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***Highway Program***

# Development of a Conductivity Spectrum Probe (CSP) to Determine Concrete Chloride Permeability

Final Report for Highway-IDEA Project 69

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TRANSPORTATION RESEARCH BOARD • THE NATIONAL ACADEMIES

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## EXECUTIVE SUMMARY

The durability of concrete transportation structures is closely related to its permeability. Both reinforced and prestressed concrete can deteriorate because of ingress of aggressive substances such as: sulfates, acids, and chlorides present in the environment. It is important to specify and access the ability of concrete to resist the infiltration of corrosive chemicals.

The work described in this report explores a new method for measuring the chloride permeability of concrete. The method is based on the use of a Conductivity Spectrum Probe (CSP). The probe is a surface contact device that can measure both the conductivity and dielectric permittivity of a material over a specified range of frequencies. The conductivity is proportional to the permeability, and the permittivity is directly related to moisture content. The measurement can be made either in-place or on samples removed from the structure. The CSP does not require exposure of the sample to any ionic solutions that may react with the concrete. It is possible to work with unsaturated samples, since the measured conductivity could be normalized to 100% saturation using the dielectric permittivity data. The use of a range of frequencies allows for the possibility of variation in the depth of influence of the probe. Such a depth sensitivity which can be used to adapt to field conditions and to the presence of reinforcement.

This report describes initial experimental results using the CSP and comparing the CSP data with permeability measured by traditional means. The experiments were conducted on concrete block, concrete mortar cylinders, and concrete slabs. Different concrete mixes were represented in these tests. The concrete mortar cylinders representing four mix designs were tested directly for chloride permeability by W. R. Grace as part of their ongoing research. CSP data reflects the mix different mix characteristics. Comparison of CSP data collected on these samples on 44 samples with directly measured permeability showed some correlation, but not in all cases. The direct permeability data was limited and highly scattered, so complete correlation could not be conducted.

The method shows promise, but would benefit from a more comprehensive laboratory evaluation program.

# 1. Introduction

## 1.1 Overall Objectives

The durability and integrity of concrete transportation structures such as pavements and bridges, throughout their life span is of major concern to the engineers dealing with transportation infrastructure worldwide. It is well known that durability of concrete is closely related to its permeability. Both reinforced and prestressed concrete can deteriorate because of ingress of aggressive substances such as: sulfates, acids, and chlorides present in the environment. A major concern associated with the permeability of concrete is the corrosion of reinforcing steel in concrete as the result of chloride permeation and/or diffusion. In fact, chloride induced corrosion has been identified as the major problem and cause of our transportation infrastructure deterioration. However, permeability of concrete to chlorides and other destructive material has not been used as a design and construction specification because it is difficult to quantify.

The prediction of chloride penetration in concrete using current methods is slow and unreliable, and cannot be implemented on in-place concrete. The *ASTM C1202-91, 90-Day Ponding Test* was developed before the new generation of high performance concrete, and does not allow adequate penetration for reliable measurements. The *Rapid Chloride Permeability Test* is known as *The AASHTO T 277-93*, which measures penetration indirectly through electrical conductivity but introduces factors such as: heating, chloride, bonding, and unknowns (e.g., lack of full saturation) which have undesirable effects on the measurement.

In order to address these limitations, a new method based on the use of a Conductivity Spectrum Probe (CSP) has been proposed. The probe is a surface contact device that can measure both the conductivity and dielectric permittivity of a material over a specified range of frequencies. The measurement can be made either in-place or on samples removed from the structure. The CSP does not require exposure of the sample to any ionic solutions that may react with the concrete. Samples do not have to be fully saturated. However, the measured conductivity needs to be normalized to 100% saturation using the dielectric permittivity data. The use of a range of frequencies allows for variation in the depth of influence of the probe, which can be used to adapt to field conditions and to the presence of reinforcement. The CSP is applicable to the evaluation of newly constructed concrete as well as to concrete that has been in service. The technology for making the measurement is currently available and ready for use in this application.

The program described in this report has involved experimentation and data evaluation using a prototype Conductivity Spectrum Probe (CSP). Concrete samples for testing were provided by W. R. Grace, Inc. as part of their ongoing concrete evaluation program. The objective of the program has been to evaluate the relationship of the CSP data to concrete mix type. Within a given mix, the objective was to evaluate the relationship between CSP data and directly measured chloride permeability.

## 1.2 Background

Compressive strength and water-to-cement ratio have long been used as measurements of the quality of concrete, and as a basis for laying down specifications and guidelines for structural design and proportioning concrete mixtures. Permeability of concrete to chlorides and other destructive material, although greatly affected by these two factors, has not been used in the specifications due to difficulties in measurement.

Researchers have noted inconsistencies within the Rapid Chloride Permeability Test itself, and incompatibilities or lack of correlation between the Rapid Chloride Permeability Test and The 90-Day Ponding Test. Inconsistencies within the Rapid Chloride Permeability Test itself include variable results when certain mineral admixtures such as silica fume are included in the concrete mixture. A warning within the AASHTO and ASTM tests states that the use of calcium nitrite in the concrete mixture could produce misleading results. Other warnings state that the presence of reinforcing steel or other electrically conductive material may significantly affect the test results. The Rapid Chloride Permeability Test specification notes that concrete treated with penetrating sealers may indicate low chloride ion penetration by the Rapid Chloride Permeability Test but higher chloride ion penetration than by The 90-Day Ponding Test.

The Rapid Chloride Permeability Test is based on measuring the charge passed throughout hardened concrete under standardized conditions. This parameter is influenced by the electrical resistivity of the concrete, which can be significantly altered by various chemical admixtures and additives (i.e., fly ash, silica fume, corrosion inhibitors, etc.) and mix proportions which have no direct relationship to the permeability of the concrete. Therefore, there is a need to develop a method of prediction (with respect to chloride penetration) independent of mix proportions and components.

Researchers have found a better relationship between The 90-Day Ponding Test and actual field performance. This test procedure can easily distinguish between the good quality concrete made with low w/c ratio concrete and a poor quality concrete made with high w/c ratio and other additives. Although the Ponding Test is generally regarded as an appropriate test, it takes a long time to get results (90 days) for conventional concrete and may take considerably longer for high performance concrete. The 90-day ponding period considered sufficiently long when the test was initially adopted by AASHTO, but less appropriate with today's low w/c, high performance concretes mixes for today's high performance concretes.

Finally, both of these tests are noted as being for evaluation of materials for research and design purposes; neither one is specifically noted as appropriate for acceptance or rejection of concrete based on resistance to chloride ion penetration. The inconsistencies with the Rapid Chloride Permeability Test and the length of time required for the Ponding Test suggest that neither is suitable for use in construction specifications for acceptance or rejection of concrete. Rather, a reliable, consistent test that can be completed in a shorter time period is needed for this application. As a result, a need has emerged to develop a practical test, and to use this test to define a measurable limit on the permeability of new concrete to chloride ions. In order to appreciate this need, and to develop a basis for the proposed CSP method, the following paragraphs review the two existing methods in further detail.

There have been efforts to improve the Rapid Permeability test with some modifications such as using voltage other than 60 V, use of AC source rather than DC, correlating only the initial current passed with the degree of permeability, and directly measuring the chloride crossed the specimen by a chloride selective electrode.*c*

All these methods have one thing in common, which is to correlate conductivity or resistivity of concrete with its permeability. This is a valid approach since both diffusion of chlorides into concrete and corrosion of steel are electrochemical processes that are directly a function of concrete permeability. Such processes in porous media are strongly influenced by the hydraulic connectivity of pore structure, the strength of electrostatic field due to the dissolved ions, the characteristics of the pore surface, temperature, and level of saturation. Energizing the chloride ions or other ions by inducing an external potential is the major cause of all discrepancies observed. A proposed CSP method that takes advantage of the conductivity of concrete without all the side effects should be an optimum solution for measuring the permeability of concrete.

### 1.3 Description of Concept

The Conductivity Spectrum Probe (CSP) is a surface contact device which can measure both the conductivity and dielectric permittivity of a material over a specified range of frequencies. The measurement can be made in-place or on samples removed from the concrete. It does not require exposure of the sample to any ionic solutions.

The basic idea of the method is that the frequency spectrum of dielectric permittivity and conductivity includes information not only about the ability for chlorides to penetrate the concrete, but also about the degree of saturation, the presence of admixtures, and the influence of reinforcing steel. The probe is capable of conducting measurement over a range of frequencies. The use of a range of frequencies allows for sensitivity to variation in the depth of influence of the probe, which can be used to adapt to field conditions and to the presence of reinforcement. Also, the conductivity spectrum provides a complete pattern of data, rather than a single value, for each concrete mix, and thus has the potential to provide more information than is available from current methods. With the CSP, electrical measurements can be performed on the concrete in-place, without coring. Measurements on cores in the lab are also possible. The measured permittivity and conductivity spectra, along with appropriate data processing software, would be used to predict the chloride ion penetration of the concrete.

The measurement apparatus consists of a radio-frequency (RF) near-field probe, a step-frequency transmitter/receiver (T/R) unit, directional coupler, laptop computer and analysis software. A system block diagram of the CSP measurement apparatus is shown in Figure 1. A detailed view of the **RF near-field probe** is shown in Figure 2. Essentially, the probe consists of an open-ended coaxial waveguide with a diameter of 10.0 cm *(1)*. The probe is similar in concept to dielectric probes that are available commercially, for example from Hewlett-Packard. However, the probe is larger than most commercial probes and is especially designed to average the effects of large-grain heterogeneity's that are present in many concrete mixtures.

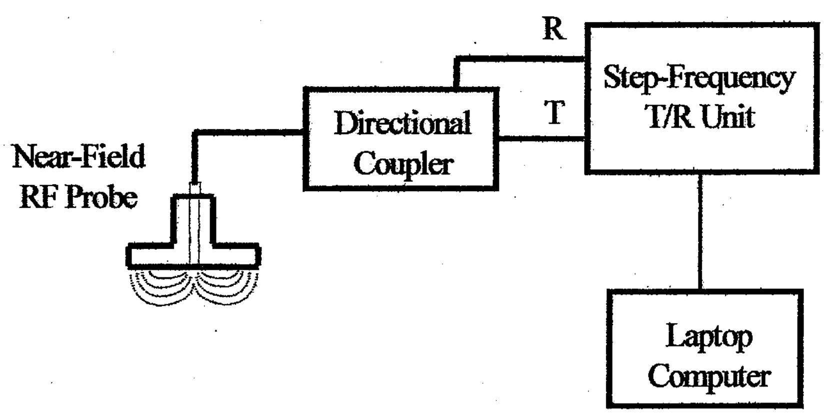



Figure 1 – Schematic of Conductivity Spectrum Probe (CSP) Measurement Apparatus

Much work has been done on the analysis of this probe *(2, 3)* and numerical models for analyzing the response of the probe for various materials have been developed *(4)*. Data inversion techniques for extracting the dielectric permittivity and conductivity of the "test media" from the measurement data are available *(5)*.

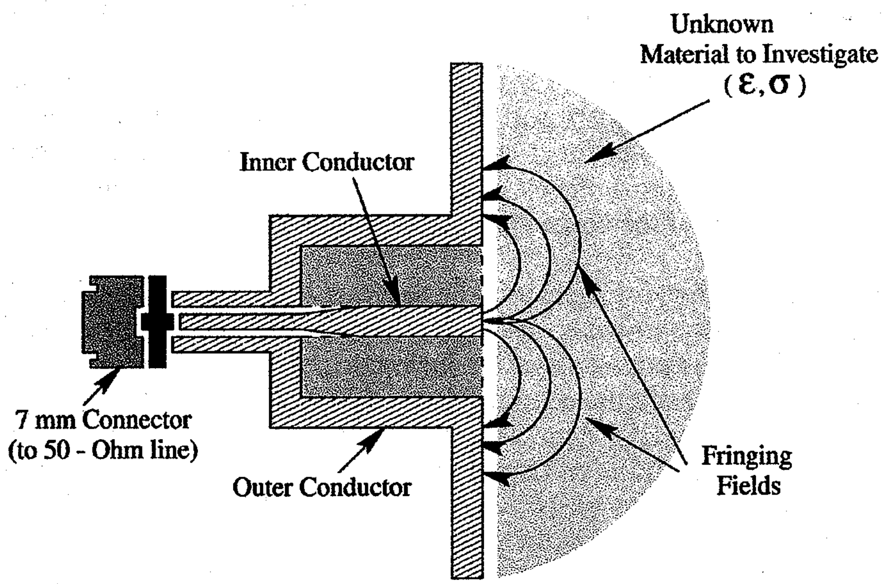



Figure 2 – Details of Near-field RF Probe

**The transmitter/receiver (T/R) unit** for the research and evaluation purposes of this program was a standard HP model HP 8753D Network Analyzer. It is primarily a piece of research equipment, but it serves the basic purposes of demonstrating the feasibility of the CSP concept. For final prototype development (Phase II), a stand-alone T/R can be obtained. For example, Coleman Research Inc., (Orlando, FL) has developed a T/R Unit as part of a stepped frequency Earth-Penetration Radar Imaging System (EPRIS) that was developed under DOD and DOE funding. The system, intended primarily for underground imaging, has a frequency of 80 MHz to 1000 MHz and an output power level of 5 mW. Since the frequency range and power level, size and weight are suitable for our application, we used this T/R unit for our application. The EPRIS step-frequency T/R unit is contained in a 7 x 9 x 4 inch ABS plastic enclosure, weighs only a few pounds, and is run on batteries. The unit contains a RF synthesizer and digital processing electronics for extracting and digitizing the RF data. Connections to the T/R unit include a RF transmit (output) connection, a RF receive (input) connection, and a digital data output port. The digital data was then be sent to a laptop PC for analysis. The EPRIS T/R unit demonstrates the feasibility and availability of implementing a compact and lightweight T/R unit to replace the Network Analyzer in a prototype device, and the use of such a unit in the Phase II prototype made the CSP system portable and convenient to use for commercial field purposes.

A **directional coupler** was needed for converting the RF near-field probe, a single-port device, to an EPRIS type T/R unit, since it is a dual-port device. Essentially, the directional coupler allows the transmitted signal from the T/R unit to pass through directly to the near-field probe. The reflected signal from the probe is then separated from the transmitted signal by directional coupler and passed to the T/R receiver input, rather than routing the signal back to the transmitter. The HP has its own directional coupler, so such a device was note needed for the initial testing.

A **laptop computer** is used to extract digital data from the Network Analyzer, and ultimately from the prototype T/R unit. The laptop computer is also used to calibrate the measurements and convert the raw measurement data to frequency-dependent dielectric permittivity and conductivity values. These curves will ultimately be used to estimate the chloride diffusivity.

The complex dielectric permittivity is computed from the magnitude and phase data produced by the equipment described above. The imaginary part of the complex permittivity is directly proportional to conductivity, and serves as direct measure of the concrete's susceptibility to chloride penetration. The real part of the complex permittivity, or dielectric constants, is a function of the degree of saturation of the concrete.

The CSP concept is based on the same principle used by the Rapid Chloride Permeability Test, but the CSP approach can potentially provides much more information, and can be implemented without some of the Rapid Chloride Permeability Test limitations. A considerable amount of research has been carried out to evaluate the conductivity and dielectric permittivity of concrete, which served as a basis for processing CSP data. The reported research includes analytic models and experiments on concrete samples. Most of the reported work has considered measurement frequencies, which range from 100 kHz to 3 GHz. Al-Qadi et. al. *(6)* has shown conductivity and dielectric spectra in the range of 0.1 to 40.1 MHz for curing concrete, and has quantified the influence of chloride on these spectra. Wilson and Whittington *(7)* and Olp, Otto, et. al. *(8)* have made measurements from 1 to 100 MHz on concrete samples during the first 24 hours of curing. Their results show the influence of the curing process on the concrete conductivity and dielectric permittivity. All of the above work used a transmission line technique in which the sample of material is placed in a holder, which becomes a part of the transmission line. Otto, Chew, et. al. *(9)* have developed a probe which can make the same measurements, but requiring only single-sided access. It is this work that produced the dielectric probe that was used in the reported work.

The theoretical models generally consider the concrete as an array of interconnected pores, whose conductivity is related to their volume fraction and the size distribution of solid particles. However, it is known that the tortuousity and constrictivity of the pore structure affects both the conductivity and the penetration of chloride. Northwood and MacDonald *(10)* have proposed a method that compares the measured conductivity to a predicted value in order to quantify the tortuousity and constrictivity of the pore structure. This ratio produces what is called a "Lithological Factor", which can be used to determine the real diffusivity of concrete from a predicted value. The paper develops a relationship between the conductivity and the diffusivity lithological factors and suggests this as a means of determining diffusivity from conductivity measurements. This method represents a means of data interpretation that will be considered in conjunction with the CSP method.

Ordinarily, the presence of reinforcement can distort a conductivity measurement. The advantage of the CSP method is that the range of frequencies used represents a range of depth penetration. If the steel is 1.5 inches down from the surface of the sample, then it is desirable to focus on the top 1.5 inches of concrete. In the field, one can make several measurements at different positions relative to rebar placement. Since the (horizontal) location of the rebar for each measurement will be different, the portion of the spectrum which is affected by reinforcement can be ignored, and the data can focus on the shallow penetrating higher frequencies.

There are a number of theoretical constitutive models that relate the composition of concrete to the conductivity and dielectric properties. Using such models, Halabe, et. al. *(11)* as shown that both the conductivity and dielectric permittivity of concrete vary almost linearly with degree of saturation. Experiments carried out by Halabe et. al. partially confirmed these findings. Bell and Leonards *(12)* similar experimental work 30 years ago reached the same conclusion regarding the dielectric permittivity. This means that a conductivity measurement made on unsaturated concrete can be scaled up to an equivalent value for fully saturated concrete by using the dielectric permittivity as a measure of degree of saturation. This capability is particularly valuable for high performance concrete where full saturation is difficult to achieve.

# 2. Description of Research

## 2.1 Objectives

The goal of this Phase I effort has been to evaluate the viability and accuracy of the CSP concept for the measurement of concrete permeability by collecting and evaluating CPS data on control concrete specimens covering a range of concrete parameters. The specific objective has been to identify a predictable correlation, which can be implemented into automated processing software for a prototype CSP device. Once this goal is achieved, specifications can be prepared for a prototype commercial device, which would be tested in Phase II.

The plan for achieving these goals included (a) preliminary testing; (b) testing on controlled samples, and (c) testing on concrete slabs. The objective of the preliminary testing was to ensure that reasonable data can be collected using the CSP measurement arrangement. The objective of the testing on controlled samples was to establish relationships between the CSP output, mix design, and directly measured chloride permeability. The objective of data collection on slabs was to investigate spatial variability and to investigate the influence of reinforcing steel. The following sections describe these tests in further detail.

## 2.2 General Testing Arrangements

Testing of the CSP involves measurements using a network analyzer. The network analyzer is a highly sensitive device whose output must be regularly calibrated to know conditions. Standard use of the network analyzer includes calibrations with a 50 ohm load, an open circuit, and a short circuit. These tests are carried out with the appropriate test terminals collected to the end of the measurement cable. The results of these calibrations are directly incorporated into the instrument and used for all subsequent measurements.

Once the instrument with cable was calibrated, the probe was attached to the cable and the following additional calibrations were conducted:

a) Short circuit;
b) Brass cavity;
c) Aluminum cavity;
d) Combined cavity

The results of these calibrations are used in the calculation procedure which converts the complex impedance data collected by the network analyzer to the dielectric permittivity and conductivity.

The above calibrations were carried out prior to each test sequence. In addition to these calibrations, tests were carried out with the CSP in contact with water and air. Water and air have dielectric permittivities of 81 and 1 respectively. These known permittivity values are used to check the calculation procedure, and to ensure that the actual results area appropriately bracketed between these two extremes.

For each test, the network analyzer was set to measure 101 frequency points in a range between 50 MHz and 3 GHz. The result of each test is a complex reflection coefficient (magnitude and phase) which was saved as an ASCII file. Algorithms previously developed for extracting concrete conductivity and dielectric permittivity from this complex reflection coefficient were utilized to obtain the results reported here.

## 2.3 Preliminary Testing

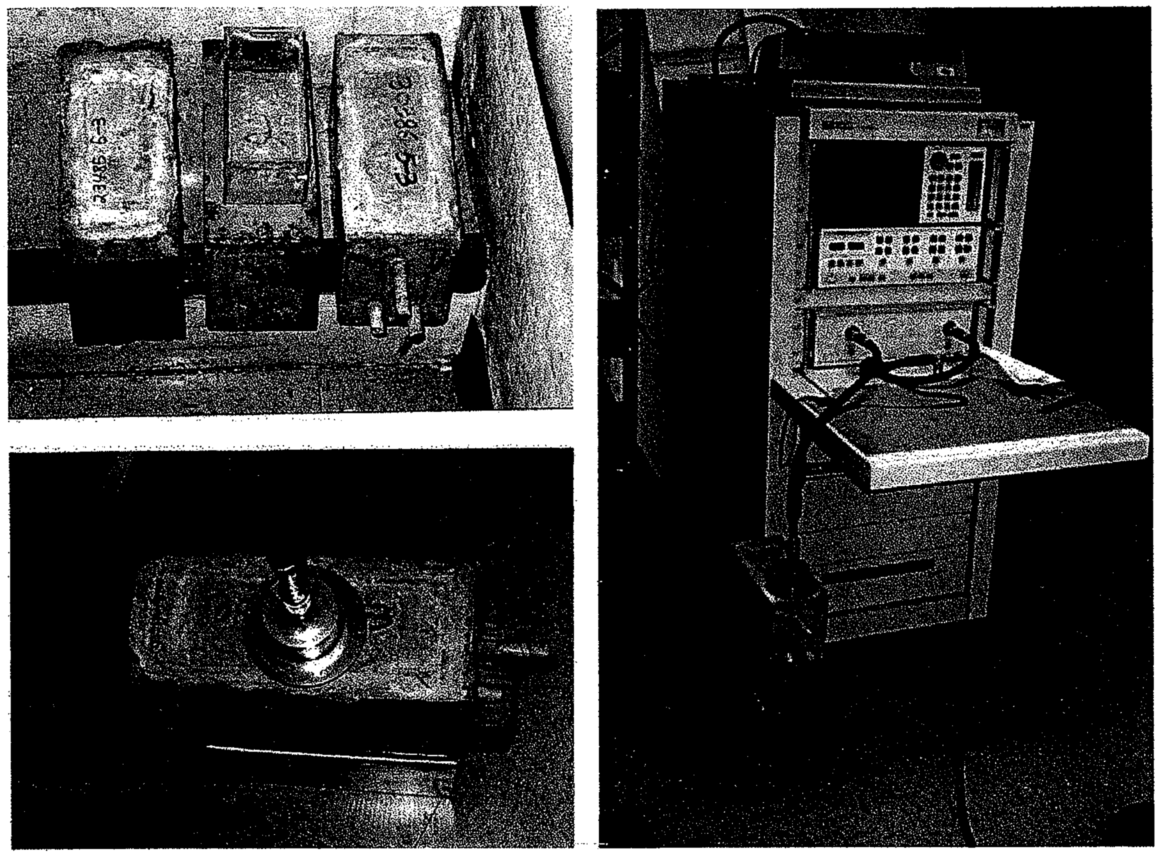
Preliminary testing of the CSP was carried out using test samples shown in Figure 3. The objective of the preliminary testing was to obtain experience with the measurement and data processing techniques, and to identify any issues of concern for the subsequent test program. Preliminary tests were conducted on existing rectangular samples of concrete provided by W. R. Grace. The samples had the following properties:

stone max size 3/8",
sand fineness modulus 2.62,
sp. gr=2.61,

The air/slump/unit weight for each individual sample were as follows:

| SAMPLE NUMBER | AIR (%) | SLUMP (INCHES) | UNIT WEIGHT ($LBS/FT^3$) | $F'_C$ (PSI) |
|---|---|---|---|---|
| 23485 5 | 6.0 | 7.5 | 148 | – |
| 30386 5 | 7.0 | 3.0 | 142 | 5074 |
| 25296 2 | 5.3 | 3.5 | 147 | 5563 |

Two of these samples had reinforcing steel, and the third (25296) had none. Tests were carried out with the probe located at several positions along each concrete sample — 3 positions (left edge, center, and right edge) along each of the top, side, and bottom of each sample. The results varied with position of the probe as would be expected due to the different geometric arrangement and proximity of boundaries. The tests taken in the center of each face were used for reference, since these were furthest from the boundaries. A typical result is shown in Figure 4.

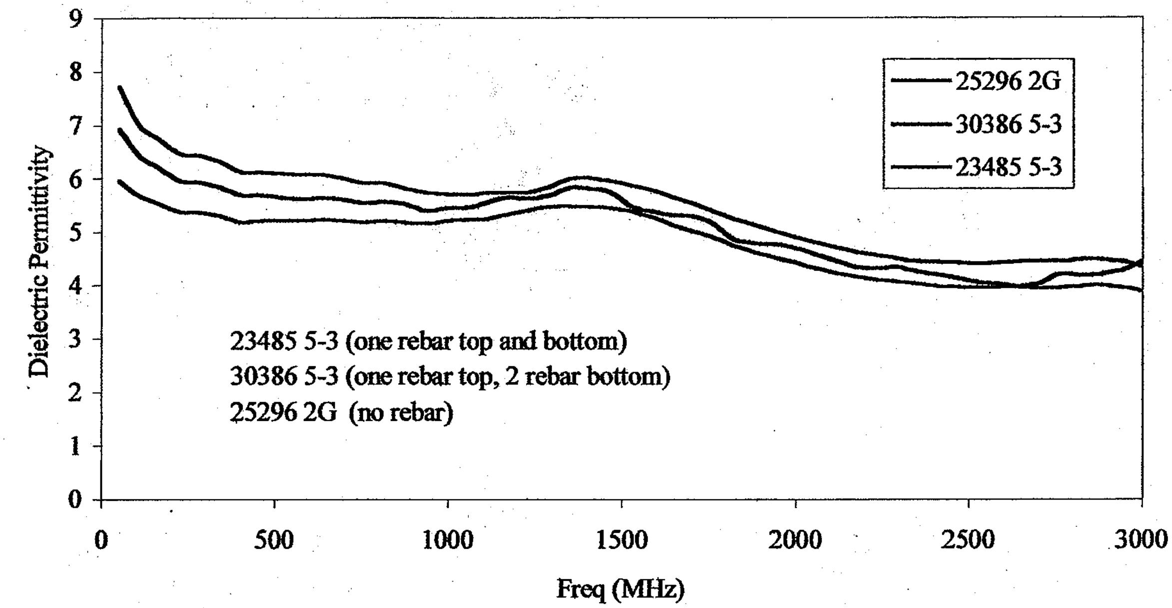


Samples (top) and Testing | Overall Setup with Network Analyzer

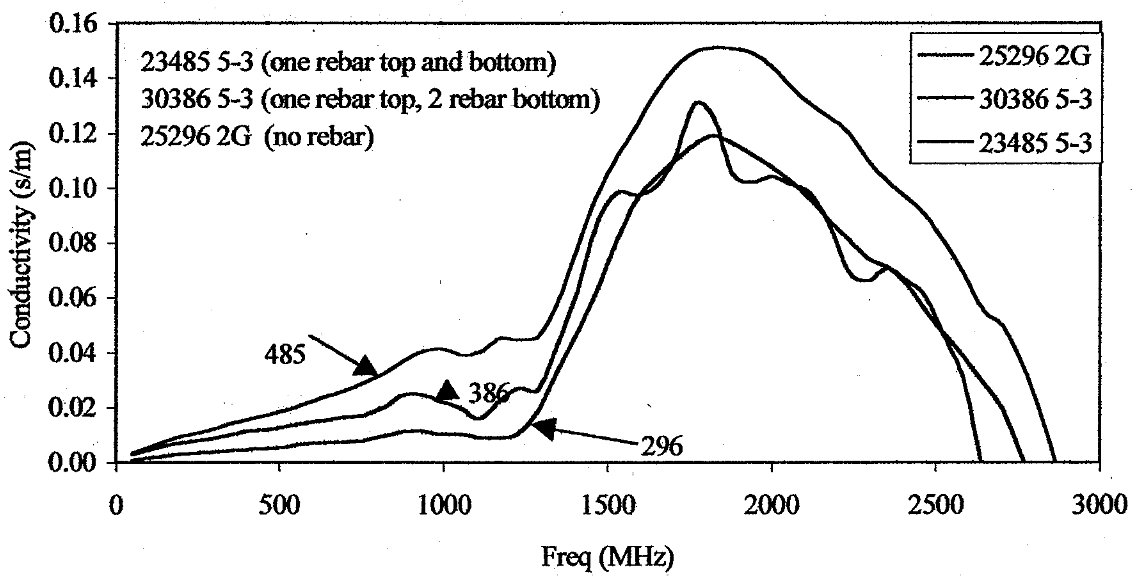
Figure 3 – Preliminary Testing of Concrete Samples using the CSP

The results on Figure 4 are typical of the pattern shown for all of these tests. The conductivity is presented in S/m, which refers to siemens/meter. (Siemens are an SI unit of conductivity, formerly referred to as mhos and equivalent to $ohms^{-1}$.) Note that the sample without steel shows both a lower permittivity and conductivity. However, there are other features that distinguish these mixes from one another, so no general conclusions can be reached.

The preliminary tests concluded that the measurements could be reasonably and consistently made, and that the processed data produced values which were within a range of expectation. The tests also indicated that the results were sensitive to the position of the probe relative to the sample boundary.




(a) Dielectric Permittivity




(b) Conductivity

Figure 4 – Typical CSP Data (Measured at the Bottom Center of Sample)

## 2.4 Sample Testing Program

Testing was carried out on 44 samples representing four different mortar mixes. The four mixes tested represent two w/c ratios, one mix with silica fume, and one mix with fly ash. Table 1 shows the properties of the four mixes.

Table 1 – Properties of the Four Tested Mixes

| Mix # | w/c | Cement Factor ($kg/m^3$) | Sand ($kg/m^3$) | Pozzolan ($kg/m^3$) |
|---|---|---|---|---|
| 1 | 0.485 | 500 | 1375 | 0 |
| 2 | 0.40 | 559 | 1375 | 0 |
| 3 | 0.485 | 392 | 1375 | 98 (fly ash) |
| 4 | 0.485 | 456 | 1375 | 40 (silica fume) |

The samples, provided by W. R. Grace, were 6 inch diameter and 7 inches high. Two reinforcing bars were placed transverse to the sample axis, one 1 inch from the base, and one 3 inch from the top. The top two inches of each sample was then removed by saw cutting and saved for future reference testing. After saw cutting, the top of the sample was 1 inch above the top rebar. The top of each sample was then exposed to 3% chloride solution by ponding inside with a Plexiglas berm. The samples were monitored electrically, and the test was finished when the electrical readings indicated that corrosion had begun at the top rebar. Once the test was finished, the concrete was evaluated for the chloride content profile as a function of sample depth.

Figure 5 shows the 5 inch high portion of the samples as they were being exposed to the chloride solution. Figure 5(a) shows the samples on a rack with the electrode connection to the top and bottom rebar of each sample. The onset of corrosion was detected by monitoring the potential across these connectors. Figure 5(b) shows the details of the ponding arrangement.

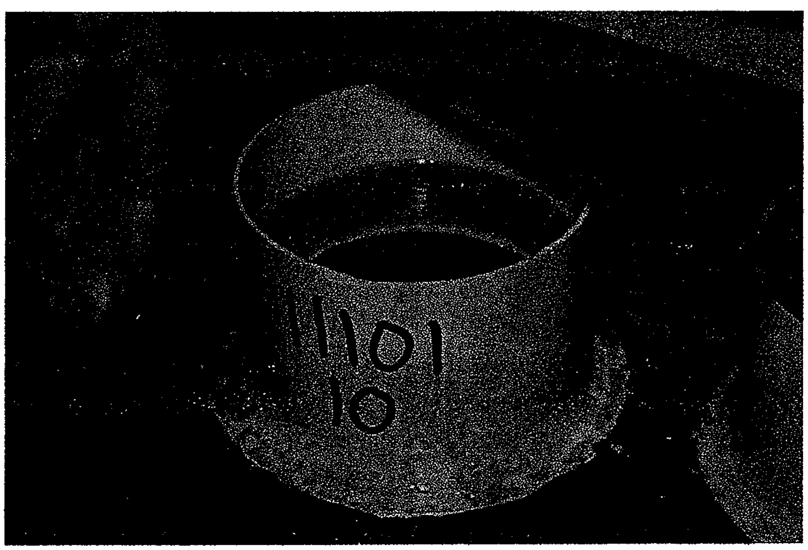
CSP readings were made on the 2 inch high cap portions removed from these samples. The group of these samples is shown in Figure 6. Each sample was tested as shown in Figure 7. The samples were set on a base of dry Nevada sand. The sand provided a homogeneous base condition which afforded repeatable measurements. Earlier tests with the samples stacked on one another showed that the contact condition at the base had an influence on the results, and this finding led to the sand bed arrangement.

A thin plastic sheet was placed on top of the sand so that, for the wet samples, there would be no moisture transfer from the sample into the sand. Six measurements were carried out on each sample, three on each face. The three measurements on each face were taken after the probe was moved and repositioned. These repeat measurements were intended to provide some measure of variability and scatter. The two faces were tested to account for variability of the concrete properties with depth. Also, the top face of each sample was the finished face, and has surface conditions that were likely to differ from the interior face. A centering ring, shown in Figure 7, was used to ensure that the probe was reasonably centered on the face of the sample for each measurement.

Each measurement produced a data file, containing the real and imaginary part of the impedance of the probe at the concrete interface. This impedance is reported as a function of frequency, with

100 frequency points ranging from 50 to 3000 MHz. This data was then processed to yield the conductivity and dielectric permittivity of the sample. A sample processed result of this testing is shown in Figure 8.

(a) Ponded Samples on Testing Rack

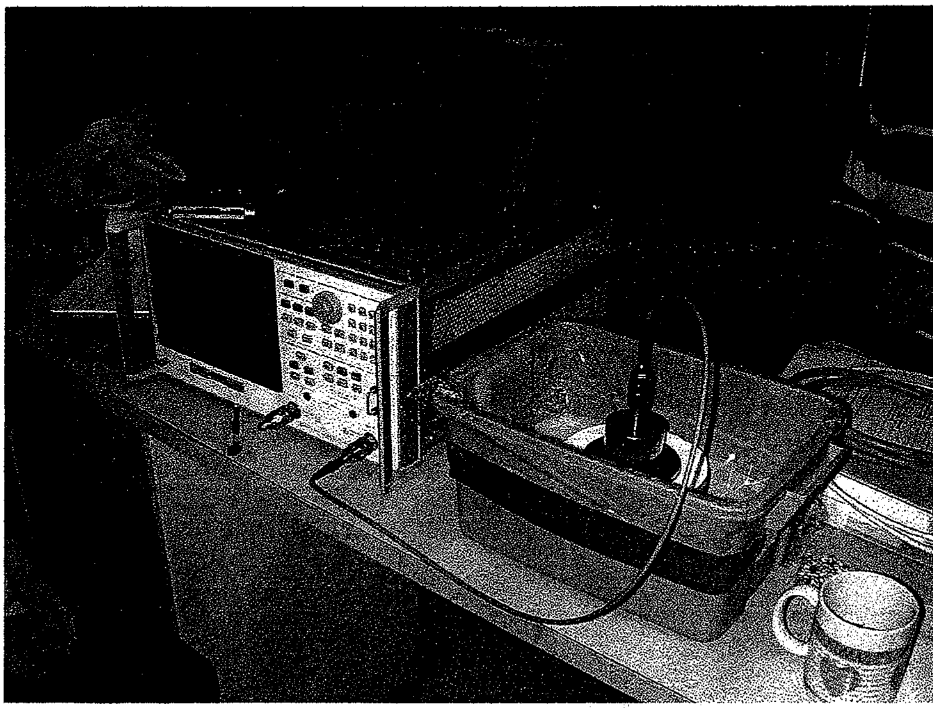


(b) Individual Sample Showing Ponding Arrangement

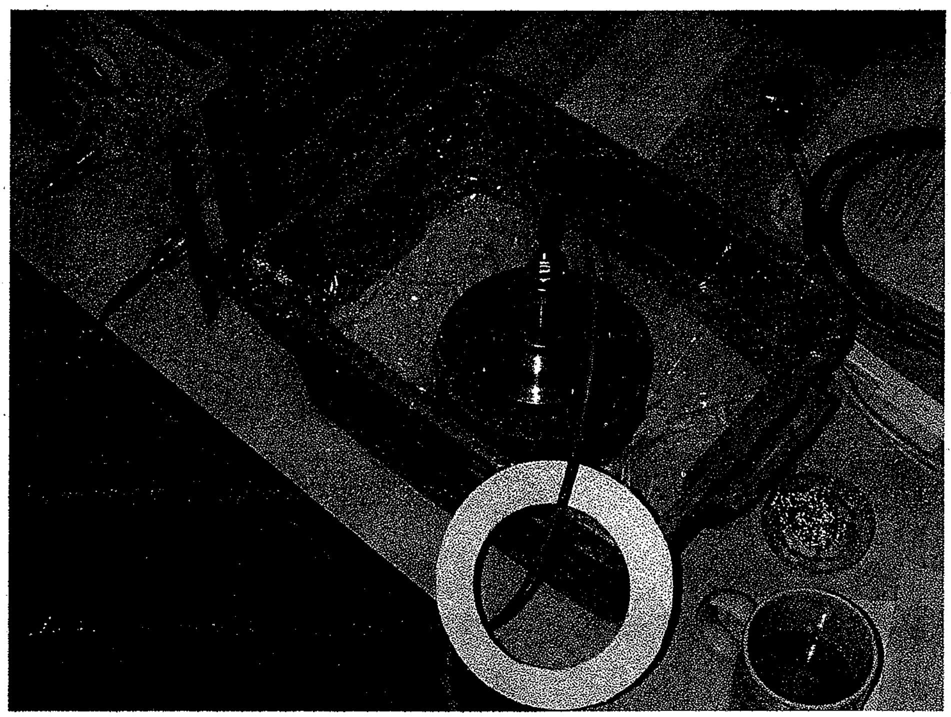
Figure 5 – Samples Subject to Chloride Solution Ponding

Figure 6 – Cap Samples Used for CSP Testing

The samples were tested under three different moisture conditions—oven dried, fully saturated, and partially saturated. The oven dry samples were heated in a laboratory oven for a period of 72 hours prior to testing. Once they were tested, the samples were placed in a water bath for 6 days, and then tested immediately after being removed from the water bath. Finally, the samples were allowed to partially dry under ambient laboratory conditions for 3 days and tested again.



(a) Overall Setup with Network Analyzer, Test Sample, and Test Bed



(b) Sample in Test Bed

Figure 7 – Testing Concrete Cap Samples

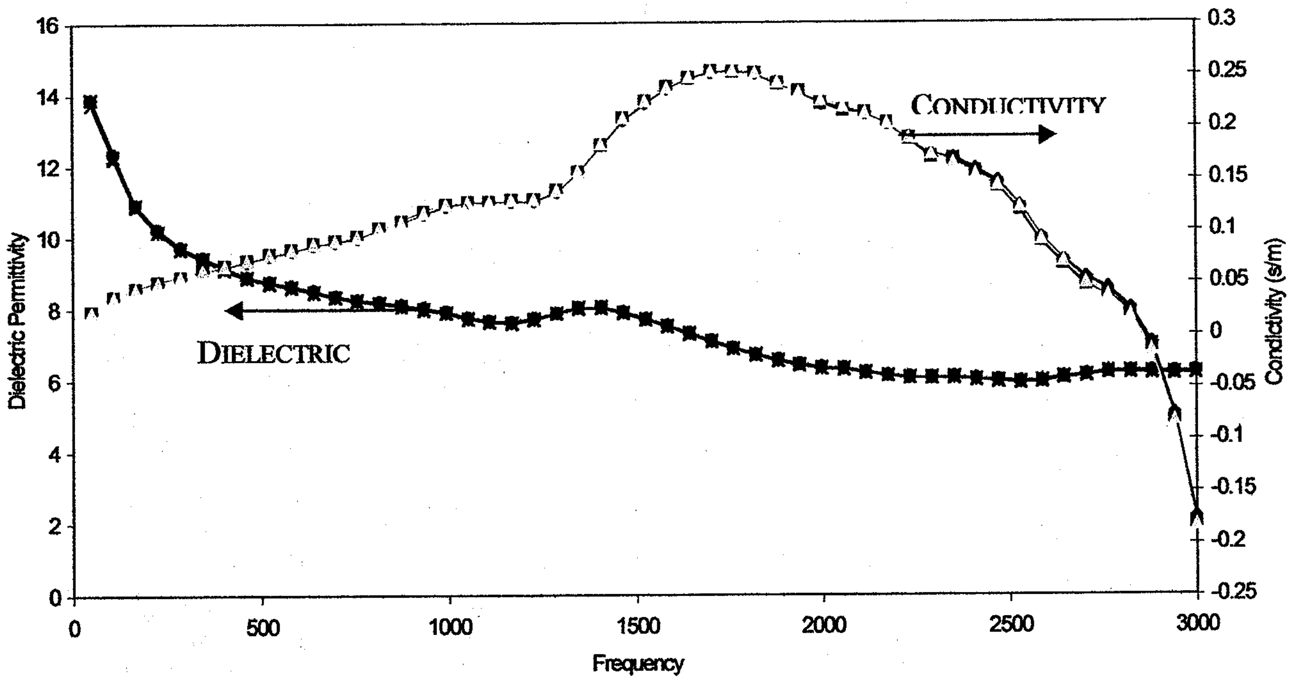



Figure 8 – Sample of Processed Data for One Test Specimen

The test results shown in Figure 8 is typical for these tests. The result represents a plot of 100 frequency points ranging from 50 MHz to 3 GHz. The left axis is the relative dielectric permittivity, a dimensionless number representing the ratio of the dielectric permittivity of a given material to that of a vacuum. The dielectric permittivity is a measure of the ability of a medium to displace (rather than conduct) electric charge. By definition, the relative dielectric permittivity of air is 1. Also, the relative dielectric permittivity of water is 81. Therefore, moisture content has a significant impact on relative dielectric permittivity. Values of the relative dielectric permittivity typically fall in a range of 3-16 for most common materials. The Figure 8 plot shows that the dielectric permittivity varies sharply between 50and 500 MHz, but is relatively uniform from 500 MHz to 3 GHz.

The right axis is the conductivity, which is measured in siemens/meter. Siemens is the SI unit of conductivity, and is the inverse of the ohms. The conductivity of a material is a measure of the ability of a substance to transfer electrical charge. For porous solids like concrete, the conductivity is heavily influence by the connectivity of the pores and the presence of a conductive fluid in the pores. This is why conductivity has been found to be a good measure of chloride permeability. The conductivity is also frequency dependent, increasing until a maximum is reached between 1.5 and 2.0 Hz.

Table 2 shows typical numerical output from a series of tests of cap samples for a given mix. A plot of this data is shown in Figure 9.

## Table 2 – Conductivity Data from Multiple Samples of Mix 4

| | Test Sample | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Freq | 4B | 4C | 4E | 4F | 4G | 4H | 4I | 4J | 4L | 4M | 4O | Avg | Adj. Avg |
| 50 | 0.0337 | 0.0178 | 0.0185 | 0.0257 | 0.0214 | 0.0239 | 0.0185 | 0.0075 | 0.0260 | 0.0093 | 0.0046 | 0.0188 | 0.0217 |
| 109 | 0.0354 | 0.0217 | 0.0208 | 0.0269 | 0.0234 | 0.0260 | 0.0223 | 0.0109 | 0.0268 | 0.0127 | 0.0071 | 0.0213 | 0.0240 |
| 168 | 0.0400 | 0.0259 | 0.0236 | 0.0294 | 0.0264 | 0.0291 | 0.0263 | 0.0139 | 0.0295 | 0.0158 | 0.0092 | 0.0245 | 0.0272 |
| 227 | 0.0438 | 0.0291 | 0.0251 | 0.0311 | 0.0283 | 0.0311 | 0.0293 | 0.0160 | 0.0314 | 0.0181 | 0.0105 | 0.0267 | 0.0293 |
| 286 | 0.0474 | 0.0320 | 0.0271 | 0.0329 | 0.0301 | 0.0332 | 0.0324 | 0.0177 | 0.0332 | 0.0201 | 0.0120 | 0.0289 | 0.0316 |
| 345 | 0.0508 | 0.0349 | 0.0284 | 0.0345 | 0.0317 | 0.0349 | 0.0350 | 0.0198 | 0.0351 | 0.0218 | 0.0131 | 0.0309 | 0.0335 |
| 404 | 0.0531 | 0.0370 | 0.0298 | 0.0360 | 0.0329 | 0.0363 | 0.0371 | 0.0209 | 0.0362 | 0.0233 | 0.0144 | 0.0324 | 0.0350 |
| 463 | 0.0557 | 0.0386 | 0.0302 | 0.0368 | 0.0338 | 0.0374 | 0.0389 | 0.0222 | 0.0371 | 0.0246 | 0.0153 | 0.0337 | 0.0361 |
| 522 | 0.0589 | 0.0413 | 0.0325 | 0.0386 | 0.0356 | 0.0389 | 0.0414 | 0.0238 | 0.0393 | 0.0265 | 0.0163 | 0.0357 | 0.0382 |
| 581 | 0.0620 | 0.0434 | 0.0335 | 0.0402 | 0.0372 | 0.0405 | 0.0435 | 0.0257 | 0.0407 | 0.0281 | 0.0175 | 0.0375 | 0.0399 |
| 640 | 0.0651 | 0.0459 | 0.0353 | 0.0423 | 0.0393 | 0.0425 | 0.0461 | 0.0274 | 0.0430 | 0.0303 | 0.0186 | 0.0396 | 0.0420 |
| 699 | 0.0675 | 0.0474 | 0.0360 | 0.0433 | 0.0402 | 0.0435 | 0.0480 | 0.0285 | 0.0440 | 0.0313 | 0.0196 | 0.0408 | 0.0432 |
| 758 | 0.0724 | 0.0502 | 0.0391 | 0.0453 | 0.0433 | 0.0473 | 0.0522 | 0.0311 | 0.0476 | 0.0341 | 0.0215 | 0.0440 | 0.0464 |
| 817 | 0.0836 | 0.0582 | 0.0477 | 0.0560 | 0.0532 | 0.0566 | 0.0610 | 0.0371 | 0.0587 | 0.0414 | 0.0263 | 0.0527 | 0.0559 |
| 876 | 0.0921 | 0.0639 | 0.0563 | 0.0656 | 0.0618 | 0.0657 | 0.0683 | 0.0426 | 0.0674 | 0.0462 | 0.0297 | 0.0600 | 0.0641 |
| 935 | 0.1012 | 0.0725 | 0.0647 | 0.0729 | 0.0671 | 0.0758 | 0.0749 | 0.0474 | 0.0772 | 0.0530 | 0.0347 | 0.0674 | 0.0721 |
| 994 | 0.1068 | 0.0783 | 0.0675 | 0.0801 | 0.0691 | 0.0776 | 0.0785 | 0.0506 | 0.0795 | 0.0551 | 0.0381 | 0.0710 | 0.0758 |
| 1053 | 0.1001 | 0.0749 | 0.0583 | 0.0716 | 0.0591 | 0.0678 | 0.0741 | 0.0481 | 0.0698 | 0.0525 | 0.0356 | 0.0647 | 0.0680 |
| 1112 | 0.0955 | 0.0678 | 0.0499 | 0.0604 | 0.0515 | 0.0602 | 0.0683 | 0.0427 | 0.0621 | 0.0473 | 0.0309 | 0.0579 | 0.0600 |
| 1171 | 0.0934 | 0.0649 | 0.0474 | 0.0584 | 0.0517 | 0.0603 | 0.0683 | 0.0390 | 0.0591 | 0.0437 | 0.0272 | 0.0558 | 0.0586 |
| 1230 | 0.0955 | 0.0652 | 0.0493 | 0.0609 | 0.0556 | 0.0627 | 0.0710 | 0.0374 | 0.0612 | 0.0429 | 0.0240 | 0.0569 | 0.0608 |
| 1289 | 0.1150 | 0.0791 | 0.0677 | 0.0773 | 0.0780 | 0.0835 | 0.0872 | 0.0483 | 0.0814 | 0.0555 | 0.0317 | 0.0732 | 0.0792 |
| 1348 | 0.1415 | 0.1012 | 0.0948 | 0.1083 | 0.1086 | 0.1144 | 0.1128 | 0.0659 | 0.1114 | 0.0748 | 0.0444 | 0.0980 | 0.1074 |
| 1407 | 0.1700 | 0.1277 | 0.1269 | 0.1400 | 0.1378 | 0.1495 | 0.1405 | 0.0884 | 0.1417 | 0.0992 | 0.0644 | 0.1260 | 0.1377 |
| 1466 | 0.1930 | 0.1546 | 0.1493 | 0.1660 | 0.1549 | 0.1663 | 0.1608 | 0.1089 | 0.1644 | 0.1212 | 0.0835 | 0.1475 | 0.1595 |
| 1525 | 0.2063 | 0.1687 | 0.1552 | 0.1736 | 0.1581 | 0.1675 | 0.1696 | 0.1223 | 0.1702 | 0.1333 | 0.0972 | 0.1566 | 0.1661 |
| 1584 | 0.2117 | 0.1757 | 0.1559 | 0.1729 | 0.1581 | 0.1673 | 0.1748 | 0.1306 | 0.1694 | 0.1423 | 0.1062 | 0.1604 | 0.1677 |
| 1643 | 0.2102 | 0.1761 | 0.1532 | 0.1673 | 0.1603 | 0.1669 | 0.1789 | 0.1352 | 0.1654 | 0.1468 | 0.1125 | 0.1612 | 0.1669 |
| 1702 | 0.2162 | 0.1794 | 0.1584 | 0.1695 | 0.1676 | 0.1774 | 0.1854 | 0.1419 | 0.1728 | 0.1535 | 0.1197 | 0.1674 | 0.1729 |
| 1761 | 0.2158 | 0.1815 | 0.1636 | 0.1731 | 0.1711 | 0.1806 | 0.1891 | 0.1491 | 0.1777 | 0.1593 | 0.1289 | 0.1718 | 0.1767 |
| 1820 | 0.2090 | 0.1730 | 0.1577 | 0.1649 | 0.1638 | 0.1747 | 0.1846 | 0.1491 | 0.1700 | 0.1568 | 0.1316 | 0.1668 | 0.1698 |
| 1879 | 0.2066 | 0.1683 | 0.1587 | 0.1601 | 0.1672 | 0.1774 | 0.1848 | 0.1492 | 0.1701 | 0.1579 | 0.1354 | 0.1669 | 0.1695 |
| 1938 | 0.2040 | 0.1652 | 0.1638 | 0.1651 | 0.1726 | 0.1837 | 0.1829 | 0.1508 | 0.1749 | 0.1567 | 0.1396 | 0.1690 | 0.1726 |
| 1997 | 0.2107 | 0.1691 | 0.1776 | 0.1843 | 0.1786 | 0.1994 | 0.1908 | 0.1558 | 0.1893 | 0.1607 | 0.1456 | 0.1784 | 0.1842 |
| 2056 | 0.2151 | 0.1752 | 0.1818 | 0.1984 | 0.1627 | 0.1853 | 0.1935 | 0.1612 | 0.1927 | 0.1638 | 0.1523 | 0.1802 | 0.1842 |
| 2115 | 0.2073 | 0.1787 | 0.1538 | 0.1786 | 0.1282 | 0.1515 | 0.1786 | 0.1576 | 0.1600 | 0.1594 | 0.1531 | 0.1643 | 0.1614 |
| 2174 | 0.1816 | 0.1687 | 0.1149 | 0.1379 | 0.0999 | 0.1117 | 0.1543 | 0.1476 | 0.1202 | 0.1466 | 0.1494 | 0.1394 | 0.1297 |
| 2233 | 0.1535 | 0.1407 | 0.0832 | 0.0972 | 0.0851 | 0.0918 | 0.1306 | 0.1317 | 0.0858 | 0.1283 | 0.1386 | 0.1151 | 0.1021 |
| 2292 | 0.1283 | 0.1175 | 0.0745 | 0.0733 | 0.1019 | 0.0978 | 0.1226 | 0.1222 | 0.0729 | 0.1163 | 0.1294 | 0.1051 | 0.0943 |
| 2351 | 0.1190 | 0.0965 | 0.0941 | 0.0775 | 0.1399 | 0.1328 | 0.1239 | 0.1157 | 0.0920 | 0.1098 | 0.1242 | 0.1114 | 0.1081 |
| 2410 | 0.1390 | 0.0932 | 0.1360 | 0.1261 | 0.1552 | 0.1653 | 0.1395 | 0.1200 | 0.1399 | 0.1185 | 0.1262 | 0.1326 | 0.1364 |
| 2469 | 0.1569 | 0.1130 | 0.1356 | 0.1531 | 0.1089 | 0.1370 | 0.1456 | 0.1319 | 0.1416 | 0.1297 | 0.1328 | 0.1351 | 0.1335 |
| 2528 | 0.1477 | 0.1192 | 0.0824 | 0.1039 | 0.0406 | 0.0737 | 0.1153 | 0.1296 | 0.0844 | 0.1224 | 0.1353 | 0.1050 | 0.0885 |

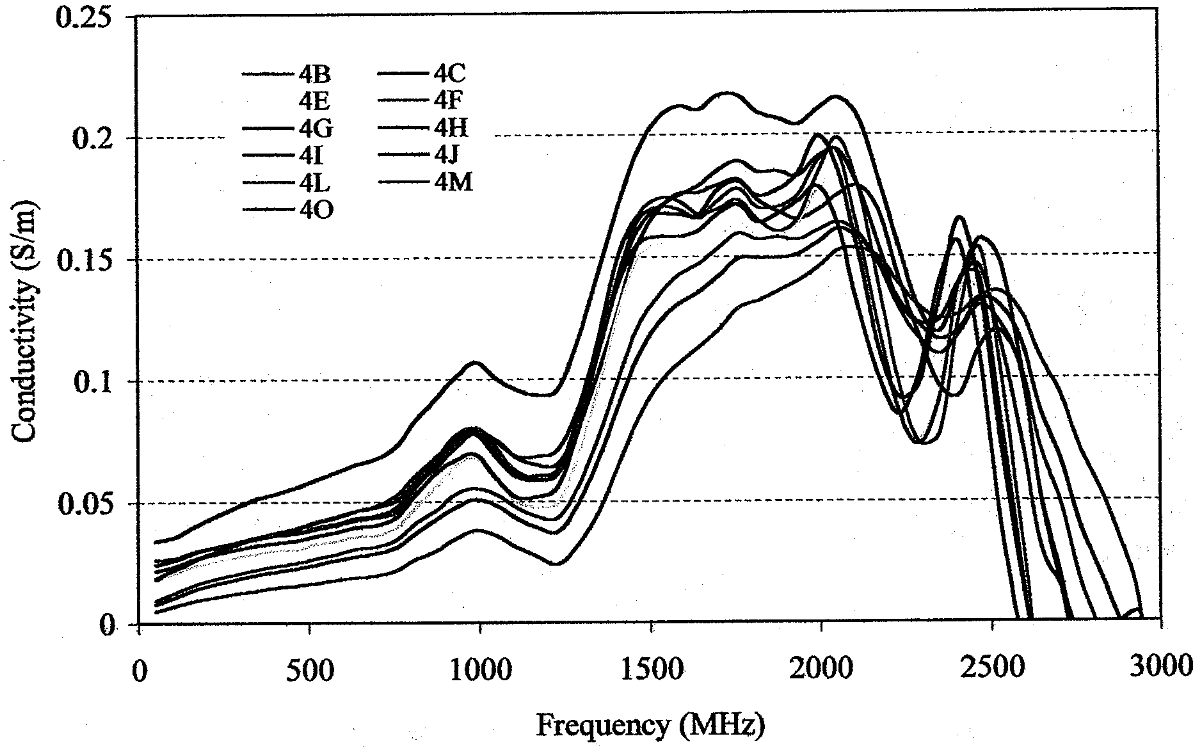



Figure 9 – Mix 4: Saturated Results for Conductivity

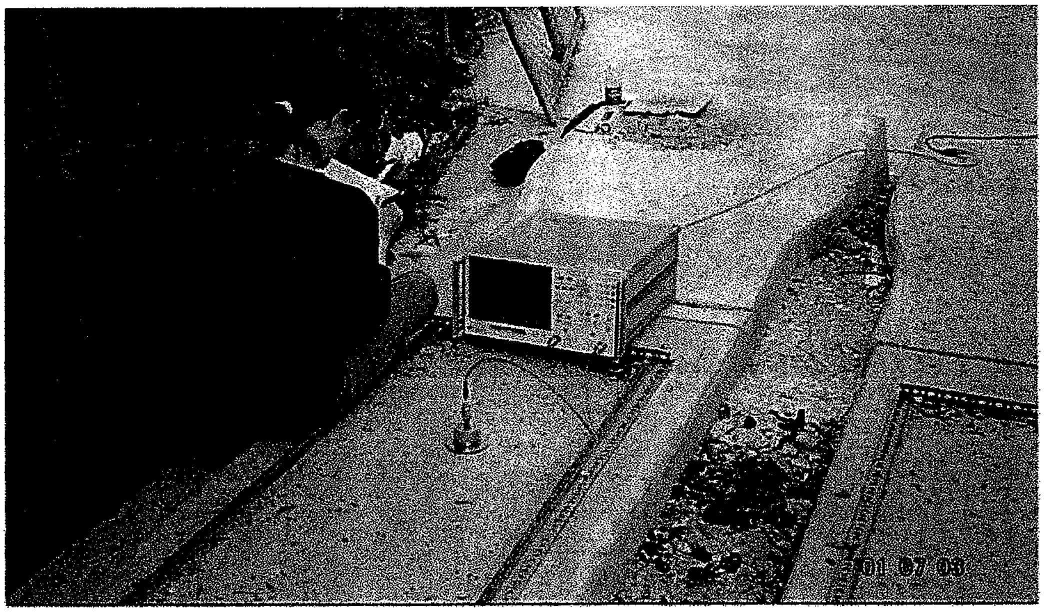
The results for the multiple samples of the same mix shown in Figure 9 exhibit similar behavior. However, three of the group appear as outliers. Additional testing revealed that the data for these outliers was repeatable, leading to the conclusion that the behavior was associated with the properties of the samples themselves rather than associated with the measurement arrangement.

Evaluation of the data collected on the two faces of each sample revealed that the most consistent data was collected at the bottom, where the sample had been saw cut from the original cylinders. The top surface of the sample was rough due to the concrete finishing and curing, and did not produce results which appeared to be very sensitive to the exact placement of the probe. Consequently, further data analysis was confined to the data collected at the saw-cut bottom of each sample.

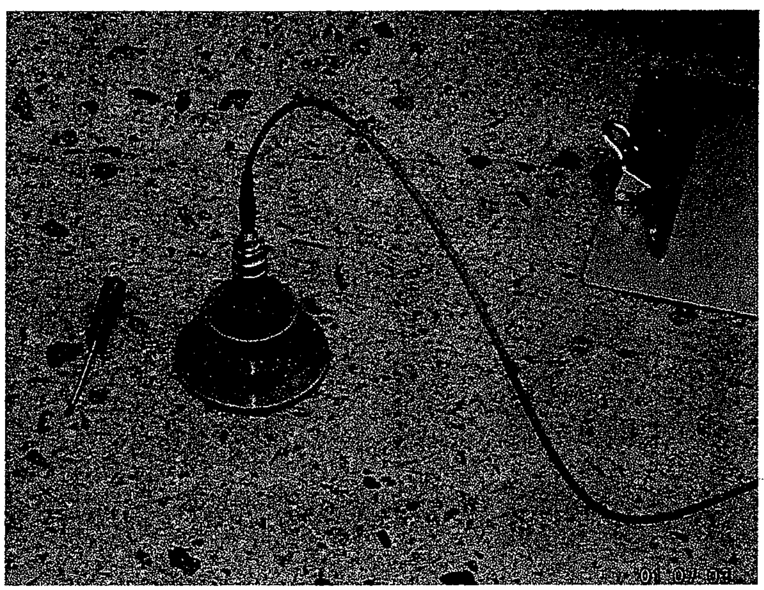
For analysis in which the average conductivity or permittivity of a sample was sought, these outliers were removed from the average. This leads to an "adjusted average" as shown in the last column of Table 2.

## 2.5 Testing on Plain and Reinforced Concrete Slabs

Testing was carried out on plain and reinforced concrete slabs to evaluated the influence both of the slab geometry and assess the reinforcing steel on the CSP measurement. A series of test slabs were at the W. R. Grace facility in Cambridge, Massachusetts were made available for this testing. Figure 10 shows the testing setup for the slab tests.



(a) Setup for Slab Tests



(b) CSP on Concrete Slab

Figure 10 – Tests on Concrete Slabs

The slab tests were conducted along a series of survey lines. Survey lines were established parallel and perpendicular to the long axis of the slab. Measurements were made at 1 inch spacing along a survey line. The purpose of this spacing was to investigate the variability of the measurement and its relationship to the homogeneity of the material. For the reinforced sections a second objective was to investigate the influence of reinforcement. With a survey line perpendicular to the axis of reinforcement, and reinforcement typically spaced at 6 inches, the CSP measurements would occur at several different positions relative to the location of the reinforcement. If the reinforcement had an influence on the CSP reading, this would be evident in the pattern of measured data along the survey line.

Table 3 presents a description of the slabs that were tested and the survey lines that were covered for the individual slabs.

Table 3 – Description of Slab Tests

| SLAB # | DESCRIPTION | SURVEY LINE | REINFORCING | DIRECTION |
|---|---|---|---|---|
| 1 | Mix 1, small aggregate | 1A | yes | longitudinal |
| | | 1B | no | longitudinal |
| 2 | Mix 2, large aggregate | 2A | yes | longitudinal |
| | | 2B | yes | transverse |
| | | 2C | no | longitudinal |
| 3 | Mix 3, large aggregate | 3A | no | longitudinal |
| | | 3B | yes | longitudinal |
| 5 | Mix 5, large aggregate | 5A | yes | longitudinal |
| | | 5B | no | longitudinal |

# 3. Description of Test Results

## 3.1 CSP Testing of Cylindrical Mortar Samples

As discussed in Section 2, samples were tested in three different moisture states: oven dry, saturated, and air dried after saturation. The third state was intended to represent partial saturation.

Figures 11 and 12 show the conductivity and permittivity results for the four mixes under the three moisture conditions. The results represent the adjusted average result for multiple samples of the same mix.

The results show that the conductivity and dielectric permittivity are most sensitive to mix type in the saturated state. This is expected, since saturation maximizes both the conductivity and the dielectric permittivity. On the other hand, there is very little difference among the four different mixes in the oven-dry state.

Amongst the data in the saturated state, the high w/c ratio mix with no additives (Mix 1) showed the highest conductivity, while the silica fume mix (Mix 4) showed the lowest conductivity. This is to be expected, since the high water cement ratio yields more permeable concrete, while the introduction of silica fume is known to decrease the permeability of the concrete. The conductivity values for the low water cement ratio mix (Mix 2) and the fly ash mix (Mix 3) fall in between those of the other mixes.

The dielectric permittivity results of Figure 12 follow a somewhat different pattern for the four mixes. Mix 3, with the high water cement ratio and the fly ash additive has the highest permittivity, while Mix 2 with the low water cement ratio and no additives showed the lowest permittivity. Since the dielectric permittivities of the samples were equal when dry, the change in dielectric permittivity due to saturation will be primarily sensitive to quantity of moisture, which in turn is a function of pore volume. This indicates that the Mix 3 has the highest porosity, and Mix 2 has the lowest porosity. Note that porosity does not necessarily correlate with permeability, since permeability is more a function of the connectivity of the pores rather that the volume of the pores.

The results of Figure 11 indicate that, using Mix 1 as a reference, the additives (Mixes 3 and 4) have a more significant effect on the reduction of conductivity than the lower water cement ration (Mix 2). Assuming the correlation of conductivity with chloride permeability, the statement would be true regarding the influence of these additives on chloride permeability.

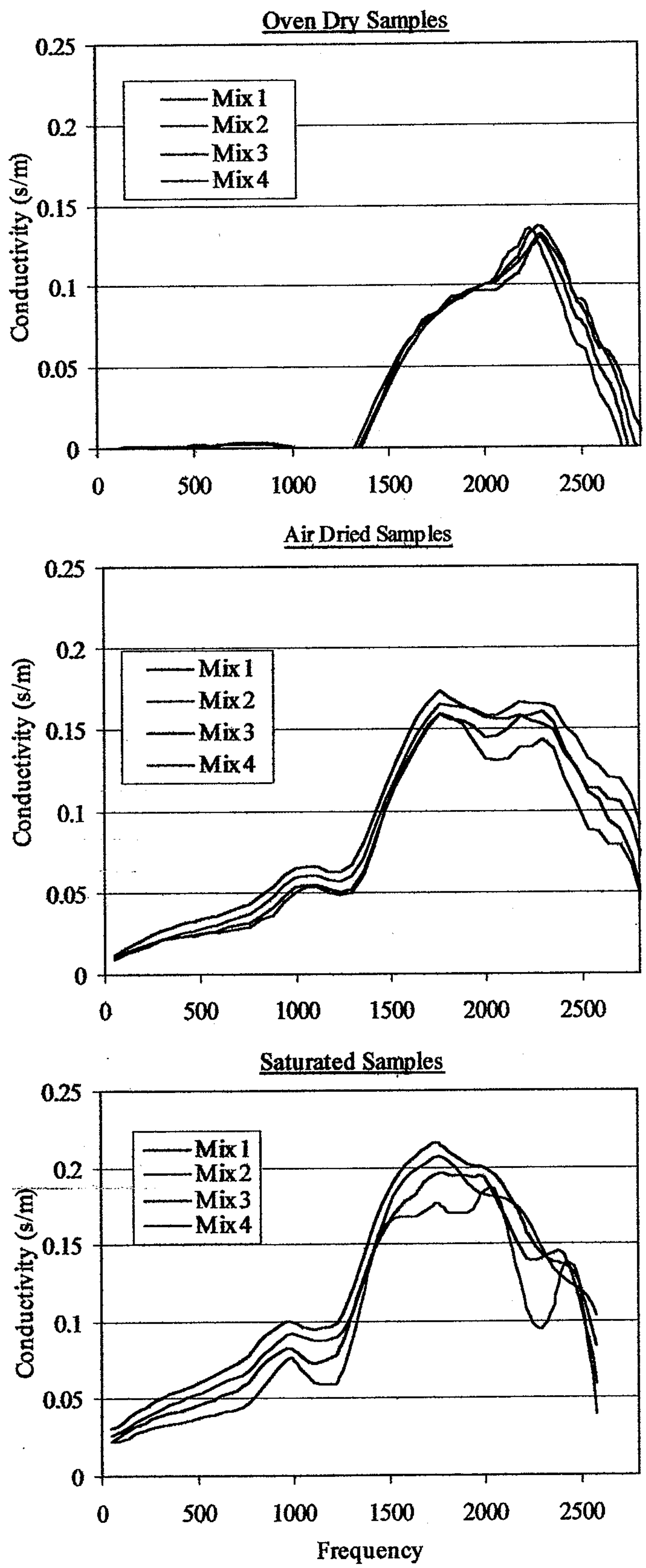



Figure 11 – Adjusted Average Conductivity vs. Frequency for Different Moisture States

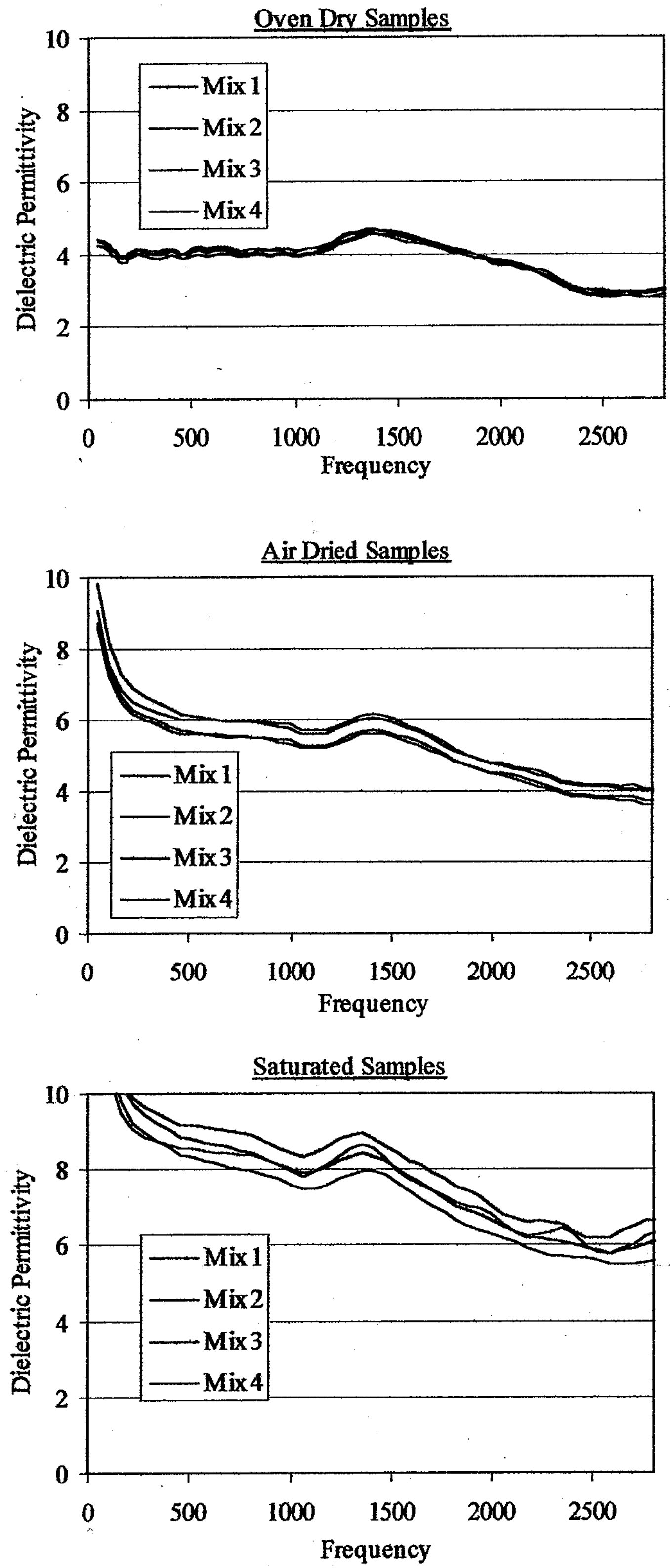



Figure 12 – Average Dielectric Permittivity vs. Frequency for Different Moisture States

## 3.2 Chloride Penetration (Ponding) Tests

The chloride permeability for each sample was calculated from the ponding test results. Table 4 summarizes these results. The table presents the basis for calculation of the effective diffusivity, $D_{eff}$, which is obtained by analyzing the chloride concentrations at various depths, after the sample is exposed.

Table 4 – Results of Chloride Ponding Tests

| Sample ID | $D_{eff}$ | Days in testing | started to corrode | Calculated Cl at the rebar (20 mm) | | | |
|---|---|---|---|---|---|---|---|
| | | | | when corrosion started | | after test is completed | |
| | $cm^2/s$ | days | days | lbs/yd3 | kg/m3 | lbs/yd3 | kg/m3 |
| **Mix 1** | | | | | | | |
| 1B | 2.02E-07 | 52 | 42 | 3.68 | 2.18 | 5.70 | 3.38 |
| 1F | 1.969E-07 | 94 | 71 | 8.73 | 5.18 | 11.60 | 6.88 |
| 1H | 4.532E-07 | 87 | 71 | 13.96 | 8.28 | 16.70 | 9.91 |
| 1I | 3.752E-07 | 108 | 98 | 12.70 | 7.53 | 14.20 | 8.42 |
| 1J | 3.116E-07 | 45 | 35 | 4.49 | 2.66 | 5.70 | 3.38 |
| 1K | 2.109E-07 | 87 | 71 | 6.48 | 3.85 | 7.60 | 4.51 |
| 1L | 2.715E-07 | 74 | 63 | 8.67 | 5.14 | 10.00 | 5.93 |
| **Mix 2** | | | | | | | |
| 2L | 1.027E-07 | 87 | 77 | 3.73 | 2.21 | 3.42 | 2.03 |
| **Mix 3** | | | | | | | |
| 3C | 3.827E-07 | 31 | 21 | 2.90 | 1.72 | 4.95 | 2.94 |
| 3E | 2.806E-07 | 45 | 35 | 6.17 | 3.66 | 9.35 | 5.55 |
| 3F | 1.167E-06 | 17 | 7 | 2.50 | 1.48 | 6.80 | 4.03 |
| 3H | 1.383E-07 | 94 | 78 | | | | |
| 3I | 3.682E-07 | 31 | 21 | 4.35 | 2.58 | 7.10 | 4.21 |
| 3M | 1.022E-06 | 10 | 3 | 0.18 | 0.11 | 4.02 | 2.39 |
| 3N | 2.826E-07 | 38 | 28 | 3.21 | 1.91 | 7.00 | 4.15 |
| **Mix 4** | | | | | | | |
| 4B | 1.252E-07 | 141 | 150 | 10.65 | 6.32 | 11.60 | 6.88 |
| 4C | 1.228E-07 | 140 | 122 | 11.02 | 6.54 | 13.10 | 7.77 |
| 4D | 1.373E-07 | 122 | 112 | 10.12 | 6.00 | 11.75 | 6.97 |
| 4E | 1.727E-07 | 110 | 93 | 8.56 | 5.08 | 10.50 | 6.23 |
| 4G | 2.918E-07 | 31 | 21 | 1.62 | 0.96 | 3.50 | 2.08 |
| 4I | 1.853E-07 | 90 | 77 | 7.55 | 4.48 | | |
| 4J | 2.569E-07 | 60 | 49 | 6.48 | 3.85 | 8.45 | 5.01 |
| 4K | 1.493E-07 | 160 | 147 | 12.18 | 7.23 | 8.39 | 4.98 |
| 4L | 1.849E-07 | 92 | 76 | 7.60 | 4.51 | | |
| 4N | 1.494E-07 | 94 | 86 | 7.26 | 4.31 | 13.47 | 7.99 |
| 4C | 1.228E-07 | 140 | 122 | 11.02 | 6.54 | 13.10 | 7.77 |
| 4D | 1.373E-07 | 122 | 112 | 10.12 | 6.00 | 11.75 | 6.97 |
| 4G | 2.788E-07 | 31 | 21 | 1.62 | 0.96 | 3.50 | 2.08 |
| 4J | 2.569E-07 | 60 | 49 | 6.48 | 3.85 | 8.45 | 5.01 |

Table 4 shows the number of days that each sample was exposed to the chloride solution prior to the onset of corrosion, along with the total exposure. The calculation of $D_{eff}$ also considers the initial concentrations of chloride in the material prior to testing (not shown on the table).

Note that the time to corrosion is a somewhat random process, and thus the results are highly variable. The calculated $D_{eff}$ is not based on the time to corrosion, however, but rather on the chloride concentration established over the time period of the testing. Nevertheless, the $D_{eff}$ results determined from the ponding tests show a great deal of variability. In several cases the tests were discontinued due to lack of onset of corrosion. In the case of Mix 2, only one sample reached corrosion, and consequently only one data point was reported for this point. A number of points appear to be outliers, such as samples 3F and 3M, whose results appear to be almost an order of magnitude higher than those of other samples in the batch.

## 3.3 Correlation of CSP Data to Ponding Data

### 3.3.1 Sample Averages

The CSP data was correlated with the ponding data using overall averages for a given mix type and using the individual test data. Note that this correlation is inherently limited by the limited quantity of ponding data. Nonetheless, it is best to make some comparison to see if there are any trends or promising correlations. Figure 13 shows the relationship between the average conductivity per mix vs. the average $D_{eff}$ per mix. The conductivity data is that presented in Figure 11 for the measurements on saturated samples. Note that Mix 2 has only one value in the $D_{eff}$ average. The CSP data has been presented for the three selected frequencies shown. These frequencies were chosen to represent the distinct ranges which appeared in the CSP data.

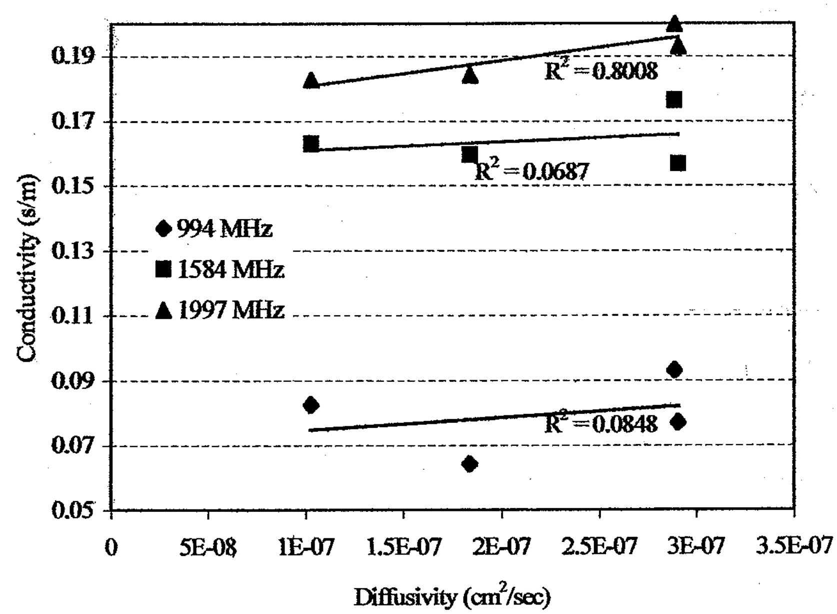



Figure 13 – Average Saturated Conductivity vs. Average $D_{eff}$ for each of the four Mixes

Figure 14 shows similar data relating the relative dielectric permittivity measured using the CSP vs. the diffusivity. The same three frequencies shown in Figure 13 are represented here.

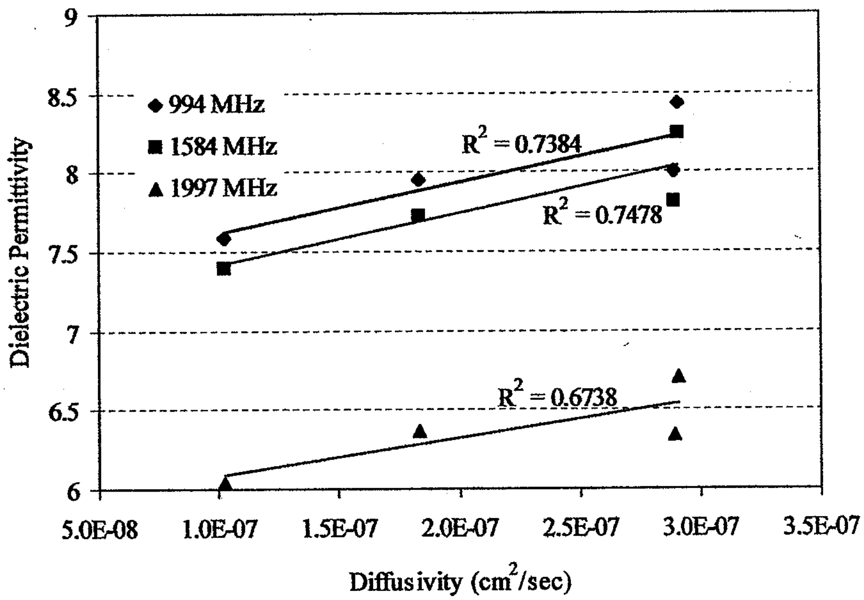



Figure 14 – Average Saturated Permittivity vs. Average $D_{eff}$ for Each of the Four Mixes

Note that the CSP conductivity measurements correlate well with the ponded diffusivity data only at the highest (1997 MHz) frequency. The $R^2$ for that line is 0.80. The data at the other two frequencies show no correlation. The situation is different for the CSP dielectric permittivity measurements. The data in Figure 14 show a good correlation between permittivity and ponded diffusivity for each of the three selected frequencies.

### 3.3.2 Individual Sample Correlations

Data for individual samples was correlated to obtain relationships between CSP measurements of conductivity and permittivity, and the diffusivity results obtained from the ponded samples. The correlation was carried out by mix type. Note that since not all of the ponded samples were available for CSP testing, and since not all of the ponded samples had useful results, only four to five samples from each mix were available for this correlation.

Figure 15 shows a series of plots relating CSP conductivity at 1700 MHz with diffusivity. This frequency was chosen because it is the approximate location of a peak in the conductivity-frequency curve. The plots are presented for both the saturated and partially saturated CSP measurements. No plots are available for Mix 2 because there is only one diffusivity data point.

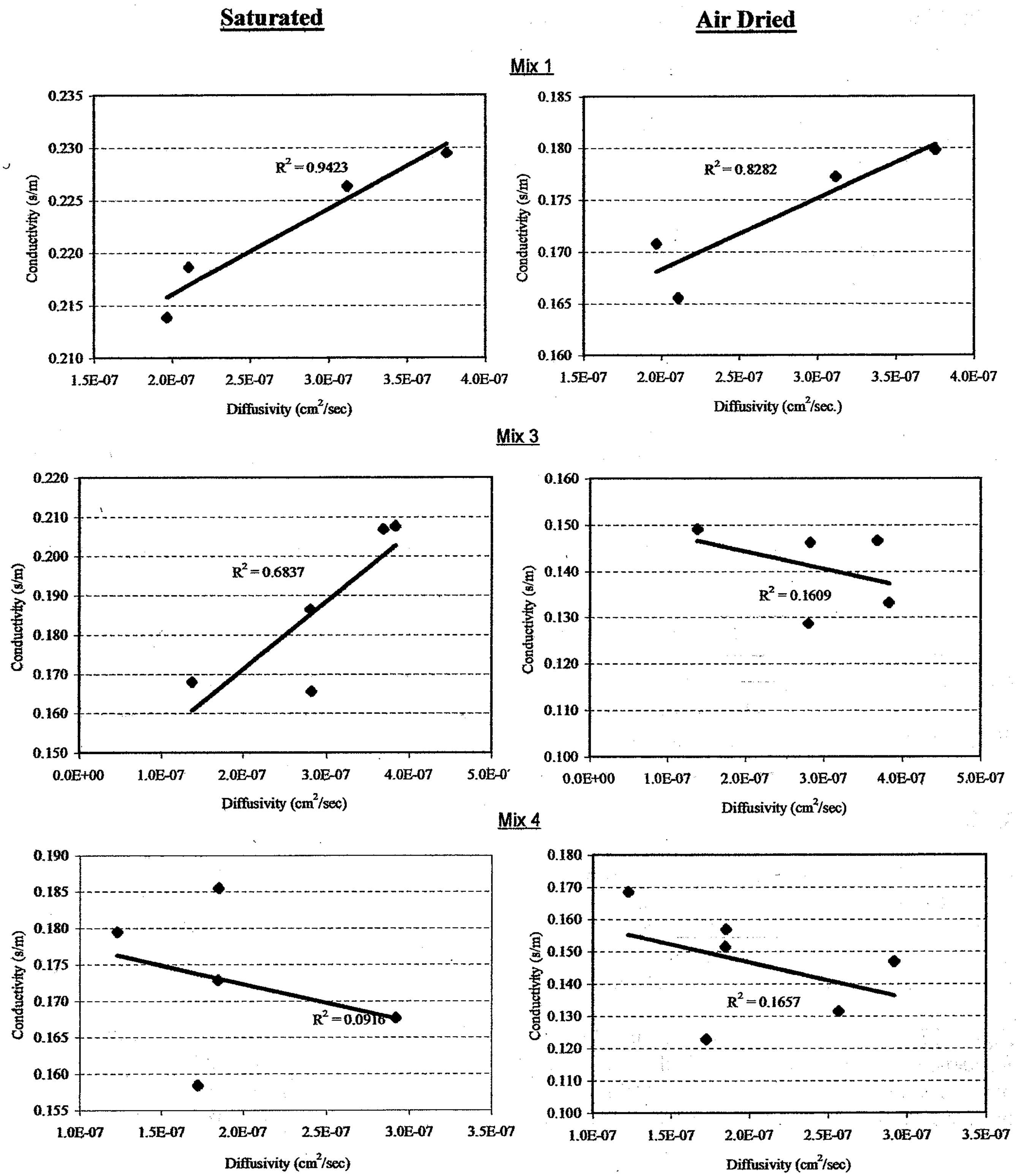



Figure 15 – 1700 MHz Conductivity vs. Diffusivity for Different Mixes at Two Moisture States

The results of Figure 15 show some correlation between conductivity and diffusivity for Mix 1 and Mix 3 in the saturated condition, and for Mix 1 in the partially saturated condition. Mix 4 does not show a correlation, and the trend is in the opposite direction from what would be expected.

Figure 16 shows similar results for dielectric permittivity vs. diffusivity. The Figure 16 data fails to reveal any consistent correlation between these two measurements on a sample by sample basis.

## 3.4 Results of Slab Testing

Data from the test slabs was processed to reveal spatial variability of the data collected by the CSP. The advantage of the slab tests is that they are independent of the sample boundaries, and they represent actual concrete as cast in place.

The slab data analysis was similar to the cylinder data analysis. For each measurement point, conductivity and permittivity was calculated as a function of frequency. Since there was a sequence of measurement points spaced at one inch, the data at a given frequency was plotted as a function of distance. The results of this analysis are shown in Figure 17.

Figure 17 presents example conductivity vs. distance plots for plain and reinforced survey lines on slab number 3. The plots have been provided for data at four different frequencies, from 994 to 1997 MHz. The plots show that the conductivity measurement is reasonably stable as a function of position on the slab. The high and low frequency data appear to be independent of position, whereas the middle frequencies, 1525 and 1702, show the greatest sensitivity. For the unreinforced data line, these middle frequencies appear to be reflecting some continuous variation in concrete properties. For the reinforced data line, there appears to be some periodicity which is most likely associated with the presence of reinforcing. Unfortunately information on the exact spacing of the reinforcement was not available for comparison.

The variation of dielectric permittivity with position is shown in Figure 18. The permittivity variation appears to follow that of the conductivity. The exception is that the spatial variation is exhibited at all frequencies.

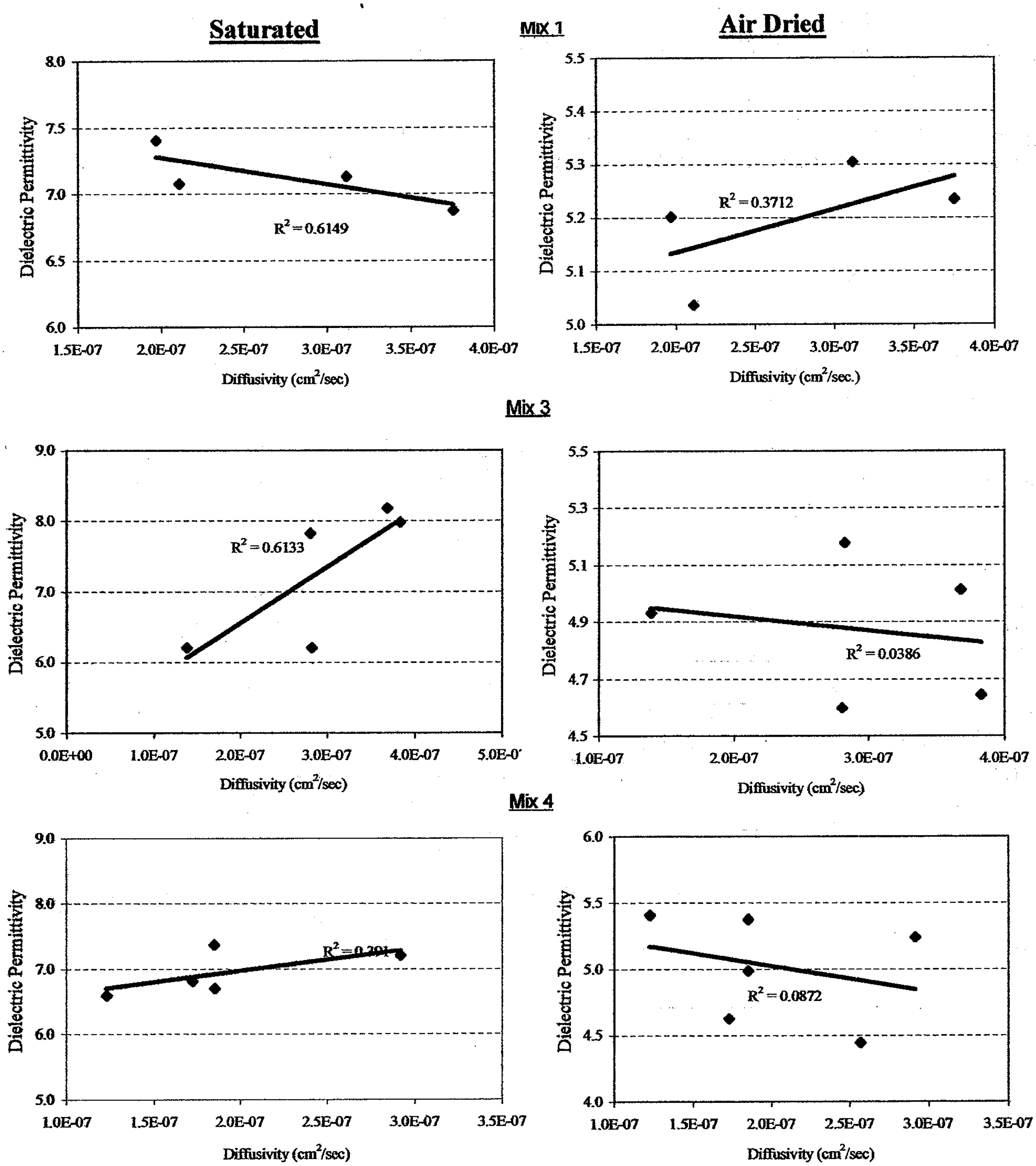
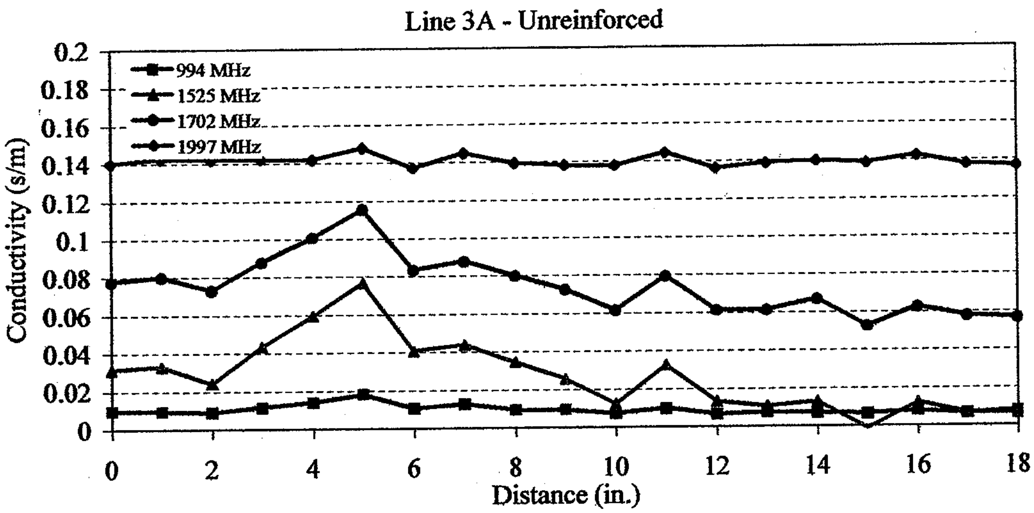



Figure 16 – 1700 MHz Permittivity vs. Diffusivity for Different Mixes at Two Moisture States



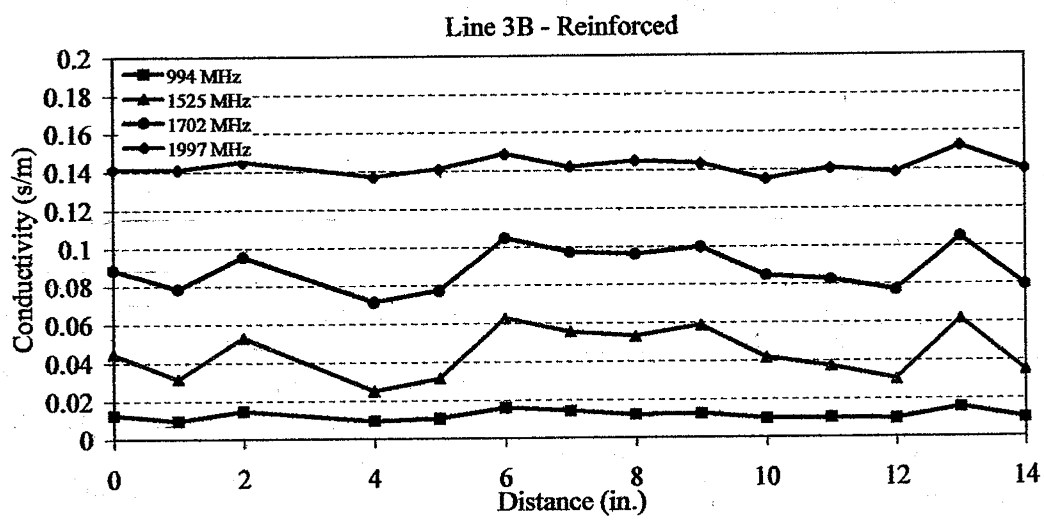




Figure 17 – Conductivity vs. Distance Measured on Test Slabs

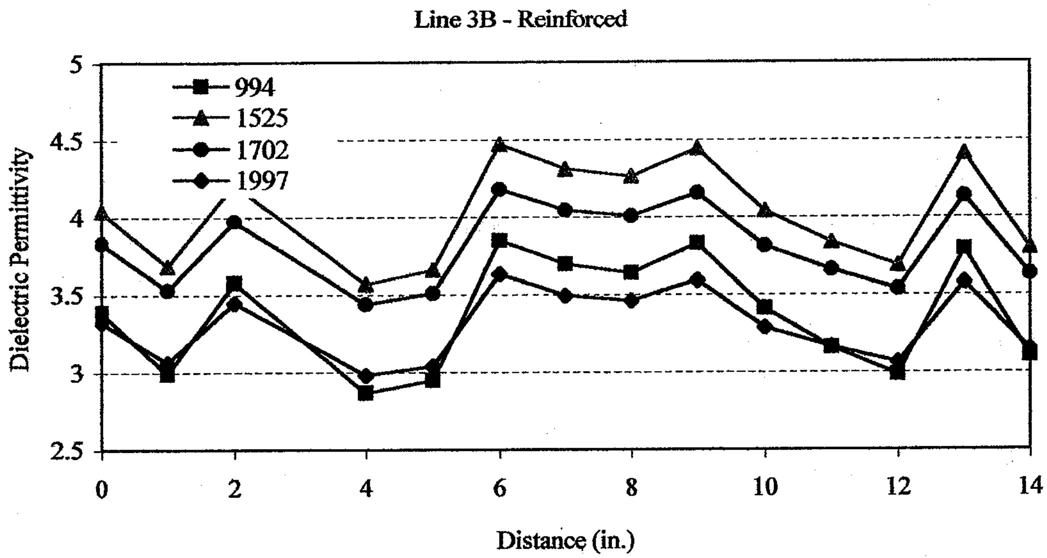



Figure 18 – Permittivity vs. Distance Measured on Test Slab 3

## 4. Discussion of Results

The test results described above show the following:

a. For the mortar samples tested, saturated sample averages show that the CSP measured conductivity and dielectric permittivity vary with the properties of the mix.
b. For these same mortar mix samples, saturated sample averages show that the CSP measured dielectric permittivity correlates with the concrete diffusivity measured by exposing the each sample to a ponded chloride solution.
c. Sample averages discussed in (b) did not yield a correlation with CSP conductivity values, as would be expected from theory.
d. Correlation of data from individual samples did yield a correlation between CSP conductivity and diffusivity for Mixes 1 and 3 in the saturated condition, and Mix 1 in the partially saturated condition.
e. No variation in CSP conductivity or permittivity could be detected for oven dry samples.
f. Measurements on concrete slabs were consisted with those made on the mortar samples. The spatial variation was found to be consistent with possible spatial variability in concrete properties.

It is important to note that the statements regarding the correlation between CSP measurements and diffusivity are based on a very small number of samples. The limitations in the diffusivity data are based in part on the constraints of the test program. The diffusivity testing was carried out by W. R. Grace as part of their ongoing testing program, and was not conducted specifically for this research project. Therefore the project was able to utilize the results for the limited budget available, but was not able to control the testing process to maximize the generation of useful data. Many of the ponded samples were not analyzed for diffusivity because corrosion initiation was not detected. This protocol resulted in the lost diffusivity data that otherwise would have been useful.

## 5. Conclusions and Recommendations

The conclusion of this work is that the CSP method has shown some potential for providing a measure of the chloride permeability of concrete. However, the amount of data has been too limited to reach any stronger conclusions. There have been some positive correlations under certain, but not all conditions. There is a relationship with dielectric permittivity which has not been fully explored.

Evaluation of the full potential of this method requires a more extensive, dedicated test program, one which was beyond the scope of this effort. In such a program it would be desirable to work with concrete slabs rather than mortar cylinders. The slabs could be subjected to the standard 90 day ponding test, and the concrete permeability could be directly measured from the chloride penetration of the slab. Prior to chloride penetration, the slab could be tested using the CSP under a variety of moisture and temperature conditions, and cores could be removed for more detailed laboratory evaluation. Such a program could provide a more significant opportunity to evaluate the potential of these methods.

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