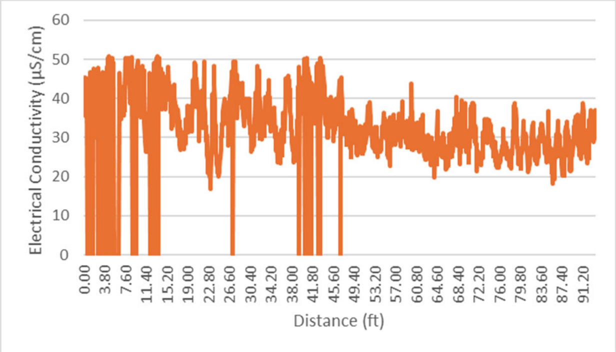

Figure 2. the results of calculated electrical conductivity from GPR dielectric constant for Test Site

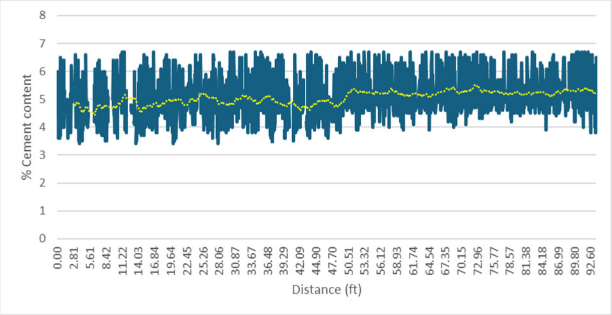

Figure 3. Result of the estimated cement content for Test 1

3 SUMMARY

The integration of dielectric constant and electrical conductivity offers non-destructive framework for evaluating cement content in soil cement layer. By determining the physical electromagnetic behavior of samples across depths and curing stages, the combined dielectric – conductivity model bridges laboratory testing with field assessment.

4 LIMITATIONS

Environmental factors such as temperature, subsurface heterogeneity and equipment calibration may introduce variability in real world applications. The application of water post construction for dust control may pose a challenge for data collection on the field. This study examined discrete levels of cement (0, 3, 6 and 9) % and moisture contents (4, 8, 12) % which may not capture all intermediate behaviors. A more continuous range of mixed proportions could yield finer correlations and improved models.

5 ACKNOWLEDGEMENTS

The work presented in this project is an extension of a research project (RP 19-21) sponsored by the Georgia Department of Transportation, United States. The contents of this paper reflect the views of the authors, who are solely responsible for the facts and accuracy of the data, opinions, and conclusions presented herein. The contents may not reflect the views of the funding agency or other individuals. The authors would like to acknowledge the financial support from the Georgia Department of Transportation in the United States.

6 REFERENCES

AASHTO., American Association of State Highway and Transportation Officials. Standard Specifications for Transportation Materials and Methods of Sampling and Testing. s.l. : AASHTO, 2020.

FHWA., Federal Highway Administration. Cement Stabilization of Subgrade Soils: A State of the Practice Review. s.l. : FHWA, 2018. FHWA-HIF-17-007.

Guthrie W.S., ,Sebesta, S., & Scullion, T. Selecting Optimum Cement Contents for Stabilizing Aggregate Base Materials. s.l. : Texas Transportation Institut, 2002. FHWA/TX-03/0-4114-2.

Reeder G.D, Harrington D.S, Ayers M.E, Adaska W. Guide to Full-Depth Reclamation (FDR) with Cement. s.l. : National Concrete Pavement Technology Center, 2019.

Luhr., D.R, Adaska W.S., Halsted G.E. Guide to full depth reclamation (FDR) with cement. s.l. : Portland Cement Association, 2005.

ACI-Committee. Report on Soil Cement. s.l. : American Concrete Institue, 2009.

Howard., I.L, Sullivan W.G, Anderson B.K, Shannon J, Cost T. Design and Construction Control Guidance for Chemically Stabilized Pavement Base Layers. s.l. : Mississippi Department of Transportation, 2013.

Gross and Adaska. Guide to Cement stabilized Subgrade Soil. s.l. : Portland Cement Association, National Concrete Pavement Technology Center, 2020.

AASHTO-M147. Standard Specification for Materials for Aggregate and Soil aggregate Subbase, Base and Surface Courses.

Luhr., A.R, Adaska W.S, Halsted G.E. Soil-Cement Construction Handbook. s.l. : Portland Cement Association, 1995.

Evans, Mark. Use ofGround Penetrating Radar in a Pavement Management System. s.l. : Arkansas State Highway and Transportation Department, 2005.

Khazanovich., L. Pavement thickness Evaluation using 3D Ground Penetrating Radar. s.l. : Minnesota Department of Transportation, 2021.

A review of Ground Penetrating Radar Antenna Design and Optimization. Travassos., X.L, Avila S.L, Da R.L, Adriano S, Ida N. 2018, Journal of microwaves, Optoelectronics and Electromagnetic Applications.

Pokkuluri., K. Effect of admixtures, Chlorides, and moisture on dielectric properties of portland cement concrete in low microwave frequency range. s.l. : Virginia Polytechnic Institute and State University, 1998.

Optimization of Ground-Penetrating Radar Data to Predict Layer Thicknesses in Flexible Pavements. Loulizi., A, Al-Qadi I.L and Lahouar S. 2003, Journal of Transportation Engineering, pp. 93-99.

Humbolt. H-4112 Percometer Manual. s.l. : Humbolt Manufacturing Company, 2017.

Kwon J., Seo Y, Kaplan A, Yang J. Full depth Pavement Reclamation: Performance Assessment and Recommendations for Best Performance. s.l. : Georgia Department of Transportation, 2020.

Effect of Chlorides on Conductivity and Dielectric Constant hardened Cement Mortar: NDT for Durability Evaluation. Kim., S, Kang J, Lee S and Ahn Y.H. 2016, Advances in Materials Science and Engineering.

Estimation of the Electrical Conductivity of Saturated Paste Extract Using a Dielectric Sensor. Kargas., G, Popescou P., Kaliontzis N, Marougas D and Kerkides P. 2017, Journal of Irrigation and Drainage Engineering.

Identification of contaminated soils by dielectric constant and electrical conductivity. Kaya and Fang. 1997, Journal of environmental engineering, pp. 169-177.

Saha., S. Ph.D Dissertation: Characterization of unbound and stabilized materials and improved consideration of their effects on pavement performance. Texas : Texas A& M University, 2019.

Utilizing Dielectric Constant and Electrical Conductivity to Estimate Cement Content in Stabilized Subgrade Soils. Hall and Kim S. 2025, Transportation Geotechnics.

GSSI. Radan 7 User Manual. Geophysical Survey Systems, Inc. 2023.

Saarenketo., T. Electrical properties of road materials and Subgrade soils and the use of ground penetrating radar in traffic infrastructure surveys. Ph.D dissertation,. s.l. : University of Oulu, 1998.

GDOT., Georgia Department of Transportation. Pavement Design Manual. 2018.