ABSTRACT

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The strength and durability properties of concrete are related to its water cement ratio. Previous studies have shown that electrical properties of concrete appear to be related to both the water and cement contents of a mixture as well. In this study, a new technique and device were developed to measure the apparent dielectric constant of a concrete mixture at early stages of hydration. The ability of the device to be used as a tool for fundamental understanding of dielectric properties of fresh concrete and its potential to be used as field testing for quality control during early stage of concrete were analyzed.

Differences on the apparent dielectric constant measurements due to external variables such as time and frequency were studied. Analysis was made for variations of the apparent dielectric constant due to changes in the mixtures components such as water, cement and fly ash contents. The effects on the apparent dielectric constant due to inclusion of water reducing admixture were also analyzed. The relationship between apparent dielectric constant and the compressive strength of the concrete was of special interest for this study.

The method was found to be potentially useful in identifying changes which would cause differences in compressive strength among similar mixtures. The analysis showed a limitation for using the apparent dielectric constant alone in order to identify between any given mixtures.

EFFECTS OF MIXTURE COMPOSITION AND TIME ON DIELECTRIC CONSTANT OF FRESH CONCRETE

by

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CHAPTER 1. INTRODUCTION

1.1 Background

The properties of a concrete mixture such as strength, permeability and durability are fundamentally related to its water cement (w/c) ratio [Abrams, 1918]. Concrete is normally specified by its compressive strength at 28 days. Concrete mixture acceptance or rejection is therefore delayed until 28 days after it is cast. The time required can significantly affect construction planning.

Currently, quality control of fresh concrete is maintained through batch control and the slump test [ASTM C 143]. These methods have limitations, however. Batch control provides the data necessary to determine the nominal water cement ratio of the mixture. It is limited by its inability to identify variations to the mixture after batching, such as unrecorded water addition. As a practical matter, control of w/c ratio is often attempted by trying to limit the water added on site.

The slump test was first approved in 1922. It was originally created to examine fresh concrete consistency. At that time and under laboratory conditions, it could be used to identify higher water content mixtures and, for a constant cement content, reductions in compressive strength. Presently, due to the great number of changes in concrete technology such as admixtures, plus the variability of production and testing, the slump test can only be used to identify changes from batch to another of similar mixtures, with the assumption that changes which most affect the slump are the addition of water, either accidentally or on purpose. Its use as a reliable quality control tool with modern

concretes can be questioned, however.

A significant reason for the development of the microwave method for determining water content was to overcome the limits of the slump test. Heating a sample of concrete in a microwave oven [AASHTO T318, 2002] to drive off free water can identify large changes in water content of a mixture but cannot, in itself, estimate the potential strength of a mixture.

There is a need for a rapid method of verifying the potential strength of concrete, as delivered on the project. The development of the capacitance-based test described in the thesis was an approach to satisfying this need and overcoming the limitations of the slump test and microwave based water content determination.

1.2 Problem Statement

Previous studies [Taylor, 1974; Gu and Beaudoin, 1996; McCarter, *et al.,* 1981; Monfore, 1968; Hager and Domszy, 2004; Zhang, *et al.*, 1996; Camp and Bilotta, 1989] have shown that the electrical properties of concrete appear to be related to both the water and cement contents and the hydration progress. These studies have generally been concerned with the changes in how the water was bound as a function of hydration. There is no reported use of electrical characteristics of fresh concrete mixtures as a quality control tool.

A new technique and device was developed to overcome some of the difficulties reported in earlier studies. Feasibility studies developing and testing this new device and technique [Taylor, 2001; Treish, 2001; Mahoney, 2003] indicated that the apparent dielectric

constant of concrete could possibly be used to identify differences in water cement ratio of concrete mixtures.

This thesis describes the theoretical basics of the device and methodology developed in the feasibility studies. Further investigation was done analyzing the effects of the mixture composition on the apparent dielectric constant to give a fundamental understanding of the relationship between the components of the mixture and the dielectric properties. The study also analyzed the device potential as a tool for quality control at the field by studying the relationship between the apparent dielectric constant of fresh concrete and the compressive strength of hardened concrete.

CHAPTER 2. THEORY AND LITERATURE REVIEW

2.1 Fundamentals of Cement Hydration

The two main components of portland cement are tricalcium silicate (3Ca SiO_2 or C_3S in standard oxide notation), comprising about 50% of the unhydrated cement, and dicalcium silicate (2Ca SiO_2 or C_2S), comprising about 25%. The remaining compounds include calcium aluminate (3Ca Al_2O_3 or C_3A, about 10% in Type I cements), calcium alumino-ferrite (4Ca Al_2O_3 Fe_2O_3 or C_4AF, about 10% in Type I cements), calcium and alkali sulfates (about 3%) and trace compounds.

The products of the reaction of the calcium silicate reaction largely determine the mechanical properties of hardened concrete. When portland cement is mixed with water, the calcium silicate compounds go into solution and immediately form an insoluble calcium silicate hydrate (C-S-H) hydrate, along with calcium hydroxide (CH). The approximate C_3S reaction is shown below in Equation 2.1; the reaction of C_2S is similar. As indicated in Equation 2.1, the reaction uses only a fixed amount of water. Extra water, often termed "water of convenience" is added for workability. The extra water does not become a part of the hydration product.

$$2C_3S + 6H = C_3S_2H_3 \text{ (approximately)} + 3CH \textit{ (exothermic)} \qquad \text{Equation 2.1}$$

The compounds exist in unhydrated cement as irregular grains on the order of 10 micrometers (microns) in size [Neville, 1996]. When water is first added, the C-S-H forms a thin insoluble skin around the grain effectively stopping further hydration for some period of time which depends on temperature, compound composition, admixtures,

and mechanical mixing action. This is the "induction period" and normally lasts from 10 minutes to 30 minutes. As osmotic pressures build and continued mixing abrades the C-S-H, the thin layer of C-S-H is broken and additional compounds become available for hydration [Mehta and Monteiro, 2006].

After the induction period, the cementitious mass begins to solidify rapidly. The particles of C-S-H begin to form agglomerations. The volume of C-S-H produced is close to twice the volume of the original anhydrous cement. The C-S-H agglomerations occupy space previously occupied by water, reducing voids and creating a solid structure capable of supporting external loads [Mehta and Monteiro, 2006].

Initial set, the time at which the mass becomes rigid, typically occurs about 90 minutes after water has first been added for mixtures at room temperature containing a Type I, or ordinary portland cement, without admixtures. Final set, the end of the solidification process, usually occurs in four to six hours. Hydration continues indefinitely as long as moisture is available. The rate of hydration slows as more water and cement are taken up in hydration and the mean free path of water to the site of unhydrated cement increases.

Water exists in a variety of states in hardened concrete. Water can exist as a part of the hydrate, or the unreacted mixing water, or in various adsorbed states. The Feldman-Sereda [1970] model postulates four different states of water in a hydrated cement paste. Water can be chemically bound in hydration products, including C-S-H and CH. Interlayer water is strongly held, but not chemically bound, in very small spaces, from about 1 to 3 nanometers, in the C-S-H agglomerations. Interlayer water does not directly affect the strength of concrete. Water can also be adsorbed onto the surface of the C-

S-H particles. Adsorbed water is held by weakly attractive, surface, or van der Waals forces which become rapidly weaker with distance. Water can also exist in larger pores. This water may be considered of two kinds: free water and capillary water. Free water is not considered to be subjected to attraction forces and its removal does not have an effect on the volume of the paste. Capillary water is located in smaller pores and is subjected to capillary tension forces. Removal of capillary water results in only a slight reduction in paste volume. Since hydrates exist from the time water is added, water can also exist in all of these forms during the initial stages of hydration, although the relative quantities in each state is considerably different in the first few hours and after long periods of curing [Mehta and Monteiro, 2006, Neville, 1996].

The capillary pore volume, that is, the space not occupied by either solid hydrate or gel pores, which are too small to significantly affect engineering properties, is inversely related to compressive strength in a non-linear manner [Neville, 1996]. An increase in water cement ratio will increase the pore volume and therefore decrease strength; additional hydration reduces pore volume and therefore increases strength. Free, capillary, and adsorbed water occupy the pore volumes which control most engineering properties of concrete. The state in which the water exists is expected to affect the electrical characteristics of the concrete, as explained below.

2.2 Electrical Properties of Materials

The extrinsic, or macroscopic, electrical characteristics of a material such as concrete are a function of the intrinsic electrical properties of the material, the geometry of the specimen, and the nature of the applied electrical field, including frequency and

strength [Bartnikas and Eichorn, 1983; Hill, et al, 1969; Buchanan, 1986; Neff, 1981]. The intrinsic properties are fundamental material properties.

Extrinsic characteristics are measured directly and include capacitance and resistance. An expression for the conductance or resistance and the capacitance of an element may be developed for a given specimen geometry, based on intrinsic properties including resistivity ρ, (ohm-meters) or its inverse conductivity (σ, siemens per meter), and relative permittivity (ε, farads/meter). The electrical properties of concrete are strongly affected by the water content [Bartnikas and Eichorn, 1983; Hill, et al., 1969].

Resistance and resistivity are the opposition of a material to current flow. Numerically, resistance is the voltage drop across the material divided by the current flowing through it. Resistivity is the resistance per unit volume for a given cross section of material resisting electron flow. Capacitance is the ability to store electric energy. It is defined as the amount of charge (coulomb, C) able to be stored for a given electric field strength [Halliday and Resnic, 1962]. Capacitance is given in Farads (F), which is 1 coulomb per volt of potential difference.

2.2.1 Electrical Characteristics of a Simple Capacitor

A simple capacitor can be made by connecting an electric source to two parallel plates separated by some distance (see Figure 2.1). Electrons flow from the negative pole of the battery to one plate while the electrons from the other plate flow to the positive pole of the battery, resulting in a potential difference between the plates. The system reaches equilibrium when the voltage between the plates equals the energy source voltage and

electron flow stops.

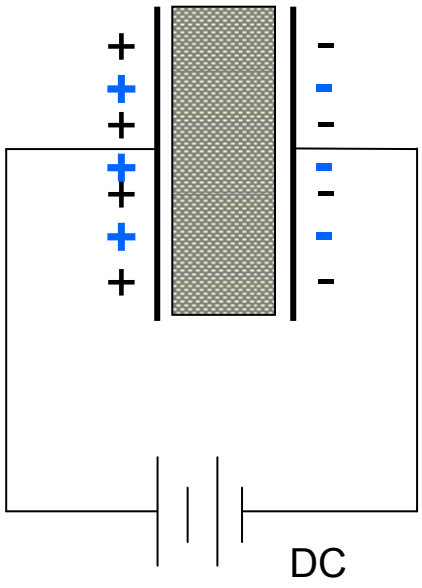


Figure 2.1 Simple Capacitor

Capacitance is proportional to the permittivity of the material between the plates, whether a vacuum, air, or other specific material, typically an insulator in electronics applications to prevent current flow between the plates. The dielectric constant of a material is the ratio of the relative permittivity of the material to the permittivity of free space and is dimensionless.

The dielectric properties of a medium are related to the ability of the medium to polarize an electric field. Polarization reduces the electric field inside the medium. With a smaller electric field in the dielectric medium, a capacitor has the capacity to store a greater amount of charge, increasing its capacitance. Water is a highly polar molecule and has a relatively high dielectric constant, approximately 80 [Halliday and Resnick, 1962]. The dielectric constant of air is approximately 1, and the dielectric constant for most

ceramics, such as aggregates and dry, hardened cement paste, ranges from 4 to 8 [Bartnikas, 1983].

Applying Gauss' theory to the geometry in Figure 2.1, it may be shown that the capacitance of this device is [Halliday and Resnick, 1962]:

$$C = \varepsilon_0 \varepsilon' A/d \qquad \text{Equation 2.2}$$

where C is capacitance (F),

ε_0 is the permittivity of free space (8.85×10^{-12}),

ε' is the dielectric constant of the material between the plates,

A is the area of the plate (m), and

d is the distance between the plates (m).

2.2.2 Electrical Behavior of a Capacitor over Time

An electric field applied across any real material will cause a shift in the alignment (rotation) of polar molecules and the movement (translation) of ions and polar molecules which are free to move. The pore solution in concrete contains significant amounts of dissolved solids as ions [Mehta and Monteiro, 2006], and water molecules are highly polar. The resistance to movement of ions and molecules in the pore solution results in an electrical resistance component. The rotation of the dipolar water molecules lags the application of voltage and therefore also contributes to electrical resistance as well as the

capacitance.

The application of a direct current (d-c) field to a concrete specimen which is not fully dry will cause the movement of water molecules and ions dissolved in the water towards the electrodes. This movement will reduce the effect of the external field so the measured resistance changes over time. Studies of the electrical characteristics of cementitious material or concrete are therefore normally conducted using alternating current circuits [see, for example, Hope, Ip, and Manning, 1985].

By applying a sinusoidally varying, alternating current (a-c) field, charge build-up at the electrodes due to purely electrical considerations is eliminated, although chemical reactions at the electrodes can complicate this problem [Bartnikas and Eichhorn, 1983]. Use of an a-c circuit with a frequency between several hundred hertz to 1 kilohertz (kHz) reduces ion movement effects over time so concrete tests are normally conducted at 1 kHz and above [Camp and Bilotta, 1989]. Molecular dipoles such as water will lag the applied voltage as they try to align themselves with the changing field, which also contributes to electrical resistance of the material. The frequency of the field affects polarization and therefore the dielectric properties of a material. This relationship is called dielectric spectroscopy. Electrical measurements will therefore be functions of the frequency.

The lag, or delay, in response of dipole water molecules to changes in the applied field is termed relaxation. At low frequencies the relaxation is due to ionic and dipole relaxations. Ionic relaxation is related with ionic conductivity and losses are introduced to

the system Dipole relaxation is related to the reorientation of the dipole molecules to the electric field.

2.2.3 Equivalent Circuits

An equivalent, analogous circuit is normally used to electrically model real materials with both capacitive and resistance effects. The resistance and the capacitance elements are modeled as pure components in parallel, as shown in Fig 2.2.

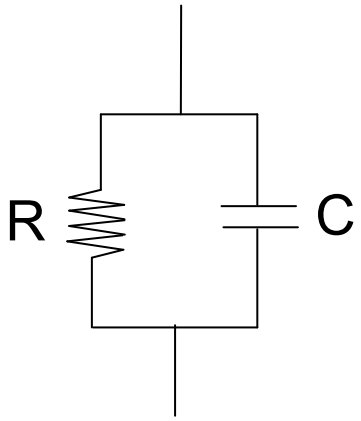


Figure 2.2 Equivalent Electrical Circuit for Materials

Impedance (Z) is the total opposition of a circuit to current flow. Impedance is a complex number and the impedance of the circuit shown in Figure 2.2 is the sum of the resistance and the capacitive reactance, as given in Equation 2.3. The real component of the impedance vector is the resistance (R) and the imaginary component is the reactance (X_c).

$$Z = R + j(\omega C)^{-1} \qquad \text{Equation 2.3}$$

where Z is the (complex) impedance,

R is the resistance (ohms, Ω),

C is the capacitance (F),

$\omega = 2\,\pi f$, where f is the frequency, and

j is the square root of -1.

As shown in Equation 2.3, the capacitive reactance is proportional to the frequency of the circuit and the total capacitance. Similar to resistance, the reactance is measured in ohms. It differs from resistance in that reactance does not transfer electric energy to heat. An ideal capacitor therefore does not consume energy. Some energy is lost in real capacitors, however. These losses may be due to resistance losses or dielectric losses. Resistance losses are electrical energy transferred to heat due to current flowing through the leads and plates of the capacitor. Dielectric losses occur due to heat produced during the change in the molecular structure of the dielectric due to the changes in polarity [Fowler, 1999].

The quality of a capacitor may be measured by considering how much energy is lost in operation. A capacitor which has been damaged or in which the insulator used as the dielectric deteriorates, the capacitor may become "lossy," that is, the device begins to lose the ability to hold sufficient charge. Three different factors are used to measure capacitor quality: power factor, quality and dissipation factor. In this study, the dissipation factor (D) was typically used to measure the quality of the data for any given test since a high D

would indicate a likely short circuit in the test set up. This is discussed in more detail in Chapter 3. The dissipation factor is the ratio between resistance and reactance.

2.3 Review of Previous Studies

2.3.1 Development of the Device – Basic Concepts

This section and the next section are drawn from a paper with additional authors, in preparation. Measured capacitance is a function of the proportions of each material in the sample, the dielectric constant of each material, and the geometry of the sample and conductors. Since the dielectric constant of water is about 80, the dielectric constant of most ceramic materials, including aggregate and cement, is between 4 and 10 [Bartnikas, 1983], and the dielectric constant of air is 1, relatively small differences in the water content were expected to have a relatively large effect on the measured capacitance. The design of the device was originally based on using these large differences in dielectric constants of the components to estimate the water content of fresh concrete.

An important factor in the development of the device was the use of a thin insulating layer between the concrete and at least one of the conductors. This would create, in effect, an infinite resistance and ensure that the only impedance effects in the measurement would be due to ionic or dipole relaxation. This configuration would eliminate or minimize many complicating factors in resolution due to effects such as the relatively low resistivity of fresh concrete and sensitivity to relatively minor differences in chemical composition including the effects of various admixtures [Whiting, 1992].

A plastic cylindrical mold commonly used to fabricate compressive strength specimens

would provide the needed thin insulating layer, is easily obtained, and, if the device were successful, the device would be easy to adapt to conventional fabrication and testing programs. The geometry of the mold is also convenient (see Figure 2.3). By placing a cylindrical conductor in the center of the mold and a conductor on the outside of the mold, then filling the resulting annulus with concrete, the device becomes a coaxial capacitor. The device was filled in three approximately equal layers, rodded 25 times for each layer, in general accordance with ASTM C39. Centering the rod is critical. Ensuring no electrical contact between the concrete in the mold and the conductor on the outside of the mold is also critical.

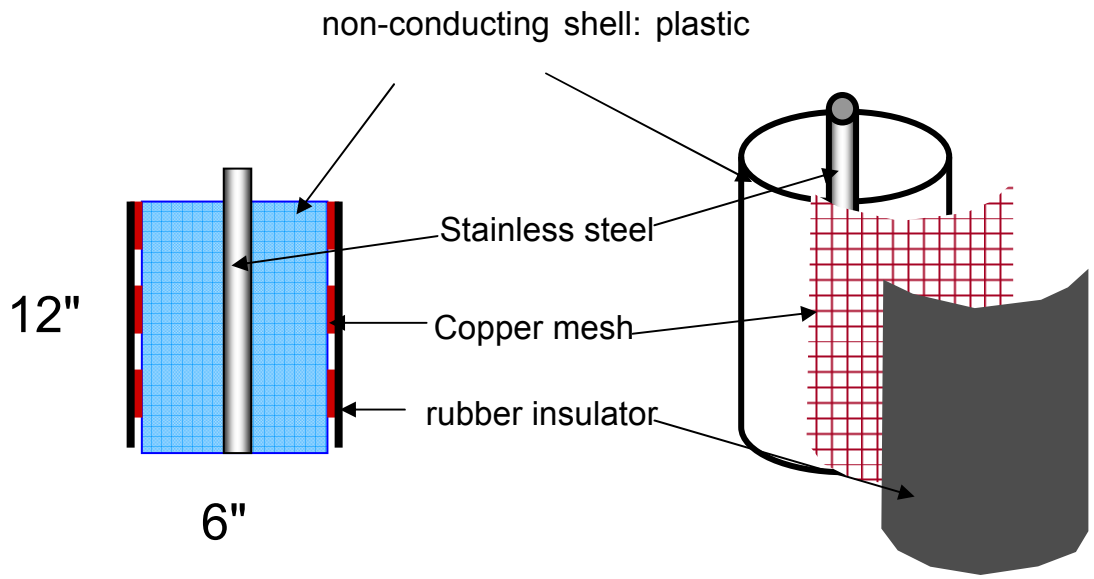


Figure 2.3 Schematic of the Device of the Feasibility Study

Applying Gauss' theory for determining the electric field outside a charged cylinder and integrating along the radial line, the capacitance of the filled cylinder may be shown to be [Halliday and Resnick, 1962]:

$$C = 2 \pi \varepsilon_0 \varepsilon' L / \ln (b/a) \qquad \text{Equation 2.4}$$

where C is capacitance (F),

ε_0 is the permittivity of free space (8.85×10^{-12}),

ε' is the dielectric constant of the material in the annulus,

L is the length of the material in the annulus (the height of concrete in the mold),

ln is the natural logarithm,

b is the outside diameter of the outside conductor, and

a is the diameter of the internal conductor (b and a must be in consistent units).

Examination of Equation 2.4 shows that the capacitance is directly proportional to the apparent dielectric constant of the fresh concrete and to the length of the sample. The capacitance is inversely proportional to ln (b/a). The sensitivity of the device can be improved by increasing the length of the sample and decreasing the distance between the inner and outer conductors. Since the length of the device was limited to no more than about 300 mm (12 in.), and the diameter of the outer conductor was set at 150 mm (6 in.), the size of the cylindrical mold, the only variable in the design, at least initially, was the diameter of the inside conductor. Initially the outer conductor was copper mesh, which was covered by a rubber sheet to insulate the mesh from contact with the concrete.

The inside conductor should be as large as possible while not interfering with placing and consolidating the fresh concrete. The inside conductor was not insulated to minimize the effect of charge build-up during the test. The material used could not be aluminum or any other material which would react chemically with the fresh concrete during the test. Stainless steel was selected to minimize both chemical reaction with fresh concrete during the test and maintenance over many tests. Several sizes of conductor were considered. Since the capacitance of this device is inversely related to the log of the ratio of the diameters of the mold and the internal rod, a large difference in the ratio would have only a small to moderate effect on measured capacitance. A 19 mm (3/4 in.) diameter bar was found to be relatively easy to handle and permitted the mold to be easily and quickly filled, although a slightly larger diameter (25 mm, 1 in.) could also be used. A lexan plate about 5 mm (1/4 in.), with a hole cut in the center to hold the stainless steel rod, was placed at the bottom of the cylinder to center and stabilize the rod. A similar plate was originally provided for the top, but was later found to be unnecessary.

The dielectric constant of a composite material is not necessarily the average of the dielectric constants of the components, weighted by volumetric proportions [see, for example, Bartnikas, 1983]. Free water has a dielectric constant value of about 80, but the effects of ions in solution, adsorption by or hydration with cement, and boundary layer were not known. Several publications noted the very high apparent dielectric constant found in hardened concrete [Camp and Bilotta, 1989; Ford, *et al*., 1997; Gu and Beudoin, 1996]. Several different speculative explanations of this observation, including refutation in one case, were made by various authors, but no definitive explanation was found.

Taylor [2001] developed the device and test method, resulting in several modifications before the device was used in the studies described in the next section. His work was primarily concerned with prototype development but included testing a number of mixtures. Two sizes of cylindrical molds, in combination with a variety of internal conductors, centering methods, different types of external conductors, two different capacitance meters, and insulation or electrical isolation requirements were tested. Mixtures for these tests were similar. A sample of a mixture was tested in the device, then water was added to the original batch, which was remixed and a second sample taken for another test in the device. In all cases, a difference in capacitance was found. This level of testing was adequate for initial development of the test device but a feasibility study was necessary to confirm proof of concept and to determine the validity of the basic model assumptions.

2.3.2 Results of Preliminary Studies

2.3.2.1 First Preliminary Study

A feasibility study was conducted by Treish [2001] using small batches. He made two series of mixtures with Type I cement and #57 stone as coarse aggregate. All of the mixtures were non-air entrained for simplicity.

Prior to testing with concrete, the capacitance of the device itself was measured. The capacitance of the device alone would be subtracted from the measured capacitance of the device containing fresh concrete to obtain the capacitance of the fresh concrete annulus. The capacitance of the device alone was 0.59 nF.

The first set of mixtures were intended to have the same water content with different cement contents, but a mistake in batching procedure resulted in slightly different water contents as well. The second set of mixtures was intended to determine the effect of using a water reducing admixture, which is a surfactant and could be expected to change the adsorption of the water on the cement [Mehta and Monteiro, 2006]. The second set of mixtures was modified to complement the mixtures in the first set so that the effects of water content could be compared directly and some estimate of reproducibility could be made. Capacitance was determined at a frequency of 1000 Hertz (1 kHz), using a hand held meter.

The mixtures and the test results are given in Table 2.1. The proportions are given in pounds per cubic yard (pcy). The proportions listed have been adjusted for yield and so are not exactly equivalents. The length shown is the depth of the sample, that is, the effective length of the coaxial capacitor. The apparent dielectric constant was calculated using Equation 2.3.

Table 2.1 Data Summary of Feasibility Study

Cement (pcy)	470	550	620	560	620	560	560
Sand (pcy)	1480	1420	1360	1420	1360	1420	1410
Stone (pcy)	1650	1650	1650	1680	1680	1680	1680
Water (pcy)	315	312	310	298	301	298	296
WRA	no	no	no	no	no	no	yes
w/c	0.67	0.57	0.5	0.53	0.49	0.53	0.53
C (nF)	1.40	1.54	1.52	1.56	1.57	1.49	1.57
length (in.)	11.6	11.6	11.6	11.5	11.3	11.0	11.5
ε'	103	120	118	124	128	120	126
"pcy" is pounds per cubic yard; "WRA" is water reducing admixture; "nF" is nanofarads, "in." is inches							

The apparent dielectric constant was much higher than that expected using a simple, volumetric basis, and was greater than 80 in all cases. This finding was similar to that reported in the literature [Moss, *et al.*, 1996; Camp and Bilotta, 1989; Ford, *et al*., 1997; Gu and Beudoin, 1996]. Treish also found that the apparent dielectric constant was much more closely related to w/c ratio than to water content. Figure 2.4 shows the relationship between w/c and apparent dielectric constant.

The scatter in the data was higher than desired, suggesting that reproducibility, device sensitivity, or both, should be improved, if possible. The correlation between w/c and apparent dielectric constant was fairly high, -0.83. Batching accuracy was also a concern in this study, however.

Due to the limited number of mixtures and the variability, Treish could not determine if using a water reducing admixture had any meaningful effect on the apparent dielectric constant. Triesh also noted that time appeared to affect the measurement and that some of the variability in the data might be related to measurements taken at different times after initial mixing. Analysis also indicated reasonably strong correlations between the apparent dielectric constant and the volume of paste (correlation = 0.62), volume of water (correlation = -0.57) and volume of cement (correlation = 0.77), although less strong than the correlation with w/c. These volumes and the w/c ratio are all clearly correlated physically.

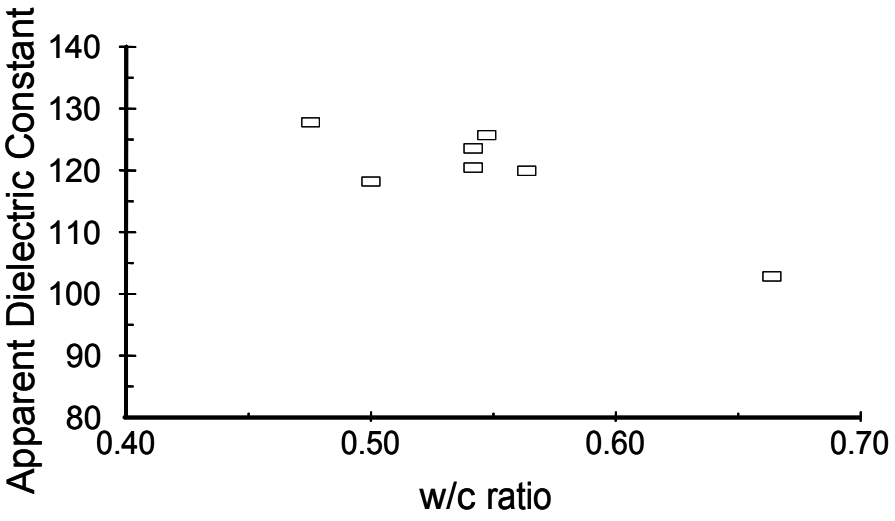


Figure 2.4 Relationship Between W/C and Apparent Dielectric Constant, Feasibiltiy Study

Treish's study found that the device was promising as an indicator of w/c ratio, rather than water content. This was an important finding since the w/c ratio is much more important than the water content alone. The feasibility study also found that the relationship between the apparent dielectric constant and mixture composition was more complicated than the simple volumetric model would suggest. Additional studies were required to address these problems plus the effects of time and air content, reproducibility, and the effects of additional components, such as fly ash or slag.

2.3.2.2 Second Preliminary Study and Field Trials

Mahoney [2003] conducted a second study with two phases. In the first phase, the effect of time on measured capacitance was examined. One mixture was tested under laboratory conditions. After that, a field study examined the capacitance over time of two commercial mixtures produced at a ready-mixed concrete plant. One was a nominal 4000 psi (28 MPa) mixture and the other was a nominal 3500 psi (24.5 MPa) mixture. Both mixtures were air entrained.

Field tests were intended to help assess the potential of the device as a quality control tool and would also provide sufficient concrete for time effects analysis. The field trials were conducted using a fresh sample of concrete at each time interval tested. This was to ensure that any effects due to bleeding, which could affect the dipole layer, would be minimized, and provided an opportunity to determine variability of the reading from the meter to ensure consistency in the measured capacitance by taking two readings back to back at each time interval.

The other phase was a reexamination of data from the previous study by Treish, augmented with data from her study. Additional analysis included a more detailed study of the dissipation factor and its derivative, conductance, and possible cross-correlation effects with the volumes of cement, water, and paste. Treish had examined correlations between volumes of components and apparent dielectric constant, but had not considered cross-correlation.

In the laboratory portion, the mixture was produced in general accordance with ASTM

C192 [2006], that is, the batch is mixed for 3 minutes, allowed to rest for 3 minutes, then mixed for an additional 2 minutes, at which point it is discharged from the mixer into a holding tub or wheelbarrow. At that point it is remixed quickly to overcome any segregation occurring during discharge from the mixer and the test device filled. This means there is a minimum of about 12 minutes after initial mixing of water and cement under ideal conditions, and typically at least 15 minutes, before the first capacitance measurement can be taken. The mixture used in the lab portion of Mahoney's study contained a large amount of cement, 925 pcy, with a moderate w/c ratio of 0.42. A cement rich mixture was used to reduce setting time to hopefully make any time effect more evident. Since water reducing admixtures were not used, the water content of this mixture was also large, 386 pcy. This mixture was also intended to provide additional data for comparison of w/c and apparent dielectric constant. The effects of time on measured capacitance and apparent dielectric constant are shown in Table 2.2, below.

Table 2.2 Effect of Time on Capacitance and Apparent Dielectric Constant

time (min)	C (nF)	apparent dielectric constant
19	1.355	100
22	1.362	100
25	1.360	100
40	1.400	105
50	1.403	106
65	1.409	107

The lab portion of the study found only a slight effect due to time. The apparent dielectric constant was lower than expected, however, indicating that effects other than

the w/c ratio alone may affect the capacitance.

Figure 2.5 shows the results of the field trials. The data show what appears to be considerable scatter in the data. Much of this variability is due to differences in the length of the coaxial capacitor, that is, the depth of the fresh concrete since each test was conducted with a fresh sample. Due to an error in determining the length, the apparent dielectric constant cannot be determined reliably for this set of data.

One important finding is that reproducibility of the capacitance measurement appeared to be quite good. Readings a minute or so apart are essentially identical.

Another important finding is that the two mixtures were clearly distinguishable at similar ages, although some estimate of the age of the concrete would be needed to identify the mixture based only on apparent dielectric constant. Figure 2.5 shows that time appears to have an effect, but that the effect may not be substantial after about 30 minutes. Time of batching is commonly recorded in normal quality control or quality assurance testing, however, so practical limitations on the use of the device to identify mixtures based on age appeared to be slight.

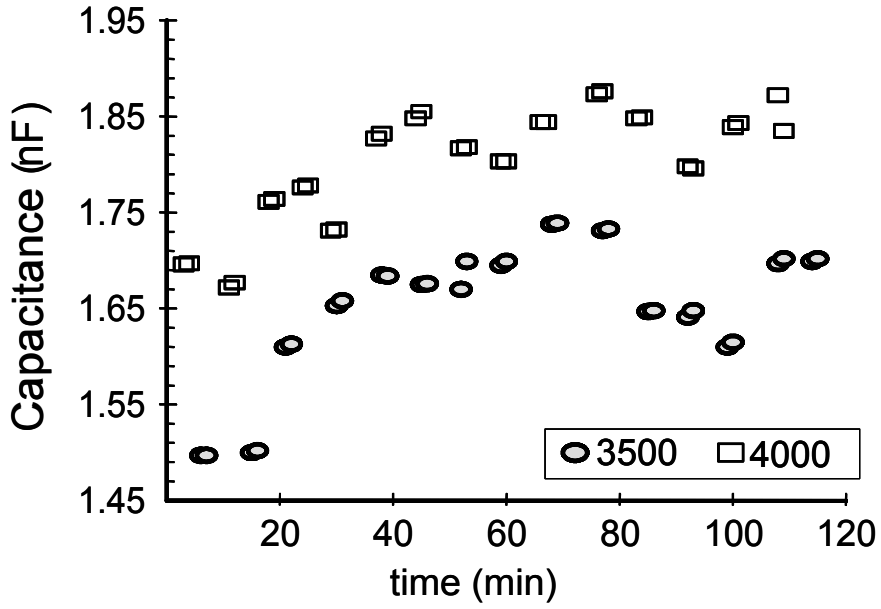


Figure 2.5 Capacitance over Time for Two Concrete Mixtures

The difference between the mixtures in Figure 2.5, at least after about 30 minutes, even when considering the scatter in the data, is important in several respects. The batches tested were typical, commercial concrete mixtures with similar proportions, including fly ash, water reducing, and air entraining admixtures, and essentially equal water contents. The field trials indicated that the device had the potential to identify critical differences in concrete mixtures on the job site.

The ability to differentiate between mixtures with nominal differences in strength of 500 psi (3.5 MPa) is useful for several reasons. ACI 318 [2005] establishes f'_c - 500 psi (f'_c - 3.5 MPa) as the point at which a compressive strength test result indicates a structural concern. Difference of 500 psi (3.5 MPa) is a practical tolerance for acceptance of concrete mixtures [Cutshall, Leming, and Johnston, 1999, Leming, 1999].

Further analysis of the correlations and cross correlations of the data from the Treish and Mahoney studies failed to identify any stronger or more useful relationship between the apparent dielectric constant and any variable other than w/c. The dissipation factor did not show any strong correlation with any variable examined. The limited data in both studies, compounded by the problems with some of the data, indicated a need for additional studies based on a more fully populated test matrix.

2.4 Published Studies

Various studies have examined electrical properties of cement pastes. Camp and Bilotta [1989] studied paste and mortar dielectric and conductivity properties over a frequency range between 100 Hz and 7 MHz. The study was made using sealed samples of different w/c ratios over a long period of time, from 4 hours to close to a year. An explanation of the effect of water bonding stages in the mixtures, and the relationship to cement hydration on conductivity and capacitance values was presented. In their study with mortar, using paste with the same *w/c* but different sand proportions, they concluded that the sand effect in both conductivity and capacitance was one of dilution giving similar and parallel curves over time. When analyzing the strength of the same mixture over time, conductance showed a linear relationship to the mortar strength.

A thin dipole interfacial layer normally forms at the electrodes [Camp and Bilotta, 1989; Hafiane, *et al.*, 1999; Ford, *et al*. 1997]. Camp and Bilotta claim that this layer, even though if it has a low dielectric constant, can cause high capacitance values due to small thickness of the layer. This can account for some of the high calculated dielectric

constant results reported..

Ford, *et al.* [1997] attributes the dielectric amplification of fresh concrete mixtures to a combination of analysis errors and microstructure effects. A polycarbonate cell, of 25.4 mm by 25.4 mm by 100 mm with two steel plates used as electrodes placed at the end of the cell was used to investigate concrete microstructural effects. Different thickness barriers representing hydration products were placed in the middle of the cell. A small hole was drilled in the barriers to simulate the percolation of water through capillary pores. Tap water was used as the system electrolyte. Results were compared to paste samples with the same geometry. Ford, *et al.* concluded that the cell model had behavior similar to cement pastes. A dielectric amplification between frequencies of 10^4 and 10^7 Hz was reported. The amplification was lower when the barrier thickness was greater. Ford, *et al.* concluded that larger pore size or a thinner hydration product layer, are both related to the w/c and extent of hydration and result in higher measured dielectric constants.

Zhang, *et al.*, [1995] analyzed the dielectric constant and electrical conductivity of cement paste using microwave techniques at frequencies between 8.2 and 12.4 GHz during the first 30 h of hydration. They analyzed different w/c paste mixtures using ordinary portland cement. Additionally they compared ordinary portland cement paste to low slag and high slag cement paste at the same w/c. Microwave techniques are not affected by the "electrode polarization" since electrodes are not used. The dielectric properties were determined measuring reflection and transmission coefficients. Zhang, *et al.* found that during the first hour ε_r drops about 2% of its initial value. They also found

that the dielectric constant is smaller at higher frequencies. They found that dielectric constant and electrical conductivity are dependent on the w/c, and that higher dielectric constant values correspond to higher values of w/c.

Different behavior was observed at early ages and was attributed to the induction period. A different rate of ε_r variation, $\varepsilon(t)/\varepsilon(t_0)$, was seen for the different water cement ratios. A higher w/c had a slower rate of variation, which the authors reported to be related to the slower rate of hydration.

McCarter, *et al.* [1999] studied the immittance spectra for mixtures with the same w/c but 10%, 25% and 40% of cement replaced with fly ash. All pastes mixtures had w/c = 0.30, mortars a w/c = 0.65, and concrete w/c = 0.45 mixtures. Measurements were taken at 60 minutes after water addition in a range of frequencies between 1 Hz to 1 MHz inclusive. In their study, higher dielectric constant values were observed with higher percentage of fly ash.

Hager and Domzy [2004] monitored cement hydration through several weeks, using frequencies between 10 and 8 GHz with small samples of cement paste with w/c of 0.40. They used a time domain reflectometry technique for the measurements. The purpose of the study was to use this technique to identify relaxation frequencies of the components of a fresh cement paste.

Other published studies of electrical measurements for fresh and hardened concrete using different techniques were also reviewed, in which the techniques, the hydration times, the frequencies and the properties and proportions of the mixtures or the raw materials used

varied. For example, McCarter, Ford and Whittintong [1981] studied the electrical resistivity and conductivity of concrete for different w/c. Hope and Manning [1985] studied the relationship of electrical impedance of concrete and the corrosion in reinforcing concrete. Gu and Beaudoin [1996] studied the dielectric behavior of hardened cement pastes using frequencies between 1 MHz and 1 GHz. Other authors, including Taylor, *et al,*[1974], Scuderi, *et al*.[1991], Sihai Wen, *et al.*[2001], Moss *et al.*[1996] have also conducted research in this field.

No investigation was found using a similar technique, that is, using a thin insulator between the concrete and one of the conductors to minimize resistance and electrode effects on bulk interface when examining the relationship between apparent dielectric and composition. Additionally, no study developing a practical device to be used for quality control in fresh concrete using dielectric properties was found.

CHAPTER 3. METHODOLOGY

3.1 Introduction

Two phases of testing were conducted in this study. One phase consisted of the review and modification of the device developed in previous studies. Measurements were taken with different modifications of the device in an attempt to improve accuracy and efficiency. The other phase of the study consisted of testing a variety of different mixtures, in a range of frequencies between 1 kHz and 1 MHz inclusive, over time. This phase was conducted to

(1) address questions identified in previous studies regarding the effects of mixture composition and time of testing,

(2) determine if the modifications to the device improved performance,

(3) determine the optimum frequency for testing between 1 kHz and 1 MHz, and

(4) determine if the device could be used to estimate w/c and be developed into a useful field test.

A second part of phase two consisted in use the device to test commercial concrete mixtures to compare results to the concepts observed during the first part.

3.2 Phase I

The original device with the 6x12 mold was modified just by using aluminum foil instead of the stainless steel sheet or copper mesh that covered the plastic cylinder. The

aluminum foil was covered with plastic wrap and tape to prevent any electrical contact with concrete inside.

Additionally a different kind of device was tested. This modification consisted of a 4 in diameter and ½ in thick PVC tube. The length of the device was 12 in. The rationale for this modification was to use a device with a smaller outside to inside diameter ratio and a longer coaxial conductor, or greater length. Two devices of this kind were fabricated. Based on equation 2.4 a smaller diameter ratio and a longer length will provide a higher capacitance reading. It was hoped this would improve precision. (see Figure 3.1)

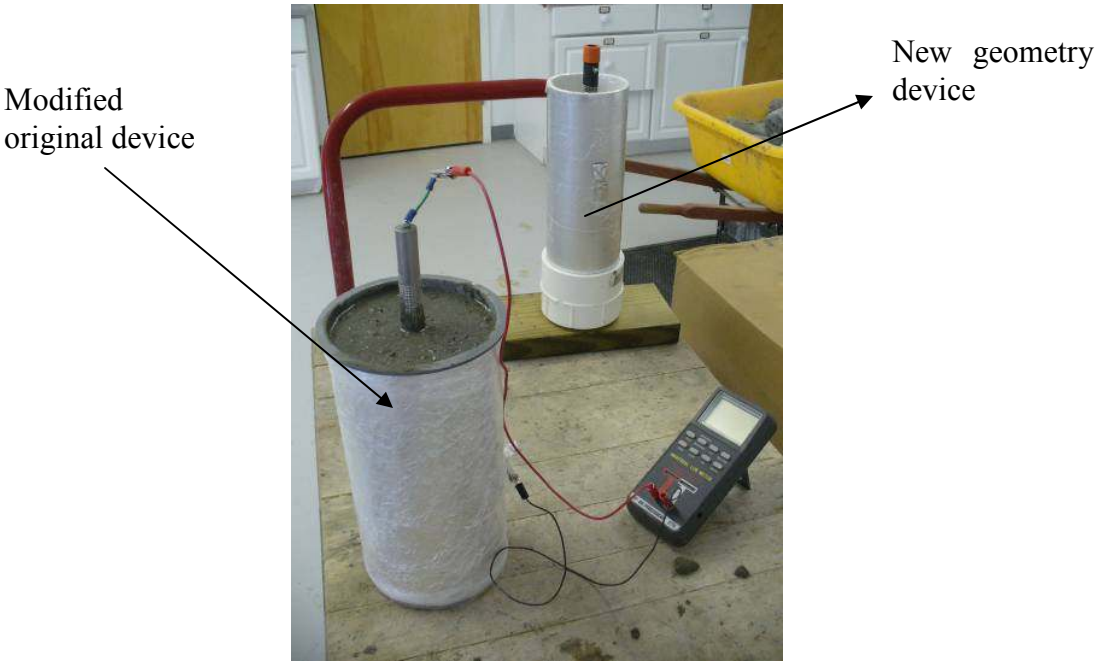


Figure 3.1 Testing Device for Capacitance Measurements

3.3 Phase II

3.3.1 Variable Identification

Detailed and complex studies have been done in order to determine the equivalent dielectric properties of heterogeneous materials based on the dielectric properties of its pure components [Bergman, 1978]. It was considered that for this project it was sufficient to acknowledge the fact that dielectric properties of a heterogeneous material such as concrete depend in some manner on the dielectric properties and volume fractions of its pure components, and on the states of at least some of these components.

No detailed analysis of the precise relationship was conducted in this project. The continuous chemical reaction in the hydration process of the cement, especially at early stages, is variable and not completely understood. It would be impractical to use a complex theory to determine an accurate equivalent dielectric constant of a composite based on its pure components when the pure components, their volume fractions and their dielectric properties are constantly changing.

Different proportions between concrete mixtures will have different distributions of volumes of aggregates, hydration products, unhydrated cementitious material, and water at different stages. This study attempted to identify the functional relationship between dielectric values and proportions from one mixture to another, in order to determine the potential utility of capacitance based tests in quality control and quality assurance testing of fresh concrete. Therefore, a detailed analysis of variations in the volume percentages of paste, water, cements and fly ash, and these variation effects on the dielectric constant

was conducted.

3.3.1.1 External Testing Effects – Time and Frequency

3.3.1.1.1 Time of Testing

From the feasibility studies and literature review dielectric properties of concrete are known to be dependent of time. Concrete composition is constantly changing over time due to cement hydration process and this is reflected in its dielectric constant. The focus of this study was to analyze mixtures at early stages and recognize how variations over time could affect the ability to differentiate one mixture from another. Measurements taken after water addition were made at 15, 30, 45 and 60 minutes and in some cases an additional measurement was taken at close to 75 min.

3.3.1.1.2 Frequency

The dielectric relaxation of a composite has an effect on capacitance. When under the influence of an electric field, ions travel through the medium increasing its ability to store energy. The dipolar moment of water particles also has an effect on the ability to store energy. Due to the dipolar moment, water molecules are not only subject to translation, but, when subject to higher frequencies, ions orientation varies aligning with the electric field.

In Chapter Two, the different stages of water in a fresh concrete mixture were discussed. The attraction forces of water molecules vary between free, capillary, adsorbed, interlayer and chemically bound. The electric field within the range of frequencies at which these

tests were carried, 1 to 1000 kHz, was expected to have a relaxation effect mostly in the free, capillary and, perhaps, adsorbed water since an ionic dielectric relaxation was expected in molecules with low attraction forces. For free water with capillary attraction forces and for adsorbed water at the hydration products surfaces, a dipolar moment relaxation was expected. Dielectric properties of free, capillary and adsorbed water were anticipated to be variable since the capillary attraction forces affecting free water and the degree to which adsorbed water is fixed vary within the mixture as well.

3.3.1.2 Mixture Components

The response to a changing electric field was expected to be affected by the amount of cement, the amount of fly ash, and the inclusion or lack of water reducing and air entraining admixture in the concrete. The higher the cement content in the mixture for the same amount of water, the higher percentage of water is expected to be adsorbed or affected by capillary forces. With the inclusion of fly ash, the rate of hydration in the fresh concrete varies. The surface chemistry differs considerably from that of cement and the volume is greater, so for a given time, even with the same amount of water and cementitious material, the distribution of water would be influenced. The amount of free water is expected to be higher at a given time during the first hour of hydration.

Water reducing admixtures (WRA) are surfactants and affect the dispersion of water and cement in a mixture [Mehta and Monteiro, 2006]. The addition of a WRA reduces the amount of water and therefore the total cementitious material in a mixture at the same w/c. The use of a WRA was expected to have an effect on attraction forces between the

water molecules and therefore expected to affect electrical properties.

3.3.1.2.1 Water Cement Ratio

The water cement ratio has a great effect on the engineering properties of concrete. For a given set of raw materials, the amount of water per unit volume is constant for a given workability [Kosmatka, 1988]. In this study, the amount of water used was 300 pounds per cubic yard (pcy) for the mixtures without a water reducer and 275 pcy for ones with a water reducer. In order to vary the w/c between the mixtures the amount of cementitious material was modified. ACI 318 defines w/c as the ratio of water to total cementitious material, including Fly Ash if present. The dielectric constant was expected to be affected not only by the volume of water but also by the distribution of the water in the different states.

Concrete strength is related to the w/c in a non linear fashion [Abrams, 1918]. In two instances, capacitance testing with the device appeared to be grossly in error. Comparing results between two sets of mixtures with w/c of 0.45 and 0.50 appeared to indicate that the device could not be used reliably to identify differences in w/c. Compressive strength results, however, confirmed that the capacitance based testing had correctly identified the mixtures and that labels on the raw materials had been switched accidentally. Labeling was corrected for all further analysis.

3.3.1.2.2 Water Reducing Admixture

A water reducer is an organic chain with one hydrophilic end and the other end with anionic polar groups attached to it [Mehta and Monteiro, 2006] In construction practice it

has three applications. The first application is to increase workability of the mixture without varying its water cement ratio. A second application is to decrease the water cement ratio by reducing the amount of water, and therefore increase the concrete strength, while keeping the workability of the batch. The last application is to use this admixture to reduce the amount of water and maintain the water cement ratio by reducing the cement. This purpose is commonly used in practice because of its economic advantage since cement is the most expensive component in concrete. This last application was used in this study.

The inclusion of this type of admixture was expected to affect dielectric properties in at least two ways: by affecting attraction forces and therefore the dielectric relaxation and by reducing the volume of paste due to both the reduction of water and cement. A paired comparison of concrete mixtures with same water cement ratio, with and without the admixture, and therefore with higher or lower paste content, was done in order to identify its effect.

3.3.1.2.3 Air Entraining Admixture

An air entraining molecule is an organic chain with one hydrophilic and one hydrophobic end. The polar, hydrophilic end, bonds to the cement grain, leaving the non-polar end oriented away from the cement grain giving the cement grain hydrophobic properties. Water will not be attracted to the cement grain and air bubbles will be formed between the cement grains. Air entraining admixtures also reduce the surface tension of water [Mehta and Monteiro, 2006].

It was expected that air entraining agent (AEA) would have an effect on the capacitance of the mixture by affecting the distribution of cement, water and air particles. The AEA could also affect ionic and dipolar dielectric relaxation by changing surface tension. During the initial experiments of Phase II, the air content was kept approximately constant in order to observe the effect of the other variables, since most commercial concrete are air entrained. Additional data was taken for a set of cement only mixtures with the same proportions as the cement only mixtures previously analyzed, except that an air entraining agent was not included. Data was compared to identify the effects of the air content.

3.3.1.2.4 Fly Ash

Fly ash is commonly used in commercial mixtures for its pozzolanic properties. It is used for economic purposes to reduce the amount of cement in a mixture by taking advantage of the cementitious properties of the pozzolan and to improve durability. The rate of hydration is slower in a concrete mixture with fly ash than in a mixture with only portland cement and the same water to cementitious material ratio. The fly ash surface has a different interaction with water molecules than cement. Testing has shown workability increases in mixtures with fly ash included [Mehta and Monteiro, 2006]. Differences in surface interaction could affect the apparent dielectric constant. The volume of paste is also affected by the use of fly ash. The lower specific gravity of fly ash means a higher volume even with the same mass of fly ash. More fly ash is typically used than portland cement reduced to overcome the difference in strength at 28 days. All these factors were expected to influence the dielectric properties. A paired comparison

between mixtures with and without fly ash was done to identify the overall effect of the fly ash on ε_r.

3.3.1.3 Mixture Properties

One of the primary goals of quality control and quality assurance testing is to ensure adequate compressive strength in the completed structure. A general comparison between strength and ε_r of all the mixtures was analyzed due to the importance of this property. Compressive strength specimens were made in accordance with ASTM C31 [2006] and tested in accordance with ASTM C39 [2005]. Four 4 x 8 inch cylinders were made for each mixture, except from the mixtures made at Mann Hall; two of the cylinders were tested at 7 days and two at 28 days. For the field testing two 4 x 8 inch cylinders were made, both were tested at 7 days. As with the other variables, analysis was also done by group and by paired comparison.

Entrained air used in concrete is important for frost durability. An increase in the amount of air in concrete normally results in a lower strength [Neville, 1996]. Data were determined in accordance with ASTM C231 [2004] and analyzed to determine if the dielectric constant was dependant on the air content, or if any effects found were due to cross correlations with characteristics such as paste volume or w/c. Unit weight was also determined, in accordance with ASTM C138 [2001], in order to confirm air content and calculate yield for volume adjustments. The slump was determined for all mixtures for completeness. Slump was determined in accordance with ASTM C143 [2005].

3.3.2 Capacitance Measurement

Two instruments were used to measure the capacitance. Initially a Universal LCR Meter was used and measurements were made at 1 kHz and 1 V as in the previous study. This device is relatively inexpensive and is highly portable. It is commonly used to determine values, including resistance, inductance, and capacitance, of commercial electronic devices. Later the Hewlett Packard 4284 A Precision LCR meter was also used. The HP Precision LCR meter is much larger, but capable of providing measurements with greater precision and over a much wider range of frequencies, up to 1 MHz. In addition, measurements of capacitance could be conducted at 1 V or at 2 V.

3.3.2.1 Sample Preparation

The mixing procedures for the testing were in general accordance with the ASTM C192 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory [2006]. This standard was used for samples made by both machine and hand mixing. For filling the specimens a procedure based on ASTM C31, Standard Practice for Making and Curing Concrete Test Specimens in the Field [2006], was used with modifications explained below due to the nature of the test.

The test cylinder was placed on a rigid surface. The cylinder was already covered by the aluminum foil and plastic wrap. The center bar was centered and secured inside the cylinder. The device was filled in three layers of approximately equal depth. The final layer did not reach the top of the cylinder but was somewhere between 0 and 2 inches from the top. The space between the top of the cylinder and the top of the concrete was

measured and recorded. The effective length of the coaxial capacitor was calculated as 12 in. less the length of the space between the top of the cylinder and the top of the concrete.

3.3.2.2 Measurement

Once the cylinder was filled, the positive pole of the LCR meter was connected to the outer electrode (aluminum foil) and the negative pole to the inner electrode (stainless or black steel bar). When using the BK Precision meter, measurements were made at 1 kHz frequency and 1 V. When using the HP 4284 meter, measurements were taken at frequencies of 1, 10, 100, 1000 kHz at 1 V. In addition some measurements were taken at 2 V. No difference in capacitance was found when testing at 2 V, so all data reported in this study is that tested at 1 V. The data recorded were the capacitance (C, nF) and the dissipation factor (D) measured by the instruments.

The first measurements were taken as soon as possible after filling the device. The time was recorded. Normally the time was just below 15 minutes. Further measurements were taken at 15, 30, 45 and 60 minutes. In some cases an additional measurement was taken at 75 minutes. The cables were disconnected from the electrodes and the poles of the device were short circuited in between measurements to reduce the polarization and dipole layer effects.

3.3.3 Test Matrix

Fourteen mixtures were made at a laboratory. The initial ten mixtures were made in Ready Mixed Concrete Lab (RMC) in Raleigh, NC under the guidance of Mr. Ken Vickers, Quality Control manager for RMC. Preparation of raw materials, batching and

fabrication and testing of all specimens except capacitance was done by RMC employees, all of whom were certified ACI Field Technicians, Grade I. The ten mixtures were made in two different days. Mixtures from the groups without water reducing agent (Group C and Group FA) were tested the first day. The remaining mixtures (Group CW and Group FW) were tested a second day. Each batch had a volume of approximately 3.5 cubic feet.

The next set of mixtures consisted of three small volume batches, approximately 0.25 cubic feet, with the same proportions as the original cement only mixtures made at RMC. These mixtures were made at Mann Hall. The test matrix is shown in Table 3.1.

Additionally, two commercial mixtures were tested later in the field at the Thomas Concrete Lab, in Morrisville, NC. The total batch had a volume of approximately 10 cubic yards (cy). Samples, approximately 1.5 cubic feet in volume, were taken from the mixer truck in a wheelbarrow and divided in three equal portions for testing. Testing was done with the collaboration of a Thomas Concrete employee, also a certified ACI Field Technicians, Grade I. Proportions for these mixtures are given in section 4.8.

Table 3.1 Test Matrix

Mixture	Times (min)	Frequency (kHz)
C60	15, 30, 45, 60, 75	1
C50	15, 30, 45, 60	1, 10, 100, 1000
C45	15, 30, 45, 60	1
FA60	15, 30, 45, 60	1, 10, 100, 1000
FA50	15, 30, 45, 60	1, 10, 100, 1000
FA45	15, 30, 45, 60	1, 10, 100, 1000
CW50	<15, 15, 30, 45, 60	1, 10, 100, 1000
CW45	<15, 15, 30, 45, 60	1, 10, 100, 1000
CW40	<15, 15, 30, 45, 60, 75	1, 10, 100, 1000
FW45	15, 30, 45, 60	1, 10, 100, 1000
FW50	15, 30, 45, 60	1,3,5,10 30, 50, 100 300, 500, 1000
Cm60	<15, 15, 30, 45, 60	1,3,5,10 30, 50, 100 300, 500, 1000
Cm50	<15, 15, 30, 45, 60	1,3,5,10 30, 50, 100 300, 500, 1000
Cm45	<15, 15, 30, 45, 60	1, 3, 5,10 30, 50, 100 300, 500, 1000

Notes:
- Groups
C Cement Only
FA Cement with 20% fly ash
CW Cement + Water Reducing Admixture
FW Cement with 20 % fly ash + Water Reducing Admixture
* mixture id suffix = w/c x 100

-Electrical measurements of Capacitance and DF (dissipation factor) were taken for all mixtures.

-Times for measurements as shown in the table

-Frequencies for measurements as shown in table

-Slump, Air, Unit Weight and Temperature of fresh concrete tested for all mixtures except Cm60, Cm50 and Cm45

-Compressive strength tested for all mixtures exept Cm60, Cm50 and Cm45 (2(4x8) cylinders at 7 days and 2(4x8) cylinders at 28 days)

Table 3.2 Mixtures Proportions

Mixtures Proportions by Mass												
	Units	C60	C50	C45	FA60	FA50	FA45	CW50	CW45	CW40	FW50	FW45
Cement	pcy	500	600	667	400	480	532	550	611	688	440	490
Fly Ash	pcy				100	120	135				110	121
Water	pcy	300	300	300	300	300	300	275	275	275	275	275
Sand	pcy	1276	1205	1150	1245	1163	1101	1294	1250	1214	1311	1229
Rock	pcy	1720	1720	1720	1720	1720	1720	1720	1720	1720	1720	1720
Water Reducer	oz/cwt							4	4	4	4	4
High Range Water Reducer	oz/cwt									4	4	
Air Entraining Admixture	oz/cy	1.82	4.61	3.04	3.04	3.65	4.26	1.52	1.52	1.84	3.65	2.43
Volume Percentages												
	Units	C60	C50	C45	FA60	FA50	FA45	CW50	CW45	CW40	FW50	FW45
Cement	%	9.4	11.3	12.5	7.4	9.0	10.0	10.3	11.4	13.0	8.2	9.3
Fly Ash	%	-	-	-	2.6	3.1	3.5	-	-	-	2.8	3.2
Water	%	18.6	18.6	18.6	18.4	18.6	18.6	17.0	17.1	17.2	17.1	17.4
Sand	%	28.5	27.0	25.8	27.6	26.0	24.7	28.8	27.9	27.3	29.3	27.9
Rock	%	38.2	38.3	38.3	37.8	38.2	38.2	38.0	38.1	38.4	38.1	38.8
Air Vol *	%	5.3	4.8	4.8	6.3	5.1	5.1	5.9	5.5	4.1	4.4	3.3
Paste Volume	%	28.0	29.9	31.1	28.4	30.7	32.0	27.3	28.5	30.2	28.2	29.9

"pcy" is pounds per cubic yard; "oz/cwt" is fluid ounces per hundred pounds of cementitious material; "oz/cy" is fluid ounces per cubic yard
* Measured using pressure meter (ASTM C 231)
Volumes of water reducer and high range water reducer are negligible

GROUPS	C	Cement Only
	FA	Cement and Fly Ash
	CW	Cement and Water Reducer
	FW	Cement, Fly Ash and Water Reducer

CHAPTER 4. RESULTS AND ANALYSIS

4.1 Introduction to Analysis

This chapter examines the quantitative relationships between characteristics of fresh concrete and the apparent dielectric constant. The characteristics and variables examined were selected based on theoretical concepts, information from previous studies, and effects noticed during earlier testing.

4.2 Mixture Properties

Mixtures properties are shown in Table 4.1.Complete data are given in appendices. Values for apparent dielectric constant over time and frequency are given separately (see section 4.4).

Table 4.1 Mixture Properties

MIX	w/c	Composition	Slump (in)	Air Content	Compressive Strength (psi)	
					7 days	28 days
C60	0.60	Cement only	3.00	5.3	3820	5230
C50	0.50		2.25	4.8	4370	6030
C45	0.45		2.50	4.8	4770	6490
FA60	0.60	Cement with 20 % fly ash	4.00	6.4	2410	3770
FA50	0.50		4.00	5.1	3490	4710
FA45	0.45		5.00	5.1	3700	5160
CW50	0.50	Cement + WRA	3.00	6.0	4030	5620
CW45	0.45		2.75	5.5	4670	6450
CW40	0.40		3.00	4.1	5750	7690
FW50	0.50	Cement with 20% fly ash + WRA	4.25	4.4	4090	5710
FW45	0.45		2.50	3.3	4980	6980

4.3 Devices

Problems existed with the data collected with the new, modified geometry devices. Two devices had been constructed. For all of the different mixtures, at least one of these devices was used parallel to the device with the original geometry.

For the FW mixtures, both new geometry devices were simultaneously tested for a same mixture to compare with Mahoney's data. Data obtained was not the same for both devices, causing concerns with using the modified geometry.

The new devices were made using PVC tubes and sealed with epoxy and a cap at the bottom. One of the problems seemed to exist in the bottom seal. During the testing a small leak was observed. Other factor suspected to cause differences was the difficulty in accurately centering the inside rod used as an electrode in one of the devices.

Capacitance measurements for these devices were lower than with the original geometry. With a lower outside to inside diameter, capacitance measurements were expected to be higher. The PVC used as an insulator between the concrete and the outside electrode may be too thick and affect the capacitance readings.

These problems are not suspected to be due to the geometry of the device, but from the manufacturing and materials used for the new devices. The data from the original device is used for all additional analysis, unless otherwise stated.

4.4 Time

Figures 4.1 through 4.4 show the relationship between ε_r, calculated using Equation 2.4

($C = 2 \pi \varepsilon L / \ln (b/a)$), and time of test, for frequencies of 1 kHz, 10 kHz, 100 kHz, and 1000 kHz (1 MHz), respectively. This analysis was intended to determine two things: (1) could the device be used alone to identify or classify concrete mixtures in the absence of additional data and (2) what is the effect of time, or age, on the readings.

No clear difference between mixtures based only on the apparent dielectric constant was found. It was concluded that it was not possible to identify or classify a mixture water cement ratio based on the apparent dielectric constant alone at any time or frequency. Neither was it possible to identify if the mixture had water reducing admixture, fly ash or both, based on the dielectric properties only.

Further analysis was conducted to determine if the apparent dielectric constant could be used to identify differences in similar mixtures, such as when all mixtures contained water reducing admixture or fly ash. Each group was analyzed separately to identify how each factor affected the dielectric properties. This analysis is not only important in determining the usefulness of the device in practical applications but examined important, fundamental relationships between the apparent dielectric constant at early ages and properties, proportions and raw materials used in concrete.

For comparison purposes, time values were classified into one of the following categories: <15 min, 15 min, 30 min, 45 min, 60 min, 75 min. This classification is referred in this study as “nominal time”.

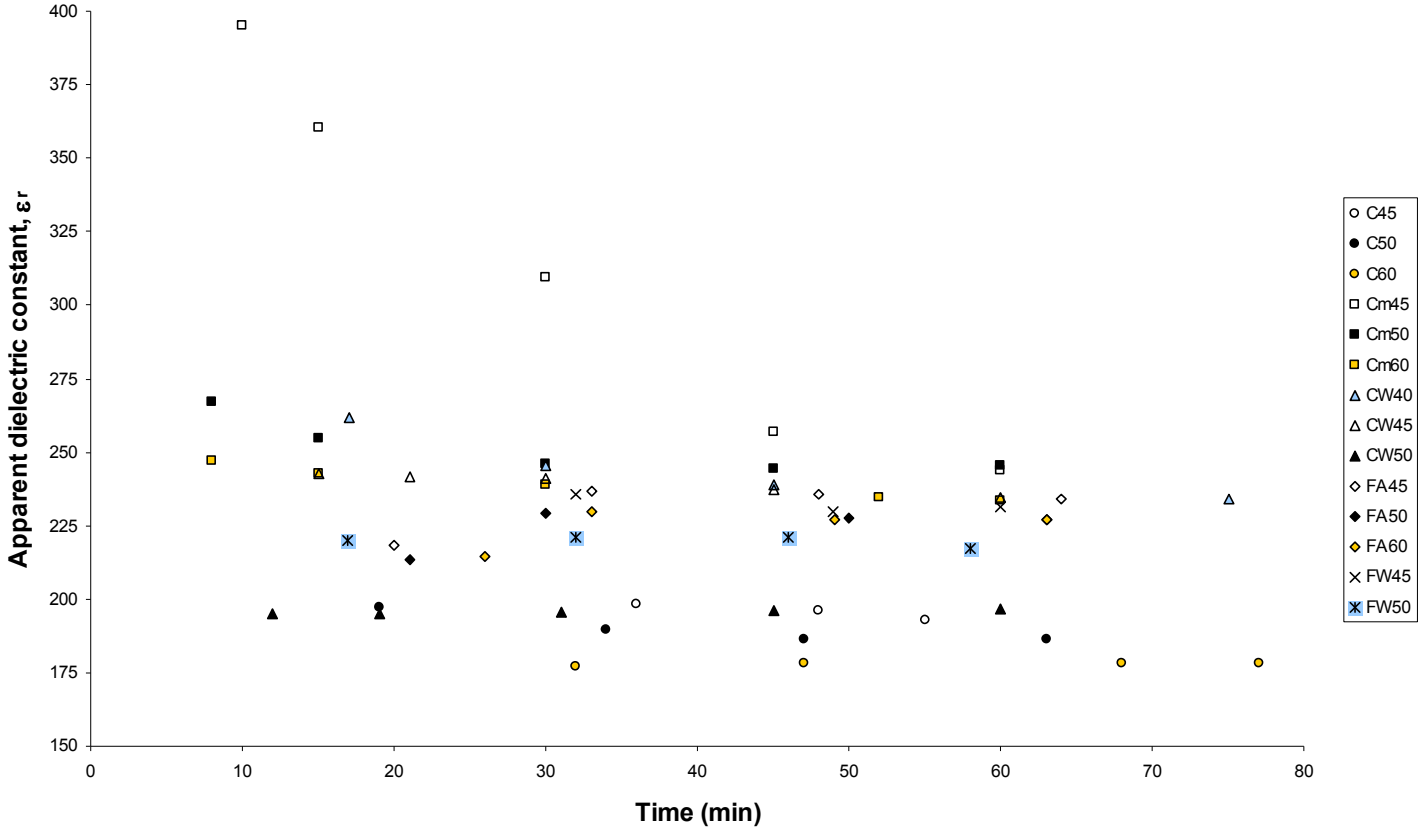


Figure 4.1 Apparent Dielectric Constant and Time Tested at 1 kHz

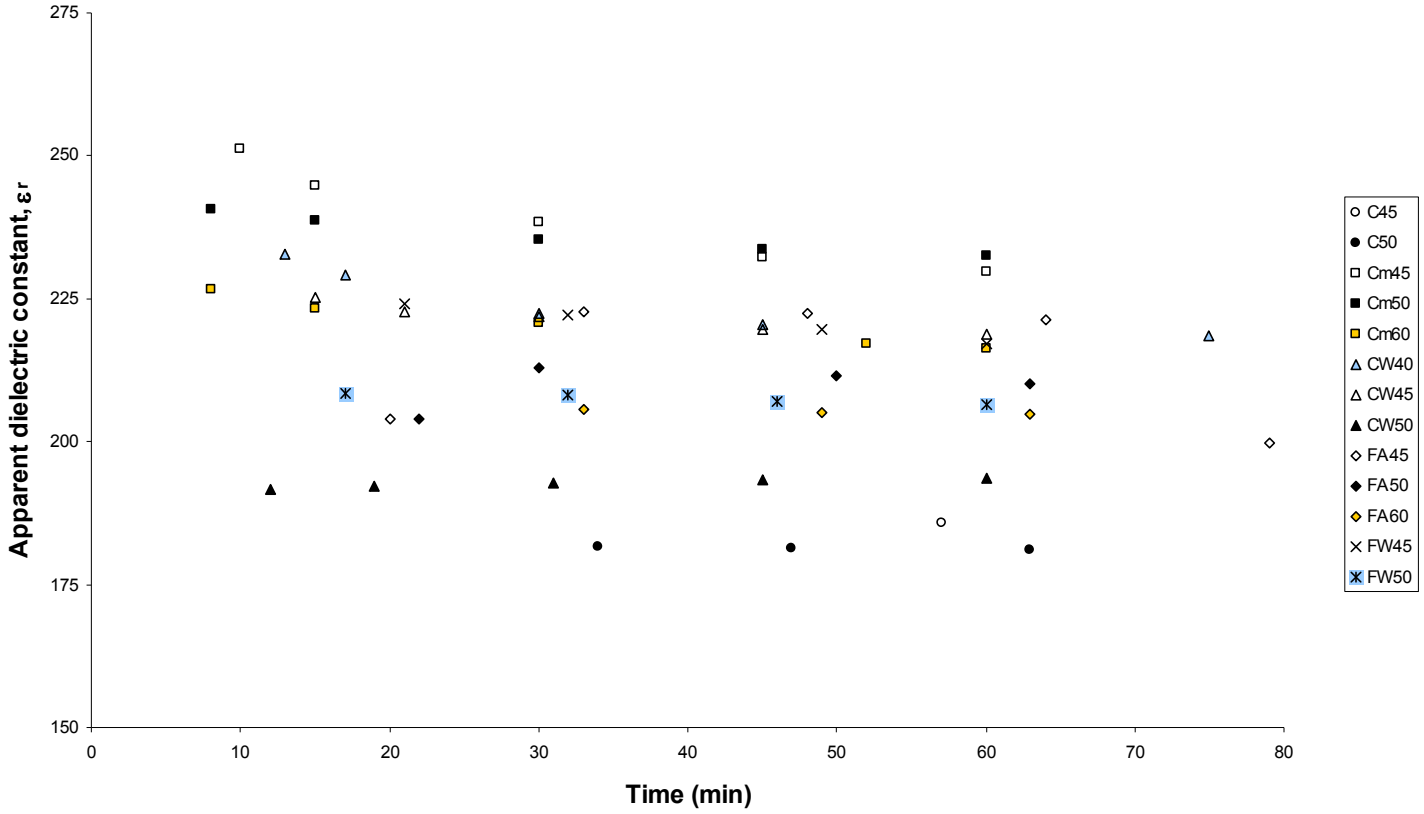


Figure 4.2 Apparent Dielectric Constant and Time Tested at 10 kHz

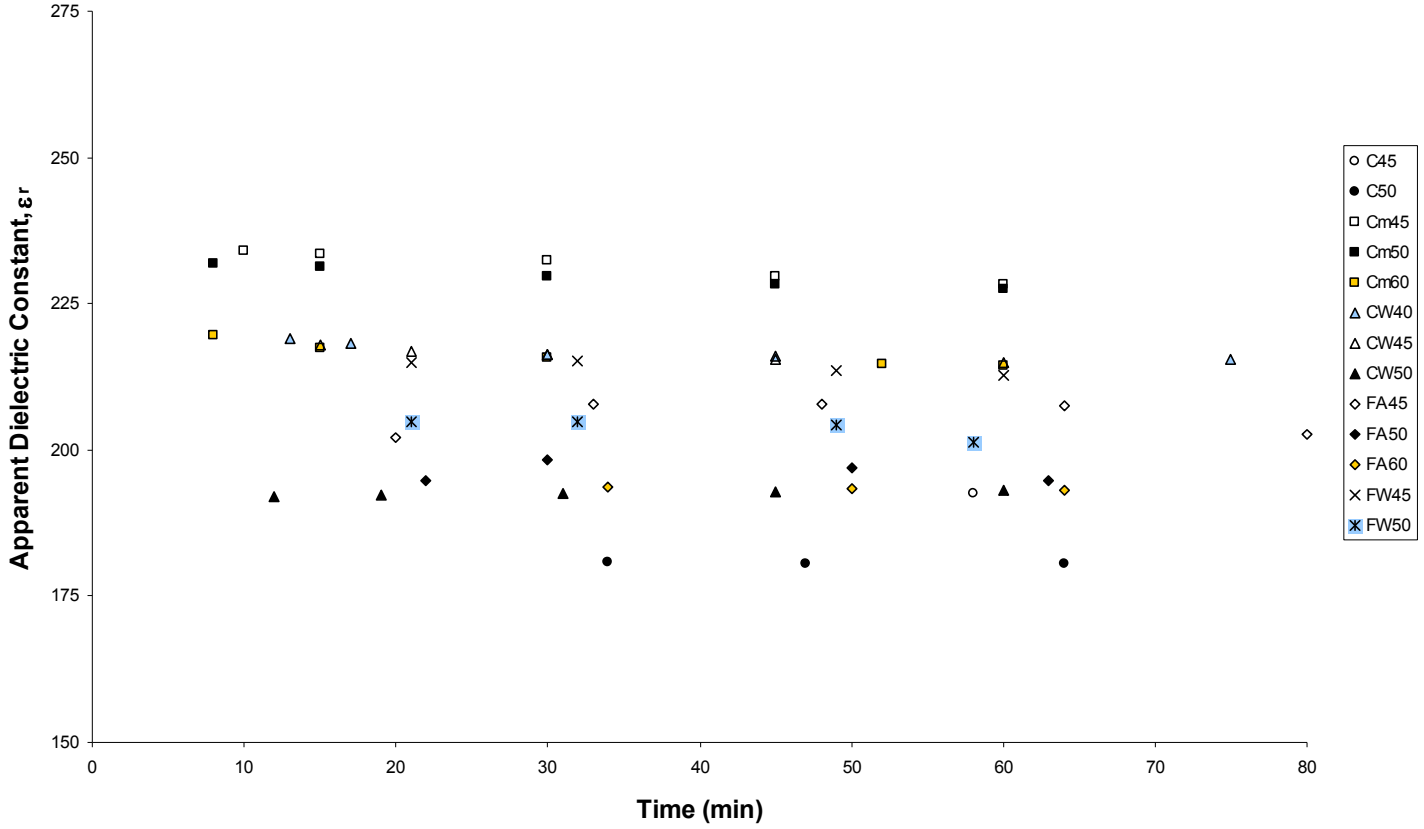


Figure 4.3 Apparent Dielectric Constant and Time Tested at 100 kHz

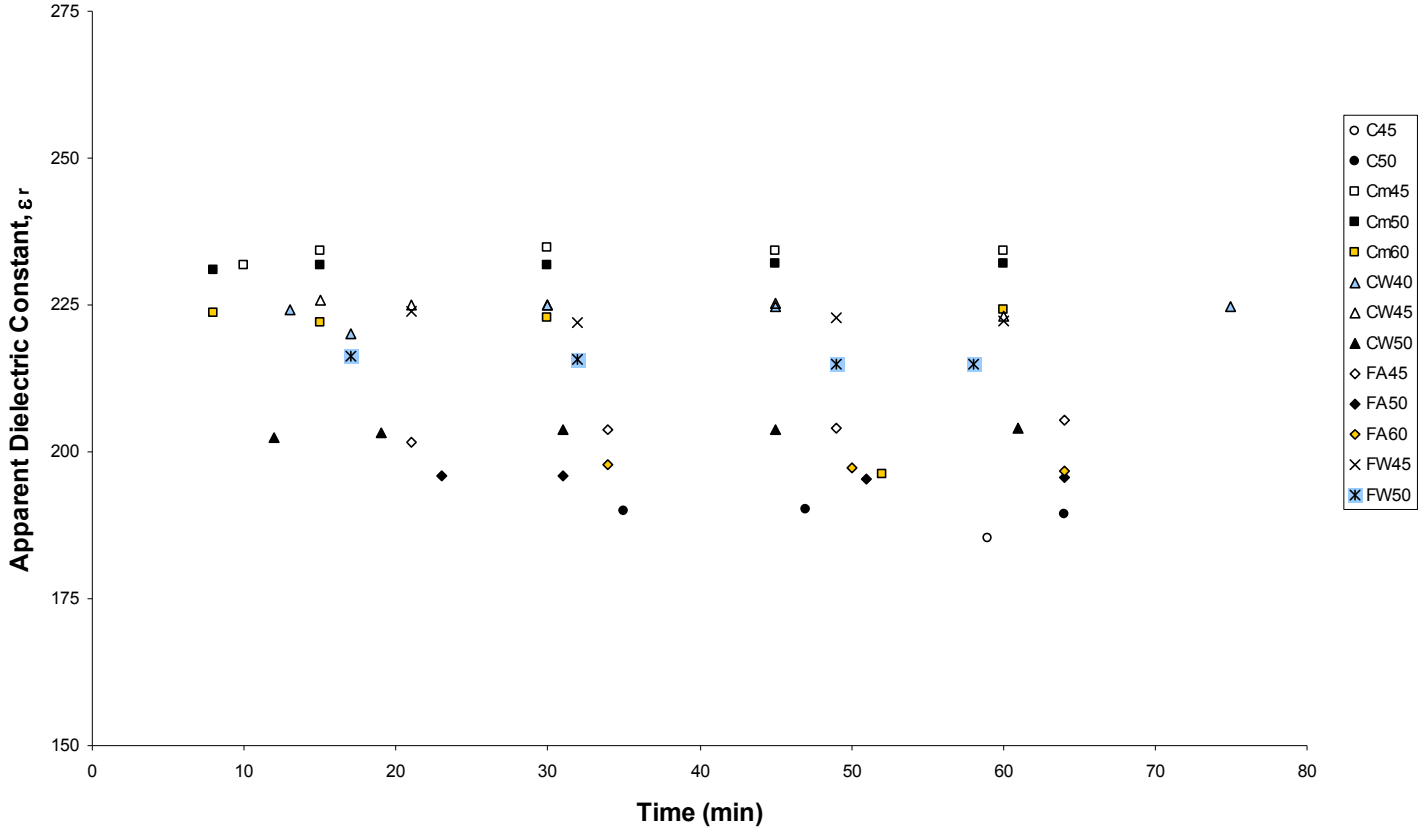


Figure 4.4 Apparent Dielectric Constant and Time Tested at 1000 kHz

4.4.1 Analysis of Cement Only Mixtures (Groups C and Cm)

Results for the cement only mixtures at 1 kHz frequency were used to analyze apparent dielectric constant variation over time (see Table 4.2 and Figure 4.5). The apparent dielectric constant values for the cement only mixtures over time at a frequency of 1 kHz appear to indicate differences between mixtures. For any given time ε_r is lower when the w/c is lower. A higher variation of ε_r is observed at the C45 and C50 mixtures compared to C60.

Table 4.2 Dielectric Properties Group C

GROUP C		
Mixture	Nom t (min)	ε_r
C60	30	177
C60	45	178
C60	60	178
C60	75	178
C50	15	197
C50	30	189
C50	45	187
C50	60	186
C45	30	198
C45	45	196
C45	60	193
* Values for 1 kHz		
Notes: Nom t = nominal time ε_r = apparent dielectric constant		

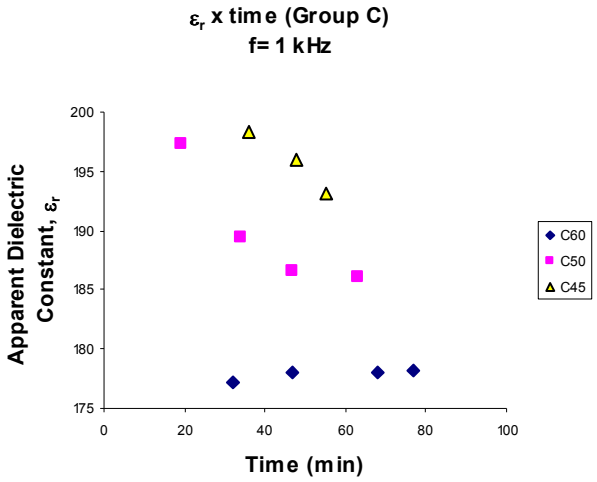


Figure 4.5 Apparent Dielectric Constant and Time, Group C

These mixtures were produced first in the series and problems with testing resulted in insufficient data for this group at frequencies other than 1 kHZ to permit a paired comparison analysis. For this reason, an additional set of small volume mixtures with the same w/c was conducted in order to observe frequency effects in the dielectric constant variation over time. These mixtures were considered in a new group designated Cm (see Table 4.3 and Figures 4.6).

At 1 and 10 kHz, data for w/c 0.45 had a high variation. Measurements at early times are higher for the 0.50 w/c mixture but after 45 minutes the values are close or even lower than the ones for the 0.50 w/c mixture. Data for the 0.60 w/c mixture is consistently lower than the other two mixtures at all frequencies at the same time. At low frequencies, especially at 1 kHZ, early data for C60 falls in the same nominal range as data taken at later times for the other two mixtures, which in practice would make it difficult to identify the mixtures. At higher frequencies, variations of values of a same mixture are

much lower and the difference between mixtures increases making identification easier.

Table 4.3 (a) through (d) Dielectric Properties and Time, Group Cm

(a)

GROUP Cm		
Mixture	Nom t (min)	ε_r
C60_2	<15	247
C60_2	15	243
C60_2	30	239
C60_2	45	235
C60_2	60	233
C50_1	<15	267
C50_1	15	255
C50_1	30	246
C50_1	45	245
C50_1	60	245
C45_1	<15	395
C45_1	15	360
C45_1	30	309
C45_1	45	257
C45_1	60	244
* Values for 1 kHz		

(b)

GROUP Cm		
Mixture	Nom t (min)	ε_r
C60_2	<15	227
C60_2	15	223
C60_2	30	221
C60_2	45	217
C60_2	60	216
C50_1	<15	241
C50_1	15	239
C50_1	30	235
C50_1	45	234
C50_1	60	233
C45_1	<15	251
C45_1	15	245
C45_1	30	238
C45_1	45	232
C45_1	60	230
* Values for 10 kHz		

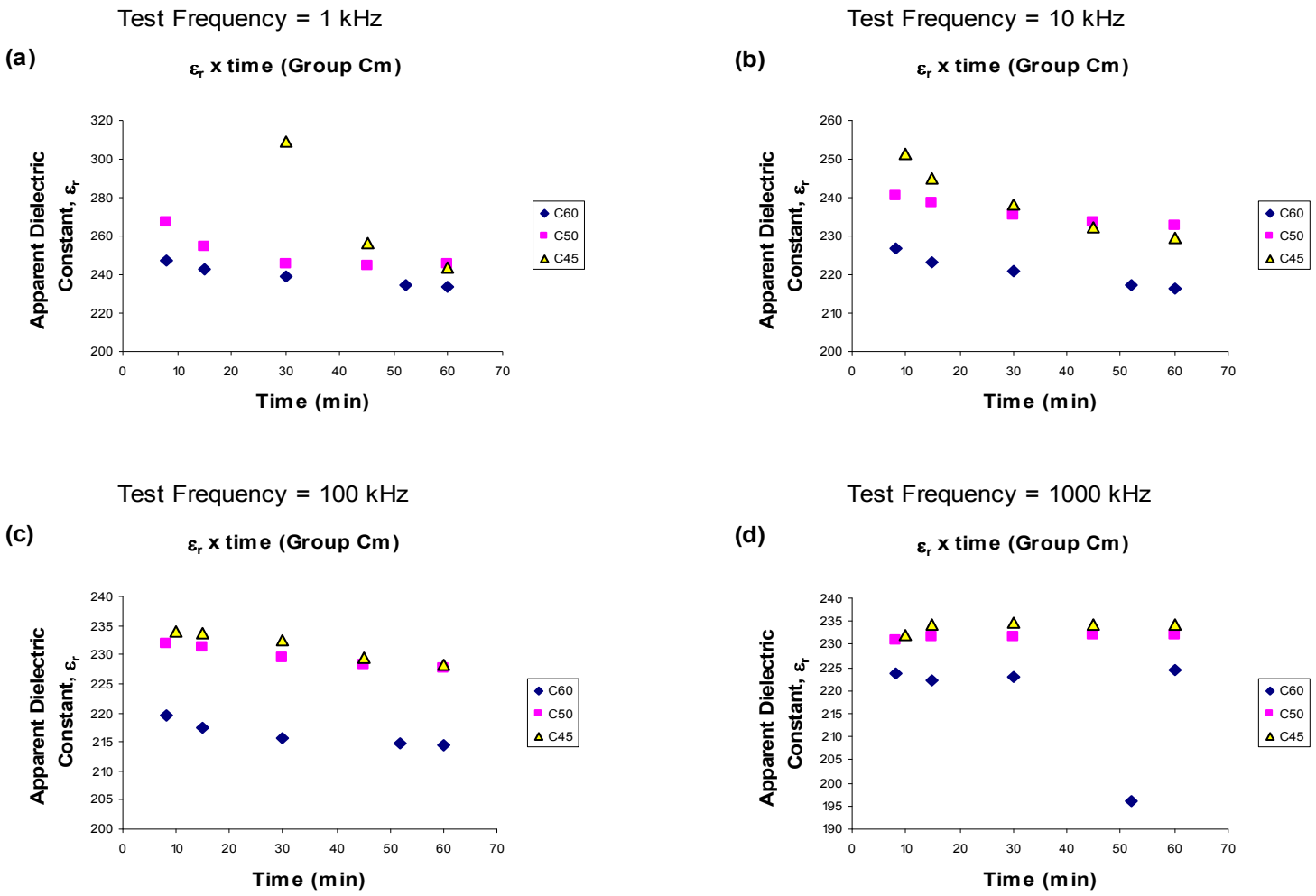
(c)

GROUP Cm		
Mixture	Nom t (min)	ε_r
C60_2	<15	220
C60_2	15	218
C60_2	30	216
C60_2	45	215
C60_2	60	214
C50_1	<15	232
C50_1	15	231
C50_1	30	230
C50_1	45	228
C50_1	60	228
C45_1	<15	234
C45_1	15	234
C45_1	30	232
C45_1	45	230
C45_1	60	228
* Values for 100 kHz		

(d)

GROUP Cm		
Mixture	Nom t (min)	ε_r
C60_2	<15	224
C60_2	15	222
C60_2	30	223
C60_2	45	196
C60_2	60	224
C50_1	<15	231
C50_1	15	232
C50_1	30	232
C50_1	45	232
C50_1	60	232
C45_1	<15	232
C45_1	15	234
C45_1	30	235
C45_1	45	234
C45_1	60	234
* Values for 1000 kHz		

Notes:
Nom t = nominal time; ε_r = apparent dielectric constant



Figures 4.6 (a) through (d) Frequency Comparison, Group Cm

Values between Cm45 and Cm50 were close for all frequencies. These batches were mixed in small quantities, however. Small variations in water could have had a disproportionate effect on w/c in the mixtures.

4.4.2 Comparison of Cement with Water Reducing Agent mixtures (Group CW)

Apparent dielectric constant behavior over time was analyzed for mixtures with water reducing admixture for frequencies of 1, 10, 100 and 1000 kHz (see Table 4.4 and Figures 4.7). The apparent water cement ratio difference between CW40 and CW45 was not reflected in the dielectric constant values. For both mixtures the apparent dielectric constant data obtained was very close. Contrary to findings on the Cm group, at higher frequencies the apparent dielectric constants between the two mixtures were essentially equal. Mixture CW40 had both a water reducing and a high range water reducing admixture, however. This could have had an effect on the dielectric properties.

Table 4.4 (a) through (d) Dielectric Properties and Time, Group CW

(a)

GROUP CW		
Mixture	Nom t (min)	ε_r
CW50	<15	195
CW50	15	195
CW50	30	196
CW50	45	196
CW50	60	197
CW45	<15	243
CW45	15	242
CW45	30	241
CW45	45	237
CW45	60	235
CW40	<15	262
CW40	15	261
CW40	30	245
CW40	45	239
CW40	75	234
* Values for 1 kHz		

(b)

GROUP CW		
Mixture	Nom t (min)	ε_r
CW50	<15	192
CW50	15	192
CW50	30	193
CW50	45	193
CW50	60	194
CW45	<15	225
CW45	15	223
CW45	30	222
CW45	45	220
CW45	60	219
CW40	<15	233
CW40	15	229
CW40	30	222
CW40	45	220
CW40	75	219
* Values for 10 kHz		

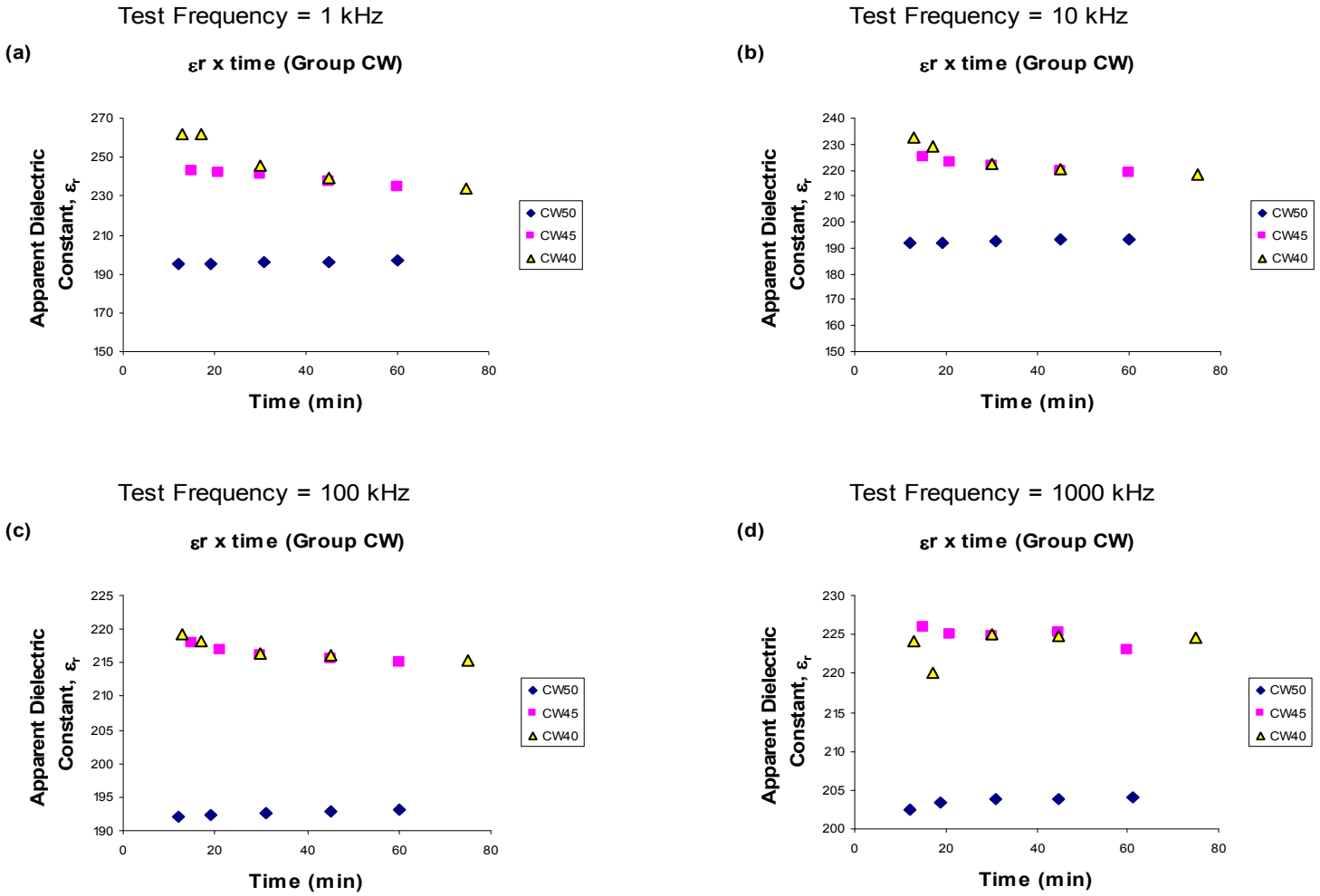
(c)

GROUP CW		
Mixture	Nom t (min)	ε_r
CW50	<15	192
CW50	15	192
CW50	30	193
CW50	45	193
CW50	60	193
CW45	<15	218
CW45	15	217
CW45	30	216
CW45	45	215
CW45	60	215
CW40	<15	219
CW40	15	218
CW40	30	216
CW40	45	216
CW40	75	215
* Values for 100 kHz		

(d)

GROUP CW		
Mixture	Nom t (min)	ε_r
CW50	<15	202
CW50	15	203
CW50	30	204
CW50	45	204
CW50	60	204
CW45	<15	226
CW45	15	225
CW45	30	225
CW45	45	225
CW45	60	223
CW40	<15	224
CW40	15	220
CW40	30	225
CW40	45	225
CW40	75	225
* Values for 1000 kHz		

Notes:
Nom t = nominal time; ε_r = apparent dielectric constant



Figures 4.7 (a) through (d) Frequency Comparison, Group CW

4.4.3 Comparison of Cement and Fly Ash mixtures (Group FA)

Dielectric properties over time were also analyzed in the mixtures with 20% of cement content by weight was replaced with fly ash. (see Table 4.5 and Figures 4.8)

When comparing ε_r values at 1 kHz differences in the apparent dielectric constant are not consistent with the variation in nominal w/c. At 10 and 100 kHz the difference between the mixtures become much more evident. At 1000 kHz there is still a difference, although smaller between 0.45 and the other two mixtures. Between FA60 and FA50 a switch in the values is observed at 1000 kHz, with FA60 now having larger apparent dielectric constant.

Table 4.5 (a) through (d) Dielectric Properties and Time, Group FA

(a)

GROUP FA		
Mixture	Nom t (min)	ε_r
FA60	15	215
FA60	30	230
FA60	45	227
FA60	60	227
FA50	15	213
FA50	30	229
FA50	45	227
FA50	60	227
FA45	15	218
FA45	30	237
FA45	45	236
FA45	60	234
* Values for 1 kHz		

(b)

GROUP FA		
Mixture	Nom t (min)	ε_r
FA60	30	205.6
FA60	45	205.1
FA60	60	204.8
FA50	15	204.0
FA50	30	213.0
FA50	45	211.5
FA50	60	210.1
FA45	15	203.9
FA45	30	222.7
FA45	45	222.5
FA45	60	221.4
FA45	75	199.7
* Values for 10 kHz		

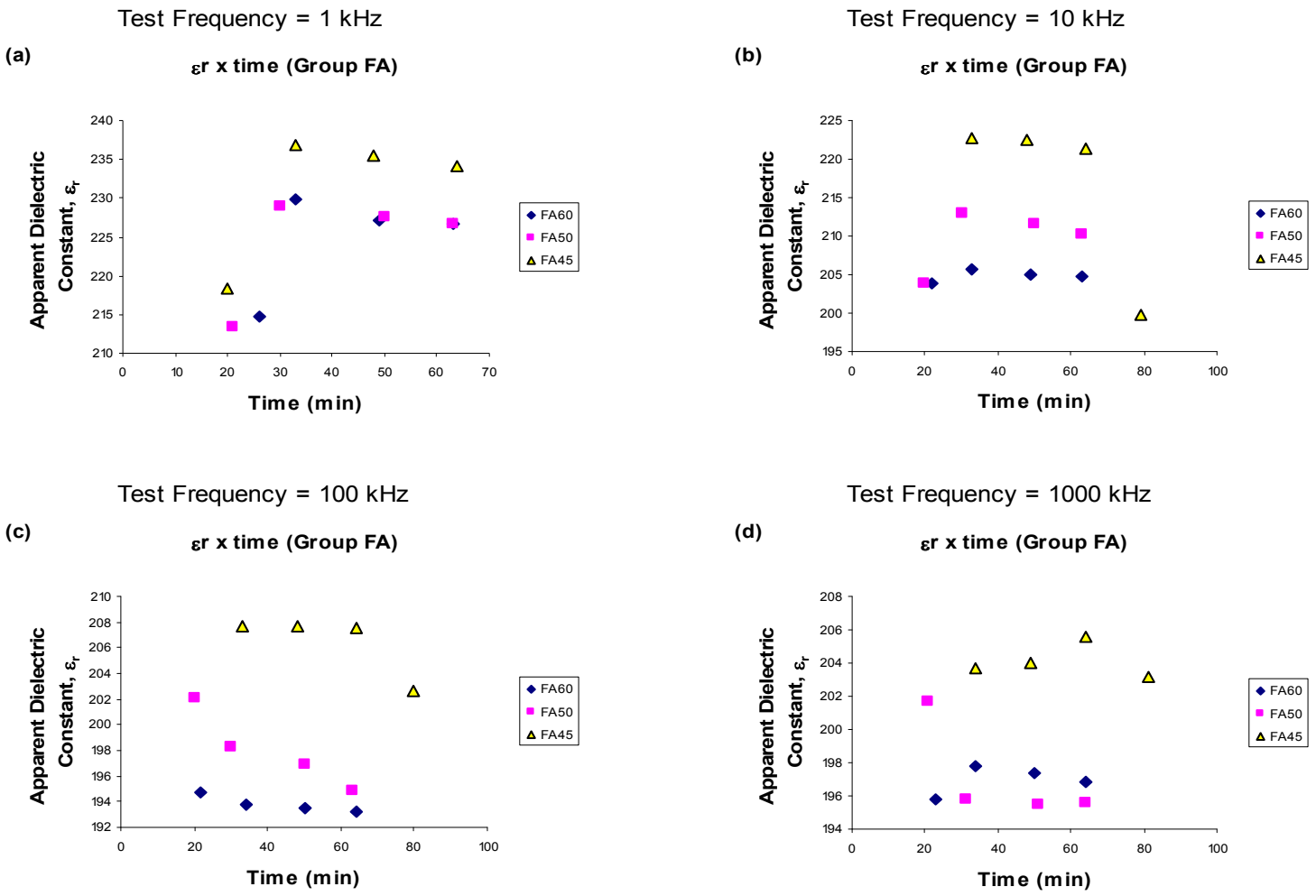
(c)

GROUP FA		
Mixture	Nom t (min)	ε_r
FA60	30	194
FA60	45	193
FA60	60	193
FA50	15	195
FA50	30	198
FA50	45	197
FA50	60	195
FA45	15	202
FA45	30	208
FA45	45	208
FA45	60	208
FA45	75	203
* Values for 100 kHz		

(d)

GROUP FA		
Mixture	Nom t (min)	ε_r
FA60	30	197.8
FA60	45	197.3
FA60	60	196.8
FA50	15	195.8
FA50	30	195.8
FA50	45	195.4
FA50	60	195.6
FA45	15	201.7
FA45	30	203.7
FA45	45	204.0
FA45	60	205.5
FA45	75	203.2
* Values for 1000 kHz		

Notes:
Nom t = nominal time; ε_r = apparent dielectric constant



Figures 4.8 (a) through (d) Frequency Comparison, Group FA

4.4.4 Comparison of Cement, Fly Ash and Water Reducing Admixture (Group FW)

The apparent dielectric values over time for different frequencies were measured for mixtures with w/c 0.45 and w/c 0.50 (see Table 4.6). The dielectric behavior over time was consistent with the previous groups where dielectric constants values were higher for a lower w/c.

Table 4.6 (a) through (d) Dielectric Properties and Time, Group FW

(a)

GROUP FW		
Mixture	Nom t (min)	ε_r
FW50	15	220
FW50	30	221
FW50	45	221
FW50	60	217
FW45	30	236
FW45	45	230
FW45	60	232
* Values for 1 kHz		

(b)

GROUP FW		
Mixture	Nom t (min)	ε_r
FW50	15	208.5
FW50	30	208.2
FW50	45	207.1
FW50	60	206.6
FW45	15	224.1
FW45	30	222.2
FW45	45	219.5
FW45	60	217.0
* Values for 10 kHz		

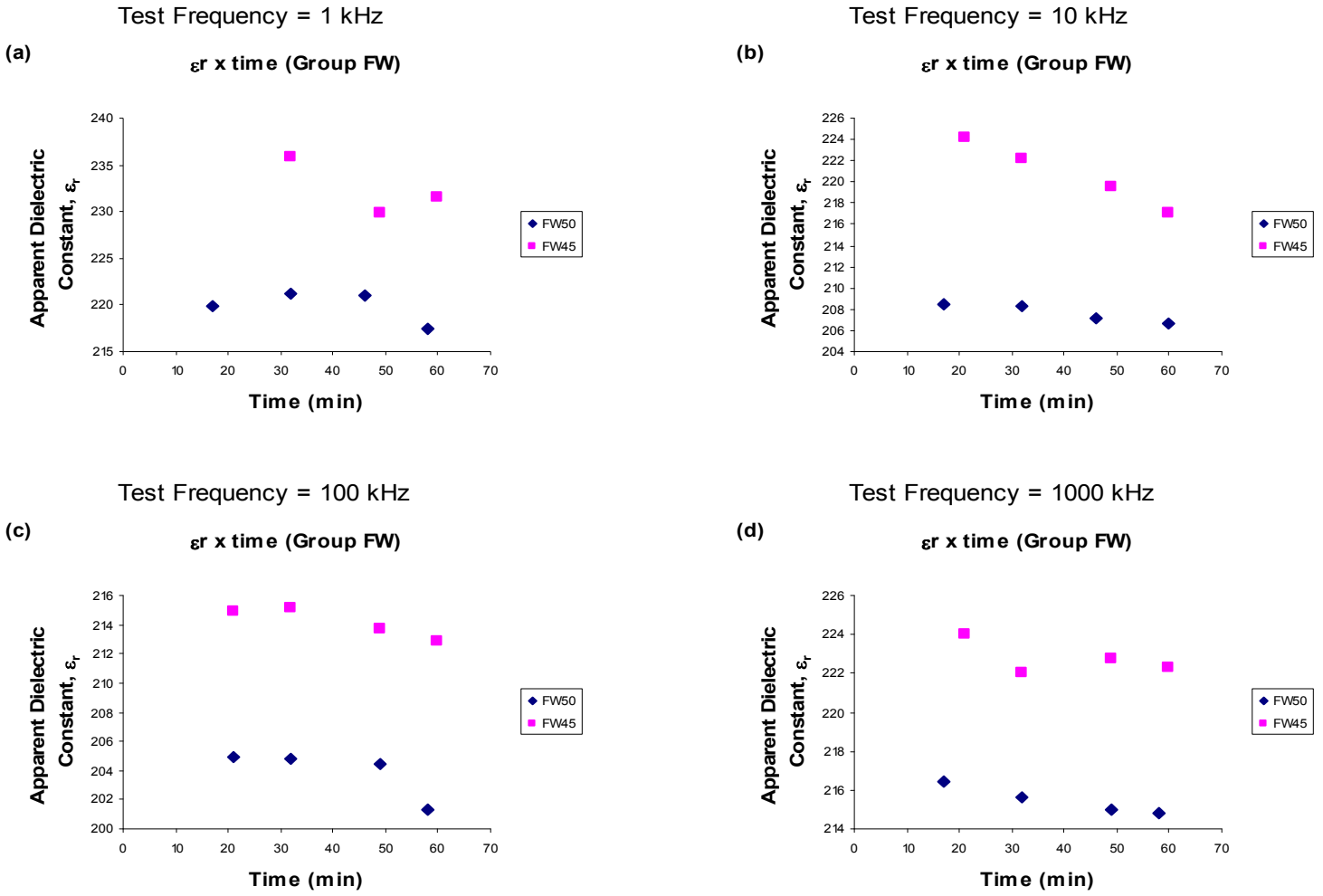
(c)

GROUP FW		
Mixture	Nom t (min)	ε_r
FW50	15	205
FW50	30	205
FW50	45	204
FW50	60	201
FW45	15	215
FW45	30	215
FW45	45	214
FW45	60	213
* Values for 100 kHz		

(d)

GROUP FW		
Mixture	Nom t (min)	ε_r
FW50	15	216.4
FW50	30	215.6
FW50	45	215.0
FW50	60	214.8
FW45	15	224.0
FW45	30	222.0
FW45	45	222.7
FW45	60	222.3
* Values for 1000 kHz		

Notes:
Nom t = nominal time; ε_r = apparent dielectric constant



Figures 4.9 (a) through (d) Frequency Comparison, Group FW

In general, during the first minutes after water addition and until somewhere close to 15 minutes, apparent dielectric constant behavior is not clear. In some cases, for example Cm45, values are considerably higher at the early stage. In some other cases, for example mixtures in group FA especially at low frequencies, apparent dielectric constant values are considerably lower. No consistent behavior was identified, even within the groups, in order to explain mixture behavior at times less than 15 minutes. After this period, the dielectric constant appears to stabilize with only small variations observed, however. Between 30 and 60 minutes the variation stays below 2% for most measurements for different mixtures and at different frequencies.

The data for times after 60 minutes has different results depending on the group. For this analysis, data from devices S1 and S2 has been included since the primary factor of interest in this part of the analysis is the variation over time and not a comparison to other devices. In the mixtures without fly ash, the variation of the dielectric constant follows the same trend as between the previous period of time. For the mixtures containing fly ash, values drop from the previous trend, however.

For practical purposes, it is reasonable to limit results to the first hour after batching. It is unrealistic to think that the test could be done at exactly the same time. If a clear relationship could be found between time passed after water addition to the batch and the apparent dielectric constant, then a correction factor could be developed and applied if the time after batching was accurately known. No clear relationship to the dielectric constant was found, however. In some cases the capacitance measurements slightly increased while in other it decreased slightly.

In practice the test should be done within a realistic tolerance for a given time. For this study apparent dielectric constant values measured at 30 minutes was used for all comparisons. These values are representative from all mixtures tested between 30 and 60 minutes.

4.5 Frequency

The dielectric behavior over time for all frequencies is, for the most part, consistent from one frequency to another. A comparison of apparent dielectric constant values measured at 30 minutes was done to identify an optimal frequency at which differences in the apparent dielectric constant could be used to clearly identify different mixtures. A general comparison was done with all the mixtures. (see Figure 4.10)

Relationships between dielectric constant of all the mixtures were not constant through all the frequency spectra. The lines crossing in Figure 4.10 show that a mixture may have a higher or lower dielectric constant value depending on the frequency at which it was measured.

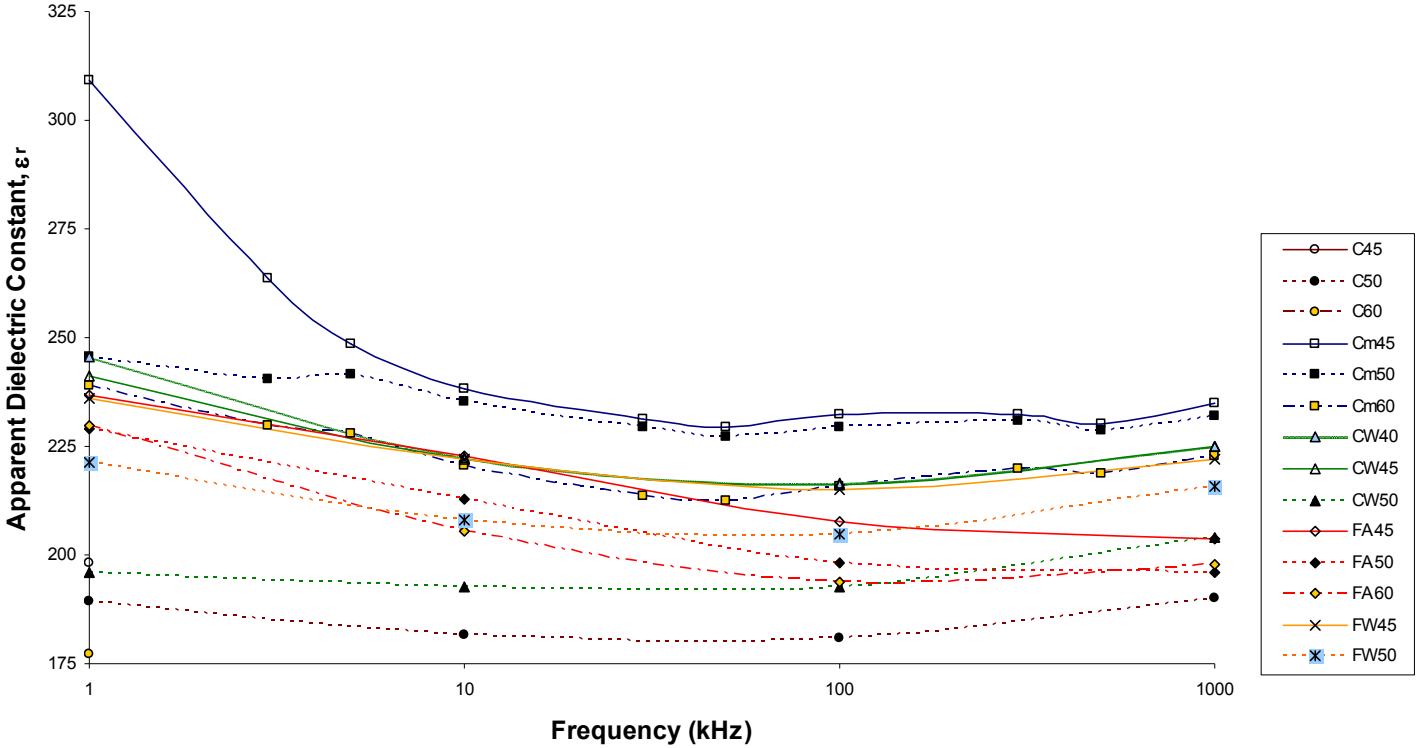


Figure 4.10 Apparent Dielectric Constant and Frequency All Mixtures (Time = 30 min)

As with time, a closer analysis was necessary to determine if a given frequency could be used to represent the overall dielectric properties behavior. An analysis per group was done, (see Figure 4.11through Figure 4.14).

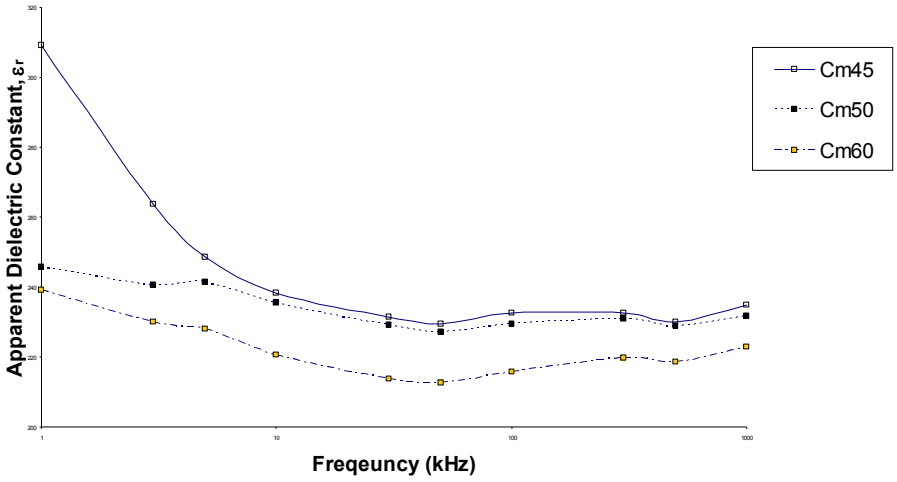


Figure 4.11 Apparent Dielectric Constant and Frequency; Group Cm

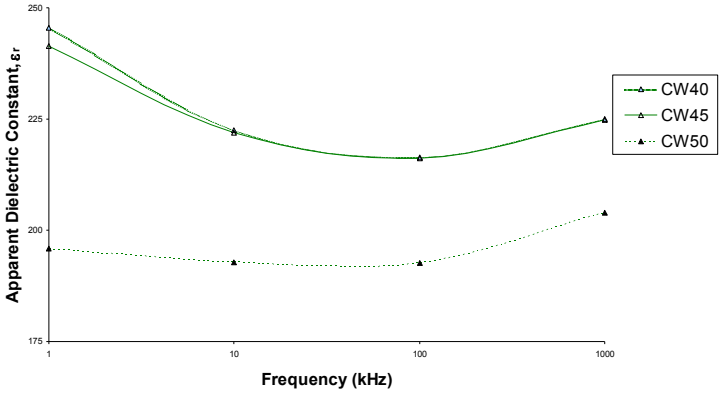


Figure 4.12 Apparent Dielectric Constant and Frequency; Group CW

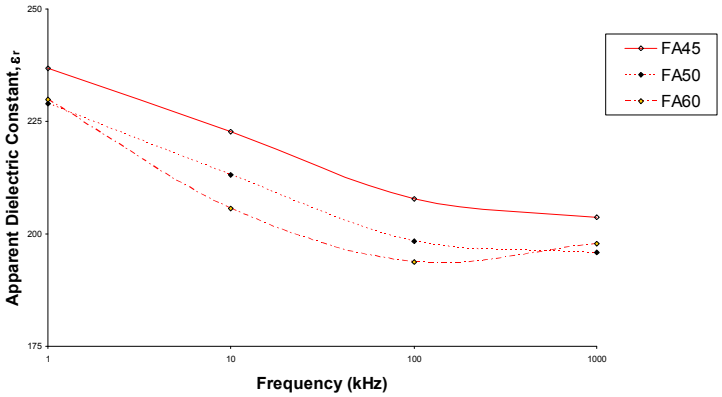


Figure 4.13 Apparent Dielectric Constant and Frequency; Group FA

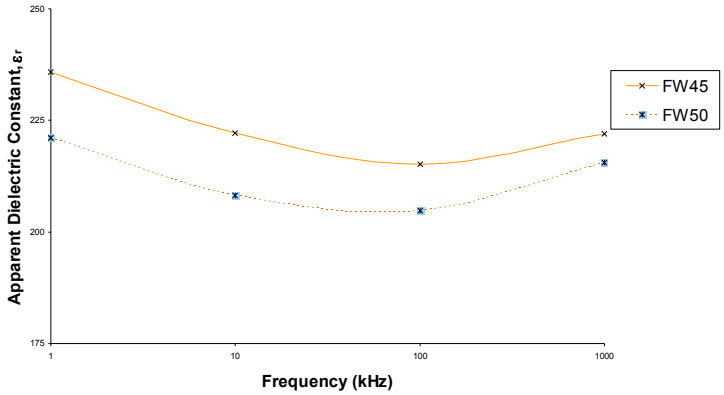


Figure 4.14 Apparent Dielectric Constant and Frequency; Group FW

Essentially the same differences are observed at 10 and 100 kHz when analyzing by group. Apparent dielectric constant values at 1 kHz have, in some cases, a greater difference between each other, which could make identification of the mixtures easier. Data at this frequency seems to be affected by other variables, however, especially in mixtures Cm40 and FA60. At 1000 kHz the difference in the apparent dielectric constant values are smaller and the results are not always consistent to that observed at lower frequencies.

Analysis of data grouped by water cement ratio was also done (see Figure 4.15 through Figure 4.17).

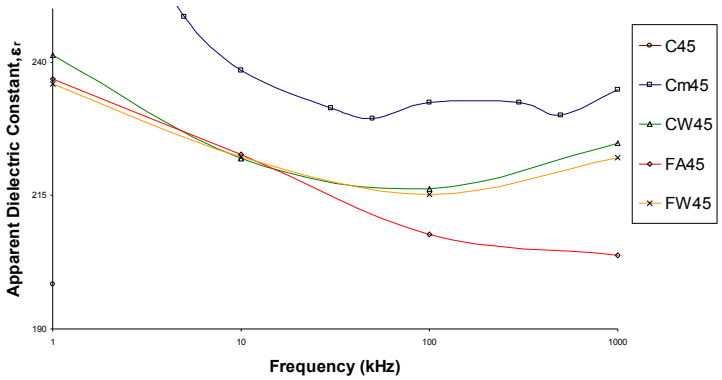


Figure 4.15 Apparent Dielectric Constant and Frequency; Water Cement Ratio = 0.45

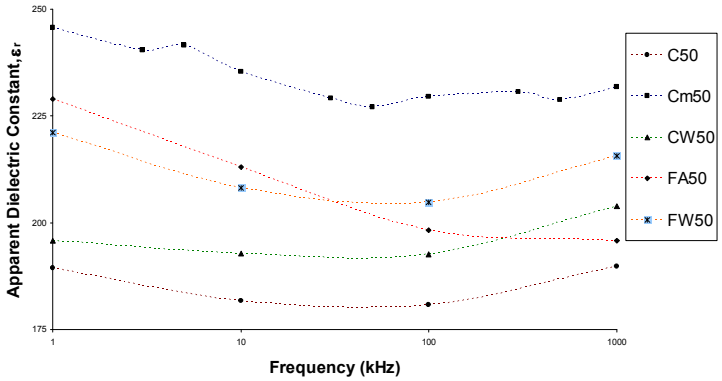


Figure 4.16 Apparent Dielectric Constant and Frequency; Water Cement Ratio = 0.50

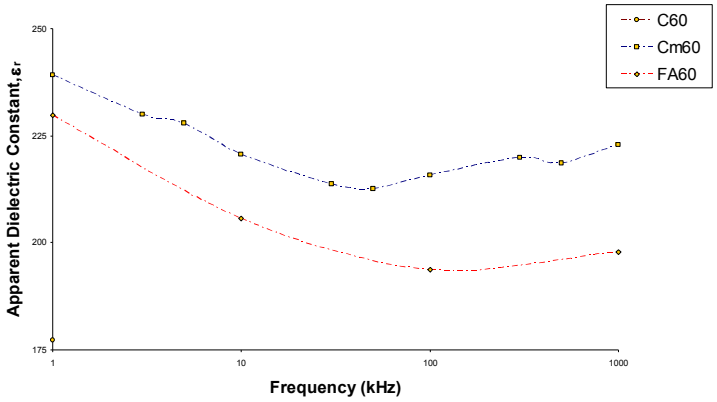


Figure 4.17 Apparent Dielectric Constant and Frequency; Water Cement Ratio = 0.60

It is observed that all mixtures have lower apparent dielectric constants at 10 kHz than at 1 kHz. Comparing values at 10 and 100 kHz there appears to be a recovery in the dielectric values. This recovery is not as significant in the FA mixtures. Consequently, mixtures with fly ash and without water reducing admixture have higher apparent dielectric values at lower frequencies and lower values at higher frequencies compared to mixtures of other groups.

Based on these observations, it was decided to conduct additional analysis on data at 10 kHz and 30 minutes. As noted in the previous sections, the 30 minutes time is reasonable from practical considerations and values were reasonably consistent between 30 and 60 minutes in time. The selection of testing frequency of 10 kHz is somewhat arbitrary. Differences in apparent dielectric constant between mixtures with similar composition but different w/c ratios did not clearly indicate an optimal testing frequency between 1 kHz and 1 MHz. Values at 10 kHz appeared to provide acceptable differentiation

between otherwise similar mixtures.

4.6 Material Effects

4.6.1 Water Cement Ratio

A paired comparison was done within each group to examine ε_r variations compared to w/c. Differences between values for mixtures compared to values for the lowest water cement ratio mixture of each group were analyzed (see Table 4.7) based on measurements at 30 min and 10 kHz, except for Group C were only data at 1 kHz was available.

The relationship between w/c and apparent dielectric constant was consistent in that a higher w/c resulted in a lower ε_r for otherwise similar mixtures. This relation is weak in two cases, however. Between Cm45 and Cm50, and between CW40 and CW45, ε_r are essentially the same. Both may be special cases since in the first case (Cm) small quantities were used for batching, and in the second case, CW40 contained a high range water reducing (HRWR) admixture in addition to the water reducing admixture. In all other cases, although lower apparent dielectric constant values were found for higher w/c, the relationship was not proportional.

Table 4.7 Differences Comparison within Groups

Group C							
Differences to w/c = 0.45							
w/c	% ε_r	% fc28	%air	% paste	% wtr	% Cmt	% FA(v)
0.50	-4.5%	-7.1%	0.0	-1.2	0.0	-1.3	0.0
0.60	-10.6%	-19.4%	0.5	-3.2	0.0	-3.2	0.0
freq	1 kHz						

Group Cm							
Differences to w/c = 0.45							
w/c	% ε_r	% fc28	%air	% paste	% wtr	% Cmt	% FA(v)
0.50	-1.3%	N.A	N.A.	-1.3	0.1	-1.4	0.0
0.60	-7.4%	N.A	N.A.	-3.1	0.2	-3.3	0.0
freq	10 kHz						

Group CW *							
Differences to w/c = 0.40							
w/c	% ε_r	% fc28	%air	% paste	% wtr	% Cmt	% FA(v)
0.45	-0.2%	-16.1%	1.4	-1.7	-0.1	-1.5	0.0
0.50	-13.4%	-26.9%	1.9	-2.9	-0.2	-2.7	0.0
freq	10 kHz						
Differences to w/c = 0.45							
w/c	% ε_r	% fc28	%air	% paste	% wtr	% Cmt	% FA(v)
0.50	-13.1%	-12.9%	0.5	-1.2	0.0	-1.2	0.0
freq	10 kHz						

Group FA							
Differences to w/c = 0.45							
w/c	% ε_r	% fc28	%air	% paste	% wtr	% Cmt	% FA(v)
0.50	-4.3%	-8.7%	0.0	-1.4	0.0	-1.0	-0.4
0.60	-7.7%	-26.9%	1.3	-3.7	-0.2	-2.6	-0.9
freq	10 kHz						

Group FW							
Differences to w/c = 0.45							
w/c	% ε_r	% fc28	%air	% paste	% wtr	% Cmt	% FA(v)
0.50	-6.3%	-18.2%	1.1	-1.7	-0.3	-1.1	-0.3
freq	10 kHz						

Notes:
- %air, % paste, % water, %Cement and % Fly Ash are volume percentages.
- Percentage differences were considered for ε_r and *fc*.
- Simple differences were considered for %air, % paste, % water, %Cement and % Fly Ash

* Comparison for w/c 0.40 and w/c 0.45 was done for group CW since CW40 contained High Range Water Reducer

The apparent dielectric constant is expected to vary as w/c varies for different reasons. Higher w/c mixtures in the same group will be expected to have a higher volume percentage of free water. The thin layer of water surrounding the cement grains will be thicker at higher w/c and water molecules will be subjected to lower attractive forces. Since free water has a higher dielectric constant, the apparent dielectric constant of concrete was expected to increase due to this effect. This effect was evident in cement paste testing in previous studies [Zhang, *et al.*, 1996; Ford, *et al.,* 1997].

Variations in water cement ratio are also related to variations in water, cement, fly ash and paste volumes. In this part of the study, water volume remained essentially constant while cementitious material proportions were increased in order to reduce w/c. Variations in ε_r within the groups, even when the amount of water remained the same, is consistent with previous studies that found that ε_r measurements do not depend solely of the volume of water in a batch.

Variations in the cement and fly ash volume have a direct effect on the mixture paste volume. When cementitious materials were reduced, the volume of paste was reduced compared to volume of aggregates in a batch. Previous studies mentioned that the addition of aggregates to a paste is evident in the apparent dielectric constant values as a dilution effect [McCarter, *et all.,*1999]. The effects observed in this study appear to be consistent with previous studies since higher reductions in ε_r values are related to higher reductions in volume of paste.

One of the problems complicating the analysis is that many variables affect apparent dielectric constant and these variables can be highly correlated physically in a way

not easy to separate. These complications contributed to the difficulty in developing a general relationship between w/c and ε_r for all mixtures.

The w/c has a strong correlation to compressive strength of concrete. The relationship between apparent dielectric constant and compressive strength at 28 days was much stronger than the relationship between apparent dielectric constant and w/c, at least within groups. Finding a stronger relationship between ε_r and compressive strength than between ε_r and w/c was initially somewhat surprising (see Figure 4.18). The importance of this finding will be described later in the study.

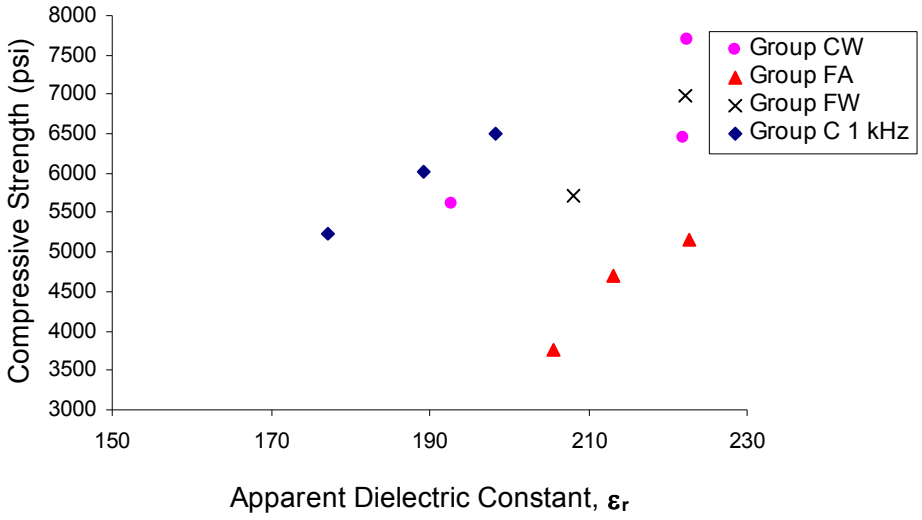


Figure 4.18 Apparent Dielectric Constant (10 kHz) and Compressive Strength

The true water content in a batch is very difficult to determine, especially in small batches where a slight error would create more significant effects. It was suspected that at least some of the difficulty in analysis may be attributed to lack of accuracy in

determining the water content and therefore the true w/c of the batches. The stronger relationship found between ε_r and strength may be beneficial in practical applications. ACI 318 [2007] establishes tolerances for strength [Cutshall, Leming, and Johnston, 1999] rather than w/c and suggests that specifications based on w/c should be enforced through more easily measured compressive strength.

The remaining analysis, based on paired comparisons, examines a number of factors for the components, to provide both insight and analytical rigor. The relationship between ε_r and strength is examined in more detail in section 4.8.

4.6.2 Fly Ash

Additional considerations were necessary when determining which values to use for comparison among mixtures of same w/c and different groups to identify admixture and supplementary cementitious material effects. Data obtained for the small batches for the cement only group had greater variations from the mixtures with the same proportions but different aggregates and with an air entraining agent. Therefore, a comparison using the original batches of cement only, where data was available only at 1 kHz, instead of the small batches. This is supported by the fact that for the same w/c, the apparent dielectric constant at 1 kHz of all mixtures, except for the FA group, differences in values were similar to those observed at 10 and 100 kHz.

Paired comparisons between groups were done to identify fly ash effects. Group FA was compared to Group C and Group FW to group CW (see Table 4.8)

Table 4.8 Paired Comparison for Fly Ash Effects

Group FA Differences from group C; frequency= 1kHz Time = 30 min							
w/c	% ε_r	% fc28	% air	% paste	% wtr	% Cmt	% FA(v)
0.45	19.4%	-20.5%	0.3	0.9	0.0	-2.6	3.5
0.50	20.9%	-21.9%	0.3	0.8	-0.1	-2.3	3.1
0.60	29.7%	-27.9%	1.1	0.4	-0.2	-2.0	2.6
Group FW Differences from group CW; frequency= 10 kHz Time = 30 min							
w/c	% ε_r	% fc28	% air	% paste	% wtr	% Cmt	% FA(v)
0.45	0.1%	8.2%	-2.2	1.4	0.3	-2.1	3.2
0.50	8.0%	1.6%	-1.6	0.9	0.1	-2.0	2.8

Notes:
- % air, % paste, % water, % Cement and % Fly Ash are volume percentages.
- Percentage differences are shown for ε_r and *fc*.
- Simple differences are shown for % air, % paste, % water, % Cement and % Fly Ash

Comparing Group FA to Group C, ε_r values are significantly higher for the mixtures containing fly ash. Apparent dielectric constant variations were between 20 and 30%. The inclusion of fly ash is expected to affect dielectric properties in several ways. Different research has shown that fly ash inclusion has an effect on the workability due to the size and the texture of its particles [Mehta and Monteiro, 2006]. The different surface properties between fly ash and cement, the slower rate of hydration and the variations in paste volume should also affect the apparent dielectric constant. For this study, 20% of the cement mass was replaced with a same mass of fly ash. Since fly ash has a lower specific gravity than cement, 2.29 for this particular product compared to 3.15 respectively, the total volume of paste increased. Water content was not a factor since it remained the same between the groups compared.

The relative variations of the dielectric constant were 30%, 21% and 19% for 0.60,

0.50 and 0.45 respectively. As opposed to w/c comparison within groups, higher values of ε_r were observed for mixtures that had lower strengths, the ones containing fly ash in this case. The inclusion of fly ash increases the dielectric properties of a mixture.

The differences in compressive strength for the three water cement ratios were between 20 and 30%. This is reasonable since studies have shown that when replacing cement for fly ash, the relation of the weight replaced should be of 1 to 1.2 or larger by mass in order to maintain similar strengths [Neville, 1996]. In this study a replacement of 1 to 1 was done in order to observe variations maintaining the same w/c.

Between FW45 and CW45, an increase in compressive strength was observed when fly ash was included. With a 1 to 1 fly ash to cement replacement a strength reduction was expected instead. As noted above, the nominal w/c values may be in error. Additional research is recommended with other percentages of fly ash and with a variety of supplementary cementitious materials including slag and silica fume.

4.6.3 Water Reducing Admixture

Water Reducing Admixture effects were analyzed comparing pairs for CW and C group, and between FW and FA group (see Table 4.9).

Table 4.9 Paired Comparison for Water Reducing Admixture Effects

Group CW							
Differences from group C; frequency= 1kHz Time = 30 min							
w/c	% ε_r	% fc28	% air	% paste	% wtr	% Cmt	% FA(v)
0.45	21.7%	-0.6%	0.7	-2.6	-1.5	-1.1	0.0
0.50	3.4%	-6.8%	1.2	-2.6	-1.6	-1.0	0.0
FW							
Differences from group FA; frequency= 10 kHz Time = 30 min							
w/c	% ε_r	% fc28	% air	% paste	% wtr	% Cmt	% FA(v)
0.45	-0.2%	35.3%	-1.8	-2.1	-1.2	-0.6	-0.3
0.50	-2.3%	21.2%	-0.7	-2.5	-1.5	-0.8	-0.3

Notes:
- % air, % paste, % water, % Cement and % Fly Ash are volume percentages.
- Percentage differences are shown for ε_r and *fc*.
- Simple differences are shown for % air, % paste, % water, % Cement and % Fly Ash

Using a water reducing admixture permitted water content to be reduced from 300 pcy to 275 pcy, an 8.3% reduction by mass and 8.2 and 8.5% reduction of the percentage of water by volume in present in the mixture for .45 and 0.50 respectively. The reduction in percent of cement per unit volume was also close to 9% for both mixtures, resulting in a reduction of the total paste volume of 8.4% for the w/c 0.45 CW mixture and 8.7% for the w/c 0.50 CW mixture.

The WRA addition was expected to affect apparent dielectric constant values. From previous studies, and consistent with findings for the w/c and fly ash analysis, the paste reduction was expected to decrease apparent dielectric constant values due to the dilution caused by a higher aggregate content. In this study, the water variations are proportional to the cement content variations when WRA was used. Therefore, the thin layer of water molecules surrounding cement grains would have virtually the same thickness, having

little effect on ε_r. The molecule adsorption was expected to be different due to the presence of the WRA effect, however. A reduction in adsorption forces was expected to increase apparent dielectric constant, although this was highly speculative before testing. With a constant w/c ratio, the presence or WRA was expected to slightly increase compressive strength due to improved dispersion of the cementitious material [Mehta and Monteiro, 2006]. The improved dispersion and adsorption by WRA molecules were both expected to affect apparent dielectric constant.

Two factors were also expected to affect the C to CW comparison: paste volume (decreasing ε_r) and water reducer admixture effect (increasing ε_r). In this case the WRA effect appears to be stronger. In the CW45 to C45 comparison, where strength results are consistent with that expected, ε_r values were considerably higher, close to 20%, for the CW mixture. Values for the CW50 were also higher than the ones for the C50 mixture; the difference is not as significant (3.4%) as with w/c 0.45, however.

Comparing CW45 to C45, compressive strength values are virtually the same, as expected. Compressive strength value for CW50 is 7% lower than C50, which is different from normal expectations.

Variation in the volume of fly ash is an additional factor, in addition to the paste volume variation and the WRA effect, and was expected to affect the apparent dielectric constant comparison between groups FW and FA. A reduction in fly ash, a factor that was observed to have a significant effect during the FA to C comparison, was expected to decrease the dielectric properties in a mixture. Variations in the cement and water were not expected to have an effect other than the one due to paste reduction. Paste

reduction was expected to decrease ε_r values for the FW group.

Apparent dielectric constant values were essentially the same for mixtures with the same nominal w/c of FW and FA groups. It is relevant to note that the strengths differences of the FW to FA, 35% and 21% for 0.45 and 0.50 respectively, were much higher than expected.

Comparing group FW to group CW, dielectric property behavior is not as clear as that observed for the groups without water reducing admixture. Mixture FW50 included HRWR in addition to the WRA, however. Although insufficient data existed to quantify the HRWR effect on $\varepsilon_{r,}$ the comparison between mixtures of group CW indicated that HRWR affected the dielectric properties of a mixture. It was also recognized that the HRWR was used in larger quantities and may have had affected the dielectric properties differently than if normally used, although insufficient data existed to quantify this effect as well. Considering the various kinds and compositions of HRWR admixtures used in commercial concretes: surfactants, polycrylates, polycarboxylates, polyethylene-based copolymers [Mehta and Monteiro, 2006], additional studies are recommended to examine the effects of this type of admixtures on dielectric properties.

The combined effect of fly ash and water reducer is observed in a paired comparison between groups FW and C (see Table 4.10). Water content in the FW group was reduced from 300 pcy to 275 pcy compared to C group. Cementitious material was also reduced in order to maintain the w/c ratio. Additionally, 20% of the cement mass was replaced with fly ash. As a result, percentages of paste volume in the FW mixtures were 1.2% and

1.7% lower for mixtures of w/c 0.45 and 0.50 respectively.

Table 4.10 Paired Comparison for Water Reducing Admixture and Fly Ash Effects

Group FW Differences to group C; frequency= 1kHz Time = 30 min							
w/c	% ε_r	% fc28	% air	% paste	% wtr	% Cmt	% FA(v)
0.45	18.9%	7.6%	-1.5	-1.2	-1.2	-3.2	3.2
0.50	16.8%	-5.3%	-0.4	-1.7	-1.5	-3.0	2.8

Use of WRA and fly ash may affect the apparent dielectric constant due to variations in thickness of the water molecule layer surrounding cementitious materials associated with differences in water and cement content. Capacitance will also be affected by differences in the percentage of paste volume and variations in the properties of the intersurface chemistry between water and cementitious materials effects due to fly ash and WRA, as shown in the previous comparisons.

The reduction in percentage of paste present in the mixture will tend to reduce the apparent dielectric constant values. The presence of both fly ash and WRA were found to have strong effects increasing the dielectric properties, however. This is evident in the results obtained where the ε_r value for FW45 is 18.9% higher than that for C45, and the FW50 value is 16.8% higher that for C50. As noted above, the difference between FW50 and C50 is also suspected to be a combined result, of several factors, including the HRWR effects. The variations on the apparent dielectric constant due to surface chemistry effects of fly ash and water reducing agent seem to be more significant than those due to paste volume variations.

4.7 Correlations

Correlation factors between the ε_r measurements and w/c and volumes of paste, cement, fly ash and air in the mixtures were analyzed at 10 and 100 kHz. (see Table 4.11 and Table 4.12)

Examining Table 4.12, the correlation between ε_r and both w/c and compressive strength at 28 days is very strong (0.82). Many of the correlations are based on physical relationships and are not informative. For example, the correlation between percentage of volume of cement and w/c (-0.84) and percentage volume of fly ash and w/c (0.31) are meaningless. Since percentage of cement, percentage of paste, percentage of water, and percentage of fly ash are all physically correlated, these were not considered in the next analysis. Since compressive strength specimens were not taken for the cement only mixtures tested at 100 kHz, that data is not considered also. Additional research is suggested to find the correlation between compressive strength and ε_r for mixtures with cement only at this frequencies.

The correlation matrix was based on data from the different groups. Some of the apparent dielectric constant values were not only affected by the differences in components volumes, but also by the surface chemistry effects of fly ash and water reducing admixture. Therefore, for the data available, a paired comparison gave a better understanding than the correlation matrix on the supplementary cementitious material and the water reducing admixture effects on the apparent dielectric constant.

Table 4.11 Correlation Table, 10 kHz

Correlation Table, frequency= 10 kHz								
	ε_r	*fc*	% air	% paste	% wtr	% Cmt	% FA(v)	w/c
er	1.00							
fc28	0.49	1.00						
% air	-0.60	-0.72	1.00					
%paste	0.72	0.07	-0.40	1.00				
%wtr	0.12	-0.71	0.29	0.62	1.00			
%Cmt	0.43	0.78	-0.26	0.19	-0.46	1.00		
%FA(v)	0.18	-0.48	-0.23	0.50	0.68	-0.72	1.00	
w/c	-0.66	-0.87	0.67	-0.45	0.40	-0.84	0.31	1.00
Notes: No data for group C was considered since data only for C50 was available %wtr = percentage volume of water to total volume %Cmt = percentage volume of cement to total volume %FA(v) = percentage volume of fly ash to total volume								

Table 4.12 Correlation Table, 100 kHz

Correlation Table, frequency= 100 kHz								
	ε_r	*fc*	% air	% paste	% wtr	% Cmt	% FA(v)	w/c
er	1.00							
fc28	**0.82**	1.00						
% air	-0.71	-0.72	1.00					
%paste	0.37	0.07	-0.40	1.00				
%wtr	-0.38	-0.71	0.29	0.62	1.00			
%Cmt	0.63	0.78	-0.26	0.19	-0.46	1.00		
%FA(v)	-0.16	-0.48	-0.23	0.50	0.68	-0.72	1.00	
w/c	**-0.82**	-0.87	0.67	-0.45	0.40	-0.84	0.31	1.00
Notes: No data for group C was considered since data only for C50 was available %wtr = percentage volume of water to total volume %Cmt = percentage volume of cement to total volume %FA(v) = percentage volume of fly ash to total volume								

4.8 Strength

Figure 4.19 shows the relationship between compressive strength and apparent dielectric constant values by similar mixtures. Values measured at 100 kHz were used for all groups except for group C where values at 1 kHz were used. The apparent dielectric

values at 1 kHz for group C were very similar to the few data obtained at 100 kHz indicating the lower frequency data for group C could be included for this comparison. Air content measurements are shown for each data point.

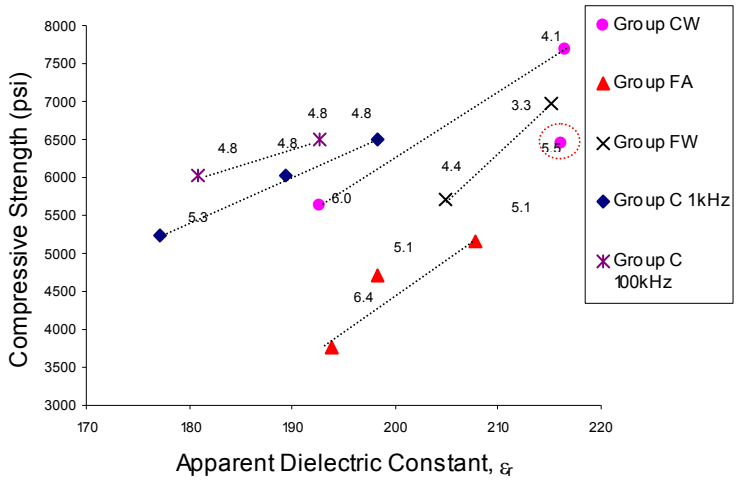


Figure 4.19 Compressive Strength and Apparent Dielectric Constant, per Group; 100 kHz

The purpose of these graphs is to show the consistent relationship between ε_r and *fc* when compared by groups. As stated previously, values for all data are significantly varied. Comparing data by group shows a more consistent relationship between εr and *fc*. Except for CW data the slope of the relationship is similar for all mixtures. One value in the CW group, corresponding to CW50, appears to not fit the trend seen for the other data. It is not known why this data point does not fit the other observations and additional study is recommended. Similarly to what required for compressive strength testing, where two or more samples are tested to identify any anomalous results, it is recommended that this test is done using two test devices simultaneously to confirm validity of the data

obtained. Figure 4.19 suggests that a relationship could be found between ε_r and *fc* for a given type of mixture, however.

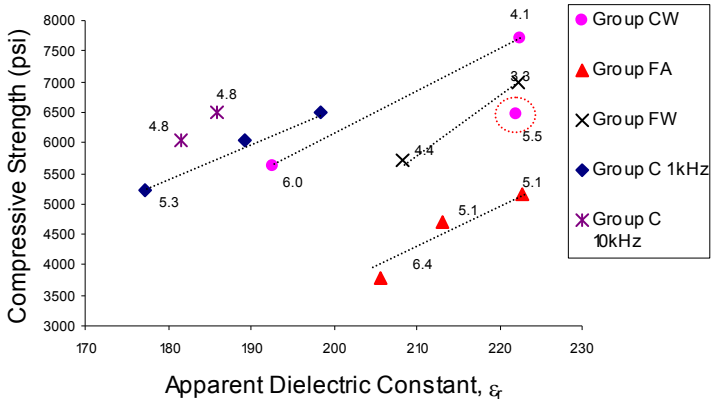


Figure 4.20 Compressive Strength and Apparent Dielectric Constant, per Group; 10 kHz

Correlation values calculated at 10 kHz between ε_r and w/c (-0.66) and ε_r and compressive strength (0.49) were lower for data at 100 kHz. Figure 4.20 shows, however, that comparing data by groups at 10 kHz a consistent relationship between ε_r and *fc* existed as well. This supports the idea that 10 kHz data is valid for comparisons between mixtures.

Figure 4.21 shows the same data, with the cement only and the fly ash groups. Connecting data for a same *w/c* with and without fly ash, another set of approximately parallel lines may be seen. A further study could confirm if the percentage of fly ash used could be determined using ε_r for mixtures with the same w/c.

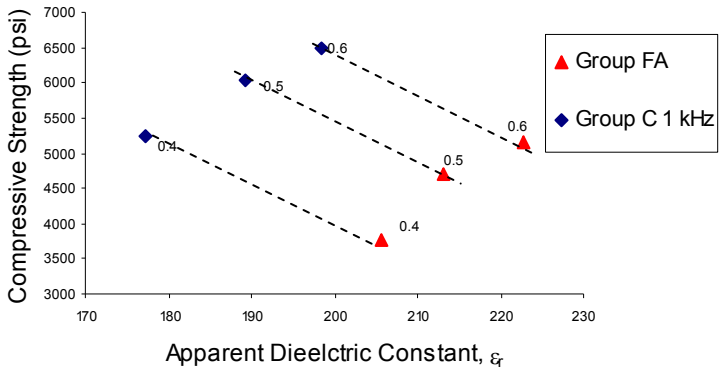


Figure 4.21 Compressive Strength and Apparent Dielectric Constant Fly Ash Effect; 10 kHz

From the data obtained, ε_r is affected by mixture composition. For a given group of mixtures with similar characteristics, ε_r could be used to identify important differences in engineering properties.

Additional investigation should be done to confirm these two findings. This device could not only be useful for development as a standard quality control test, but could be used for fundamental studies to help understand the effects of given admixtures in the cement hydration process.

Further analysis was conducted in order to determine if ε_r could be used in combination with another parameter to identify strength variations in a similar group of mixtures. Air content was found to have a significant correlation to both compressive strength (-0.72) and to ε_r (-0.71). It is recognized that compressive strength and air content are physically correlated since an increase in air will, in general reduce strength. Air has a low apparent

dielectric constant (ε_a=1), so from a volumetric point of view, it may be reasonable to think that a higher air content will result in lower apparent dielectric constant of a mixture, although this is highly speculative and more research is suggested. Figure 4.22 indicates that the combined use of percentage of air content and ε_r to determine compressive strength of a mixture looks promising.

Results for multiple regressions presented high R^2 values but analysis of error terms indicate excessive variation in data. This is consistent with the finding that analysis must be conducted on similar mixtures. No regressions were done within the groups of similar mixtures since three data points were available at most.

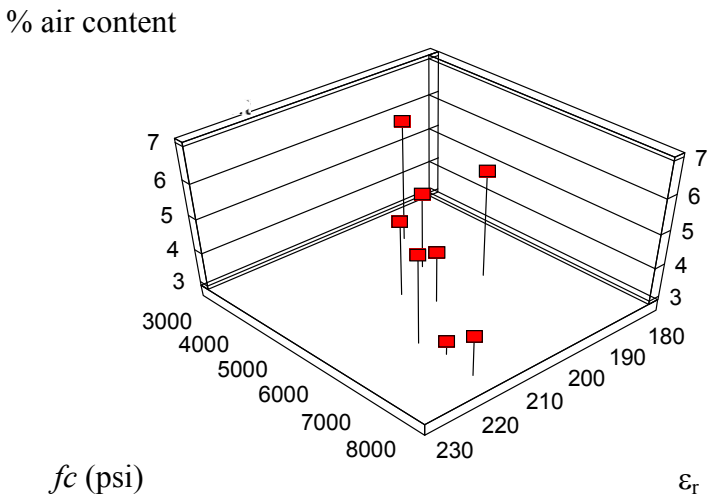


Figure 4.22 Apparent Dielectric Constant, Air Content, and Compressive Strength; 100 kHz

4.9 Field Trial Feasibility Study

Based on the findings of this study, a feasibility study was conducted in the field on two

separate but similar commercial mixtures. The purpose of the study was to see if the testing device could identify addition of water to a batch similar to that which might be experienced in the field. Water equivalent to 10 pcy and 20 pcy was added to the original batches. The dielectric properties were measured at different frequencies between 1 to 1000 kHz inclusive. Both admixtures contained fly ash and conventional water reducing admixture, and both were air entrained. The mixtures were produced at a commercial ready-mix concrete plant.

The two mixture batches had different w/c and different cementitious material. The fly ash contents were approximately the same for both mixtures, 22 % of the total cementitious material for the FWT40 and 24 % for FWT50. Details are provided in Table 4.13.

The variations in each mixture were obtained by the addition of the equivalent of 10 pcy and 20 pcy of water. This addition was done approximately 30 minutes after the initial batching. This addition has an effect on the paste volume and the w/c content of the mixture.

Table 4.13 Field Trial Mixture Proportions

Mixtures Proportions by Mass							
	Units	FWT40	FWT40_10	FWT40_20	FWT50	FWT50_10	FWT50_20
Cement	pcy	529	529	529	449	449	449
Fly Ash	pcy	145	145	145	144	144	144
Water	pcy	284	294	304	283	293	303
Sand	pcy	1080	1080	1080	1150	1150	1150
Rock	pcy	1800	1800	1800	1796	1796	1796
Water Reducer	oz/cwt	2.4	2.4	2.4	2.4	2.4	2.4
High Range Water Reducer	oz/cwt						
Air Entraining Admixture	oz/cy	6	6	6	7	7	7
Volume Percentages							
	Units	FWT40	FWT40_10	FWT40_20	FWT50	FWT50_10	FWT50_20
Cement	%	10.0	10.0	10.0	8.5	8.5	8.5
Fly Ash	%	3.8	3.8	3.8	3.7	3.7	3.7
Water	%	17.7	18.3	18.9	17.7	18.3	18.9
Sand	%	24.3	24.3	24.3	25.9	25.9	25.9
Rock	%	40.2	40.2	40.2	40.1	40.1	40.1
Air Vol *	%	4.1	3.5	2.9	4.2	3.6	3.0
Paste Volume	%	31.4	32.0	32.6	29.9	30.5	31.1
w/c		0.42	0.44	0.45	0.48	0.49	0.51
Compressive Strenghts Results							
fc 7 days	psi	3100	2600	2800	2000	2200	1900
ε_r at 10 kHz		191	205	208	234	236	267

"pcy" is pounds per cubic yard; "oz/cwt" is fluid ounces per hundred pounds of cementitious material; "oz/cy" is fluid ounces per cubic yard
* Air content was calculated using the volumetric method
Volumes of water reducer and high range water reducer are negligible
GROUPS FWT Field Trial Mixtures with Fly Ash and WRA
Legend FWT_w/c*100_+pcy.
Example FWT40_20: Group = FWT, w/c = 0.40, water added = equivalent to 20 pcy

The values of 10 pcy and 20 pcy were selected based on common industry rules of thumb. An addition of 10 pcy of water will typically result in an additional 1 inch of slump; adding 20 pcy of water typically results in an additional 2 inches of slump. The relationship is very approximate and only approximately linear in a small range. Since slump tolerances are typically specified as ± 1 in [ASTM C94, 2006] adding 10 and 20 pcy of water should provide a typical range of expected variation in a commercial mixture. After addition of water, the batch was remixed by hand and tested. Adding the water at 30 minutes is reasonable and is relevant to the use of the device for quality

control since late addition of water is normally considered a problem in construction.

The results of the field trials showed a high correlation coefficient (r = 0.98) showing a strong relationship between w/c and apparent dielectric constant measured at 10 kHz. Figure 4.23 shows a reasonably linear relationship between w/c and ε_r due to the addition of water (r^2=0.96). The correlation between w/c and apparent dielectric constant are not consistent with what observed in the previous phase, however. The slope of the relationship is opposite to that found previously. Similarly, the relationship between strength results at 7 days and the apparent dielectric constant (r^2=0.87), Figure 4.24, is also inverted. These results, both for w/c and compressive strength to apparent dielectric constant, were unexpected.

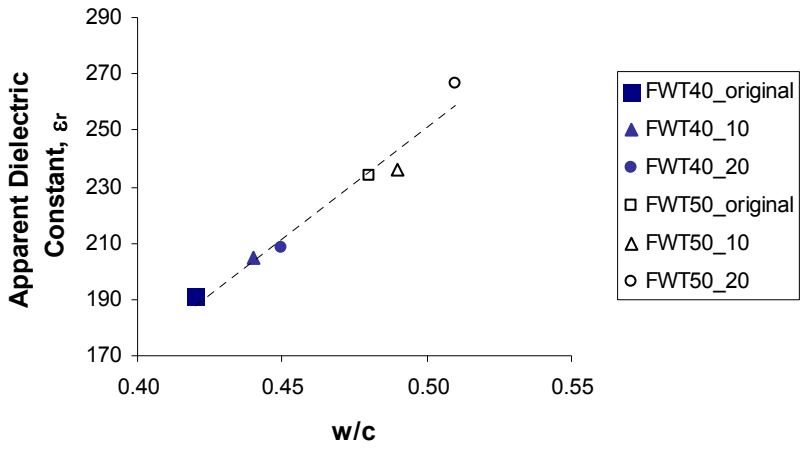


Figure 4.23 Apparent Dielectric Constant and Water Cement Ratio based on Field Testing

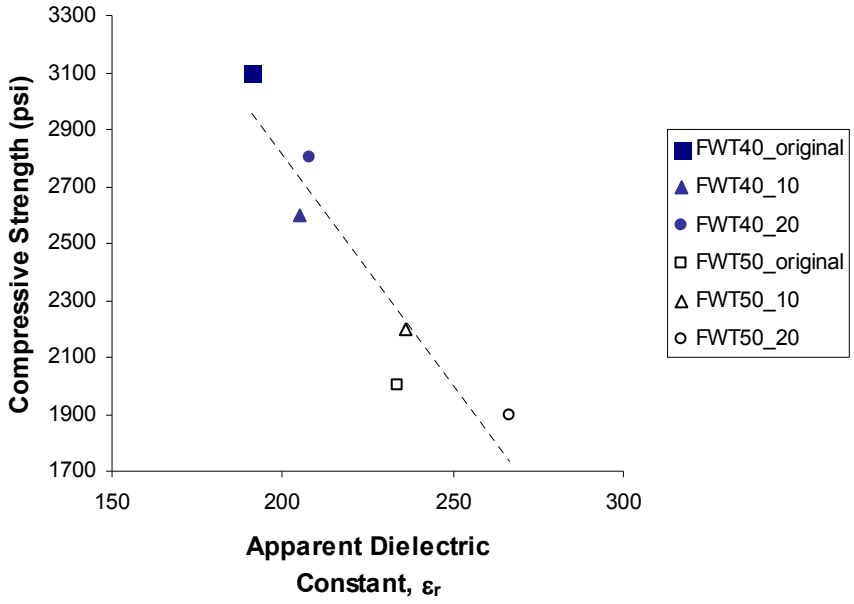


Figure 4.24 Apparent Dielectric Constant vs. Compressive Strength based on Field Testing

There is not full understanding for the reversal in slope observed. The addition of water would affect the volume of paste. From the observations in the previous testing, it appeared that a higher volume of paste could result on a higher apparent dielectric constant values. In the lab mixtures, w/c ratio was modified varying the cement content. A higher volume of paste was then related with a higher volume of cement and therefore lower w/c. In this case, the water volume was modified and a higher volume of paste was related with higher w/c ratios and lower strengths.

The time at which additional water is added could be another factor affecting the dielectric behavior. If water is added after the induction period has started, a different distribution of free and capillary water volumes may result than if water was added

during the initial batching. The different water stages are thought to affect the apparent dielectric constant. Additional studies adding water at different times are recommended to have a better understanding of the materials behavior.

The strong relationship between added water, reduction in strength, and change in apparent dielectric constant indicates the device is potentially useful. The resolution appears reasonable, given the needs of quality control or acceptance testing. Mixtures with similar apparent dielectric had similar compressive strength (see Figure 4.24), which although it is based on results at 7 days and not 28 days, it appears to be within the tolerance for acceptance criteria. More significant compressive strength differences were detected by the apparent dielectric constant results. Results confirm that the device could be used in order to identify changes for a previously calibrated mixture.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. The device used in the feasibility studies, with slight modifications to improve reproducibility and reduce errors due to short circuits, was found to be potentially useful in identifying changes in mixtures which would cause changes in compressive strength among similar mixtures based on changes in apparent dielectric constant.

2. Apparent dielectric constant values vary with time. The variations between 30 and 60 minutes remain below 2% and are small compared to variations due difference in the mixture compositions. This behavior is convenient for the considering the methodology as a quality control method at field since most concrete placement is done within an hour after batching.

3. The use of admixtures and supplementary cementitious materials in a mixture affects its dielectric properties at very early ages. In this study, fly ash and water reducing agent increased apparent dielectric constant values. Besides its effects in volumes of paste, volume of water and volume of cement, the effects on the surface interface between water and cementitious materials appears to affect dielectric properties. The variations on the apparent dielectric constant due to surface chemistry effects of fly ash and water reducing agent seem to be more significant than those due to paste volume variations.

4. The apparent dielectric constant may not be used by itself to identify water cement ratio or the compressive strength in general. When considering a set of mixtures with

similar characteristics, the apparent dielectric constant appears to be promising for detecting changes in the mixture associated with changes in compressive strength.

RECOMMENDATIONS

1. Additional studies are necessary considering the combined use of apparent dielectric constant and air content to predict concrete compressive strength.

2. Additional investigation is necessary to determine the differences between initial water and added water on dielectric properties. If a relationship is found between the apparent dielectric constant of concrete and the content of free water it could be important finding with implications for both compressive strength and durability.

3. Changes in apparent dielectric constant with frequency for mixtures containing fly ash showed a different behavior than the other groups. Analysis of apparent dielectric constant spectrum using this device could be useful for understanding the effects of supplementary cementitious materials including Class F and Class C fly ash, slag, and silica fume, on cement hydration.

4. Additional investigation is necessary to study the effects of air entraining admixture (AEA) and air content on the dielectric properties of concrete mixtures. The use of AEA in combination with other chemical and mineral admixtures is also necessary in order to have a complete understanding of the capabilities and limitations of this methodology.

5. Limitations in data prevented determination of High Range Water Reducing

admixture effects on dielectric properties. Additional research considering the different types of HRWR should be conducted. Combined effects on the electrical properties, particularly when used in combination with other admixtures as WRA is needed.

CHAPTER 6. LIST OF REFERENCES

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APPENDICES

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
AIR	A	0.00		1	T1	6	0.118	1.9	15.6	2	1	28.9	0.8	NA
AIR	A	0.00		3	T1	6	0.105	1.9	15.6	2	1	28.9	0.8	NA
AIR	A	0.00		5	T1	6	0.104	1.9	15.6	2	1	28.9	0.8	NA
AIR	A	0.00		10	T1	5	0.089	1.9	15.6	2	1	28.9	0.7	NA
AIR	A	0.00		30	T1	5	0.055	1.9	15.6	2	1	28.9	0.7	NA
AIR	A	0.00		50	T1	5	0.034	1.9	15.6	2	1	28.9	0.7	NA
AIR	A	0.00		100	T1	5	0.016	1.9	15.6	2	1	28.9	0.7	NA
AIR	A	0.00		200	T1	5	-0.001	1.9	15.6	2	1	28.9	0.7	NA
AIR	A	0.00		500	T1	5	0.001	1.9	15.6	2	1	28.9	0.7	NA
AIR	A	0.00		1000	T1	5	-0.002	1.9	15.6	2	1	28.9	0.7	NA
AIR	A	0.00		1	T1	20	0.418	1.9	15.6	2	2	28.9	2.6	NA
AIR	A	0.00		3	T1	15	0.368	1.9	15.6	2	2	28.9	2.0	NA
AIR	A	0.00		5	T1	14	0.335	1.9	15.6	2	2	28.9	1.8	NA
AIR	A	0.00		10	T1	12	0.258	1.9	15.6	2	2	28.9	1.6	NA
AIR	A	0.00		30	T1	11	0.112	1.9	15.6	2	2	28.9	1.4	NA
AIR	A	0.00		50	T1	11	0.060	1.9	15.6	2	2	28.9	1.5	NA
AIR	A	0.00		100	T1	11	0.013	1.9	15.6	2	2	28.9	1.5	NA
AIR	A	0.00		200	T1	11	-0.002	1.9	15.6	2	2	28.9	1.4	NA
AIR	A	0.00		500	T1	11	-0.003	1.9	15.6	2	2	28.9	1.4	NA
AIR	A	0.00		1000	T1	11	0.000	1.9	15.6	2	2	28.9	1.4	NA
AIR	A	0.00		1	T1	20	0.425	1.9	15.6	2	1	28.9	2.7	NA
AIR	A	0.00		3	T1	16	0.380	1.9	15.6	2	1	28.9	2.1	NA
AIR	A	0.00		5	T1	14	0.341	1.9	15.6	2	1	28.9	1.8	NA
AIR	A	0.00		10	T1	12	0.267	1.9	15.6	2	1	28.9	1.6	NA
AIR	A	0.00		30	T1	11	0.138	1.9	15.6	2	1	28.9	1.5	NA
AIR	A	0.00		50	T1	11	0.082	1.9	15.6	2	1	28.9	1.5	NA
AIR	A	0.00		100	T1	11	0.035	1.9	15.6	2	1	28.9	1.4	NA
AIR	A	0.00		200	T1	11	0.005	1.9	15.6	2	1	28.9	1.5	NA
AIR	A	0.00		500	T1	11	0.005	1.9	15.6	2	1	28.9	1.5	NA
AIR	A	0.00		1000	T1	11	0.003	1.9	15.6	2	1	28.9	1.4	NA
C45	C	0.45	36	1	T1	1436	0.088	1.9	15.6	1	1	27.4	198.3	30
C45	C	0.45	48	1	T1	1419	0.065	1.9	15.6	1	1	27.4	196.0	45
C45	C	0.45	55	1	T1	1398	0.060	1.9	15.6	2	1	27.4	193.1	60
C45	C	0.45	57	10	T1	1346	0.025	1.9	15.6	2	1	27.4	185.9	60
C45	C	0.45	58	100	T1	1395	0.073	1.9	15.6	2	1	27.4	192.7	60
C45	C	0.45	59	1000	T1	1342	0.012	1.9	15.6	2	1	27.4	185.4	60
C50	C	0.50	19	1	T1	1460	0.166	1.9	15.6	1	1	28	197.3	15
C50	C	0.50	34	1	T1	1401	0.093	1.9	15.6	2	1	28	189.4	30
C50	C	0.50	34	10	T1	1344	0.031	1.9	15.6	2	1	28	181.7	30
C50	C	0.50	34	100	T1	1338	0.010	1.9	15.6	2	1	28	180.8	30
C50	C	0.50	35	1000	T1	1405	0.045	1.9	15.6	2	1	28	189.9	30
C50	C	0.50	47	1	T1	1380	0.050	1.9	15.6	2	1	28	186.5	45
C50	C	0.50	47	10	T1	1341	0.024	1.9	15.6	2	1	28	181.3	45
C50	C	0.50	47	100	T1	1336	0.009	1.9	15.6	2	1	28	180.6	45
C50	C	0.50	47	1000	T1	1407	0.045	1.9	15.6	2	1	28	190.2	45
C50	C	0.50	63	1	T1	1377	0.030	1.9	15.6	2	1	28	186.1	60
C50	C	0.50	63	10	T1	1340	0.020	1.9	15.6	2	1	28	181.1	60

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
C50	C	0.50	64	100	T1	1335	0.009	1.9	15.6	2	1	28	180.4	60
C50	C	0.50	64	1000	T1	1401	0.044	1.9	15.6	2	1	28	189.4	60
C60	C	0.60	32	1	T1	1302	0.005	1.9	15.6	1	1	27.8	177.2	30
C60	C	0.60	47	1	T1	1308	0.006	1.9	15.6	1	1	27.8	178.1	45
C60	C	0.60	68	1	T1	1308	0.005	1.9	15.6	1	1	27.8	178.1	60
C60	C	0.60	77	1	T1	1309	0.005	1.9	15.6	1	1	27.8	178.2	75
Cm45	Cm	0.45	10	1	T1	2746	0.814	1.9	15.6	2	1	26.29	395.3	<15
Cm45	Cm	0.45	10	3	T1	2179	0.540	1.9	15.6	2	1	26.29	313.7	<15
Cm45	Cm	0.45	10	5	T1	1932	0.444	1.9	15.6	2	1	26.29	278.1	<15
Cm45	Cm	0.45	10	10	T1	1746	0.294	1.9	15.6	2	1	26.29	251.3	<15
Cm45	Cm	0.45	10	30	T1	1634	0.142	1.9	15.6	2	1	26.29	235.2	<15
Cm45	Cm	0.45	10	50	T1	1609	0.113	1.9	15.6	2	1	26.29	231.6	<15
Cm45	Cm	0.45	10	100	T1	1625	0.062	1.9	15.6	2	1	26.29	233.9	<15
Cm45	Cm	0.45	10	300	T1	1618	0.063	1.9	15.6	2	1	26.29	232.9	<15
Cm45	Cm	0.45	10	500	T1	1595	0.080	1.9	15.6	2	1	26.29	229.6	<15
Cm45	Cm	0.45	10	1000	T1	1611	0.128	1.9	15.6	2	1	26.29	231.9	<15
Cm45	Cm	0.45	10	1	T1	2700	0.824	1.9	15.6	2	2	26.29	388.7	<15
Cm45	Cm	0.45	10	3	T1	2189	0.520	1.9	15.6	2	2	26.29	315.1	<15
Cm45	Cm	0.45	10	5	T1	1917	0.430	1.9	15.6	2	2	26.29	276.0	<15
Cm45	Cm	0.45	10	10	T1	1726	0.259	1.9	15.6	2	2	26.29	248.5	<15
Cm45	Cm	0.45	10	30	T1	1614	0.124	1.9	15.6	2	2	26.29	232.3	<15
Cm45	Cm	0.45	10	50	T1	1572	0.069	1.9	15.6	2	2	26.29	226.3	<15
Cm45	Cm	0.45	10	100	T1	1554	0.060	1.9	15.6	2	2	26.29	223.7	<15
Cm45	Cm	0.45	10	300	T1	1734	0.047	1.9	15.6	2	2	26.29	249.6	<15
Cm45	Cm	0.45	10	1000	T1	1739	0.133	1.9	15.6	2	2	26.29	250.3	<15
Cm45	Cm	0.45	15	1	T1	2504	0.869	1.9	15.6	2	1	26.29	360.5	15
Cm45	Cm	0.45	15	3	T1	2025	0.526	1.9	15.6	2	1	26.29	291.5	15
Cm45	Cm	0.45	15	5	T1	1834	0.409	1.9	15.6	2	1	26.29	264.0	15
Cm45	Cm	0.45	15	10	T1	1701	0.255	1.9	15.6	2	1	26.29	244.9	15
Cm45	Cm	0.45	15	30	T1	1621	0.120	1.9	15.6	2	1	26.29	233.4	15
Cm45	Cm	0.45	15	50	T1	1603	0.097	1.9	15.6	2	1	26.29	230.8	15
Cm45	Cm	0.45	15	100	T1	1623	0.052	1.9	15.6	2	1	26.29	233.6	15
Cm45	Cm	0.45	15	300	T1	1622	0.056	1.9	15.6	2	1	26.29	233.5	15
Cm45	Cm	0.45	15	500	T1	1602	0.070	1.9	15.6	2	1	26.29	230.6	15
Cm45	Cm	0.45	15	1000	T1	1628	0.114	1.9	15.6	2	1	26.29	234.4	15
Cm45	Cm	0.45	15	1	T1	2461	0.885	1.9	15.6	2	2	26.29	354.3	15
Cm45	Cm	0.45	15	3	T1	2038	0.506	1.9	15.6	2	2	26.29	293.4	15
Cm45	Cm	0.45	15	5	T1	1831	0.394	1.9	15.6	2	2	26.29	263.6	15
Cm45	Cm	0.45	15	10	T1	1690	0.222	1.9	15.6	2	2	26.29	243.3	15
Cm45	Cm	0.45	15	30	T1	1605	0.106	1.9	15.6	2	2	26.29	231.0	15
Cm45	Cm	0.45	15	50	T1	1567	0.056	1.9	15.6	2	2	26.29	225.6	15
Cm45	Cm	0.45	15	100	T1	1552	0.054	1.9	15.6	2	2	26.29	223.4	15
Cm45	Cm	0.45	15	300	T1	1733	0.048	1.9	15.6	2	2	26.29	249.5	15
Cm45	Cm	0.45	15	1000	T1	1742	0.141	1.9	15.6	2	2	26.29	250.8	15
Cm45	Cm	0.45	30	1	T1	2148	1.105	1.9	15.6	2	1	26.29	309.2	30
Cm45	Cm	0.45	30	3	T1	1832	0.538	1.9	15.6	2	1	26.29	263.7	30
Cm45	Cm	0.45	30	5	T1	1726	0.378	1.9	15.6	2	1	26.29	248.5	30

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
Cm45	Cm	0.45	30	10	T1	1656	0.219	1.9	15.6	2	1	26.29	238.4	30
Cm45	Cm	0.45	30	30	T1	1607	0.102	1.9	15.6	2	1	26.29	231.3	30
Cm45	Cm	0.45	30	50	T1	1594	0.085	1.9	15.6	2	1	26.29	229.5	30
Cm45	Cm	0.45	30	100	T1	1615	0.045	1.9	15.6	2	1	26.29	232.5	30
Cm45	Cm	0.45	30	300	T1	1615	0.049	1.9	15.6	2	1	26.29	232.5	30
Cm45	Cm	0.45	30	500	T1	1598	0.062	1.9	15.6	2	1	26.29	230.0	30
Cm45	Cm	0.45	30	1000	T1	1631	0.099	1.9	15.6	2	1	26.29	234.8	30
Cm45	Cm	0.45	30	1	T1	2122	1.126	1.9	15.6	2	2	26.29	305.5	30
Cm45	Cm	0.45	30	3	T1	1842	0.523	1.9	15.6	2	2	26.29	265.2	30
Cm45	Cm	0.45	30	5	T1	1724	0.367	1.9	15.6	2	2	26.29	248.2	30
Cm45	Cm	0.45	30	10	T1	1647	0.187	1.9	15.6	2	2	26.29	237.1	30
Cm45	Cm	0.45	30	30	T1	1592	0.089	1.9	15.6	2	2	26.29	229.2	30
Cm45	Cm	0.45	30	50	T1	1558	0.045	1.9	15.6	2	2	26.29	224.3	30
Cm45	Cm	0.45	30	100	T1	1545	0.047	1.9	15.6	2	2	26.29	222.4	30
Cm45	Cm	0.45	30	300	T1	1725	0.039	1.9	15.6	2	2	26.29	248.3	30
Cm45	Cm	0.45	30	1000	T1	1746	0.124	1.9	15.6	2	2	26.29	251.3	30
Cm45	Cm	0.45	45	1	T1	1784	1.308	1.9	15.6	2	1	26.29	256.8	45
Cm45	Cm	0.45	45	3	T1	1678	0.504	1.9	15.6	2	1	26.29	241.6	45
Cm45	Cm	0.45	45	5	T1	1667	0.308	1.9	15.6	2	1	26.29	240.0	45
Cm45	Cm	0.45	45	10	T1	1614	0.181	1.9	15.6	2	1	26.29	232.3	45
Cm45	Cm	0.45	45	30	T1	1582	0.087	1.9	15.6	2	1	26.29	227.7	45
Cm45	Cm	0.45	45	50	T1	1572	0.074	1.9	15.6	2	1	26.29	226.3	45
Cm45	Cm	0.45	45	100	T1	1595	0.037	1.9	15.6	2	1	26.29	229.6	45
Cm45	Cm	0.45	45	300	T1	1604	0.041	1.9	15.6	2	1	26.29	230.9	45
Cm45	Cm	0.45	45	500	T1	1591	0.052	1.9	15.6	2	1	26.29	229.0	45
Cm45	Cm	0.45	45	1000	T1	1628	0.089	1.9	15.6	2	1	26.29	234.4	45
Cm45	Cm	0.45	45	1	T1	1722	1.312	1.9	15.6	2	2	26.29	247.9	45
Cm45	Cm	0.45	45	3	T1	1691	0.491	1.9	15.6	2	2	26.29	243.4	45
Cm45	Cm	0.45	45	5	T1	1642	0.320	1.9	15.6	2	2	26.29	236.4	45
Cm45	Cm	0.45	45	10	T1	1604	0.152	1.9	15.6	2	2	26.29	230.9	45
Cm45	Cm	0.45	45	30	T1	1567	0.074	1.9	15.6	2	2	26.29	225.6	45
Cm45	Cm	0.45	45	50	T1	1535	0.033	1.9	15.6	2	2	26.29	221.0	45
Cm45	Cm	0.45	45	100	T1	1525	0.038	1.9	15.6	2	2	26.29	219.5	45
Cm45	Cm	0.45	45	300	T1	1712	0.032	1.9	15.6	2	2	26.29	246.5	45
Cm45	Cm	0.45	45	1000	T1	1744	0.119	1.9	15.6	2	2	26.29	251.1	45
Cm45	Cm	0.45	60	1	T1	1693	1.399	1.9	15.6	2	1	26.29	243.7	60
Cm45	Cm	0.45	60	3	T1	1636	0.510	1.9	15.6	2	1	26.29	235.5	60
Cm45	Cm	0.45	60	5	T1	1638	0.306	1.9	15.6	2	1	26.29	235.8	60
Cm45	Cm	0.45	60	10	T1	1595	0.176	1.9	15.6	2	1	26.29	229.6	60
Cm45	Cm	0.45	60	30	T1	1569	0.083	1.9	15.6	2	1	26.29	225.9	60
Cm45	Cm	0.45	60	50	T1	1561	0.071	1.9	15.6	2	1	26.29	224.7	60
Cm45	Cm	0.45	60	100	T1	1586	0.034	1.9	15.6	2	1	26.29	228.3	60
Cm45	Cm	0.45	60	300	T1	1598	0.038	1.9	15.6	2	1	26.29	230.0	60
Cm45	Cm	0.45	60	500	T1	1587	0.050	1.9	15.6	2	1	26.29	228.5	60
Cm45	Cm	0.45	60	1000	T1	1628	0.088	1.9	15.6	2	1	26.29	234.4	60
Cm45	Cm	0.45	60	1	T1	1698	1.400	1.9	15.6	2	2	26.29	244.4	60
Cm45	Cm	0.45	60	3	T1	1655	0.500	1.9	15.6	2	2	26.29	238.2	60

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
Cm45	Cm	0.45	60	5	T1	1618	0.321	1.9	15.6	2	2	26.29	232.9	60
Cm45	Cm	0.45	60	10	T1	1588	0.150	1.9	15.6	2	2	26.29	228.6	60
Cm45	Cm	0.45	60	30	T1	1556	0.071	1.9	15.6	2	2	26.29	224.0	60
Cm45	Cm	0.45	60	50	T1	1525	0.031	1.9	15.6	2	2	26.29	219.5	60
Cm45	Cm	0.45	60	100	T1	1517	0.036	1.9	15.6	2	2	26.29	218.4	60
Cm45	Cm	0.45	60	300	T1	1707	0.028	1.9	15.6	2	2	26.29	245.7	60
Cm45	Cm	0.45	60	1000	T1	1749	0.111	1.9	15.6	2	2	26.29	251.8	60
Cm50	Cm	0.50	8	1	T1	1785	0.324	1.9	15.6	2	1	25.29	267.1	<15
Cm50	Cm	0.50	8	3	T1	1668	0.150	1.9	15.6	2	1	25.29	249.6	<15
Cm50	Cm	0.50	8	5	T1	1661	0.097	1.9	15.6	2	1	25.29	248.6	<15
Cm50	Cm	0.50	8	10	T1	1608	0.078	1.9	15.6	2	1	25.29	240.6	<15
Cm50	Cm	0.50	8	30	T1	1557	0.065	1.9	15.6	2	1	25.29	233.0	<15
Cm50	Cm	0.50	8	50	T1	1539	0.067	1.9	15.6	2	1	25.29	230.3	<15
Cm50	Cm	0.50	8	100	T1	1549	0.042	1.9	15.6	2	1	25.29	231.8	<15
Cm50	Cm	0.50	8	300	T1	1543	0.051	1.9	15.6	2	1	25.29	230.9	<15
Cm50	Cm	0.50	8	500	T1	1524	0.063	1.9	15.6	2	1	25.29	228.1	<15
Cm50	Cm	0.50	8	1000	T1	1543	0.101	1.9	15.6	2	1	25.29	230.9	<15
Cm50	Cm	0.50	11	1	T1	1745	0.297	1.9	15.6	2	2	25.29	261.1	<15
Cm50	Cm	0.50	11	3	T1	1668	0.134	1.9	15.6	2	2	25.29	249.6	<15
Cm50	Cm	0.50	11	5	T1	1635	0.101	1.9	15.6	2	2	25.29	244.7	<15
Cm50	Cm	0.50	11	10	T1	1599	0.047	1.9	15.6	2	2	25.29	239.3	<15
Cm50	Cm	0.50	11	30	T1	1546	0.053	1.9	15.6	2	2	25.29	231.4	<15
Cm50	Cm	0.50	11	50	T1	1502	0.030	1.9	15.6	2	2	25.29	224.8	<15
Cm50	Cm	0.50	11	100	T1	1484	0.049	1.9	15.6	2	2	25.29	222.1	<15
Cm50	Cm	0.50	11	300	T1	1635	0.063	1.9	15.6	2	2	25.29	244.7	<15
Cm50	Cm	0.50	11	1000	T1	1624	0.193	1.9	15.6	2	2	25.29	243.0	<15
Cm50	Cm	0.50	15	1	T1	1701	0.290	1.9	15.6	2	1	25.29	254.6	15
Cm50	Cm	0.50	15	3	T1	1642	0.128	1.9	15.6	2	1	25.29	245.7	15
Cm50	Cm	0.50	15	5	T1	1644	0.081	1.9	15.6	2	1	25.29	246.0	15
Cm50	Cm	0.50	15	10	T1	1595	0.068	1.9	15.6	2	1	25.29	238.7	15
Cm50	Cm	0.50	15	30	T1	1548	0.059	1.9	15.6	2	1	25.29	231.7	15
Cm50	Cm	0.50	15	50	T1	1532	0.062	1.9	15.6	2	1	25.29	229.3	15
Cm50	Cm	0.50	15	100	T1	1545	0.037	1.9	15.6	2	1	25.29	231.2	15
Cm50	Cm	0.50	15	300	T1	1545	0.047	1.9	15.6	2	1	25.29	231.2	15
Cm50	Cm	0.50	15	500	T1	1528	0.060	1.9	15.6	2	1	25.29	228.7	15
Cm50	Cm	0.50	15	1000	T1	1549	0.099	1.9	15.6	2	1	25.29	231.8	15
Cm50	Cm	0.50	15	1	T1	1690	0.286	1.9	15.6	2	2	25.29	252.9	15
Cm50	Cm	0.50	15	3	T1	1645	0.120	1.9	15.6	2	2	25.29	246.2	15
Cm50	Cm	0.50	15	5	T1	1620	0.091	1.9	15.6	2	2	25.29	242.4	15
Cm50	Cm	0.50	15	10	T1	1587	0.040	1.9	15.6	2	2	25.29	237.5	15
Cm50	Cm	0.50	15	30	T1	1538	0.047	1.9	15.6	2	2	25.29	230.2	15
Cm50	Cm	0.50	15	50	T1	1495	0.022	1.9	15.6	2	2	25.29	223.7	15
Cm50	Cm	0.50	15	100	T1	1479	0.038	1.9	15.6	2	2	25.29	221.3	15
Cm50	Cm	0.50	15	300	T1	1640	0.037	1.9	15.6	2	2	25.29	245.4	15
Cm50	Cm	0.50	15	1000	T1	1675	0.125	1.9	15.6	2	2	25.29	250.7	15
Cm50	Cm	0.50	30	1	T1	1642	0.264	1.9	15.6	2	1	25.29	245.7	30
Cm50	Cm	0.50	30	3	T1	1607	0.111	1.9	15.6	2	1	25.29	240.5	30

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
Cm50	Cm	0.50	30	5	T1	1614	0.068	1.9	15.6	2	1	25.29	241.5	30
Cm50	Cm	0.50	30	10	T1	1573	0.058	1.9	15.6	2	1	25.29	235.4	30
Cm50	Cm	0.50	30	30	T1	1532	0.054	1.9	15.6	2	1	25.29	229.3	30
Cm50	Cm	0.50	30	50	T1	1518	0.057	1.9	15.6	2	1	25.29	227.2	30
Cm50	Cm	0.50	30	100	T1	1534	0.031	1.9	15.6	2	1	25.29	229.6	30
Cm50	Cm	0.50	30	300	T1	1542	0.042	1.9	15.6	2	1	25.29	230.8	30
Cm50	Cm	0.50	30	500	T1	1529	0.057	1.9	15.6	2	1	25.29	228.8	30
Cm50	Cm	0.50	30	1000	T1	1549	0.100	1.9	15.6	2	1	25.29	231.8	30
Cm50	Cm	0.50	30	1	T1	1635	0.265	1.9	15.6	2	2	25.29	244.7	30
Cm50	Cm	0.50	30	3	T1	1609	0.106	1.9	15.6	2	2	25.29	240.8	30
Cm50	Cm	0.50	30	5	T1	1592	0.079	1.9	15.6	2	2	25.29	238.2	30
Cm50	Cm	0.50	30	10	T1	1566	0.030	1.9	15.6	2	2	25.29	234.3	30
Cm50	Cm	0.50	30	30	T1	1523	0.041	1.9	15.6	2	2	25.29	227.9	30
Cm50	Cm	0.50	30	50	T1	1482	0.016	1.9	15.6	2	2	25.29	221.8	30
Cm50	Cm	0.50	30	100	T1	1468	0.031	1.9	15.6	2	2	25.29	219.7	30
Cm50	Cm	0.50	30	300	T1	1638	0.031	1.9	15.6	2	2	25.29	245.1	30
Cm50	Cm	0.50	30	1000	T1	1678	0.120	1.9	15.6	2	2	25.29	251.1	30
Cm50	Cm	0.50	45	1	T1	1634	0.268	1.9	15.6	2	1	25.29	244.5	45
Cm50	Cm	0.50	45	3	T1	1596	0.113	1.9	15.6	2	1	25.29	238.8	45
Cm50	Cm	0.50	45	5	T1	1602	0.069	1.9	15.6	2	1	25.29	239.7	45
Cm50	Cm	0.50	45	10	T1	1562	0.058	1.9	15.6	2	1	25.29	233.7	45
Cm50	Cm	0.50	45	30	T1	1522	0.052	1.9	15.6	2	1	25.29	227.8	45
Cm50	Cm	0.50	45	50	T1	1509	0.054	1.9	15.6	2	1	25.29	225.8	45
Cm50	Cm	0.50	45	100	T1	1526	0.028	1.9	15.6	2	1	25.29	228.4	45
Cm50	Cm	0.50	45	300	T1	1540	0.038	1.9	15.6	2	1	25.29	230.5	45
Cm50	Cm	0.50	45	500	T1	1528	0.052	1.9	15.6	2	1	25.29	228.7	45
Cm50	Cm	0.50	45	1000	T1	1550	0.092	1.9	15.6	2	1	25.29	232.0	45
Cm50	Cm	0.50	45	1	T1	1632	0.271	1.9	15.6	2	2	25.29	244.2	45
Cm50	Cm	0.50	45	3	T1	1601	0.109	1.9	15.6	2	2	25.29	239.6	45
Cm50	Cm	0.50	45	5	T1	1582	0.081	1.9	15.6	2	2	25.29	236.7	45
Cm50	Cm	0.50	45	10	T1	1556	0.032	1.9	15.6	2	2	25.29	232.9	45
Cm50	Cm	0.50	45	30	T1	1513	0.040	1.9	15.6	2	2	25.29	226.4	45
Cm50	Cm	0.50	45	50	T1	1473	0.014	1.9	15.6	2	2	25.29	220.4	45
Cm50	Cm	0.50	45	100	T1	1461	0.028	1.9	15.6	2	2	25.29	218.6	45
Cm50	Cm	0.50	45	300	T1	1635	0.025	1.9	15.6	2	2	25.29	244.7	45
Cm50	Cm	0.50	60	1	T1	1639	0.276	1.9	15.6	2	1	25.29	245.3	60
Cm50	Cm	0.50	60	3	T1	1591	0.119	1.9	15.6	2	1	25.29	238.1	60
Cm50	Cm	0.50	60	5	T1	1595	0.073	1.9	15.6	2	1	25.29	238.7	60
Cm50	Cm	0.50	60	10	T1	1554	0.060	1.9	15.6	2	1	25.29	232.6	60
Cm50	Cm	0.50	60	30	T1	1514	0.052	1.9	15.6	2	1	25.29	226.6	60
Cm50	Cm	0.50	60	50	T1	1503	0.053	1.9	15.6	2	1	25.29	224.9	60
Cm50	Cm	0.50	60	100	T1	1521	0.027	1.9	15.6	2	1	25.29	227.6	60
Cm50	Cm	0.50	60	300	T1	1537	0.036	1.9	15.6	2	1	25.29	230.0	60
Cm50	Cm	0.50	60	500	T1	1527	0.050	1.9	15.6	2	1	25.29	228.5	60
Cm50	Cm	0.50	60	1000	T1	1551	0.091	1.9	15.6	2	1	25.29	232.1	60
Cm50	Cm	0.50	60	1	T1	1636	0.279	1.9	15.6	2	2	25.29	244.8	60
Cm50	Cm	0.50	60	3	T1	1596	0.116	1.9	15.6	2	2	25.29	238.8	60

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
Cm50	Cm	0.50	60	5	T1	1575	0.085	1.9	15.6	2	2	25.29	235.7	60
Cm50	Cm	0.50	60	10	T1	1548	0.034	1.9	15.6	2	2	25.29	231.7	60
Cm50	Cm	0.50	60	30	T1	1506	0.039	1.9	15.6	2	2	25.29	225.4	60
Cm50	Cm	0.50	60	50	T1	1467	0.013	1.9	15.6	2	2	25.29	219.5	60
Cm50	Cm	0.50	60	100	T1	1457	0.026	1.9	15.6	2	2	25.29	218.0	60
Cm50	Cm	0.50	60	300	T1	1632	0.024	1.9	15.6	2	2	25.29	244.2	60
Cm60	Cm	0.60	19	3	T1	1445	0.019	1.9	15.6	2	1	26.29	208.0	15
Cm60	Cm	0.60	19	5	T1	1452	0.011	1.9	15.6	2	1	26.29	209.0	15
Cm60	Cm	0.60	19	30	T1	1399	0.032	1.9	15.6	2	1	26.29	201.4	15
Cm60	Cm	0.60	19	50	T1	1399	0.036	1.9	15.6	2	1	26.29	201.4	15
Cm60	Cm	0.60	19	200	T1	1429	0.016	1.9	15.6	2	1	26.29	205.7	15
Cm60	Cm	0.60	19	500	T1	1456	0.050	1.9	15.6	2	1	26.29	209.6	15
Cm60	Cm	0.60	30	3	T1	1447	0.016	1.9	15.6	2	1	26.29	208.3	30
Cm60	Cm	0.60	30	5	T1	1456	0.008	1.9	15.6	2	1	26.29	209.6	30
Cm60	Cm	0.60	30	30	T1	1403	0.030	1.9	15.6	2	1	26.29	202.0	30
Cm60	Cm	0.60	30	50	T1	1403	0.034	1.9	15.6	2	1	26.29	202.0	30
Cm60	Cm	0.60	30	200	T1	1434	0.009	1.9	15.6	2	1	26.29	206.4	30
Cm60	Cm	0.60	30	500	T1	1463	0.034	1.9	15.6	2	1	26.29	210.6	30
Cm60	Cm	0.60	33	1	T1	1455	0.011	1.9	15.6	2	2	26.29	209.5	30
Cm60	Cm	0.60	33	3	T1	1448	0.014	1.9	15.6	2	2	26.29	208.4	30
Cm60	Cm	0.60	33	5	T1	1439	0.019	1.9	15.6	2	2	26.29	207.2	30
Cm60	Cm	0.60	33	10	T1	1423	-0.004	1.9	15.6	2	2	26.29	204.8	30
Cm60	Cm	0.60	33	30	T1	1400	0.018	1.9	15.6	2	2	26.29	201.5	30
Cm60	Cm	0.60	33	50	T1	1367	-0.004	1.9	15.6	2	2	26.29	196.8	30
Cm60	Cm	0.60	33	100	T1	1367	0.013	1.9	15.6	2	2	26.29	196.8	30
Cm60	Cm	0.60	33	200	T1	1438	0.016	1.9	15.6	2	2	26.29	207.0	30
Cm60	Cm	0.60	33	1000	T1	1599	0.141	1.9	15.6	2	2	26.29	230.2	30
Cm60	Cm	0.60	45	3	T1	1446	0.027	1.9	15.6	2	1	26.29	208.2	45
Cm60	Cm	0.60	45	5	T1	1455	0.026	1.9	15.6	2	1	26.29	209.5	45
Cm60	Cm	0.60	45	30	T1	1391	0.129	1.9	15.6	2	1	26.29	200.2	45
Cm60	Cm	0.60	45	50	T1	1370	0.191	1.9	15.6	2	1	26.29	197.2	45
Cm60	Cm	0.60	45	200	T1	1123	0.514	1.9	15.6	2	1	26.29	161.7	45
Cm60	Cm	0.60	45	500	T1	579	1.190	1.9	15.6	2	1	26.29	83.4	45
Cm60	Cm	0.60	49	1	T1	1454	0.011	1.9	15.6	2	2	26.29	209.3	45
Cm60	Cm	0.60	49	3	T1	1448	0.014	1.9	15.6	2	2	26.29	208.4	45
Cm60	Cm	0.60	49	5	T1	1440	0.019	1.9	15.6	2	2	26.29	207.3	45
Cm60	Cm	0.60	49	10	T1	1423	-0.005	1.9	15.6	2	2	26.29	204.8	45
Cm60	Cm	0.60	49	30	T1	1400	0.017	1.9	15.6	2	2	26.29	201.5	45
Cm60	Cm	0.60	49	50	T1	1368	-0.005	1.9	15.6	2	2	26.29	196.9	45
Cm60	Cm	0.60	49	100	T1	1368	0.010	1.9	15.6	2	2	26.29	196.9	45
Cm60	Cm	0.60	49	200	T1	1439	0.011	1.9	15.6	2	2	26.29	207.2	45
Cm60	Cm	0.60	60	3	T1	1447	0.016	1.9	15.6	2	1	26.29	208.3	60
Cm60	Cm	0.60	60	5	T1	1457	0.008	1.9	15.6	2	1	26.29	209.7	60
Cm60	Cm	0.60	60	30	T1	1406	0.029	1.9	15.6	2	1	26.29	202.4	60
Cm60	Cm	0.60	60	50	T1	1406	0.033	1.9	15.6	2	1	26.29	202.4	60
Cm60	Cm	0.60	60	200	T1	1437	0.009	1.9	15.6	2	1	26.29	206.9	60
Cm60	Cm	0.60	60	500	T1	1468	0.034	1.9	15.6	2	1	26.29	211.3	60

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
Cm60	Cm	0.60	60	1	T1	1454	0.011	1.9	15.6	2	2	26.29	209.3	60
Cm60	Cm	0.60	60	3	T1	1448	0.013	1.9	15.6	2	2	26.29	208.4	60
Cm60	Cm	0.60	60	5	T1	1440	0.018	1.9	15.6	2	2	26.29	207.3	60
Cm60	Cm	0.60	60	10	T1	1424	-0.006	1.9	15.6	2	2	26.29	205.0	60
Cm60	Cm	0.60	60	30	T1	1401	0.016	1.9	15.6	2	2	26.29	201.7	60
Cm60	Cm	0.60	60	50	T1	1370	-0.006	1.9	15.6	2	2	26.29	197.2	60
Cm60	Cm	0.60	60	100	T1	1368	0.010	1.9	15.6	2	2	26.29	196.9	60
Cm60	Cm	0.60	60	200	T1	1440	0.010	1.9	15.6	2	2	26.29	207.3	60
Cm60	Cm	0.60	8	1	T1	1718	0.040	1.9	15.6	2	1	26.29	247.3	<15
Cm60	Cm	0.60	8	3	T1	1654	0.056	1.9	15.6	2	1	26.29	238.1	<15
Cm60	Cm	0.60	8	5	T1	1641	0.047	1.9	15.6	2	1	26.29	236.2	<15
Cm60	Cm	0.60	8	10	T1	1575	0.056	1.9	15.6	2	1	26.29	226.7	<15
Cm60	Cm	0.60	8	30	T1	1518	0.053	1.9	15.6	2	1	26.29	218.5	<15
Cm60	Cm	0.60	8	50	T1	1505	0.054	1.9	15.6	2	1	26.29	216.7	<15
Cm60	Cm	0.60	8	100	T1	1525	0.027	1.9	15.6	2	1	26.29	219.5	<15
Cm60	Cm	0.60	8	300	T1	1541	0.037	1.9	15.6	2	1	26.29	221.8	<15
Cm60	Cm	0.60	8	500	T1	1530	0.052	1.9	15.6	2	1	26.29	220.3	<15
Cm60	Cm	0.60	8	1000	T1	1553	0.095	1.9	15.6	2	1	26.29	223.6	<15
Cm60	Cm	0.60	10	1	T1	1708	0.043	1.9	15.6	2	2	26.29	245.9	<15
Cm60	Cm	0.60	10	3	T1	1655	0.051	1.9	15.6	2	2	26.29	238.2	<15
Cm60	Cm	0.60	10	5	T1	1618	0.057	1.9	15.6	2	2	26.29	232.9	<15
Cm60	Cm	0.60	10	10	T1	1568	0.029	1.9	15.6	2	2	26.29	225.7	<15
Cm60	Cm	0.60	10	30	T1	1509	0.040	1.9	15.6	2	2	26.29	217.2	<15
Cm60	Cm	0.60	10	50	T1	1469	0.013	1.9	15.6	2	2	26.29	211.5	<15
Cm60	Cm	0.60	10	100	T1	1458	0.027	1.9	15.6	2	2	26.29	209.9	<15
Cm60	Cm	0.60	10	300	T1	1635	0.028	1.9	15.6	2	2	26.29	235.4	<15
Cm60	Cm	0.60	10	1000	T1	1675	0.123	1.9	15.6	2	2	26.29	241.1	<15
Cm60	Cm	0.60	15	1	T1	1686	0.042	1.9	15.6	2	1	26.29	242.7	15
Cm60	Cm	0.60	15	3	T1	1623	0.055	1.9	15.6	2	1	26.29	233.6	15
Cm60	Cm	0.60	15	5	T1	1611	0.044	1.9	15.6	2	1	26.29	231.9	15
Cm60	Cm	0.60	15	10	T1	1551	0.052	1.9	15.6	2	1	26.29	223.3	15
Cm60	Cm	0.60	15	30	T1	1500	0.049	1.9	15.6	2	1	26.29	215.9	15
Cm60	Cm	0.60	15	50	T1	1490	0.050	1.9	15.6	2	1	26.29	214.5	15
Cm60	Cm	0.60	15	100	T1	1511	0.024	1.9	15.6	2	1	26.29	217.5	15
Cm60	Cm	0.60	15	300	T1	1532	0.038	1.9	15.6	2	1	26.29	220.5	15
Cm60	Cm	0.60	15	500	T1	1522	0.059	1.9	15.6	2	1	26.29	219.1	15
Cm60	Cm	0.60	15	1000	T1	1543	0.115	1.9	15.6	2	1	26.29	222.1	15
Cm60	Cm	0.60	18	1	T1	1677	0.046	1.9	15.6	2	2	26.29	241.4	15
Cm60	Cm	0.60	18	3	T1	1623	0.055	1.9	15.6	2	2	26.29	233.6	15
Cm60	Cm	0.60	18	5	T1	1586	0.061	1.9	15.6	2	2	26.29	228.3	15
Cm60	Cm	0.60	18	10	T1	1540	0.037	1.9	15.6	2	2	26.29	221.7	15
Cm60	Cm	0.60	18	30	T1	1488	0.065	1.9	15.6	2	2	26.29	214.2	15
Cm60	Cm	0.60	18	50	T1	1447	0.056	1.9	15.6	2	2	26.29	208.3	15
Cm60	Cm	0.60	18	100	T1	1439	0.100	1.9	15.6	2	2	26.29	207.2	15
Cm60	Cm	0.60	18	300	T1	1441	0.286	1.9	15.6	2	2	26.29	207.4	15
Cm60	Cm	0.60	18	500	T1	1502	0.316	1.9	15.6	2	2	26.29	216.2	15
Cm60	Cm	0.60	18	1000	T1	1326	0.483	1.9	15.6	2	2	26.29	190.9	15

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
Cm60	Cm	0.60	30	1	T1	1661	0.046	1.9	15.6	2	1	26.29	239.1	30
Cm60	Cm	0.60	30	3	T1	1597	0.056	1.9	15.6	2	1	26.29	229.9	30
Cm60	Cm	0.60	30	5	T1	1583	0.044	1.9	15.6	2	1	26.29	227.9	30
Cm60	Cm	0.60	30	10	T1	1533	0.036	1.9	15.6	2	1	26.29	220.7	30
Cm60	Cm	0.60	30	30	T1	1484	0.045	1.9	15.6	2	1	26.29	213.6	30
Cm60	Cm	0.60	30	50	T1	1477	0.045	1.9	15.6	2	1	26.29	212.6	30
Cm60	Cm	0.60	30	100	T1	1499	0.019	1.9	15.6	2	1	26.29	215.8	30
Cm60	Cm	0.60	30	300	T1	1527	0.031	1.9	15.6	2	1	26.29	219.8	30
Cm60	Cm	0.60	30	500	T1	1519	0.050	1.9	15.6	2	1	26.29	218.7	30
Cm60	Cm	0.60	30	1000	T1	1548	0.101	1.9	15.6	2	1	26.29	222.8	30
Cm60	Cm	0.60	31	1	T1	1655	0.049	1.9	15.6	2	2	26.29	238.2	30
Cm60	Cm	0.60	31	3	T1	1597	0.053	1.9	15.6	2	2	26.29	229.9	30
Cm60	Cm	0.60	31	5	T1	1562	0.055	1.9	15.6	2	2	26.29	224.9	30
Cm60	Cm	0.60	31	10	T1	1519	0.022	1.9	15.6	2	2	26.29	218.7	30
Cm60	Cm	0.60	31	30	T1	1474	0.031	1.9	15.6	2	2	26.29	212.2	30
Cm60	Cm	0.60	31	50	T1	1439	0.004	1.9	15.6	2	2	26.29	207.2	30
Cm60	Cm	0.60	31	100	T1	1435	0.017	1.9	15.6	2	2	26.29	206.6	30
Cm60	Cm	0.60	31	300	T1	1623	0.016	1.9	15.6	2	2	26.29	233.6	30
Cm60	Cm	0.60	52	1	T1	1630	0.050	1.9	15.6	2	1	26.29	234.6	45
Cm60	Cm	0.60	52	3	T1	1565	0.055	1.9	15.6	2	1	26.29	225.3	45
Cm60	Cm	0.60	52	5	T1	1556	0.040	1.9	15.6	2	1	26.29	224.0	45
Cm60	Cm	0.60	52	10	T1	1508	0.044	1.9	15.6	2	1	26.29	217.1	45
Cm60	Cm	0.60	52	30	T1	1470	0.045	1.9	15.6	2	1	26.29	211.6	45
Cm60	Cm	0.60	52	50	T1	1466	0.051	1.9	15.6	2	1	26.29	211.0	45
Cm60	Cm	0.60	52	100	T1	1491	0.035	1.9	15.6	2	1	26.29	214.6	45
Cm60	Cm	0.60	52	300	T1	1500	0.095	1.9	15.6	2	1	26.29	215.9	45
Cm60	Cm	0.60	52	500	T1	1462	0.169	1.9	15.6	2	1	26.29	210.5	45
Cm60	Cm	0.60	52	1000	T1	1363	0.379	1.9	15.6	2	1	26.29	196.2	45
Cm60	Cm	0.60	52	1	T1	1626	0.052	1.9	15.6	2	2	26.29	234.1	45
Cm60	Cm	0.60	52	3	T1	1567	0.050	1.9	15.6	2	2	26.29	225.6	45
Cm60	Cm	0.60	52	5	T1	1537	0.050	1.9	15.6	2	2	26.29	221.3	45
Cm60	Cm	0.60	52	10	T1	1501	0.015	1.9	15.6	2	2	26.29	216.1	45
Cm60	Cm	0.60	52	30	T1	1453	-0.008	1.9	15.6	2	2	26.29	209.2	45
Cm60	Cm	0.60	52	50	T1	1430	-0.001	1.9	15.6	2	2	26.29	205.9	45
Cm60	Cm	0.60	52	100	T1	1428	0.012	1.9	15.6	2	2	26.29	205.6	45
Cm60	Cm	0.60	52	300	T1	1617	0.013	1.9	15.6	2	2	26.29	232.8	45
Cm60	Cm	0.60	60	1	T1	1622	0.050	1.9	15.6	2	1	26.29	233.5	60
Cm60	Cm	0.60	60	3	T1	1558	0.052	1.9	15.6	2	1	26.29	224.3	60
Cm60	Cm	0.60	60	5	T1	1550	0.037	1.9	15.6	2	1	26.29	223.1	60
Cm60	Cm	0.60	60	10	T1	1503	0.040	1.9	15.6	2	1	26.29	216.4	60
Cm60	Cm	0.60	60	30	T1	1467	0.037	1.9	15.6	2	1	26.29	211.2	60
Cm60	Cm	0.60	60	50	T1	1463	0.038	1.9	15.6	2	1	26.29	210.6	60
Cm60	Cm	0.60	60	100	T1	1490	0.012	1.9	15.6	2	1	26.29	214.5	60
Cm60	Cm	0.60	60	300	T1	1526	0.021	1.9	15.6	2	1	26.29	219.7	60
Cm60	Cm	0.60	60	500	T1	1524	0.036	1.9	15.6	2	1	26.29	219.4	60
Cm60	Cm	0.60	60	1000	T1	1558	0.077	1.9	15.6	2	1	26.29	224.3	60
Cm60	Cm	0.60	60	1	T1	1616	0.052	1.9	15.6	2	2	26.29	232.6	60

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
Cm60	Cm	0.60	60	3	T1	1560	0.049	1.9	15.6	2	2	26.29	224.6	60
Cm60	Cm	0.60	60	5	T1	1531	0.048	1.9	15.6	2	2	26.29	220.4	60
Cm60	Cm	0.60	60	10	T1	1496	0.013	1.9	15.6	2	2	26.29	215.4	60
Cm60	Cm	0.60	60	30	T1	1450	-0.010	1.9	15.6	2	2	26.29	208.7	60
Cm60	Cm	0.60	60	50	T1	1427	-0.002	1.9	15.6	2	2	26.29	205.4	60
Cm60	Cm	0.60	60	100	T1	1425	0.011	1.9	15.6	2	2	26.29	205.1	60
Cm60	Cm	0.60	60	300	T1	1615	0.013	1.9	15.6	2	2	26.29	232.5	60
CW40	CW	0.40	13	1	T1	1818	0.083	1.9	15.6	2	1	26.3	261.6	<15
CW40	CW	0.40	13	10	T1	1618	0.082	1.9	15.6	2	1	26.3	232.8	<15
CW40	CW	0.40	13	100	T1	1523	0.031	1.9	15.6	2	1	26.3	219.2	<15
CW40	CW	0.40	13	1000	T1	1557	0.074	1.9	15.6	2	1	26.3	224.1	<15
CW40	CW	0.40	17	1	T1	1817	0.091	1.9	15.6	2	1	26.3	261.5	15
CW40	CW	0.40	17	10	T1	1592	0.081	1.9	15.6	2	1	26.3	229.1	15
CW40	CW	0.40	17	100	T1	1517	0.030	1.9	15.6	2	1	26.3	218.3	15
CW40	CW	0.40	17	1000	T1	1530	0.113	1.9	15.6	2	1	26.3	220.2	15
CW40	CW	0.40	30	1	T1	1706	0.075	1.9	15.6	2	1	26.3	245.5	30
CW40	CW	0.40	30	10	T1	1546	0.058	1.9	15.6	2	1	26.3	222.5	30
CW40	CW	0.40	30	100	T1	1504	0.019	1.9	15.6	2	1	26.3	216.4	30
CW40	CW	0.40	30	1000	T1	1564	0.081	1.9	15.6	2	1	26.3	225.1	30
CW40	CW	0.40	45	1	T1	1662	0.053	1.9	15.6	2	1	26.3	239.2	45
CW40	CW	0.40	45	10	T1	1532	0.047	1.9	15.6	2	1	26.3	220.5	45
CW40	CW	0.40	45	100	T1	1501	0.016	1.9	15.6	2	1	26.3	216.0	45
CW40	CW	0.40	45	1000	T1	1562	0.069	1.9	15.6	2	1	26.3	224.8	45
CW40	CW	0.40	75	1	T1	1625	0.051	1.9	15.6	2	1	26.3	233.8	75
CW40	CW	0.40	75	10	T1	1519	0.040	1.9	15.6	2	1	26.3	218.6	75
CW40	CW	0.40	75	100	T1	1497	0.013	1.9	15.6	2	1	26.3	215.4	75
CW40	CW	0.40	75	1000	T1	1561	0.064	1.9	15.6	2	1	26.3	224.6	75
CW45	CW	0.45	15	1	T1	1656	0.048	1.9	15.6	2	1	25.8	242.9	<15
CW45	CW	0.45	15	10	T1	1536	0.048	1.9	15.6	2	1	25.8	225.3	<15
CW45	CW	0.45	15	100	T1	1486	0.025	1.9	15.6	2	1	25.8	218.0	<15
CW45	CW	0.45	15	1000	T1	1540	0.070	1.9	15.6	2	1	25.8	225.9	<15
CW45	CW	0.45	21	1	T1	1648	0.056	1.9	15.6	2	1	25.8	241.7	15
CW45	CW	0.45	21	10	T1	1519	0.047	1.9	15.6	2	1	25.8	222.8	15
CW45	CW	0.45	21	100	T1	1478	0.021	1.9	15.6	2	1	25.8	216.8	15
CW45	CW	0.45	21	1000	T1	1534	0.069	1.9	15.6	2	1	25.8	225.0	15
CW45	CW	0.45	30	1	T1	1645	0.057	1.9	15.6	2	1	25.8	241.3	30
CW45	CW	0.45	30	10	T1	1513	0.047	1.9	15.6	2	1	25.8	221.9	30
CW45	CW	0.45	30	100	T1	1474	0.019	1.9	15.6	2	1	25.8	216.2	30
CW45	CW	0.45	30	1000	T1	1533	0.069	1.9	15.6	2	1	25.8	224.9	30
CW45	CW	0.45	45	1	T1	1619	0.058	1.9	15.6	2	1	25.8	237.5	45
CW45	CW	0.45	45	10	T1	1498	0.044	1.9	15.6	2	1	25.8	219.7	45
CW45	CW	0.45	45	100	T1	1469	0.016	1.9	15.6	2	1	25.8	215.5	45
CW45	CW	0.45	45	1000	T1	1535	0.067	1.9	15.6	2	1	25.8	225.2	45
CW45	CW	0.45	60	1	T1	1599	0.057	1.9	15.6	2	1	25.8	234.6	60
CW45	CW	0.45	60	10	T1	1491	0.041	1.9	15.6	2	1	25.8	218.7	60
CW45	CW	0.45	60	100	T1	1466	0.015	1.9	15.6	2	1	25.8	215.0	60
CW45	CW	0.45	60	1000	T1	1521	0.064	1.9	15.6	2	1	25.8	223.1	60

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
CW50	CW	0.50	12	1	T1	1490	0.012	1.9	15.6	2	1	28.9	195.1	<15
CW50	CW	0.50	12	10	T1	1464	0.017	1.9	15.6	2	1	28.9	191.7	<15
CW50	CW	0.50	12	100	T1	1467	0.006	1.9	15.6	2	1	28.9	192.1	<15
CW50	CW	0.50	12	1000	T1	1546	0.060	1.9	15.6	2	1	28.9	202.5	<15
CW50	CW	0.50	19	1	T1	1491	0.009	1.9	15.6	2	1	28.9	195.3	15
CW50	CW	0.50	19	10	T1	1467	0.017	1.9	15.6	2	1	28.9	192.1	15
CW50	CW	0.50	19	100	T1	1468	0.007	1.9	15.6	2	1	28.9	192.2	15
CW50	CW	0.50	19	1000	T1	1553	0.056	1.9	15.6	2	1	28.9	203.4	15
CW50	CW	0.50	31	1	T1	1495	0.007	1.9	15.6	2	1	28.9	195.8	30
CW50	CW	0.50	31	10	T1	1472	0.018	1.9	15.6	2	1	28.9	192.8	30
CW50	CW	0.50	31	100	T1	1471	0.007	1.9	15.6	2	1	28.9	192.6	30
CW50	CW	0.50	31	1000	T1	1557	0.057	1.9	15.6	2	1	28.9	203.9	30
CW50	CW	0.50	45	1	T1	1498	0.006	1.9	15.6	2	1	28.9	196.2	45
CW50	CW	0.50	45	10	T1	1476	0.018	1.9	15.6	2	1	28.9	193.3	45
CW50	CW	0.50	45	100	T1	1473	0.008	1.9	15.6	2	1	28.9	192.9	45
CW50	CW	0.50	45	1000	T1	1557	0.056	1.9	15.6	2	1	28.9	203.9	45
CW50	CW	0.50	60	1	T1	1501	0.005	1.9	15.6	2	1	28.9	196.6	60
CW50	CW	0.50	60	10	T1	1478	0.018	1.9	15.6	2	1	28.9	193.6	60
CW50	CW	0.50	60	100	T1	1474	0.008	1.9	15.6	2	1	28.9	193.0	60
CW50	CW	0.50	61	1000	T1	1558	0.056	1.9	15.6	2	1	28.9	204.0	60
FA45	FA	0.45	20	1	T1	1580	0.600	1.9	15.6	2	1	27.4	218.2	15
FA45	FA	0.45	20	10	T1	1476	0.078	1.9	15.6	2	1	27.4	203.9	15
FA45	FA	0.45	20	100	T1	1463	0.036	1.9	15.6	2	1	27.4	202.1	15
FA45	FA	0.45	21	1000	T1	1460	0.081	1.9	15.6	2	1	27.4	201.7	15
FA45	FA	0.45	33	1	T1	1714	0.258	1.9	15.6	2	1	27.4	236.7	30
FA45	FA	0.45	33	10	T1	1612	0.074	1.9	15.6	2	1	27.4	222.7	30
FA45	FA	0.45	33	100	T1	1504	0.060	1.9	15.6	2	1	27.4	207.7	30
FA45	FA	0.45	34	1000	T1	1475	0.086	1.9	15.6	2	1	27.4	203.7	30
FA45	FA	0.45	48	1	T1	1705	0.202	1.9	15.6	2	1	27.4	235.5	45
FA45	FA	0.45	48	10	T1	1611	0.067	1.9	15.6	2	1	27.4	222.5	45
FA45	FA	0.45	48	100	T1	1504	0.059	1.9	15.6	2	1	27.4	207.7	45
FA45	FA	0.45	49	1000	T1	1477	0.085	1.9	15.6	2	1	27.4	204.0	45
FA45	FA	0.45	64	1	T1	1695	0.175	1.9	15.6	2	1	27.4	234.1	60
FA45	FA	0.45	64	10	T1	1603	0.103	1.9	15.6	2	1	27.4	221.4	60
FA45	FA	0.45	64	100	T1	1503	0.292	1.9	15.6	2	1	27.4	207.6	60
FA45	FA	0.45	64	1000	T1	1488	0.084	1.9	15.6	2	1	27.4	205.5	60
FA45	FA	0.45	79	10	T1	1446	0.012	1.9	15.6	2	1	27.4	199.7	75
FA45	FA	0.45	80	100	T1	1467	0.025	1.9	15.6	2	1	27.4	202.6	75
FA45	FA	0.45	81	1000	T1	1471	0.112	1.9	15.6	2	1	27.4	203.2	75
FA50	FA	0.50	21	1	T1	1550	0.090	1.9	15.6	2	1	27.5	213.3	15
FA50	FA	0.50	22	10	T1	1482	0.044	1.9	15.6	2	1	27.5	204.0	15
FA50	FA	0.50	22	100	T1	1415	0.040	1.9	15.6	2	1	27.5	194.7	15
FA50	FA	0.50	23	1000	T1	1423	0.078	1.9	15.6	2	1	27.5	195.8	15
FA50	FA	0.50	30	1	T1	1664	0.126	1.9	15.6	2	1	27.5	229.0	30
FA50	FA	0.50	30	10	T1	1548	0.070	1.9	15.6	2	1	27.5	213.0	30
FA50	FA	0.50	30	100	T1	1441	0.055	1.9	15.6	2	1	27.5	198.3	30
FA50	FA	0.50	31	1000	T1	1423	0.119	1.9	15.6	2	1	27.5	195.8	30

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
FA50	FA	0.50	50	1	T1	1653	0.052	1.9	15.6	2	1	27.5	227.5	45
FA50	FA	0.50	50	10	T1	1537	0.063	1.9	15.6	2	1	27.5	211.5	45
FA50	FA	0.50	50	100	T1	1431	0.053	1.9	15.6	2	1	27.5	196.9	45
FA50	FA	0.50	51	1000	T1	1420	0.124	1.9	15.6	2	1	27.5	195.4	45
FA50	FA	0.50	63	1	T1	1648	0.054	1.9	15.6	2	1	27.5	226.8	60
FA50	FA	0.50	63	10	T1	1527	0.069	1.9	15.6	2	1	27.5	210.1	60
FA50	FA	0.50	63	100	T1	1416	0.091	1.9	15.6	2	1	27.5	194.9	60
FA50	FA	0.50	64	1000	T1	1421	0.100	1.9	15.6	2	1	27.5	195.6	60
FA60	FA	0.60	26	1	T1	1560	0.300	1.9	15.6	2	1	27.5	214.7	15
FA60	FA	0.60	33	1	T1	1670	0.136	1.9	15.6	2	1	27.5	229.8	30
FA60	FA	0.60	33	10	T1	1494	0.082	1.9	15.6	2	1	27.5	205.6	30
FA60	FA	0.60	34	100	T1	1408	0.036	1.9	15.6	2	1	27.5	193.8	30
FA60	FA	0.60	34	1000	T1	1437	0.071	1.9	15.6	2	1	27.5	197.8	30
FA60	FA	0.60	49	1	T1	1650	0.100	1.9	15.6	2	1	27.5	227.1	45
FA60	FA	0.60	49	10	T1	1490	0.076	1.9	15.6	2	1	27.5	205.1	45
FA60	FA	0.60	50	100	T1	1406	0.035	1.9	15.6	2	1	27.5	193.5	45
FA60	FA	0.60	50	1000	T1	1434	0.070	1.9	15.6	2	1	27.5	197.3	45
FA60	FA	0.60	63	1	T1	1648	0.094	1.9	15.6	2	1	27.5	226.8	60
FA60	FA	0.60	63	10	T1	1488	0.076	1.9	15.6	2	1	27.5	204.8	60
FA60	FA	0.60	64	100	T1	1404	0.035	1.9	15.6	2	1	27.5	193.2	60
FA60	FA	0.60	64	1000	T1	1430	0.069	1.9	15.6	2	1	27.5	196.8	60
FW45	FW	0.45	21	10	T1	1605	0.052	1.9	15.6	2	1	27.1	224.1	15
FW45	FW	0.45	21	100	T1	1539	0.024	1.9	15.6	2	1	27.1	214.9	15
FW45	FW	0.45	21	1000	T1	1604	0.070	1.9	15.6	2	1	27.1	224.0	15
FW45	FW	0.45	32	1	T1	1689	0.019	1.9	15.6	2	1	27.1	235.9	30
FW45	FW	0.45	32	10	T1	1591	0.048	1.9	15.6	2	1	27.1	222.2	30
FW45	FW	0.45	32	100	T1	1541	0.022	1.9	15.6	2	1	27.1	215.2	30
FW45	FW	0.45	32	1000	T1	1590	0.081	1.9	15.6	2	1	27.1	222.0	30
FW45	FW	0.45	49	1	T1	1646	0.081	1.9	15.6	2	1	27.1	229.9	45
FW45	FW	0.45	49	10	T1	1572	0.046	1.9	15.6	2	1	27.1	219.5	45
FW45	FW	0.45	49	100	T1	1530	0.018	1.9	15.6	2	1	27.1	213.7	45
FW45	FW	0.45	49	1000	T1	1595	0.062	1.9	15.6	2	1	27.1	222.7	45
FW45	FW	0.45	60	1	T1	1658	0.028	1.9	15.6	2	1	27.1	231.5	60
FW45	FW	0.45	60	10	T1	1554	0.042	1.9	15.6	2	1	27.1	217.0	60
FW45	FW	0.45	60	100	T1	1524	0.016	1.9	15.6	2	1	27.1	212.8	60
FW45	FW	0.45	60	1000	T1	1592	0.061	1.9	15.6	2	1	27.1	222.3	60
FW50	FW	0.50	17	1	T1	1632	0.034	1.9	15.6	2	1	28.1	219.8	15
FW50	FW	0.50	17	10	T1	1548	0.036	1.9	15.6	2	1	28.1	208.5	15
FW50	FW	0.50	21	100	T1	1522	0.035	1.9	15.6	2	1	28.1	205.0	15
FW50	FW	0.50	17	1000	T1	1607	0.059	1.9	15.6	2	1	28.1	216.4	15
FW50	FW	0.50	32	1	T1	1642	0.042	1.9	15.6	2	1	28.1	221.1	30
FW50	FW	0.50	32	10	T1	1546	0.037	1.9	15.6	2	1	28.1	208.2	30
FW50	FW	0.50	32	100	T1	1521	0.014	1.9	15.6	2	1	28.1	204.9	30
FW50	FW	0.50	32	1000	T1	1601	0.060	1.9	15.6	2	1	28.1	215.6	30
FW50	FW	0.50	46	1	T1	1641	0.049	1.9	15.6	2	1	28.1	221.0	45
FW50	FW	0.50	46	10	T1	1538	0.037	1.9	15.6	2	1	28.1	207.1	45
FW50	FW	0.50	49	100	T1	1518	0.014	1.9	15.6	2	1	28.1	204.4	45

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
FW50	FW	0.50	49	1000	T1	1596	0.060	1.9	15.6	2	1	28.1	215.0	45
FW50	FW	0.50	58	1	T1	1614	0.035	1.9	15.6	2	1	28.1	217.4	60
FW50	FW	0.50	60	10	T1	1534	0.033	1.9	15.6	2	1	28.1	206.6	60
FW50	FW	0.50	58	100	T1	1495	0.014	1.9	15.6	2	1	28.1	201.4	60
FW50	FW	0.50	58	1000	T1	1595	0.055	1.9	15.6	2	1	28.1	214.8	60
FWT4	FWT	0.00	60	1	T1	1472	0.006	1.9	15.6	2	1	26.8	207.9	60
FWT4	FWT	0.00	60	3	T1	1457	0.016	1.9	15.6	2	1	26.8	205.8	60
FWT4	FWT	0.00	60	5	T1	1464	0.010	1.9	15.6	2	1	26.8	206.7	60
FWT4	FWT	0.00	60	10	T1	1452	0.020	1.9	15.6	2	1	26.8	205.0	60
FWT4	FWT	0.00	60	30	T1	1422	0.029	1.9	15.6	2	1	26.8	200.8	60
FWT4	FWT	0.00	60	50	T1	1419	0.032	1.9	15.6	2	1	26.8	200.4	60
FWT4	FWT	0.00	60	100	T1	1438	0.007	1.9	15.6	2	1	26.8	203.1	60
FWT4	FWT	0.00	60	300	T1	1463	-0.007	1.9	15.6	2	1	26.8	206.6	60
FWT4	FWT	0.00	60	500	T1	1479	0.028	1.9	15.6	2	1	26.8	208.9	60
FWT4	FWT	0.00	60	1000	T1	1516	0.066	1.9	15.6	2	1	26.8	214.1	60
FWT4	FWT	0.00	60	1	T1	1462	0.007	1.9	15.6	2	2	26.8	206.5	60
FWT4	FWT	0.00	60	3	T1	1453	0.016	1.9	15.6	2	2	26.8	205.2	60
FWT4	FWT	0.00	60	5	T1	1447	0.019	1.9	15.6	2	2	26.8	204.3	60
FWT4	FWT	0.00	60	10	T1	1418	-0.001	1.9	15.6	2	2	26.8	200.2	60
FWT4	FWT	0.00	60	30	T1	1407	0.016	1.9	15.6	2	2	26.8	198.7	60
FWT4	FWT	0.00	60	50	T1	1374	-0.006	1.9	15.6	2	2	26.8	194.0	60
FWT4	FWT	0.00	60	100	T1	1374	0.010	1.9	15.6	2	2	26.8	194.0	60
FWT4	FWT	0.00	60	300	T1	1453	-0.010	1.9	15.6	2	2	26.8	205.2	60
FWT4	FWT	0.00	68	1	T1	1562	0.029	1.9	15.6	2	1	27.9	211.9	60
FWT4	FWT	0.00	68	3	T1	1542	0.022	1.9	15.6	2	1	27.9	209.2	60
FWT4	FWT	0.00	68	5	T1	1543	0.014	1.9	15.6	2	1	27.9	209.3	60
FWT4	FWT	0.00	68	10	T1	1534	0.020	1.9	15.6	2	1	27.9	208.1	60
FWT4	FWT	0.00	68	30	T1	1522	0.035	1.9	15.6	2	1	27.9	206.5	60
FWT4	FWT	0.00	68	50	T1	1499	0.035	1.9	15.6	2	1	27.9	203.3	60
FWT4	FWT	0.00	68	100	T1	1513	0.012	1.9	15.6	2	1	27.9	205.2	60
FWT4	FWT	0.00	68	300	T1	1946	-0.158	1.9	15.6	2	1	27.9	264.0	60
FWT4	FWT	0.00	68	500	T1	1541	0.031	1.9	15.6	2	1	27.9	209.0	60
FWT4	FWT	0.00	68	1000	T1	1576	0.065	1.9	15.6	2	1	27.9	213.8	60
FWT5	FWT	0.00	35	1	T1	2223	0.835	1.9	15.6	2	1	27.9	301.5	30
FWT5	FWT	0.00	35	3	T1	1887	0.409	1.9	15.6	2	1	27.9	256.0	30
FWT5	FWT	0.00	35	5	T1	1785	0.284	1.9	15.6	2	1	27.9	242.1	30
FWT5	FWT	0.00	35	10	T1	1742	0.171	1.9	15.6	2	1	27.9	236.3	30
FWT5	FWT	0.00	35	30	T1	1712	0.093	1.9	15.6	2	1	27.9	232.2	30
FWT5	FWT	0.00	35	50	T1	1682	0.070	1.9	15.6	2	1	27.9	228.2	30
FWT5	FWT	0.00	35	100	T1	1644	0.061	1.9	15.6	2	1	27.9	223.0	30
FWT5	FWT	0.00	35	300	T1	2114	3.500	1.9	15.6	2	1	27.9	286.8	30
FWT5	FWT	0.00	35	500	T1	1664	0.061	1.9	15.6	2	1	27.9	225.7	30
FWT5	FWT	0.00	35	1000	T1	1699	0.098	1.9	15.6	2	1	27.9	230.5	30
FWT5	FWT	0.00	38	1	T1	2209	0.698	1.9	15.6	2	2	27.9	299.6	30
FWT5	FWT	0.00	38	3	T1	1799	0.338	1.9	15.6	2	2	27.9	244.0	30
FWT5	FWT	0.00	38	5	T1	1804	0.205	1.9	15.6	2	2	27.9	244.7	30
FWT5	FWT	0.00	38	10	T1	1715	0.107	1.9	15.6	2	2	27.9	232.6	30

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
FWT5	FWT	0.00	38	30	T1	1668	0.064	1.9	15.6	2	2	27.9	226.3	30
FWT5	FWT	0.00	38	50	T1	1627	0.034	1.9	15.6	2	2	27.9	220.7	30
FWT5	FWT	0.00	38	100	T1	1609	0.041	1.9	15.6	2	2	27.9	218.3	30
FWT5	FWT	0.00	38	300	T1	1949	2.830	1.9	15.6	2	2	27.9	264.4	30
FWT5	FWT	0.00	38	1000	T1	1807	0.117	1.9	15.6	2	2	27.9	245.1	30
FWT5	FWT	0.00	43	1	T1	2444	6.775	1.9	15.6	2	1	27.9	331.5	45
FWT5	FWT	0.00	43	3	T1	2095	2.740	1.9	15.6	2	1	26.8	295.8	45
FWT5	FWT	0.00	43	5	T1	1984	1.770	1.9	15.6	2	1	26.8	280.2	45
FWT5	FWT	0.00	43	10	T1	1887	0.980	1.9	15.6	2	1	26.8	266.5	45
FWT5	FWT	0.00	43	30	T1	1768	0.417	1.9	15.6	2	1	26.8	249.7	45
FWT5	FWT	0.00	43	50	T1	1724	0.286	1.9	15.6	2	1	26.8	243.5	45
FWT5	FWT	0.00	43	100	T1	1697	0.184	1.9	15.6	2	1	26.8	239.6	45
FWT5	FWT	0.00	43	500	T1	1544	0.251	1.9	15.6	2	1	26.8	218.0	45
FWT5	FWT	0.00	43	1000	T1	1401	0.421	1.9	15.6	2	1	26.8	197.8	45
FWT5	FWT	0.00	46	1	T1	2409	6.230	1.9	15.6	2	2	26.8	340.2	45
FWT5	FWT	0.00	46	3	T1	2070	2.570	1.9	15.6	2	2	26.8	292.3	45
FWT5	FWT	0.00	46	5	T1	1999	1.590	1.9	15.6	2	2	26.8	282.3	45
FWT5	FWT	0.00	46	10	T1	1911	0.871	1.9	15.6	2	2	26.8	269.9	45
FWT5	FWT	0.00	46	30	T1	1752	0.350	1.9	15.6	2	2	26.8	247.4	45
FWT5	FWT	0.00	46	50	T1	1704	0.215	1.9	15.6	2	2	26.8	240.6	45
FWT5	FWT	0.00	46	100	T1	1679	0.133	1.9	15.6	2	2	26.8	237.1	45
FWT5	FWT	0.00	46	1000	T1	1879	0.135	1.9	15.6	2	2	26.8	265.3	45
FWT5	FWT	0.42	28	1	T1	1785	0.021	1.9	15.6	2	1	27.6	244.8	30
FWT5	FWT	0.42	28	3	T1	1735	0.028	1.9	15.6	2	1	27.6	237.9	30
FWT5	FWT	0.42	28	5	T1	1710	0.033	1.9	15.6	2	1	27.6	234.5	30
FWT5	FWT	0.42	28	10	T1	1704	0.027	1.9	15.6	2	1	27.6	233.7	30
FWT5	FWT	0.42	28	30	T1	1676	0.048	1.9	15.6	2	1	27.6	229.8	30
FWT5	FWT	0.42	28	50	T1	1638	0.048	1.9	15.6	2	1	27.6	224.6	30
FWT5	FWT	0.42	28	100	T1	1605	0.051	1.9	15.6	2	1	27.6	220.1	30
FWT5	FWT	0.42	28	300	T1	1709	-0.133	1.9	15.6	2	1	27.6	234.3	30
FWT5	FWT	0.42	28	500	T1	1620	0.065	1.9	15.6	2	1	27.6	222.1	30
FWT5	FWT	0.42	28	1000	T1	1649	0.108	1.9	15.6	2	1	27.6	226.1	30
FWT5	FWT	0.42	28	1	T1	1681	-0.143	1.9	15.6	2	2	27.6	230.5	30
FWT5	FWT	0.42	28	3	T1	1722	0.017	1.9	15.6	2	2	27.6	236.1	30
FWT5	FWT	0.42	28	5	T1	1760	0.018	1.9	15.6	2	2	27.6	241.3	30
FWT5	FWT	0.42	28	10	T1	1669	0.012	1.9	15.6	2	2	27.6	228.9	30
FWT5	FWT	0.42	28	30	T1	1623	0.028	1.9	15.6	2	2	27.6	222.5	30
FWT5	FWT	0.42	28	50	T1	1577	0.010	1.9	15.6	2	2	27.6	216.2	30
FWT5	FWT	0.42	28	100	T1	1568	0.031	1.9	15.6	2	2	27.6	215.0	30
FWT5	FWT	0.42	28	300	T1	1990	-0.237	1.9	15.6	2	2	27.6	272.9	30
FWT5	FWT	0.42	28	1000	T1	1759	0.123	1.9	15.6	2	2	27.6	241.2	30
FWT4	FWT	0.48	42	1	T1	1409	0.004	1.9	15.6	2	1	27.9	191.1	45
FWT4	FWT	0.48	42	3	T1	1404	0.009	1.9	15.6	2	1	27.9	190.4	45
FWT4	FWT	0.48	42	5	T1	1413	0.001	1.9	15.6	2	1	27.9	191.7	45
FWT4	FWT	0.48	42	10	T1	1409	0.008	1.9	15.6	2	1	27.9	191.1	45
FWT4	FWT	0.48	42	30	T1	1392	0.019	1.9	15.6	2	1	27.9	188.8	45
FWT4	FWT	0.48	42	50	T1	1386	0.022	1.9	15.6	2	1	27.9	188.0	45

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
FWT4	FWT	0.48	42	100	T1	1416	0.000	1.9	15.6	2	1	27.9	192.1	45
FWT4	FWT	0.48	42	300	T1	1395	0.013	1.9	15.6	2	1	27.9	189.2	45
FWT4	FWT	0.48	42	500	T1	1473	0.025	1.9	15.6	2	1	27.9	199.8	45
FWT4	FWT	0.48	42	1000	T1	1506	0.069	1.9	15.6	2	1	27.9	204.3	45
FWT4	FWT	0.48	42	1	T1	1415	0.008	1.9	15.6	2	2	27.9	191.9	45
FWT4	FWT	0.48	42	3	T1	1410	0.011	1.9	15.6	2	2	27.9	191.3	45
FWT4	FWT	0.48	42	5	T1	1405	0.014	1.9	15.6	2	2	27.9	190.6	45
FWT4	FWT	0.48	42	10	T1	1385	-0.012	1.9	15.6	2	2	27.9	187.9	45
FWT4	FWT	0.48	42	30	T1	1383	0.008	1.9	15.6	2	2	27.9	187.6	45
FWT4	FWT	0.48	42	50	T1	1351	-0.015	1.9	15.6	2	2	27.9	183.3	45
FWT4	FWT	0.48	42	100	T1	1358	0.002	1.9	15.6	2	2	27.9	184.2	45
FWT4	FWT	0.48	42	300	T1	1412	0.013	1.9	15.6	2	2	27.9	191.5	45
WATE	W	0.00		1	T1	1465	0.010	1.9	15.6	2	1	25.49	217.5	NA
WATE	W	0.00		3	T1	1454	0.020	1.9	15.6	2	1	25.49	215.9	NA
WATE	W	0.00		5	T1	1463	0.014	1.9	15.6	2	1	25.49	217.2	NA
WATE	W	0.00		10	T1	1435	0.030	1.9	15.6	2	1	25.49	213.1	NA
WATE	W	0.00		30	T1	1398	0.057	1.9	15.6	2	1	25.49	207.6	NA
WATE	W	0.00		50	T1	1390	0.072	1.9	15.6	2	1	25.49	206.4	NA
WATE	W	0.00		100	T1	1394	0.069	1.9	15.6	2	1	25.49	207.0	NA
WATE	W	0.00		200	T1	1360	0.117	1.9	15.6	2	1	25.49	201.9	NA
WATE	W	0.00		500	T1	1261	0.276	1.9	15.6	2	1	25.49	187.2	NA
WATE	W	0.00		1000	T1	1035	0.516	1.9	15.6	2	1	25.49	153.7	NA
WATE	W	0.00		1	T1	1465	0.010	1.9	15.6	2	1	25.49	217.5	NA
WATE	W	0.00		3	T1	1454	0.020	1.9	15.6	2	1	25.49	215.9	NA
WATE	W	0.00		5	T1	1462	0.014	1.9	15.6	2	1	25.49	217.1	NA
WATE	W	0.00		10	T1	1434	0.020	1.9	15.6	2	1	25.49	212.9	NA
WATE	W	0.00		30	T1	1397	0.056	1.9	15.6	2	1	25.49	207.4	NA
WATE	W	0.00		50	T1	1390	0.071	1.9	15.6	2	1	25.49	206.4	NA
WATE	W	0.00		100	T1	1394	0.068	1.9	15.6	2	1	25.49	207.0	NA
WATE	W	0.00		200	T1	1360	0.113	1.9	15.6	2	1	25.49	201.9	NA
WATE	W	0.00		500	T1	1267	0.266	1.9	15.6	2	1	25.49	188.1	NA
WATE	W	0.00		1000	T1	1052	0.499	1.9	15.6	2	1	25.49	156.2	NA
WATE	W	0.00		1	T1	1463	0.012	1.9	15.6	2	2	25.49	217.2	NA
WATE	W	0.00		3	T1	1457	0.017	1.9	15.6	2	2	25.49	216.3	NA
WATE	W	0.00		5	T1	1448	0.025	1.9	15.6	2	2	25.49	215.0	NA
WATE	W	0.00		10	T1	1429	0.007	1.9	15.6	2	2	25.49	212.2	NA
WATE	W	0.00		30	T1	1397	0.045	1.9	15.6	2	2	25.49	207.4	NA
WATE	W	0.00		50	T1	1355	0.035	1.9	15.6	2	2	25.49	201.2	NA
WATE	W	0.00		100	T1	1344	0.075	1.9	15.6	2	2	25.49	199.5	NA
WATE	W	0.00		200	T1	1375	0.115	1.9	15.6	2	2	25.49	204.2	NA
WATE	W	0.00		500	T1	1412	0.251	1.9	15.6	2	2	25.49	209.6	NA
WATE	W	0.00		1000	T1	1133	0.481	1.9	15.6	2	2	25.49	168.2	NA
WATE	W	0.00		1	T1	1748	0.094	1.9	15.6	2	1	25.89	255.5	NA
WATE	W	0.00		3	T1	1714	0.064	1.9	15.6	2	1	25.89	250.6	NA
WATE	W	0.00		5	T1	1687	0.065	1.9	15.6	2	1	25.89	246.6	NA
WATE	W	0.00		10	T1	1658	0.068	1.9	15.6	2	1	25.89	242.4	NA
WATE	W	0.00		30	T1	1578	0.097	1.9	15.6	2	1	25.89	230.7	NA

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
WATE	W	0.00		50	T1	1536	0.117	1.9	15.6	2	1	25.89	224.5	NA
WATE	W	0.00		100	T1	1505	0.112	1.9	15.6	2	1	25.89	220.0	NA
WATE	W	0.00		300	T1	1404	0.195	1.9	15.6	2	1	25.89	205.2	NA
WATE	W	0.00		500	T1	1306	0.290	1.9	15.6	2	1	25.89	190.9	NA
WATE	W	0.00		1000	T1	1082	0.512	1.9	15.6	2	1	25.89	158.2	NA
WATE	W	0.00		1	T1	1748	0.094	1.9	15.6	2	2	25.89	255.5	NA
WATE	W	0.00		3	T1	1714	0.064	1.9	15.6	2	2	25.89	250.6	NA
WATE	W	0.00		5	T1	1687	0.065	1.9	15.6	2	2	25.89	246.6	NA
WATE	W	0.00		10	T1	1658	0.068	1.9	15.6	2	2	25.89	242.4	NA
WATE	W	0.00		30	T1	1578	0.097	1.9	15.6	2	2	25.89	230.7	NA
WATE	W	0.00		50	T1	1536	0.117	1.9	15.6	2	2	25.89	224.5	NA
WATE	W	0.00		100	T1	1505	0.112	1.9	15.6	2	2	25.89	220.0	NA
WATE	W	0.00		300	T1	1404	0.195	1.9	15.6	2	2	25.89	205.2	NA
WATE	W	0.00		500	T1	1306	0.290	1.9	15.6	2	2	25.89	190.9	NA
WATE	W	0.00		1000	T1	1082	0.512	1.9	15.6	2	2	25.89	158.2	NA
WATE	W	0.00		1	T1	1977	0.501	1.9	15.6	2	1	26.09	286.8	NA
WATE	W	0.00		3	T1	1740	0.261	1.9	15.6	2	1	26.09	252.4	NA
WATE	W	0.00		5	T1	1705	0.174	1.9	15.6	2	1	26.09	247.3	NA
WATE	W	0.00		10	T1	1634	0.129	1.9	15.6	2	1	26.09	237.0	NA
WATE	W	0.00		30	T1	1563	0.108	1.9	15.6	2	1	26.09	226.7	NA
WATE	W	0.00		50	T1	1531	0.116	1.9	15.6	2	1	26.09	222.1	NA
WATE	W	0.00		100	T1	1522	0.100	1.9	15.6	2	1	26.09	220.8	NA
WATE	W	0.00		300	T1	1432	0.205	1.9	15.6	2	1	26.09	207.7	NA
WATE	W	0.00		500	T1	1315	0.319	1.9	15.6	2	1	26.09	190.8	NA
WATE	W	0.00		1000	T1	1044	0.558	1.9	15.6	2	1	26.09	151.4	NA
WATE	W	0.00		1	T1	1986	0.508	1.9	15.6	2	2	26.09	288.1	NA
WATE	W	0.00		3	T1	1754	0.257	1.9	15.6	2	2	26.09	254.4	NA
WATE	W	0.00		5	T1	1685	0.188	1.9	15.6	2	2	26.09	244.4	NA
WATE	W	0.00		10	T1	1629	0.104	1.9	15.6	2	2	26.09	236.3	NA
WATE	W	0.00		30	T1	1556	0.097	1.9	15.6	2	2	26.09	225.7	NA
WATE	W	0.00		50	T1	1497	0.079	1.9	15.6	2	2	26.09	217.2	NA
WATE	W	0.00		100	T1	1467	0.110	1.9	15.6	2	2	26.09	212.8	NA
WATE	W	0.00		300	T1	1534	0.194	1.9	15.6	2	2	26.09	222.5	NA
WATE	W	0.00		500	T1	1469	0.297	1.9	15.6	2	2	26.09	213.1	NA
WATE	W	0.00		1000	T1	1129	0.538	1.9	15.6	2	2	26.09	163.8	NA
C60	C	0.60	36	1	S2	675	0.875	1.9	11.4	1	1	28.9	75.3	30
C60	C	0.60	49	1	S2	987	1.200	1.9	11.4	1	1	28.9	110.0	45
CW45	CW	0.45	13	1	S2	1109	3.240	1.9	11.4	2	1	26.8	133.3	<15
CW45	CW	0.45	13	10	S2	778	0.690	1.9	11.4	2	1	26.8	93.5	<15
CW45	CW	0.45	13	100	S2	543	0.338	1.9	11.4	2	1	26.8	65.3	<15
CW45	CW	0.45	13	1000	S2	395	0.193	1.9	11.4	2	1	26.8	47.5	<15
CW45	CW	0.45	20	1	S2	1411	6.080	1.9	11.4	2	1	26.8	169.6	15
CW45	CW	0.45	20	10	S2	782	1.299	1.9	11.4	2	1	26.8	94.0	15
CW45	CW	0.45	20	100	S2	565	0.404	1.9	11.4	2	1	26.8	67.9	15
CW45	CW	0.45	20	1000	S2	411	0.237	1.9	11.4	2	1	26.8	49.4	15
CW45	CW	0.45	31	1	S2	1450	8.660	1.9	11.4	2	1	26.8	174.3	30
CW45	CW	0.45	31	10	S2	787	1.770	1.9	11.4	2	1	26.8	94.6	30

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
CW45	CW	0.45	31	100	S2	597	0.433	1.9	11.4	2	1	26.8	71.7	30
CW45	CW	0.45	32	1000	S2	425	0.271	1.9	11.4	2	1	26.8	51.1	30
CW45	CW	0.45	45	1	S2	1313	9.950	1.9	11.4	2	1	26.8	157.8	45
CW45	CW	0.45	45	10	S2	809	1.760	1.9	11.4	2	1	26.8	97.2	45
CW45	CW	0.45	45	100	S2	640	0.403	1.9	11.4	2	1	26.8	76.9	45
CW45	CW	0.45	45	1000	S2	457	0.293	1.9	11.4	2	1	26.8	54.9	45
CW45	CW	0.45	60	1	S2	1313	9.670	1.9	11.4	2	1	26.8	157.8	60
CW45	CW	0.45	60	10	S2	800	1.730	1.9	11.4	2	1	26.8	96.1	60
CW45	CW	0.45	60	100	S2	642	0.393	1.9	11.4	2	1	26.8	77.2	60
CW45	CW	0.45	60	1000	S2	458	0.290	1.9	11.4	2	1	26.8	55.0	60
CW45	CW	0.45	76	10	S2	825	1.800	1.9	11.4	2	1	26.8	99.1	75
CW45	CW	0.45	77	100	S2	675	0.390	1.9	11.4	2	1	26.8	81.1	75
CW45	CW	0.45	78	1000	S2	479	0.305	1.9	11.4	2	1	26.8	57.6	75
FA45	FA	0.45	22	1	S2	1386	0.887	1.9	11.4	2	1	28.4	157.2	15
FA45	FA	0.45	22	10	S2	1220	0.215	1.9	11.4	2	1	28.4	138.4	15
FA45	FA	0.45	23	100	S2	995	0.267	1.9	11.4	2	1	28.4	112.8	15
FA45	FA	0.45	24	1000	S2	442	0.530	1.9	11.4	2	1	28.4	50.1	15
FA45	FA	0.45	35	1	S2	1349	1.069	1.9	11.4	2	1	28.4	153.0	30
FA45	FA	0.45	35	10	S2	1190	0.215	1.9	11.4	2	1	28.4	135.0	30
FA45	FA	0.45	35	100	S2	1021	0.239	1.9	11.4	2	1	28.4	115.8	30
FA45	FA	0.45	35	1000	S2	470	0.489	1.9	11.4	2	1	28.4	53.3	30
FA45	FA	0.45	49	1	S2	1240	0.914	1.9	11.4	2	1	28.4	140.6	45
FA45	FA	0.45	49	10	S2	1166	0.171	1.9	11.4	2	1	28.4	132.2	45
FA45	FA	0.45	50	100	S2	1055	0.255	1.9	11.4	2	1	28.4	119.6	45
FA45	FA	0.45	50	1000	S2	468	0.504	1.9	11.4	2	1	28.4	53.0	45
FA45	FA	0.45	66	1	S2	1220	0.800	1.9	11.4	2	1	28.4	138.4	60
FA45	FA	0.45	66	10	S2	1160	0.147	1.9	11.4	2	1	28.4	131.6	60
FA45	FA	0.45	67	100	S2	991	0.282	1.9	11.4	2	1	28.4	112.4	60
FA45	FA	0.45	67	1000	S2	357	0.759	1.9	11.4	2	1	28.4	40.5	60
FA45	FA	0.45	81	1	S2	2300	6.990	1.9	11.4	2	1	28.4	260.8	75
FA45	FA	0.45	82	10	S2	1082	1.603	1.9	11.4	2	1	28.4	122.7	75
FA45	FA	0.45	82	100	S2	947	0.364	1.9	11.4	2	1	28.4	107.4	75
FA45	FA	0.45	82	1000	S2	425	0.601	1.9	11.4	2	1	28.4	48.2	75
FA60	FA	0.60	30	1	S2	1036	1.350	1.9	11.4	2	1	28.5	117.1	30
FA60	FA	0.60	30	10	S2	944	0.219	1.9	11.4	2	1	28.5	106.7	30
FA60	FA	0.60	30	100	S2	848	0.184	1.9	11.4	2	1	28.5	95.8	30
FA60	FA	0.60	30	1000	S2	493	0.399	1.9	11.4	2	1	28.5	55.7	30
FA60	FA	0.60	34	1	S2	1004	1.371	1.9	11.4	2	1	28.5	113.5	30
FA60	FA	0.60	34	10	S2	940	0.209	1.9	11.4	2	1	28.5	106.2	30
FA60	FA	0.60	34	100	S2	820	0.210	1.9	11.4	2	1	28.5	92.7	30
FA60	FA	0.60	34	1000	S2	444	0.525	1.9	11.4	2	1	28.5	50.2	30
FA60	FA	0.60	50	1	S2	1078	1.387	1.9	11.4	2	1	28.5	121.8	45
FA60	FA	0.60	50	10	S2	1000	0.206	1.9	11.4	2	1	28.5	113.0	45
FA60	FA	0.60	51	100	S2	924	0.200	1.9	11.4	2	1	28.5	104.4	45
FA60	FA	0.60	51	1000	S2	442	0.544	1.9	11.4	2	1	28.5	50.0	45
FA60	FA	0.60	65	1	S2	1120	1.040	1.9	11.4	2	1	28.5	126.6	60
FA60	FA	0.60	65	10	S2	1048	0.164	1.9	11.4	2	1	28.5	118.4	60

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
FA60	FA	0.60	65	100	S2	959	0.206	1.9	11.4	2	1	28.5	108.4	60
FA60	FA	0.60	65	1000	S2	474	0.483	1.9	11.4	2	1	28.5	53.6	60
FA60	FA	0.60	82	1	S2	1180	0.769	1.9	11.4	1	1	28.5	133.4	75
FW45	FW	0.45	9	1	S2	1651	8.090	1.9	11.4	2	1	27.4	194.1	<15
FW45	FW	0.45	9	10	S2	1152	1.354	1.9	11.4	2	1	27.4	135.4	<15
FW45	FW	0.45	9	100	S2	832	0.398	1.9	11.4	2	1	27.4	97.8	<15
FW45	FW	0.45	9	1000	S2	529	0.376	1.9	11.4	2	1	27.4	62.2	<15
FW45	FW	0.45	23	1	S2	1602	9.300	1.9	11.4	2	1	27.4	188.3	15
FW45	FW	0.45	23	10	S2	1041	1.600	1.9	11.4	2	1	27.4	122.4	15
FW45	FW	0.45	23	100	S2	827	0.360	1.9	11.4	2	1	27.4	97.2	15
FW45	FW	0.45	23	1000	S2	547	0.378	1.9	11.4	2	1	27.4	64.3	15
FW45	FW	0.45	30	1	S2	1620	9.570	1.9	11.4	2	1	27.4	190.4	30
FW45	FW	0.45	30	10	S2	1033	1.670	1.9	11.4	2	1	27.4	121.4	30
FW45	FW	0.45	30	100	S2	825	0.366	1.9	11.4	2	1	27.4	97.0	30
FW45	FW	0.45	30	1000	S2	547	0.375	1.9	11.4	2	1	27.4	64.3	30
FW45	FW	0.45	47	1	S2	1594	9.860	1.9	11.4	2	1	27.4	187.4	45
FW45	FW	0.45	47	10	S2	1017	1.720	1.9	11.4	2	1	27.4	119.5	45
FW45	FW	0.45	47	100	S2	826	0.363	1.9	11.4	2	1	27.4	97.1	45
FW45	FW	0.45	47	1000	S2	551	0.375	1.9	11.4	2	1	27.4	64.8	45
FW45	FW	0.45	64	1	S2	1583	9.970	1.9	11.4	2	1	27.4	186.1	60
FW45	FW	0.45	64	10	S2	1010	1.720	1.9	11.4	2	1	27.4	118.7	60
FW45	FW	0.45	64	100	S2	823	0.362	1.9	11.4	2	1	27.4	96.7	60
FW45	FW	0.45	64	1000	S2	550	0.377	1.9	11.4	2	1	27.4	64.7	60
FW50	FW	0.50	9	1	S2	2031	8.230	1.9	11.4	2	1	29.2	224.0	<15
FW50	FW	0.50	9	1	S2	1826	8.600	1.9	11.4	2	1	29.2	201.4	<15
FW50	FW	0.50	9	10	S2	1327	1.360	1.9	11.4	2	1	29.2	146.4	<15
FW50	FW	0.50	9	100	S2	1000	0.448	1.9	11.4	2	1	29.2	110.3	<15
FW50	FW	0.50	9	1000	S2	536	0.444	1.9	11.4	2	1	29.2	59.1	<15
FW50	FW	0.50	20	1	S2	1737	8.570	1.9	11.4	2	1	29.2	191.6	15
FW50	FW	0.50	20	10	S2	1267	1.320	1.9	11.4	2	1	29.2	139.8	15
FW50	FW	0.50	20	100	S2	973	0.490	1.9	11.4	2	1	29.2	107.3	15
FW50	FW	0.50	20	1000	S2	538	0.434	1.9	11.4	2	1	29.2	59.3	15
FW50	FW	0.50	25	1	S2	1710	8.620	1.9	11.4	2	1	29.2	188.6	30
FW50	FW	0.50	25	10	S2	1242	1.349	1.9	11.4	2	1	29.2	137.0	30
FW50	FW	0.50	25	100	S2	924	0.420	1.9	11.4	2	1	29.2	101.9	30
FW50	FW	0.50	25	1000	S2	534	0.390	1.9	11.4	2	1	29.2	58.9	30
FW50	FW	0.50	33	1	S2	1524	9.370	1.9	11.4	2	1	29.2	168.1	30
FW50	FW	0.50	33	10	S2	1057	1.520	1.9	11.4	2	1	29.2	116.6	30
FW50	FW	0.50	33	100	S2	822	0.390	1.9	11.4	2	1	29.2	90.7	30
FW50	FW	0.50	33	1000	S2	519	0.352	1.9	11.4	2	1	29.2	57.2	30
FW50	FW	0.50	45	1	S2	1483	9.640	1.9	11.4	2	1	29.2	163.6	45
FW50	FW	0.50	45	10	S2	1036	1.540	1.9	11.4	2	1	29.2	114.3	45
FW50	FW	0.50	45	100	S2	816	0.384	1.9	11.4	2	1	29.2	90.0	45
FW50	FW	0.50	45	1000	S2	518	0.354	1.9	11.4	2	1	29.2	57.1	45
FW50	FW	0.50	60	1	S2	1505	9.790	1.9	11.4	2	1	29.2	166.0	60
FW50	FW	0.50	60	10	S2	1035	1.570	1.9	11.4	2	1	29.2	114.2	60
FW50	FW	0.50	60	100	S2	814	0.388	1.9	11.4	2	1	29.2	89.8	60

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
FW50	FW	0.50	60	1000	S2	519	0.349	1.9	11.4	2	1	29.2	57.2	60
FW50	FW	0.50	58	1	S2	1503	9.680	1.9	11.4	2	1	29.2	165.8	60
FW50	FW	0.50	58	10	S2	1036	1.550	1.9	11.4	2	1	29.2	114.3	60
FW50	FW	0.50	58	100	S2	814	0.387	1.9	11.4	2	1	29.2	89.8	60
FW50	FW	0.50	58	1000	S2	519	0.349	1.9	11.4	2	1	29.2	57.2	60
C45	C	0.45	29	1	S1	741	0.179	1.9	11.4	1	1	29	82.3	<15
C45	C	0.45	35	1	S1	810	1.590	1.9	11.4	1	1	29	90.0	30
C45	C	0.45	48	1	S1	761	4.320	1.9	11.4	1	1	29	84.5	45
C45	C	0.45	60	1	S1	733	4.700	1.9	11.4	2	1	29	81.4	60
C45	C	0.45	60	10	S1	565	0.737	1.9	11.4	2	1	29	62.7	60
C45	C	0.45	61	100	S1	464	0.223	1.9	11.4	2	1	29	51.5	60
C45	C	0.45	62	1000	S1	394	0.095	1.9	11.4	2	1	29	43.7	60
C50	C	0.50	22	1	S1	1547	10.000	1.9	11.4	1	1	27.1	183.9	15
C50	C	0.50	32	10	S1	933	2.910	1.9	11.4	2	1	27.1	110.9	30
C50	C	0.50	32	100	S1	697	0.570	1.9	11.4	2	1	27.1	82.8	30
C50	C	0.50	32	1000	S1	520	0.262	1.9	11.4	2	1	27.1	61.8	30
C50	C	0.50	49	10	S1	882	2.860	1.9	11.4	2	1	27.1	104.8	45
C50	C	0.50	50	100	S1	660	0.555	1.9	11.4	2	1	27.1	78.4	45
C50	C	0.50	51	1000	S1	513	0.258	1.9	11.4	2	1	27.1	60.9	45
C50	C	0.50	65	10	S1	862	2.750	1.9	11.4	2	1	27.1	102.5	60
C50	C	0.50	66	100	S1	656	0.524	1.9	11.4	2	1	27.1	78.0	60
C50	C	0.50	66	1000	S1	512	0.260	1.9	11.4	2	1	27.1	60.8	60
CW40	CW	0.40	15	1	S1	1367	7.100	1.9	11.4	2	1	28.5	154.5	15
CW40	CW	0.40	15	10	S1	920	1.247	1.9	11.4	2	1	28.5	104.0	15
CW40	CW	0.40	15	100	S1	686	0.338	1.9	11.4	2	1	28.5	77.5	15
CW40	CW	0.40	15	1000	S1	553	0.244	1.9	11.4	2	1	28.5	62.5	15
CW40	CW	0.40	17	10	S1	874	1.300	1.9	11.4	2	1	28.5	98.8	15
CW40	CW	0.40	19	1	S1	1293	8.450	1.9	11.4	2	1	28.5	146.1	15
CW40	CW	0.40	19	10	S1	835	1.470	1.9	11.4	2	1	28.5	94.4	15
CW40	CW	0.40	19	100	S1	668	0.311	1.9	11.4	2	1	28.5	75.5	15
CW40	CW	0.40	19	1000	S1	560	0.231	1.9	11.4	2	1	28.5	63.3	15
CW40	CW	0.40	30	1	S1	1309	9.730	1.9	11.4	2	1	28.5	147.9	30
CW40	CW	0.40	30	10	S1	800	1.766	1.9	11.4	2	1	28.5	90.4	30
CW40	CW	0.40	30	100	S1	655	0.320	1.9	11.4	2	1	28.5	74.0	30
CW40	CW	0.40	30	1000	S1	574	0.215	1.9	11.4	2	1	28.5	64.9	30
CW40	CW	0.40	46	10	S1	802	2.020	1.9	11.4	2	1	28.5	90.6	45
CW40	CW	0.40	46	100	S1	654	0.351	1.9	11.4	2	1	28.5	73.9	45
CW40	CW	0.40	46	1000	S1	580	0.208	1.9	11.4	2	1	28.5	65.5	45
CW40	CW	0.40	60	10	S1	806	2.070	1.9	11.4	2	1	28.5	91.1	60
CW40	CW	0.40	60	100	S1	653	0.360	1.9	11.4	2	1	28.5	73.8	60
CW40	CW	0.40	60	1000	S1	581	0.202	1.9	11.4	2	1	28.5	65.7	60
CW50	CW	0.50	17	1	S1	1500	7.580	1.9	11.4	2	1	28.1	171.9	15
CW50	CW	0.50	17	10	S1	704	1.850	1.9	11.4	2	1	28.1	80.7	15
CW50	CW	0.50	17	100	S1	550	0.369	1.9	11.4	2	1	28.1	63.0	15
CW50	CW	0.50	17	1000	S1	489	0.168	1.9	11.4	2	1	28.1	56.0	15
CW50	CW	0.50	22	1	S1	1473	9.710	1.9	11.4	2	1	28.1	168.8	15
CW50	CW	0.50	22	10	S1	688	2.290	1.9	11.4	2	1	28.1	78.9	15

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
CW50	CW	0.50	22	100	S1	547	0.395	1.9	11.4	2	1	28.1	62.7	15
CW50	CW	0.50	22	1000	S1	494	0.170	1.9	11.4	2	1	28.1	56.6	15
CW50	CW	0.50	30	10	S1	692	2.700	1.9	11.4	2	1	28.1	79.3	30
CW50	CW	0.50	30	100	S1	550	0.443	1.9	11.4	2	1	28.1	63.0	30
CW50	CW	0.50	30	1000	S1	498	0.173	1.9	11.4	2	1	28.1	57.1	30
CW50	CW	0.50	47	10	S1	683	2.280	1.9	11.4	2	1	28.1	78.3	45
CW50	CW	0.50	47	100	S1	550	0.389	1.9	11.4	2	1	28.1	63.0	45
CW50	CW	0.50	46	1000	S1	501	0.163	1.9	11.4	2	1	28.1	57.4	45
CW50	CW	0.50	62	10	S1	688	2.260	1.9	11.4	2	1	28.1	78.9	60
CW50	CW	0.50	62	100	S1	549	0.389	1.9	11.4	2	1	28.1	62.9	60
CW50	CW	0.50	62	1000	S1	502	0.160	1.9	11.4	2	1	28.1	57.5	60
CW50	CW	0.50	82	1	S1	1326	9.750	1.9	11.4	2	1	28.1	152.0	75
CW50	CW	0.50	82	10	S1	680	2.100	1.9	11.4	2	1	28.1	77.9	75
CW50	CW	0.50	82	100	S1	544	0.371	1.9	11.4	2	1	28.1	62.3	75
CW50	CW	0.50	82	1000	S1	500	0.154	1.9	11.4	2	1	28.1	57.3	75
FA50	FA	0.50	25	10	S1	879	3.000	1.9	11.4	2	1	27.6	102.6	30
FA50	FA	0.50	25	100	S1	673	0.558	1.9	11.4	2	1	27.6	78.5	30
FA50	FA	0.50	26	1000	S1	496	0.287	1.9	11.4	2	1	27.6	57.9	30
FA50	FA	0.50	32	10	S1	899	3.420	1.9	11.4	2	1	27.6	104.9	30
FA50	FA	0.50	32	100	S1	677	0.613	1.9	11.4	2	1	27.6	79.0	30
FA50	FA	0.50	32	1000	S1	499	0.300	1.9	11.4	2	1	27.6	58.2	30
FA50	FA	0.50	53	10	S1	907	3.540	1.9	11.4	2	1	27.6	105.8	60
FA50	FA	0.50	53	100	S1	696	0.613	1.9	11.4	2	1	27.6	81.2	60
FA50	FA	0.50	53	1000	S1	498	0.320	1.9	11.4	2	1	27.6	58.1	60
FA50	FA	0.50	65	10	S1	879	3.630	1.9	11.4	2	1	27.6	102.5	60
FA50	FA	0.50	65	100	S1	696	0.606	1.9	11.4	2	1	27.6	81.2	60
FA50	FA	0.50	65	1000	S1	496	0.320	1.9	11.4	2	1	27.6	57.9	60
FA50	FA	0.50	80	10	S1	813	4.130	1.9	11.4	2	1	27.6	94.8	75
FA50	FA	0.50	80	100	S1	669	0.644	1.9	11.4	2	1	27.6	78.0	75
FA50	FA	0.50	80	1000	S1	488	0.306	1.9	11.4	2	1	27.6	56.9	75
FW45	FW	0.45	21	1	S1	4060	4.550	1.9	11.4	2	1	28.8	454.0	15
FW45	FW	0.45	21	10	S1	1082	2.180	1.9	11.4	2	1	28.8	121.0	15
FW45	FW	0.45	21	100	S1	695	0.473	1.9	11.4	2	1	28.8	77.7	15
FW45	FW	0.45	21	1000	S1	587	0.264	1.9	11.4	2	1	28.8	65.6	15
FW45	FW	0.45	25	1	S1	3640	4.660	1.9	11.4	2	1	27.1	432.6	15
FW45	FW	0.45	25	10	S1	1080	2.170	1.9	11.4	2	1	27.1	128.4	15
FW45	FW	0.45	25	100	S1	694	0.465	1.9	11.4	2	1	27.1	82.5	15
FW45	FW	0.45	25	1000	S1	592	0.255	1.9	11.4	2	1	27.1	70.4	15
FW45	FW	0.45	30	1	S1	3520	4.800	1.9	11.4	2	1	27.1	418.3	30
FW45	FW	0.45	30	10	S1	1081	2.130	1.9	11.4	2	1	27.1	128.5	30
FW45	FW	0.45	30	100	S1	699	0.461	1.9	11.4	2	1	27.1	83.1	30
FW45	FW	0.45	30	1000	S1	600	0.251	1.9	11.4	2	1	27.1	71.3	30
FW45	FW	0.45	45	1	S1	3210	5.420	1.9	11.4	2	1	27.1	381.5	45
FW45	FW	0.45	45	10	S1	1017	2.190	1.9	11.4	2	1	27.1	120.9	45
FW45	FW	0.45	45	100	S1	704	0.440	1.9	11.4	2	1	27.1	83.7	45
FW45	FW	0.45	45	1000	S1	611	0.238	1.9	11.4	2	1	27.1	72.6	45
FW45	FW	0.45	62	1	S1	3362	3.850	1.9	11.4	2	1	27.1	399.6	60

Appendix 1_Capacitance Lab Data

Mix Id	Grp	w/c	Time	freq	Device	Cap	D	a	b	Eq	Voltage	Hc	er	Nom t
FW45	FW	0.45	62	10	S1	1005	1.805	1.9	11.4	2	1	27.1	119.4	60
FW45	FW	0.45	62	100	S1	699	0.379	1.9	11.4	2	1	27.1	83.1	60
FW45	FW	0.45	62	1000	S1	612	0.224	1.9	11.4	2	1	27.1	72.7	60
FW50	FW	0.50	16	1	S1	2848	7.010	1.9	11.4	2	1	29.4	312.0	15
FW50	FW	0.50	16	10	S1	952	2.480	1.9	11.4	2	1	29.4	104.3	15
FW50	FW	0.50	16	100	S1	722	0.449	1.9	11.4	2	1	29.4	79.0	15
FW50	FW	0.50	16	1000	S1	593	0.275	1.9	11.4	2	1	29.4	64.9	15
FW50	FW	0.50	30	1	S1	3041	8.090	1.9	11.4	2	1	29.4	333.1	30
FW50	FW	0.50	30	10	S1	974	2.930	1.9	11.4	2	1	29.4	106.7	30
FW50	FW	0.50	30	100	S1	728	0.507	1.9	11.4	2	1	29.4	79.8	30
FW50	FW	0.50	30	1000	S1	610	0.271	1.9	11.4	2	1	29.4	66.8	30
FW50	FW	0.50	45	1	S1	3129	8.510	1.9	11.4	2	1	29.4	342.8	45
FW50	FW	0.50	45	10	S1	991	3.100	1.9	11.4	2	1	29.4	108.6	45
FW50	FW	0.50	45	100	S1	729	0.538	1.9	11.4	2	1	29.4	79.9	45
FW50	FW	0.50	45	1000	S1	615	0.269	1.9	11.4	2	1	29.4	67.4	45
FW50	FW	0.50	60	1	S1	2914	8.450	1.9	11.4	2	1	29.4	319.2	60
FW50	FW	0.50	60	10	S1	963	2.940	1.9	11.4	2	1	29.4	105.5	60
FW50	FW	0.50	60	100	S1	727	0.501	1.9	11.4	2	1	29.4	79.6	60
FW50	FW	0.50	60	1000	S1	616	0.262	1.9	11.4	2	1	29.4	67.5	60
FW50	FW	0.50	55	1	S1	2965	8.190	1.9	11.4	2	1	29.4	324.8	60
FW50	FW	0.50	55	10	S1	964	2.930	1.9	11.4	2	1	29.4	105.6	60
FW50	FW	0.50	55	100	S1	726	0.500	1.9	11.4	2	1	29.4	79.5	60
FW50	FW	0.50	55	1000	S1	615	0.263	1.9	11.4	2	1	29.4	67.4	60

Appendix 2: Mixtures Data

READY MIXED CONCRETE COMPANY

CLIENT:	Ready Mixed Concrete Company					REVIEWED:	Godwin Amekuedi		
PROJECT:	NCSU_Research_Part I					DATE:			
REGION:	Corporate Research Center					TEST LOCATION:	Corporate Research Center		
CONTACT:	Ken Vickers / Dr. Mike Leming					Test Date:	August 8, 2006		
Comments:					1st Curve			3rd Curve		
					C60	C50	C45	N/A		
					MIX 1	MIX 2	MIX 3	MIX 7	MIX 8	MIX 9
Material	TYPE	SOURCE		UNITS	(SSD)	(SSD)	(SSD)	(SSD)	(SSD)	(SSD)
Cement	I/II	Roanoke		lb/pcy	500	600	667	#DIV/0!	#DIV/0!	#DIV/0!
Fly Ash	F	Boral		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Slag	0	N/A		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Sand 2	C-33	N/A		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Sand 1	C-33	Mid-East Services_Riverside		lb/pcy	1276	1205	1150	#DIV/0!	#DIV/0!	#DIV/0!
Rock 1	C-33	Wake Stone-Triangle #67		lb/pcy	1720	1720	1720	#DIV/0!	#DIV/0!	#DIV/0!
Rock 2	C-33	N/A		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Water	C-29	City		lb/pcy	300	300	300	#DIV/0!	#DIV/0!	#DIV/0!
Air				%	5.00	5.00	5.00	0.00	0.00	0.00
Admix A	g	BASF	Pozzolith 80	oz/cwt	0.0	0.0	0.0	0.0	0.0	0.0
Admix B	g	0	0	oz/cwt	0.0	0.0	0.0	0.0	0.0	0.0
Admix C	g	0	0	oz/cwt	0.0	0.0	0.0	0.0	0.0	0.0
Admix D	g	0	0	oz/cwt	0.0	0.0	0.0	0.0	0.0	0.0
Admix E	g	BASF	Micro Air	oz/pcy	1.82	3.04	4.61	#DIV/0!	#DIV/0!	#DIV/0!
FRESHLY MIXED CONCRETE PROPERTIES										
Intial Slump				inch	3.00	2.50	2.25	0.00	0.00	0.00
Final Slump				inch	3.00	2.50	2.25	0.00	0.00	0.00
Unit Weight				lbs/pcf	142.30	144.00	144.26	0.00	0.00	0.00
Air Content				%	5.30	4.80	4.80	0.00	0.00	0.00
Concrete Temperature				°F	69	69	69	0	0	0
Ambient Temperature				°F	64	68	67	0	0	0
Set Time				H:M	##########	##########	##########	0:00	0:00	0:00
Water/Cementitous Ratio				W/C	0.60	0.50	0.45	#DIV/0!	#DIV/0!	#DIV/0!
HARDENED CONCRETE PROPERTIES										
Compressive Strength	3 Days			Psi						
Compressive Strength	7 Days			Psi	***3820***	***4770***	***4370***			
Compressive Strength	28 Days			Psi	***5230***	***6490***	***6030***			
Compressive Strength	56 Days			Psi						
Comments:					2nd Curve			4th Curve		
					FA60	FA50	FA45	N/A		
					MIX 4	MIX 5	MIX 6	MIX 10	MIX 11	MIX 12
Material	TYPE	SOURCE		UNITS	(SSD)	(SSD)	(SSD)	(SSD)	(SSD)	(SSD)
Cement	I/II	Roanoke		lb/pcy	400	480	532	#DIV/0!	#DIV/0!	#DIV/0!
Fly Ash	F	Boral		lb/pcy	100	120	135	#DIV/0!	#DIV/0!	#DIV/0!
Slag	0	N/A		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Sand 2	C-33	N/A		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Sand 1	C-33	Mid-East Services_Riverside		lb/pcy	1245	1163	1101	#DIV/0!	#DIV/0!	#DIV/0!
Rock 1	C-33	Wake Stone-Triangle #67		lb/pcy	1720	1720	1720	#DIV/0!	#DIV/0!	#DIV/0!
Rock 2	C-33	N/A		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Water	C-29	City		lb/pcy	300	300	300	#DIV/0!	#DIV/0!	#DIV/0!
Air				%	5.00	5.00	5.00	0.00	0.00	0.00
Admix A	g	BASF	Pozzolith 80	oz/cwt	0.0	0.0	0.0	0.0	0.0	0.0
Admix B	g	0	0	oz/cwt	0.0	0.0	0.0	0.0	0.0	0.0
Admix C	g	0	0	oz/cwt	0.0	0.0	0.0	0.0	0.0	0.0
Admix D	g	0	0	oz/cwt	0.0	0.0	0.0	0.0	0.0	0.0
Admix E	g	BASF	Micro Air	oz/pcy	3.04	3.65	4.26	#DIV/0!	#DIV/0!	#VALUE!
FRESHLY MIXED CONCRETE PROPERTIES										
Intial Slump				inch	4.00	4.00	5.00	0.00	0.00	0.00
Final Slump				inch	4.00	4.00	5.00	0.00	0.00	0.00
Unit Weight				lbs/pcf	141.13	142.17	141.93	0.00	0.00	0.00
Air Content				%	6.40	5.10	5.10	0.00	0.00	0.00
Concrete Temperature				°F	69	69	70	0	0	0
Ambient Temperature				°F	69	70	70	0	0	0
Set Time				H:M	##########	##########	##########	0:00	0:00	0:00
Water/Cementitous Ratio				W/C	0.60	0.50	0.45	#DIV/0!	#DIV/0!	#DIV/0!
HARDENED CONCRETE PROPERTIES										
Compressive Strength	3 Days			Psi						
Compressive Strength	7 Days			Psi	***2410***	***3490***	***3700***			
Compressive Strength	28 Days			Psi	***3770***	***4710***	***5160***			
Compressive Strength	56 Days			Psi						

CLIENT:	Ready Mixed Concrete Company	REVIEWED:	Godwin Amekuedi
PROJECT:	NCSU_Research_Part II	DATE:	
REGION:	Corporate Research Center	TEST LOCATION:	Corporate Research Center
CONTACT:	Ken Vickers / Dr. Mike Leming	Test Date:	August 17, 2006

Comments:

					1st Curve			3rd Curve		
					CW50	CW45	CW40	N/A		
					MIX 1	MIX 2	MIX 3	MIX 7	MIX 8	MIX 9
Material	TYPE	SOURCE		UNITS	(SSD)	(SSD)	(SSD)	(SSD)	(SSD)	(SSD)
Cement	I/II	Roanoke		lb/pcy	550	611	668	#DIV/0!	#DIV/0!	#DIV/0!
Fly Ash	F	Boral		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Slag	0	N/A		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Sand 2	C-33	N/A		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Sand 1	C-33	Mid-East Services_Riverside		lb/pcy	1294	1250	1214	#DIV/0!	#DIV/0!	#DIV/0!
Rock 1	C-33	Wake Stone-Triangle #67		lb/pcy	1720	1720	1720	#DIV/0!	#DIV/0!	#DIV/0!
Rock 2	C-33	N/A		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Water	C-29	City		lb/pcy	275	275	275	#DIV/0!	#DIV/0!	#DIV/0!
Air				%	5.00	5.00	5.00	0.00	0.00	0.00
Admix A	g	BASF	Pozzolith 80	oz/cwt	4.0	4.0	4.0	0.0	0.0	0.0
Admix B	g	BASF	Rheobuild 1000	oz/cwt	0.0	0.0	4.0	0.0	0.0	0.0
Admix C	g	0	0	oz/cwt	0.0	0.0	0.0	0.0	0.0	0.0
Admix D	g	0	0	oz/cwt	0.0	0.0	0.0	0.0	0.0	0.0
Admix E	g	BASF	Micro Air	oz/pcy	1.52	1.52	1.84	#DIV/0!	#DIV/0!	#DIV/0!
FRESHLY MIXED CONCRETE PROPERTIES										
Intial Slump				inch	3.00	2.75	3.00	0.00	0.00	0.00
Final Slump				inch	3.00	2.75	3.00	0.00	0.00	0.00
Unit Weight				lbs/pcf	142.11	143.08	146.76	0.00	0.00	0.00
Air Content				%	6.00	5.50	4.10	0.00	0.00	0.00
Concrete Temperature				°F	68	68	69	0	0	0
Ambient Temperature				°F	68	70	70	0	0	0
Set Time				H:M	0:00	0:00	0:00	0:00	0:00	0:00
Water/Cementitous Ratio				W/C	0.50	0.45	0.40	#DIV/0!	#DIV/0!	#DIV/0!
HARDENED CONCRETE PROPERTIES										
Compressive Strength	3 Days			Psi	N/A	N/A	N/A			
Compressive Strength	7 Days			Psi	4030	4670	5750			
Compressive Strength	28 Days			Psi	5620	6450	7890			
Compressive Strength	56 Days			Psi						

Comments:

Disregard Mixes FW50, FW45 & FW40. Contaminated Materials

					2nd Curve			4th Curve		
					FW50	FW45	FW40	N/A		
					MIX 4	MIX 5	MIX 6	MIX 10	MIX 11	MIX 12
Material	TYPE	SOURCE		UNITS	(SSD)	(SSD)	(SSD)	(SSD)	(SSD)	(SSD)
Cement	I/II	Roanoke		lb/pcy	440	490	550	#DIV/0!	#DIV/0!	#DIV/0!
Fly Ash	F	Boral		lb/pcy	110	121	138	#DIV/0!	#DIV/0!	#DIV/0!
Slag	0	N/A		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Sand 2	C-33	N/A		lb/pcy	0	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Sand 1	C-33	Mid-East Services_Riverside		lb/pcy	1311	1229	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Rock 1	C-33	Wake Stone-Triangle #67		lb/pcy	1720	1720	1720	#DIV/0!	#DIV/0!	#DIV/0!
Rock 2	C-33	N/A		lb/pcy	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Water	C-29	City		lb/pcy	275	275	275	#DIV/0!	#DIV/0!	#DIV/0!
Air				%	5.00	5.00	5.00	0.00	0.00	0.00
Admix A	g	BASF	Pozzolith 80	oz/cwt	4.0	4.0	4.0	0.0	0.0	0.0
Admix B	g	BASF	Rheobuild 1000	oz/cwt	4.0	0.0	0.0	0.0	0.0	0.0
Admix C	g	0	0	oz/cwt	0.0	0.0	0.0	0.0	0.0	0.0
Admix D	g	0	0	oz/cwt	0.0	0.0	0.0	0.0	0.0	0.0
Admix E	g	BASF	Micro Air	oz/pcy	3.65	2.43	0.00	#DIV/0!	#DIV/0!	#VALUE!
FRESHLY MIXED CONCRETE PROPERTIES										
Intial Slump				inch	2.50	4.25	0.00	0.00	0.00	0.00
Final Slump				inch	2.50	4.25	0.00	0.00	0.00	0.00
Unit Weight				lbs/pcf	146.66	143.71	0.00	0.00	0.00	0.00
Air Content				%	3.30	4.40	0.00	0.00	0.00	0.00
Concrete Temperature				°F	70	70	0	0	0	0
Ambient Temperature				°F	70	72	0	0	0	0
Set Time				H:M	0:00	0:00	0:00	0:00	0:00	0:00
Water/Cementitous Ratio				W/C	0.50	0.45	0.40	#DIV/0!	#DIV/0!	#DIV/0!
HARDENED CONCRETE PROPERTIES										
Compressive Strength	3 Days			Psi	N/A	N/A	N/A			
Compressive Strength	7 Days			Psi	4980	4090				
Compressive Strength	28 Days			Psi	6980	5710				
Compressive Strength	56 Days			Psi						