DURABILITY OF PAVEMENT CONCRETE WITH REPLACEMENT OF CEMENT BY FLYASH AND PORTLAND LIMESTONE CEMENT

by

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ABSTRACT

CLAYTON DAVIS MEDLIN Durability of pavement concrete with replacement of cement by fly ash and limestone cement (Under direction of Dr. BRETT Q. TEMPEST)

The durability of concrete can be directly related to the permeability of the concrete. While the permeability is not the only characteristic that can relate to durability, it is amongst the most important predictors of service life. Lower permeability is related to increased durability. The less permeable a concrete mixture is the less likely the concrete will deteriorate from freezing action and ingress of deleterious chemicals.

Durability measured through the use of permeability testing was used on different pavement concrete mixtures for this study. The North Carolina Department of Transportation provided mixtures that are best representative of the actual mixtures used in the state for pavement. The pavement mixtures varied in composition of cementitious materials. Different cements and cementitious materials, including a portland limestone cement and cement replacement by fly ash, were used in the mixtures to provide a durability comparison. The *w/cm* ratio, slump, and air content were kept constant to provide a better comparison for the effects of the cement and replacements of cement. To give a control mix for better comparison, an ordinary portland cement mixture (OPC) was compared against OPC mixtures with fly ash and portland limestone cement mixtures (PLC) both with and without fly ash.

The permeability of the concrete can be measured by a variety of permeability tests. The tests used in this study are the rapid chloride penetration test, the surface resistivity test, the sorptivity test and the air permeability test. Some of these tests are very well established, such as the rapid chloride penetration test (RCPT), and others like the surface resistivity test, and were compared to the more established tests to determine if it was a viable test to be used. The surface resistivity test and RCPT were found to be very well correlated, which agreed with the literature. When trying to analyze the results, it was determined that a better way to categorize the permeability of the concrete was needed. To try to better categorize the mixtures, the major permeability tests mentioned were used to create a permeability index.

When analyzing the results from the permeability test, it is obvious that the mixtures containing both fly ash and limestone have a lower permeability; this means these mixtures will have higher durability. The fly ash addition had the greatest reduction effect on the permeability of the mixtures. The mixtures containing portland limestone cement did not have as significant of a reduction in permeability when compared to when fly ash was added, but the reduction was present. The limestone only aided in reduction of permeability when fly ash was present in the mixture. These results were expected based on the literature. One main reason for the increase in durability is from the increase in particle packing that reduces the size of the pores and decreases the permeability. The results also show that some test methods are much more representative of the actual permeability than others.

The results proved that the addition of fly ash and limestone gave significant reductions in permeability. This significant reduction would mean an increase in durability of the concrete that would be very useful for the NCDOT to increase the service life of their pavements used around the state. The permeability index used to help prove this significant reduction had some very good correlations to the test methods used to develop the index, but a wider range of mixtures would help validate the index.

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CHAPTER 1: INTRODUCTION

1.1 The Use of Supplementary Cementitious Materials Effects on Concrete Quality

The concrete industry is seeking alternative materials to offset the use of portland cement in concrete mixtures in order to reduce costs, energy use and emissions. For each new supplementary cementitious material (SCM) that can potentially replace a portion of the portland cement, there must be a thorough evaluation to ensure the original quality of the concrete is not compromised (FHWA). Through research it has been clearly demonstrated that some of the SCMs have a positive impacts on the concrete mixture compared to mixtures that only contain portland cement. A few of these SCMs are: fly ash, slag, and limestone. Use of fly ash as an SCM in concrete has been researched heavily and some of the resulted positive impacts are higher late age strength gain and lower permeability (Thomas 2007). The process of inter-grinding limestone with portland cement clinker has been researched less frequently, but some research results suggest that the limestone can increase early strength through additional hydration processes (Tennis et al, 2011) and also reduce permeability (Tsivilis et al, 2003).

1.2 Problem Statement

It has been found that there are benefits to using both fly ash and portland cement containing inter-ground limestone in concrete mixtures (Hooton et al., 2007). Very little existing research was found pertaining to this combination of PLC and SCMs, and the studies that were available suggested additional positive impacts to this combination (Yoshitake et al., 2013). Durability impacts were one of the areas not highlighted in this research.

The research study presented in this thesis was performed to help fill the gap of durability performance of concrete mixtures when portland limestone cement is used in combination with fly ash.

1.3 Scope of Research

The research performed was done by comparing concrete mixtures with either a Portland cement with inter-ground limestone (PLC) or an ordinary Portland cement (OPC). Fly ash was used as a cement replacement in some of the PLC and OPC mixtures to determine the effect of fly ash addition. The control mixture was an OPC mixture with no cement replacement by fly ash.. Durability tests were performed on each mixture at various ages of curing. The mixtures were pavement mixtures specified by the NCDOT with local cements and aggregates used to better represent the mixtures that the NCDOT might use in the field. To facilitate performance comparisons, these mixtures were held to a single specific water to cement ratio (*w/cm*) ratio, and were each batched at slumps and air contents that were held to a tight tolerance.

1.4 Research Objectives

The research objectives are as follows:

- First, to determine the positive and negative attributes that inter-ground limestone cement and fly ash can impart when they are used in the concrete mixture.

- Second, to design, batch, and perform durability tests on concrete mixtures that use combinations of inter-ground limestone cement, fly ash and portland cement together in a ternary system.
- Third, compare the results from the durability testing to those of similar mixtures that do not include the combination of fly ash and portland limestone cement.
- Fourth, draw conclusions on the concrete durability from the results and make recommendations on the use of the fly ash as an SCM and the inter-ground limestone cement .

CHAPTER 2: LITERATURE REVIEW

2.1 Effects of Fly Ash on Concrete Durability

Supplementary cementitious materials (SCMs) such as fly ash, silica fume, slag and many others are used in concretes to replace a portion of the cement used in the mix. SCMs have a cementitious characteristic due to hydraulic activity, pozzolanic activity, or a combination of the two. Pozzolans are siliceous and aluminous materials that react with moisture and calcium hydroxide to form cementitious compounds (Thomas 2007). The SCMs also have much durability, strength, economic and cost saving benefits when used in the concrete.

Fly ash is a byproduct of a coal burning power plant. The coal is pulverized before it is placed into the furnace and then ignited. The fly ash is the ash that stays in the exhaust gas from the furnace and is collected in the exhaust filtering systems. The ash is collected from the filtering systems and stored either dry, or it is placed in a pond for holding. The ash can then be distributed for many uses in geotechnical and structural materials. This study only describes the use of fly ash as a supplementary cementitious material (American Coal Ash Association 2003).

Fly ash particles are typically very fine spherical shapes. Particles diameters range from 10 to 100 microns and are generally smaller than portland cement particles and limestone particles. Fly ash particles consist mainly of silicon oxide, aluminum oxide, iron oxide, and calcium oxide (American Coal Ash Association 2003). The two allowable classifications of fly ash used in concrete are: Class C fly ash and Class F fly ash based on ASTM C 618: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (ASTM 2015). Class C ash is normally produced by plants that burn sub-bituminous coal and are made primarily of alumino-silicate glass, quartz, tri-calcium, and calcium oxide (lime). The Class C fly ash normally has twenty percent or more lime content by mass and is considered a high calcium fly ash. Class C ash may contribute cementitious characteristics through the hydration of calcium oxide and other hydraulically active phases. The Class F fly ash is obtained from the burning of bituminous coal consisting of alumino-silcate glass, quartz, mullite, and magnetite. Class F fly ash typically has less than ten percent lime and is considered a low calcium fly ash (American Coal Ash Association 2003). Both Class C and Class F fly ash can be used as mineral admixtures in a concrete mix design.

The use of fly ash in concrete has many benefits. The spherical shape of the particles helps improve the workability of the concrete and can increase the slump of the concrete without addition of a water reducing admixture or extra water (Langan and Ward 1990). The fly ash also increases the ultimate strength of the concrete if given proper curing time (Neville 2012). The fly ash improves durability by reducing permeability, resisting sulfate attack, resisting alkali-silica reactivity (ASR) and reducing shrinkage (American Coal Ash Association 2003). Using fly ash in concrete can also reduce the amount of cement used which can have an economical benefit as well as an environmental benefit (American Coal Ash Association 2003).The increase in compressive strength is given by the additional calcium silicate hydrate (C-S-H) produced in a reaction of the silica from the fly ash and left over calcium hydroxide from the cement reaction (American Coal Ash Association 2003; Thomas 2007).

Some disadvantages are present with fly ash also. The presence of fly ash can cause lower early strength in the concrete, and it tends to reduce effectiveness of air entraining admixtures if the fly ash has a high carbon content (American Coal Ash Association 2003; Thomas 2007).

One of fly ash's most beneficial impacts is reducing the amount of calcium hydroxide left over from the hydration process. Calcium hydroxide is highly soluble in water and can cause air voids in the concrete as it is removed from the matrix by dissolution. This reduces strength and increase permeability (Smith 1984). The calcium hydroxide reacts with the silica and alumina from the fly ash to form calcium silicates, and calcium aluminates which hydrate just like cementitious compounds. This pozzolanic reaction can continue until there is very little calcium hydroxide left (Smith 1984).

2.2 Effects of Portland Limestone Cement on Concrete Durability

Portland limestone cement (PLC), containing inter-ground limestone, also reduces the amount of cement used in concrete mix designs. The use of PLC is governed by state DOT specifications as well as the standard ASTM C595: Standard Specification for Blended Hydraulic Cements (ASTM 2015). The document considers a limestone addition of 5% to 15%. In the "State of the Art Report on Use of Limestone in Cements at Levels of up to 15%, Tennis et al. (2011) state that the limestone addition can provide equivalent performance when compared to other similar concretes.

The limestone can be added to the cement at many different stages of the cement and concrete production. Limestone can be interground with the clinker, it can be added to the cement as a powder and mixed in before the concrete production, or it can be added in with the cement in the concrete production process (Tennis et al., 2011).

Use of PLC in concrete can provide equivalent strength and durability characteristics when compared to ordinary portland cement (OPC) concrete performance. Uses can have positive impacts on the performance of the concrete from the limestone contributing to the microstructure of the concrete when the fineness and chemistry are optimized. The PLC can have a positive effect on hydration and react with the calcium aluminate to form the pozzolonic effect (Tennis et al., 2011). The limestone can improve the particle size distribution of the cement due to the fact that the limestone has a tendency to be softer than the clinker and grinds to a finer powder when inter-ground into the clinker (Tennis et al., 2011). The better particle size distribution from the inter-grinding of the limestone and clinker comes from the limestone making up the majority of the smaller particle sizes that range from 7 to 10 µm, and the clinker particle sizes being closer to 15 µm which means the concrete will exhibit a lower water demand (Tennis et al., 2011).

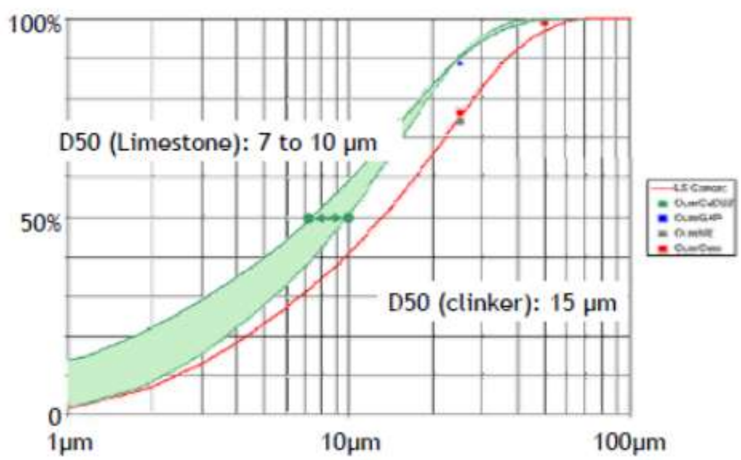

Figure 2.1: Limestone particle size distribution (Tennis et al., 2011)

The addition of limestone has also been shown to increase early compressive strength as long as a lower percentage of limestone is added <8% replacement of cement and the limestone is ground finer than the cement (Tennis et al., 2011). When levels of limestone exceed 15%, it has been shown to have a negative impact on the compressive strength (Tennis et al., 2011). Another measure of performance in which PLC shows largely equivalent results in is the freeze thaw test. These data came mainly from non-air entrained mixtures from European studies, and very little data was found on air entrained studies (Tennis et al., 2011).

Tsivilis et al. (2003) conducted a study on the permeability of PLC concretes and found that the gas permeability of the concrete increased compared to ordinary portland cement (OPC) concrete, while sorptivity and liquid permeability decreased with the addition of ground limestone. In this study, researchers analyzed concrete produced using limestone replacement amounts of 15% to 35%, showing that the increase in limestone resulted in a trend of increasing porosity. This study states that permeability of concrete is not just a function of porosity but a combination of its size, distribution, tortuosity, and continuity of the pores. In different tests, different means are utilized to measure characteristics of the concrete. Gas permeability is more highly correlated to the overall porosity, and the liquid permeability being affected by the size and kinds of pores in the concrete (Tsivilis et al., 2003). The ground limestone has a much smaller particle size, 7 to 10μm, which in turn increases particle packing and helps block capillary pores. As a result, permeability is reduced (Githachuri and Alexander 2013). This effect can be increased based on the how fine the limestone is ground. The limestone can range from a course limestone particle around 100 microns and down to the fine particle size of around 0.3 microns or lower for the powder limestone (Hooton et al., 2007).

Arora et al. (2016) used PLC and slag in concrete mixtures to determine the attributes given to the concrete with these materials. This study also found that the addition of the limestone gave the mixture a better particle packing. One of the most relevent findings from this study was of the porsitiy and pore size of the concrete mixtures. This study found that both the pore size and porsity of the concrete mixtures was lower in the control OPC mixture than in the PLC-slag mixture at 28 days. The study states that this is likely due to the limestone and slag not having the same hydration as cement.

The study focuses on the pore size diameter as well. The finding for the pore size diameter were that the critical pore diameter representents the permeability of the concrete. It was found that the PLC-slag mixtures had evidence of pore size refinement by decreasing pore size with increasing levels of cement replacement. The refinement was found for many different levels of replacement and at higher leveles of replacement the porosity if the concrete was reported to increase but the pore size still showed refinement. The conculsion that was found was that the change in pore size was within a small range and the replacement of cement does not have a adverse effect on trnasport-controlling pores (Arora et al. 2016).

PLC has many non-performance based positive impacts on the concrete process such as a reduction of CO_2 emissions, improved workability of the concrete. The reduced CO_2 emission comes from the replacement of cement. The cement undergoes a much more energy-intensive manufacturing process than the limestone. The limestone refining process also does not produce as many greenhouse gas emissions, leading to a total reduction in emissions with higher percentages of interground limestone used in the cement. This reduction can be seen when limestone is inter-ground in the cement and when it is used as an additive but is more effective when inter-ground due to reductions in emissions associated with packaging and transporting of the limestone (Hooton et al., 2007).

The addition of limestone also gives an increase in work ability similar to the fly ash addition. The limestone is normally ground finer that the cement during the inter-grinding process and results in better particle size distribution of the cement paste. The better particle size distribution creates a better flow of the cement (Hooton et al., 2007).

2.3 Effects of Utilizing Portland Limestone Cement and Fly Ash on Concrete Durability

Fly ash is one of the largest industrial wastes from coal-burning power plants. It is produced daily as a byproduct and is piled up all over the world (Yoshitake et al., 2013). Limestone is the most widely used mineral in the cement industry and is composed of calcium carbonate (Thongsanitgarn et al., 2010). Limestone when used in concrete is known to help gain strength at an early age while fly ash is known to help gain strength at a mature age (Hooton et al., 2007). For this reason alone, there is a desire to replace an optimal amount of cement in a concrete mixture with a combination of limestone and fly ash to optimize strength and durability.

The use of replacement materials such as fly ash and limestone in portland cement have been increasing over recent years. Yilmaz (2008) conducted a study of cements and mortars containing fly ash and limestone replacements. This study built upon previous studies that resulted in cement containing limestone exhibiting higher early strength compared to ordinary portland cement. With the knowledge gained that fly provides late age strength gains, this study combined the two. The materials used in the Yilmaz study were portland cement (PC), coal fly ash, limestone and dolomitic limestone. The fly ash met the general requirements of ASTM class F (Yilmaz and Olgun 2008). In this study, replacement rates of 5-40% fly ash, 5-15% limestone, and 5-15% dolomitic limestone were utilized in the concrete mixtures. It was stated that the increase of concrete early strength was an effect of the limestone having an active role in the hydration process. In this study, it was found that the addition of limestone helped increase the early compressive strengths compared to just fly ash alone. Also, the increase of early strength was more pronounced in the use of fly ash and limestone compared to the dolomitic limestone and the same fly ash (Yilmaz and Olgun 2008). Other studies have confirmed that the limestone does increase early age strength and can be used to offset the lower early age strength fly ash causes (Yoshitake et al., 2013).

Yoshitake (2013) states that fly ash can improve the workability and durability of cement concretes. Limestone is known for its effect of strengthening concrete at an early age (Yoshitake et al., 2013). The fly ash mixed with limestone may help develop an early age strength that a mixture with fly ash alone may not (Yoshitake et al., 2013). In this study, fly ash, cement, and limestone were used. The fly ash, similar to Yilmaz's study, had properties similar to Class F fly ash. The cement used was ordinary portland cement. This study took place during the summer because environmental conditions in that season are most severe for concrete cracking (Yoshitake et al., 2013). All concretes were made in a concrete plant and were transported to the field. The specimens were tested for uniaxial tensile and flexural strengths at 1, 2, 3, 5, 7 and 28 days. Results show that limestone fillers increase the strength at an early age even in high volume fly ash concrete (Yoshitake et al., 2013).

One of the downsides of use of fly ash in concrete is its impact on the rate of early age strength gain, which is typically slower (Yoshitake et al., 2013). However, it appears that limestone cement can offset this downfall by increasing the compressive strength at early ages (Yoshitake et al., 2013). Concrete containing fly ash will continue to have a high later age strength, so the combination has positive effects both economically and structurally. Future research can be conducted on concretes containing fly ash and limestone cements in the areas of lower temperature rise, lower permeability, and a larger carbonation depth than pure cement mixtures (Jin and Mengyuan 2014). The use of fly ash and inter-ground limestone in cement will continue to become the rule rather than an exception (Langan and Ward 1990).

2.4 Permeability on Concrete Durability

Concrete is inherently a durable material (Mindess et al., 2003). It is essential for concrete to withstand harsh conditions, as planned for, without deterioration of the structure. Deterioration of concrete is rarely caused by a single factor. Internal (chemical) and external (physical) factors can combine to break down the concrete's pore structure (Neville 2012; Mindess et al., 2003). The difficulty that arises when trying to predict a structure's long term durability is determining the behavior of the in-service concrete on the basis of short term test results.

The most influential parameter linked to concrete durability is the water to cement ratio (*w/cm*) which affects the permeability of the concrete (Mindess et al., 2003). Permeability determines the ease of which a concrete sample can become saturated with water. This is important because the water that enters into the concrete may be filled with a variety of aggressive chemicals that could deteriorate the concrete (Mindess et al., 2003). Permeability is related to the initial pore structure of the concrete mixtures (Neville 2012). While some applications, such as permeable concrete, are designed for water infiltration, most structures are required to be to be impermeable as much as practicable.

Increasing life cycle expectations of concrete structures has led to extensive research on the relationship between durability, permeability, and porosity (Hearn et al., 2006; Mindess et al., 2003). There are three accepted conditions to account for porosity: 1) porosity of the aggregates, 2) water and air filled voids after consolidation and final set, and 3) water and air filled voids after partial hydration of the cement (Hearn et al., 2006). The pores can influence the concrete in many ways: strength and elasticity, permeability, shrinkage, freezing and thawing, and others (Hearn et al., 2006). There are various pore types that affect the concrete differently. The size of the pores increases from inter particle spacing between C-S-H sheets, capillary voids, entrained air bubbles, and entrapped air voids. The pore structures are changed throughout the concrete's lifespan due to water entering the pores, evaporating, and increasing the air flow through the concrete. This is just one example; water is not the only substance that can enter a structure's pore system (Hearn et al., 2006).

Concrete, as a whole, can be considered a mixture of different pore sizes and structures. The structure is constantly changing due to hydration, drying and wetting, and the deterioration process. This allows for porosity to provide data for a specific mixture at a specific time (Hearn et al., 2006). As research continues, there will likely be more developments in the understanding of the relationships between permeability, porosity and durability to accurately determine the structure's service life.

Another durability consideration that is highly affected by permeability is the joint durability of the concrete pavements (Prannoy, et al., 2016). Prannoy et al., (2016) discussed the use of chloride based de-icing salts used on the road ways throughout the country. These deicing salts make roadway and bridge surfaces safer for pedestrians and the environment. However, the salt solution placed on the road ways can enter the concrete through the joints and form a product called calcium oxychloride (Prannoy, et al. 2016). Calcium oxychloride is an expansive substance which can lead to joint deterioration from concrete spalling. Due to the formation of calcium oxychloride, it is important to know the permeability of not just water into the concrete, but, also, the movement of chloride into the concrete (Prannoy, et al. 2016).

2.5 Tests to Evaluate Concrete Permeability

Concrete durability can be measured and predicted by many different methods and characteristics. The some of the characteristics are permeability, compressive strength, and freeze thaw resistance. Many of the different characteristics correlate and have dependence on the air void system (Mohr, et al. 2000). In a very basic definition, durability is the concrete's ability to resist physical and chemical attacks (Mohr, et al. 2000). Neville (1981) states, that permeability is one of the largest ways to determine the concrete's vulnerability to external chemicals. For a concrete to be durable, it must have a low permeability. The permeability of concrete is important to understand because it can have a major effect on the life span of the concrete. If the concrete is very permeable a deleterious chemical can enter into the pores of the concrete and react with the concrete matrix or the reinforcing steel that is embedded in the concrete. These reactions can have negative effects by causing the concrete to deteriorate. Some examples are corrosion of steel reinforcement or making the concrete more susceptible to freeze thaw failures such as scaling (Mohr et al., 2000; Yasarer and Nahhar 2014; Neville 2012). Permeability is very dependent of the capillary pore structure and specifically the interconnectivity of capillary pores (Mohr et al., 2000).The pore size, distribution, and continuity has an effect on the porosity (Neville 2012).

2.5.1 Rapid Chloride Penetration Testing

The Rapid Chloride Penetration Test (RCPT) is one of many tests to determine the permeability of the concrete (ASTM 2012). In the RCPT, the transfer of charge by chloride ions caused by creating a voltage potential across a concrete cylinder, is used to represent the permeability of the concrete to chloride (ASTM 2012).

Mohr et al., (2000) mentions that in the RCPT testing that the location from which the samples are saw cut from the core or cylinder are important because of the varying results that can be obtained depending on the depth of the sample. It is also stated that there can be a correlation of RCPT values to the compressive strength of the concrete with higher compressive strength being associated with lower permeability and the results in Mohr’s research support this statement (Mohr et al., 2000). These results were found from testing OPC pavements where no SCMs were used in the concrete. As stated before, intent of using SCMs is to reduce concrete permeability.

Even though the RCPT is traditionally used on bridge decks the test can be useful on pavements due to the joint deterioration from deicing salts (Prannoy, et al. 2016). The more resistant the concrete is to the chloride penetration the less likely the calcium oxychloride product will be formed. Due to the expansive nature of the calcium oxychloride if the product is formed the joints could begin spalling (Prannoy, et al. 2016).

Table 2.1 gives a qualitative scale relating RCPT index from ASTM C1202. Higher amounts of charge passed are indicative of higher permeability to the chloride ion.

Table 2.1: ASTM C1202 RCPT index

Charge Passed (Coulombs)	Chloride Ion Permeability
>4,000	High
2,000-4,000	Moderate
1,000-2,000	Low
100-1,000	Very Low
<100	Negligible

2.5.2 Sorptivity Testing

When concrete is properly designed and constructed, it can resist storms and intense weather conditions (Hooton 2010). Today, more time is being spent finding ways to assess the material properties of concrete and durability (Hall 1989). Dewar (1984) stated that the surface of concrete is the area in most need of effort in durability testing. One problem of durability is the movement of aggressive liquids into the pore structure of exterior surfaces causing physical and chemical changes to the concrete leading to deterioration (Desouza et al., 1998).

The sorptivity is an easily measured property in which a porous material absorbs and transmits water by capillary suction (Hall 1989). Sorptivity testing requires only the surface to be manipulated based on ASTM C1585: Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes (2013). This shows different measures of the concrete quality based on varying curing methods. The goal is for concrete structures to have long lifespans. In order for this to happen, the cover concrete between the reinforcement and the exterior surface must be durable (Desouza et al., 1998). Durability will result if the concrete has a low *w/cm* ratio, however this is not the only factor.

Sorptivity is influenced by many factors, such as the continuity of the capillary pore system, the water to cementitious ratio, the addition of supplementary cementing materials, and the degree of hydration. However, measuring sorptivity, or the rate of capillary absorption, is relatively inexpensive, fast, and is directly related to permeability (Desouza et al., 1998). The addition of PLC and/or fly ash in a concrete mixture has been shown to reduce the sorptivity values, which have a direct relationship to permeability (Hooton and Beal 1993).

Gopalan (1996) conducted a study that measured the sorptivity of cement and fly ash concretes in order to compare the durability between the two (Gopalan 1996). In the beginning, the pore structure and alkalinity of the cover concrete were found to be the most important properties that would result in affecting the durability. These are measured by sorptivity and carbonation (Gopalan 1996). The materials used in this study were 20 and 10 mm size crushed gravel, river sand, Type A normal portland cement (similar to ASTM type 1) and a bituminous fly ash (ASTM Class F). The testing samples were 25 mm thick cylinders to complete the study in a timely fashion. For consistency, the top surface of the samples was always used for measuring the absorption factor (Gopalan 1996).

The samples were conditioned to have an identical testing condition. All the samples were dried overnight as recommended by ASTM C1585 (2013) and British standard 1881 (2011) (Gopalan 1996). The samples were split up and some were placed in fog curing while the others were placed in an oven for “drying.” Three cylinders from each curing condition were used to test for compressive strength and two were used for water absorption.

Results for this study showed that the concrete under “drying” had higher sorptivity than those cured in the fog room. The results were used to analyze the factors influencing the durability of the concrete. Curing conditions were shown to have an important influence that affected the durability of the samples. Within the curing results it was determined that the when the samples were properly cured the fly ash samples had a 37% reduction in sorptivity. (Gopalan 1996).

2.5.3 Air Permeability

Concrete structures are designed to withstand harsh weather conditions and to ensure acceptable limits of deformation and ultimate strength values. Recent studies have shown compressive strength to be the one of the main indicators for durability (Sanjuan and Munoz-Martialay, 1995). Now, a new topic is of interest to some researchers: air permeability. The air permeability test can give a different look into the permeability of the concrete due to the fact that the air can permeate through the pores with less resistance than other fluids such as water (Sanjuan and Munoz-Martialay, 1996). There are many factors to consider with regards to air permeability in concrete samples. Grading of aggregate is important in reducing air permeability. Also, prolonged curing reduces the air permeability (Neville, 1981). Permeability of concrete to air is a topic of much interest in design of sewage tanks and gas purifiers, systems under a specific internal pressure (Neville, 1981).

The durability of concrete structures is mainly affected by the transport of gaseous and liquid substances through the pores. Substances entering the pore structure can potentially result in concrete deterioration the concrete over time. Studies are being conducted to take into account the permeability of concrete structures to understand how concrete is affected by the water to cement ratio, temperature, and pressure. The biggest factor of these is the water to cement ratio. An important change in air permeability has been noticed when water to cement ratio and preconditioned temperatures are studied (Sanjuan and Munoz-Martialay, 1995).

Sanjuan and Munoz-Martialay (1995) conducted a study that focused on an air permeability testing procedure that proved to be a reliable method in determining concrete durability. Six slabs with a water to cement ratio of 0.37 were prepared. An experimental device was used to measure the air permeability of each specimen. The device was comprised of two metallic cells placed at each side of the specimen. Different pressures through the cells were used to measure air flow. The air permeability coefficient, D_{air}, was calculated according to the Hagen-Poiseuille equation (Sanjuan and Munoz-Martialay, 1995). The specimens were tested at various times over twenty years. The method for studying air permeability gave reliable results over time: the air permeability coefficient reaches an almost stable value after twenty years. The pore evaporated water creates an air pathway which increases the permeability of the concrete (Sanjuan and Munoz-Martialay 1995).

With air permeability being a topic of more recent interest, more research needs to be conducted to ensure the reliable results obtained thus far. A benefit of this research is to find other factors that affect the overall durability of concrete structures.

2.5.4 Compressive Strength

Many studies have been performed to study the compressive strength of concrete produced with portland cement alone, cement mixed with fly ash or limestone. A wide range of strengths are attainable depending on the ratio of cement replacement and curing time (Celik et al., 2015). An increase in early strength due to limestone can come from the participation in cement hydration and filler effects (Yilmaz and Olgun 2008). Jin (2014) stated that limestone improves compressive strength by filling small pores, which helps promote the hydration of cement. Multiple studies have come to similar conclusions about the compressive strength of cement with fly ash and limestone replacements (Jin and Mengyuan 2014; Yilmaz and Olgun 2008). Yilmaz states that results of combined fly ash and limestone have positive effects on compressive strength. One of the positive effects would be that portland cement replaced with fly ash and limestone exhibit higher compressive strength than samples containing only fly ash at all ages of the research (Thongsanitgarn et al., 2010). Overall, the compressive strength increases when the concrete mixtures have inter-ground limestone present and some cement is replaced with fly ash (Celik et al., 2015).

2.5.5 Surface Resistivity

There are several current methods for characterizing the resistance to chloride penetration. One of these methods which were previously discussed is the RCPT. However, these methods are expensive and time consuming, which, in result, lowers their routine use as a quality control tool (Kessler and Paredes 2005). There is a need for alternative methods in order to reduce the costs and amount of time required for testing. There have been many studies conducted on such a method, surface resistivity, which is proving to be a promising test (Rupnow and Icenogle 2011; Weiss 2015). There are many methods of measuring the electrical resistivity of concrete samples. A few of these methods are the Wenner method, disc method, the use of two electrodes, or the use of four electrodes (Polder 2001). The use of these methods can be planned, which would include metal electrodes being placed before casting, or on site without the embedded electrodes (Polder 2001).

The electric resistivity of water-saturated concrete is increasingly being used to predict a wide range of concrete characteristics (Morris et al., 1996). Concrete resistivity is used to relate the corrosion likelihood and protection of reinforcement in varying concrete structures and samples. The resistivity of a structure exposed to chloride indicates the risk of early corrosion damage (Polder 2001). AASHTO TP 95-11(2011) provides a test procedure for surface resistivity (SR). A benefit of electrical resistivity is that is can be measured relatively easily and provides insight into corrosion rates (Larsen et al., 2006). Resistivity measurements can be performed on parts of structures that are exposed to the air. These measurements can be made at any point during the lifecycle of a structure and under any use or environmental conditions. (Polder 2001).

Concrete resistivity is a material property that describes the electrical resistance, the ratio between applied voltage and resulting current in a unit cell (Polder 2001). The resistivity of concrete can vary based on moisture content of the cement and the composition it is made up of. Resistivity varies with other factors that may affect the concrete; such as permeability, age, and temperature. In any case, areas with low resistivity will have a relatively high corrosion rate after depassivation (Polder 2001).

Gowers and Millard state that the Wenner technique is becoming more prominently used for measuring the resistivity of reinforced concrete (Gowers and Millard 1999). The Wenner array probes can be used quickly and with no special preparation. The ability to conduct these tests without immense preparation saves time, which is desirable to departments of transportation (DOT). Morris et al. conducted a study using the Wenner array probe. In this study, two types of configurations were assumed: placing the test point array longitudinally centered, or having the test centered on one end face of a test cylinder (Morris et al., 1996). It was noted that the second configuration was much more convenient. The procedure used correlations between measurements with water-filled concrete test cylinder plastic molds, and independent water resistivity measures (Morris et al., 1996). The test cylinders were cut at different mold sizes ranging from two inches to six inches in diameter. Four metallic electrodes were placed in the center of each of the testing cylinders. Multiple tests were performed using a mix of tap water and distilled water. The measurements of apparent resistivity were measured by using a CNS RM MKII resistivity meter which has a Wenner probe provided to make contact, or with a Nilsson model 400 soil resistivity meter. Both measurements were stated as providing the same results (Morris et al., 1996).

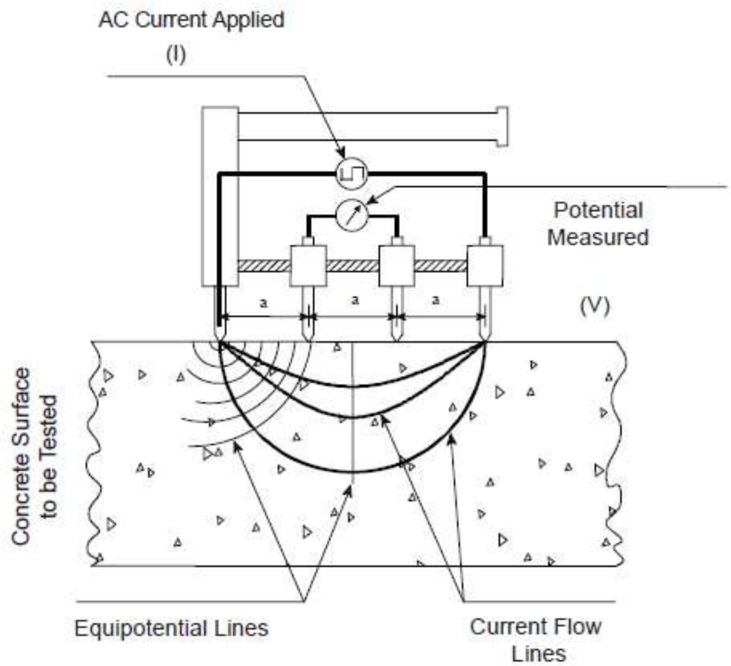

Figure 2.2: Four point Wenner array probe test set up (American Association of State Highway and Transportation Officials 2011)

Conclusions from this study were that concrete resistivity can be quickly determined with a four-point Wenner array probe. The resistivity readings show moderate variability from differing aggregates. The average of many tests can give a better resistivity estimate. By testing various concrete samples, the resistivity, with the presence of differing compositions and environmental factors, can be used to slow the corrosion process and make the samples and structures more durable (Kessler and Paredes 2005).

Conclusions have been made that surface resistivity can be used to replace RCP testing methods. SR can be used to find the same information in a much timelier fashion: minutes versus three days. It was also noted that SR provides better precision than the RCPT method. It has been determined that surface resistivity should be conducted on the specimens immediately after removal from the moist storage environment to eliminate drying effects. Upcoming studies will be steered from the previous and current works to continue advancing techniques to protect current structures and prevent corrosion as much as possible now and in the future (Kessler and Paredes 2005).

An important study of the surface resistivity test, and its correlation to the RCPT, was conducted by Rupnow and Icenogle study (2011). In this study, the correlation was determined for the surface resistivity test and RCPT. This correlation was found to be very strong with R^2 coefficient of 0.89. To determine this correlation, the study compared the average 14 and 28-day surface resistivity readings with an average of the 58 day RCPT readings. The study also contributed to creation of the AASHTO TP95 permeability rating table (American Association of State Highway and Transportation Officials 2011). The study enables considerable annual savings by implementing the surface resistivity test as an alternative to the RCPT test and a method of quality assurance (Rupnow and Icenogle 2011).

The table shown gives the permeability rating based on the surface resistivity reading of the concrete from AASHTO TP95-11 (Table 2.2).

Table 2.2: AASHTO TP95-11 surface resistivity index

4”x8” Cylinder (kilo-ohm-cm)	Chloride Ion Permeability
<12	High
12-21	Moderate
21-37	Low
37-254	Very Low
>254	Negligible

2.6 Research Needs

There are many research needs in the durability evaluation of portland limestone cement (PLC) concrete with fly ash replacement (Yoshitake et al., 2013). Research has already be performed on the benefits of the limestone helping to offset the reduction of early age strength from the addition of fly ash but the durability aspect of the concrete has not been evaluated in the same depth (Yilmaz and Olgun 2008). It has been established that durability is greatly influenced by permeability and with this statement Langan (1990) stated that future research should be performed to evaluate the lower permeability of the PLC/fly ash mixtures.

In the evaluation of concrete durability two recently developed test methods were used. These test methods are the surface resistivity test method (American Association of State Highway and Transportation Officials 2011) and the sorptivity test method (ASTM 2013). Both of these methods are needed to be reproduced for better evaluation of results. The use of materials, cement mixture characteristics, and SCM's could be adjusted to help provide a wider range of results. The surface resistivity, if accepted, can be used to eliminate the Rapid Chloride Penetration Test (Morris et al., 1996).

More correlation testing can be performed for the surface resistivity test and rapid chloride penetration test to ensure that the correlations found are repeatable for different curing periods and mixture compositions (Rupnow and Icenogle 2011).

CHAPTER 3: MIXTURE DESIGN AND TESTING METHODS

The research tasks for this project were designed to meet the North Carolina Department of Transportation's (NCDOT) needs for local MEPDG calibration data for rigid pavements. The scope of this document includes the study of the durability of the concretes. Additional data about the same concretes are available in (Blanchard 2016) and (Reddy 2016). The mixtures described in this chapter consisted of combinations of different fine aggregates, coarse aggregates, cements, and supplementary cementitious materials (SCM). The SCMs for this project were two Class F, fly ashes and inter-ground limestone.

The concrete mixtures were designed in a way to explore the characteristics of typical pavement concretes used across the state. Due to the geography of the state, coarse aggregates were sourced from the Coastal, Piedmont and Mountain regions. The primary fine aggregate that was used was manufactured sand, with only a few mixtures including natural sand for comparison. Three cements were evaluated including ordinary portland cement (cement B), portland limestone cement (cement BL) (from the same manufacturer as cement B), and an ordinary portland cement (cement A) from a second manufacturer. Two different Class F fly ash sources were also used for comparison. An air entraining admixture and a mid-range water reducing admixture were used to achieve the target parameters of 1.5 inch slump (±1 inch) and 5.5% (±0.5%) air content. Each mix design used a 0.48 water to cement ratio, and the water demand was adjusted for each material's absorption. The development matrix for these mixtures is shown in Figure 3.1 to portray the relationship of the different material variables.

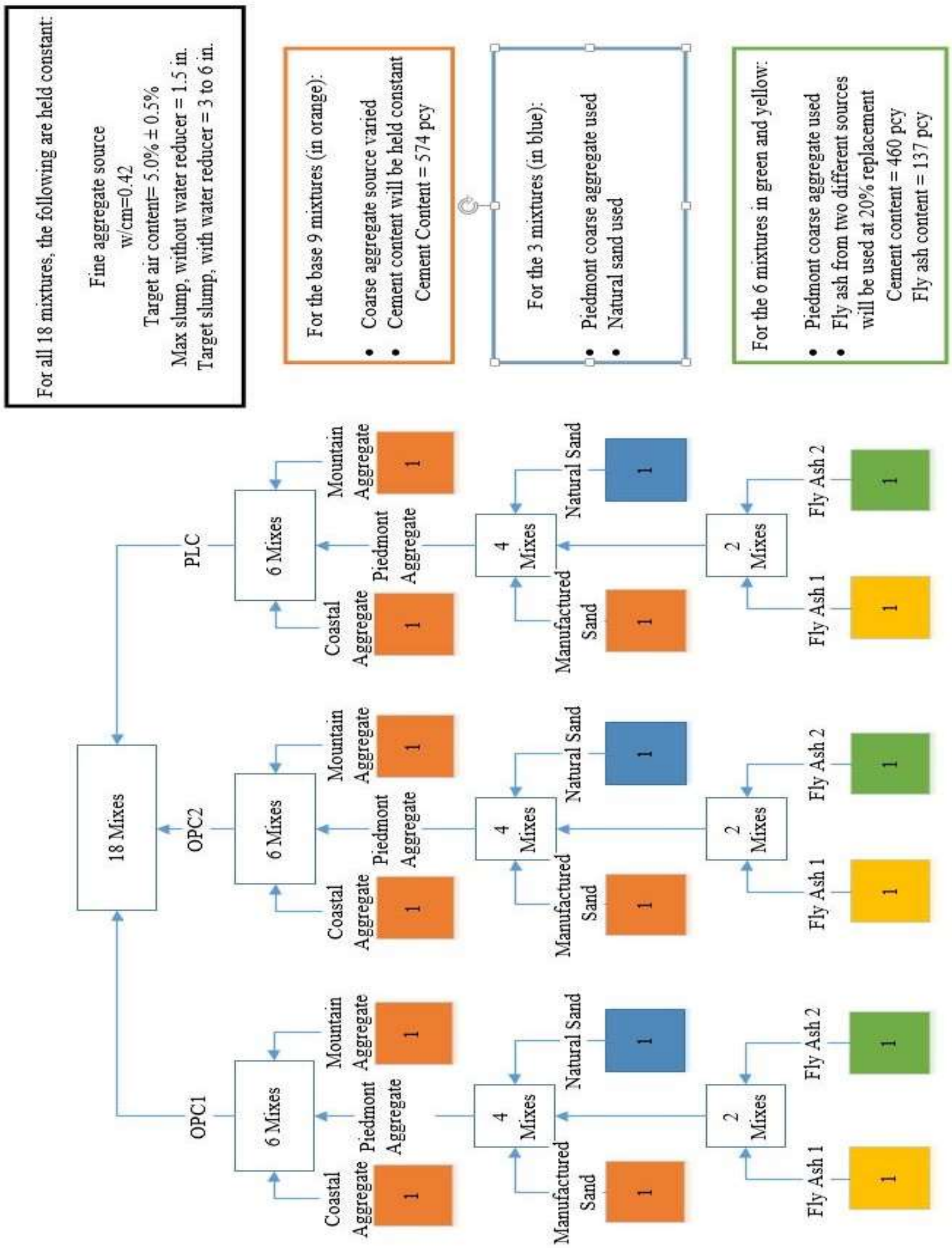

Figure 3.1: Mixture design matrix

3.1 Materials

3.1.1 Cements

Three different cements were used in this study based on the use of these cements for NCDOT pavements. The cements were shipped to the concrete lab in sealed containers to ensure that no moisture was able to enter the cement. The first cement, cement A, is an ordinary portland cement produced in Tennessee that the NCDOT uses in the mountain area of the state. The other two cements are another brand of ordinary portland cement, cement B, and portland limestone cement, cement BL; both came from the same manufacturer in South Carolina, and are used in the Piedmont regions of the state. The PLC has 12% limestone inter-ground in with the clinker. The clinker is the same in cement B and cement BL. The mill sheets for these cements are provided in Appendix A. The notation for each mix can be interpreted as followed first letter (C, P, or M) is the aggregate (Coastal, Piedmont, or Mountain) second letter (A, B, BL) is the type of cement, third letter (N, A, B) is the source of fly ash with N being no fly ash present in the mix, and the final letter (M or N) is the sand (Manufactured or Natural). The table below illustrates the mixtures used in this document (Table 3.1).

Table 3.1: Mixture descriptions

	Coarse Aggregate			Cement			Fly Ash			Fine Aggregate	
Mixture	Piedmont	Coastal	Mountain	A	B	BL	A	B	None	Natural	Manufactured
P.A.N.M	■			■					■		■
P.B.N.M	■				■				■		■
P.BL.N.M	■					■			■		■
C.A.N.M		■		■					■		■
C.B.N.M		■			■				■		■
C.BL.N.M		■				■			■		■
M.A.N.M			■	■					■		■
M.B.N.M			■		■				■		■
M.BL.N.M			■			■			■		■
P.A.A.M	■			■			■				■
P.B.A.M	■				■		■				■
P.BL.A.M	■					■	■				■
P.A.B.M	■			■				■			■
P.B.B.M	■				■			■			■
P.BL.B.M	■					■		■			■
P.A.N.N	■			■					■	■	
P.B.N.N	■				■				■	■	
P.BL.N.N	■					■			■	■	

3.1.2 Supplementary Cementitious Materials

The SCMs used in this project included two different sources of fly ashes. Both fly ashes are classified and marketed as Class F. The fly ash replacement amount used was 20% by weight for all mixtures either type of fly ash.

3.1.3 Aggregates

The fine and coarse aggregates were varied in the mixture matrix. The aggregates were chosen based on the geological makeup and historical aggregate use in the three regions of the state.

Three coarse aggregates were chosen to represent the aggregates used in the state. One from the Coastal, Piedmont, and Mountain regions of North Carolina were chosen by the NCDOT. Selection was made based on the prevalence of materials from the quarry in recent pavement projects. The aggregates were placed in 55 gallon barrels and transported to UNC Charlotte where they were placed inside the concrete laboratory and spread out to dry in ambient laboratory conditions. Each aggregate was given ample time to "air dry" before it was used in the concrete mixture. The moisture was checked periodically, and the batch water was adjusted if needed.

Two different types of fine aggregates were used in this study. One manufactured fine aggregate and one natural fine aggregate. Both aggregates were sourced from the piedmont region due to its central location. The Piedmont coarse aggregate was sourced from the Charlotte, NC region, the Mountain coarse aggregate from the Asheville, NC region, and the Coastal coarse aggregate from the Wilmington, NC region. The manufactured aggregate was used in 15 out of the 18 mixtures. The natural sand was used only with the piedmont aggregate in order to compare the two fine aggregates due to budget and scope of project limitations. Both fine aggregates were oven dried for 24 hours then placed in 5 gallon buckets with lids and stored in a controlled temperature room until used in the mixtures.

The aggregates detailed information is best summarized in Table 3.2 with the gradations in Appendix A.

Table 3.2: Detailed Aggregate Information

	Specific Gravity	Absorption	Mineralogy	Fineness
Mountain	2.62	1.10%	Granite	---
Piedmont	2.62	0.80%	Granite	---
Coastal	2.42	2.40%	Marine Limestone	---
Natural Sand	2.64	0.74%	---	2.54
Manufactured Sand	2.65	0.30%	---	2.54

3.1.4 Admixtures

Two admixtures were used in this project to reach the given parameters of the pavement mix. A mid-range water reducer was used to obtain the slump while keeping the *w/cm* ratio the same. An air entraining admixture was used to achieve a target air content of 5.5% (+/- 1%) in all of the mixture designs.

The mid-range water reducer used was MasterPolyheed 997 from BASF. BASF recommended a dosage 3 to 15 fluid ounces per 94 pounds of cement. The actual dosage varied from mix to mix based on the characteristics of the mix (Figure D.3, Appendix D) (BASF 2015). The coastal mixtures required more water reducer due to the higher absorption of these aggregates.

The air entraining admixture used is MasterAir AE 200 from BASF. BASF recommended a dosage of 0.125 to 1.5 fluid ounces per 94 pounds of cement (BASF 2015). Again, the dosage amount varied based on the mix. Due to utilizing fly ash in a number of mixtures, the dosage was increased to counteract the effect of residual carbon in the fly ash reducing the effectiveness of the air entraining admixture.

3.2 Batching Procedures

The batching procedure and sampling of the standard specimens were performed according to ASTM C192: Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory (2015). During the batching procedure, care was taken to ensure the lab was maintained at room temperature of roughly 70 degrees Fahrenheit. There were no deviations from the standard for the mixing process. To help reduce operator error and variation, a single operator performed each test throughout the batching process.

When sampling the standard test specimens, such as the cylinders and beams, ASTM C192 (2015) was also followed. The same oil-based form release was used throughout the preparation of samples.

3.3 Sample Preparations

3.3.1 Sorptivity Samples

The sorptivity samples were prepared to the specifications of ASTM 1585 (2013) standard in which a diamond tip wet concrete saw was used to slice a 4”x8” cylinder into 2” puck-like specimens. This method was used for both the suction and ponding technique of the sorptivity test. Then, the samples were conditioned per the standard. The samples were taken from the top down on the cylinder, and the same saw cut surface was used in both tests. This can be seen in the figure below (Figure 3.**2**). All sorptivity samples were tested at a curing age near 240 days (± 8 days).

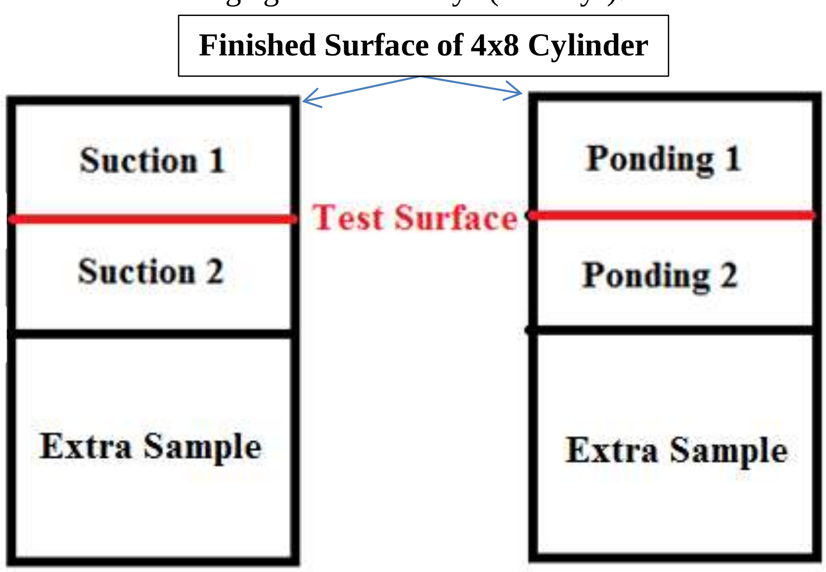

Figure 3.2: Sorptivity samples

3.3.2 Rapid Chloride Penetration Samples

The Rapid Chloride Penetration Test (RCPT) samples were prepared according to ASTM C1202: Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (2012). The samples were obtained by taking 2" pucks out of a 4"x8" cylinder with a diamond tip wet concrete saw. The samples were taken from the bottom of the cylinder up, and only two samples were taken from each cylinder. The samples were taken from the bottom in order to avoid the rough finished top surface. Four samples total were prepared for testing, and the location of the sample was alternated based on the test day. The RCPT was performed on the 28th day after casting and the 90th day after casting. This can be seen in the figure below (Figure 3.**3**).

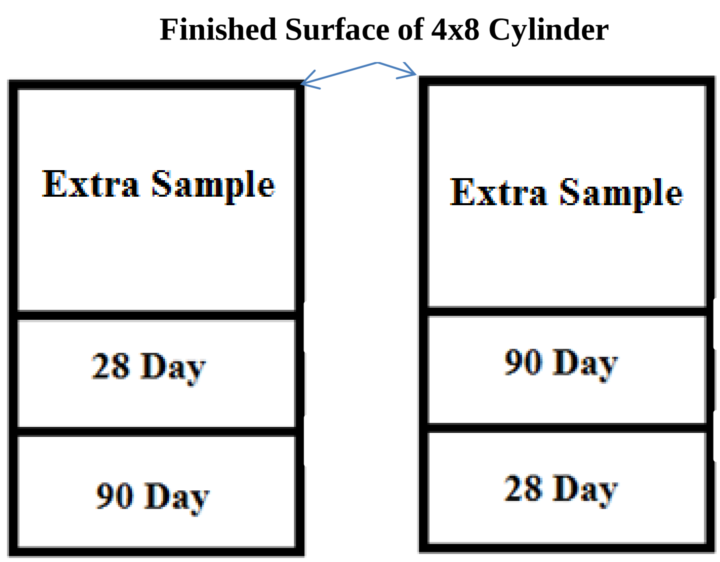

Figure 3.3: RCTP samples

3.3.3 Air Permeability Samples

The air permeability samples were prepared from the flexural beams that were used for this project. The beams were made and cured as called for in ASTM-C78:

Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) (2015). The beams were stored inside the misting room until the flexural test had been performed at 28 days after casting. After the flexural test had been performed, the beams were stored in the testing lab that was maintained at room temperature and ambient, building humidity. The samples were examined before testing to ensure there was no major damage to the testing air that would alter the permeability reading. Each beam was at least 200 days of age at the time of testing with a maximum difference of 72-days between curing times of the oldest and youngest samples.

3.3.4 Surface Resistivity Samples

The surface resistivity samples were the same 4”x8” cylinders used for the compressive strength tests. The samples were made and cured as per ASTM-C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (2015). The samples were stored in a moist curing room until the tests were performed. The test was performed before the compressive strength test to ensure the surface had not been damaged.

3.4 Testing Procedures

Each test procedure is based on an ASTM and/or ASHHTO standard, and any deviation from that standard is mentioned below. Each test was performed by the same operator as often as possible to minimize potential variability. The testing procedures were performed by one operator for all samples tested to reduce error.

3.4.1 Sorptivity Testing

The sorptivity testing was done using the suction method and ponding method. The suction method is the standard test method shown in ASTM 1585 (2013). The suction method was performed according to the ASTM standard with the only deviation of placing plastic wrap over the entire test set up to avoid the water level dropping due to evaporation. The test set up for the suction method can be seen below (Figure 3.4).

Figure 3.4: Suction method test set up

The ponding method follows the ASTM 1585 (2013) standard except for the samples being placed in 0.039”-0.120” of water, 0.039”-0.120” of water is placed on top of the samples after the sides of the sample is sealed. The samples were sealed by wrapping the samples in duct tape leaving adequate overhang off the top of the sample to pond 0.12” of water on top. After the duct tape was applied, a 4” hose clamp was placed around the duct tape to apply pressure and to ensure the duct tape has an adequate seal. Velcro strips were used under the hose clamp to prevent the clamp from cutting the duct tape and to help evenly distribute the pressure onto the samples. After the samples were fitted for the ponding method, the same testing procedure is followed as used for the suction method with the variation of the water was placed on top of the sample. Plastic wrap was also placed over the ponding method samples to ensure not water level change due to evaporation. The ponding test set up can be seen in Figure 3.5.

Figure 3.5 Ponding test set up

3.4.2 Rapid Chloride Penetration Testing

The rapid chloride penetration test (RCPT) that was performed was based on ASTM C1202 (2012). The conditioning procedure was followed per the standard, and the actual test was done using the Germann Instruments' Proove'it system shown in the Figure 3.**6** and Figure 3.**7** (Germann Instruments 2016).

Figure 3.6: RCPT samples conditioning

The samples were then placed in the containers provided for the Proove'it system (Figure 3.7). The samples were exaimend for any major air voids near the rubber seal of the container. If an air void was found, the void was filled with silicone to prevent the system from leaking. Each container was filled with distilled water prior to testing to again ensure there was no leak in the system. Once no leaks were present, the containers were filled with the correct chemicals as per the standard and the Proove'it was used to perform the test.

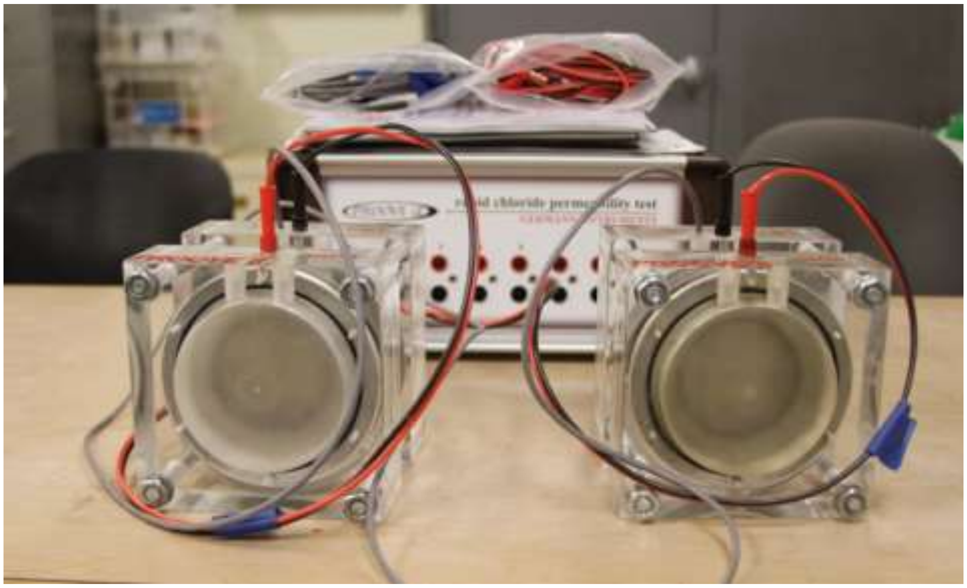

Figure 3.7: RCPT sample test set up

3.4.3 Surface Resistivity Testing

The surface resistivity testing was performed in accordance to ASSHTO TP95-11 (2011). Surface resistivity testing was performed on the same 4”x8” cylinders used for compressive strength testing that was performed on 3, 7, 14, 28, and 90 days of curing. The Proceq (Proceq 2016) system were used to take the resistivity measurements. The samples were examined for any major air voids before each measurement and the measurement position was slightly adjusted to avoid the air void to ensure accurate data was recorded. The samples were also dampened with a wet towel before each reading to ensure equal dampness on all measurement to help ensure consistent and comparable readings. The surface resistivity set-up can be seen below using the Proceq instrument.

Figure 3.8: Surface resistivity Proceq set up

3.4.4 Air Permeability Testing

The Proceq Torrent was used on the 6”x6”x21” flexural beams to determine the concrete cover air permeability of the different concrete mixtures. The Torrent device suction cup was placed in the center of one of the smooth surfaces of the flexural beam to ensure adequate bond, and that there was enough surrounding concrete to get a true permeability representation (Figure 3.9). Once the suction cup was placed on the concrete, a vacuum was pulled on the cup for one minute. After the initial minute, the vacuum was closed off from the suction cup. The suction cup was maintained on the concrete with the vacuum created from the minute of vacuum draw for twelve minutes. During this time, the change in pressure was measured to determine the vacuums loss in the suction cup. This value gave an indication into how permeable the concrete was based on how much vacuum was lost. Each sample was tested once on each half of the flexural beam. Due to the beams being broken, if one side or half seemed damaged another position was selected to ensure accurate data.

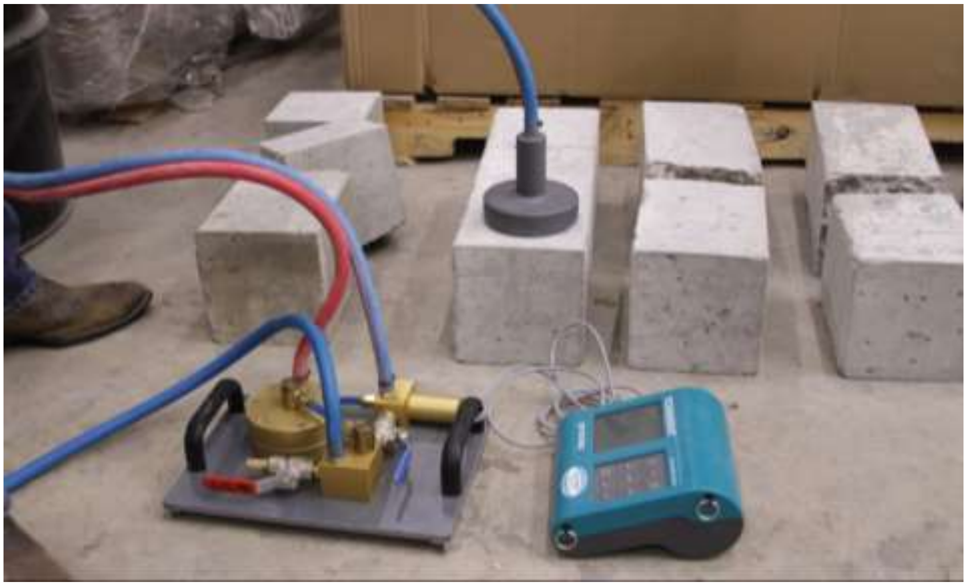

Figure 3.9: Torrent air permeability set up

The Torrent manual provided the index for the quality of the concrete cover based on air permeability shown below in Table 3.3. The index is based only on the coefficient of permeability, *Kt*.

Table 3.3: Torrent concrete cover air permeability index

Quality of Cover Concrete	Index	*Kt* ($10^{-16}m^2$)
Very Bad	5	>10
Bad	4	1.0-10
Normal	3	0.1-1.0
Good	2	0.01-0.1
Very Good	1	<0.01

CHAPTER 4: TEST RESULTS

The tests results from the different durability tests, select mechanical test, and select fresh concrete results can be found in the following chapter. The durability results followed are from the rapid chloride penetration test (RCPT), surface resistivity test (SR), air permeability test, and sorptivity tests. The fresh and mechanical mixture results are shown in the tables below (Table 4.1-Table 4.2).

Table 4.1: Mixture fresh properties

Designation	Slump (in)	Air Content (%)	Unit Weight (PCF)
P.A.N.M	1.4	5.4	145
P.B.N.M	1.9	6.0	143
P.BL.N.M	2.2	5.6	144
C.A.N.M	1.1	5.8	138
C.B.N.M	1.4	5.6	139
C.BL.N.M	1.1	5.5	139
M.A.N.M	2.0	5.3	145
M.B.N.M	2.4	5.4	144
M.BL.N.M	2.3	5.1	145
P.A.A.M	2.7	5.7	141
P.B.A.M	2.3	5.2	142
P.BL.A.M	2.5	5.2	142
P.A.B.M	2.4	5.6	142
P.B.B.M	2.3	5.7	141
P.BL.B.M	2.3	5.6	141
P.A.N.N	1.9	5.3	143
P.B.N.N	3.3	5.4	142
P.BL.N.N	2.8	5.5	143

Table 4.2: Mixture mechanical properties

Designation	Compressive Strength (psi)				MOE (psi)	Poisson's Ratio	MOR (psi)
	3 Day	7 Day	28 Day	90 Day			
P.A.N.M	3,370	4,020	5,020	5,230	2,920,000	0.20	680
P.B.N.M	3,660	3,960	4,850	5,500	3,340,000	0.20	670
P.BL.N.M	3,720	4,340	5,020	6,170	2,430,000	0.18	660
C.A.N.M	3,650	4,890	5,360	6,010	3,730,000	0.22	730
C.B.N.M	4,340	4,770	5,960	5,690	3,490,000	0.21	750
C.BL.N.M	4,290	4,850	5,560	5,610	3,690,000	0.22	680
M.A.N.M	3,060	3,930	5,030	5,530	2,540,000	0.18	570
M.B.N.M	3,800	4,130	5,100	5,390	2,760,000	0.20	640
M.BL.N.M	3,670	4,130	4,790	5,530	3,020,000	0.20	610
P.A.A.M	2,620	3,550	4,270	5,560	3,220,000	0.23	650
P.B.A.M	2,460	3,050	4,050	4,380	2,700,000	0.21	540
P.BL.A.M	2,210	2,960	3,750	4,620	2,690,000	0.16	650
P.A.B.M	2,130	2,390	3,780	5,490	2,840,000	0.22	570
P.B.B.M	2,040	2,410	3,140	4,340	2,510,000	0.18	620
P.BL.B.M	2,330	2,500	3,780	4,370	2,720,000	0.19	560
P.A.N.N	2,720	4,080	5,400	6,060	3,400,000	0.15	740
P.B.N.N	3,010	3,420	4,390	5,450	3,510,000	0.19	720
P.BL.N.N	3,270	3,930	5,190	5,800	3,040,000	0.15	750

4.1 Sorptivity Test Results

The sorptivity test results are summarized by finding the initial sorptivity, secondary sorptivity, and the *x* and *y* coordinates of the nick point (Table 4.3) (Weiss 2015). These different values obtained from the sorptivity data can be used to compare the mixtures. However, the sorptivity testing did not meet the required regression constant of >0.98 for all of the initial and secondary sorptivity value. An example of a sorptivity graph can be seen in Figure 4.1. In this graph, the initial absorption can be seen as the slope of the blue data set, the secondary absorption can be seen as the slope of the red data set, and the nick point is where the two trend lines intersect. This graph is representing the regression constant within the ASTM approved range for both the initial and the secondary absorption. It should be noted that the regression values given from the graphs are in R^2 values, so the actual regression for the graphs are the square root of the given value. The ASTM minimum regression of R^2 is equal to 0.96.

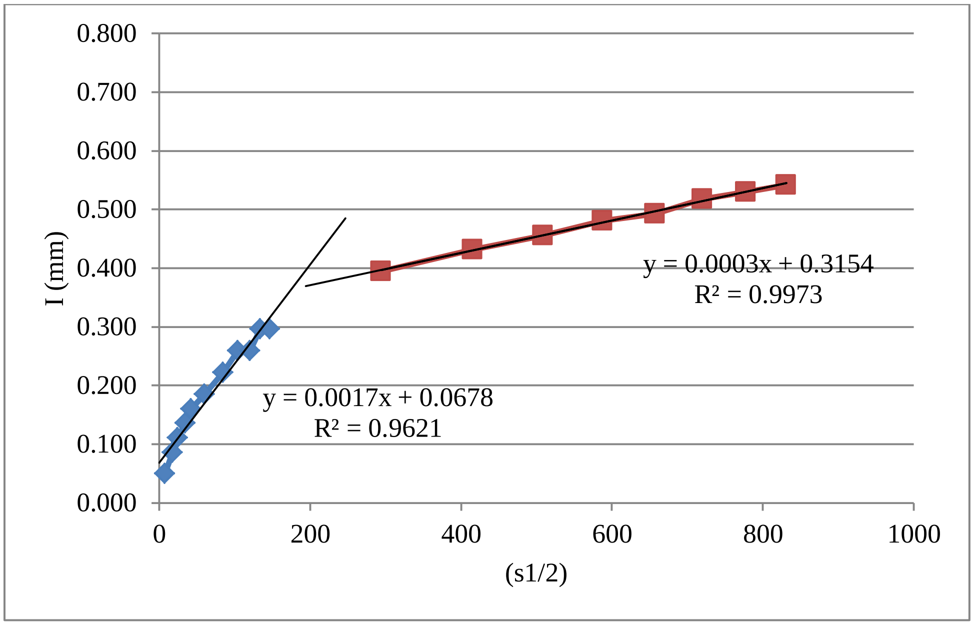

Figure 4.1: Example sorptivity graph (Sample P.B.B.M)

The slope of the initial absorption, secondary absorption, and intersection of the initial and secondary absorption slopes all represent an aspect of the concrete's absorption characteristics. These data points are shown graphically in Figure 4.7. Figure 4.6 and Figure 4.7 are mixtures that share similar materials for better comparison.

The trend that can be seen is that the initial suction sorptivity is higher for the mixtures containing fly ash (Figure 4.4). The mixtures containing both fly ash and limestone are higher than the mixtures containing only fly ash. These findings contradict the findings of the literature which indicate that concrete mixtures containing fly ash normally have lower initial absorption rates (Hooton and Beal 1993). In Figure 4.5 the secondary rate of absorption is plotted for every mix. To better compare any changes from the type of cement and fly ash select mixtures were compared. These select mixtures are the mixtures that used the same aggregates both fine and coarse (Figure 4.6 & Figure 4.7).

Table 4.3: Suction sorptivity method test results

Suction				
Mix	*X* (Sec$^{1/2}$)	*Y* (mm)	Initial (mm/Sec$^{1/2}$)	Secondary (mm/Sec$^{1/2}$)
P.A.N.M	289.000	0.311	0.00080	0.00039
P.B.N.M	282.364	0.245	0.00059	0.00005
P.BL.N.M	479.500	0.299	0.00054	0.00026
C.A.N.M	226.143	0.336	0.00083	0.00012
C.B.N.M	166.857	0.283	0.00102	0.00032
C.BL.N.M	144.500	0.306	0.00139	0.00042
M.A.N.M	201.167	0.243	0.00081	0.00020
M.B.N.M	136.000	0.227	0.00093	0.00029
M.BL.N.M	159.200	0.230	0.00076	0.00027
P.A.A.M	218.917	0.364	0.00150	0.00030
P.B.A.M	208.500	0.320	0.00127	0.00032
P.BL.A.M	217.231	0.454	0.00107	0.00032
P.A.B.M	185.733	0.366	0.00166	0.00019
P.B.B.M	176.857	0.368	0.00169	0.00028
P.BL.B.M	211.444	0.533	0.00213	0.00030
P.A.N.N	207.500	0.213	0.00068	0.00027
P.B.N.N	353.000	0.257	0.00049	0.00029
P.BL.N.N	215.500	0.322	0.00089	0.00031

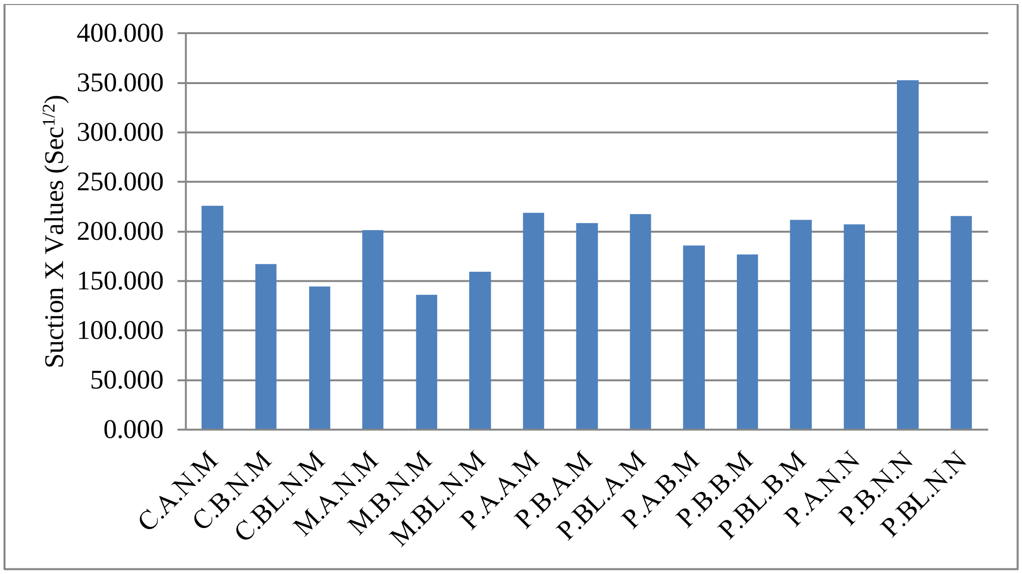

Figure 4.2: Suction *X* value of sorptivity nick point

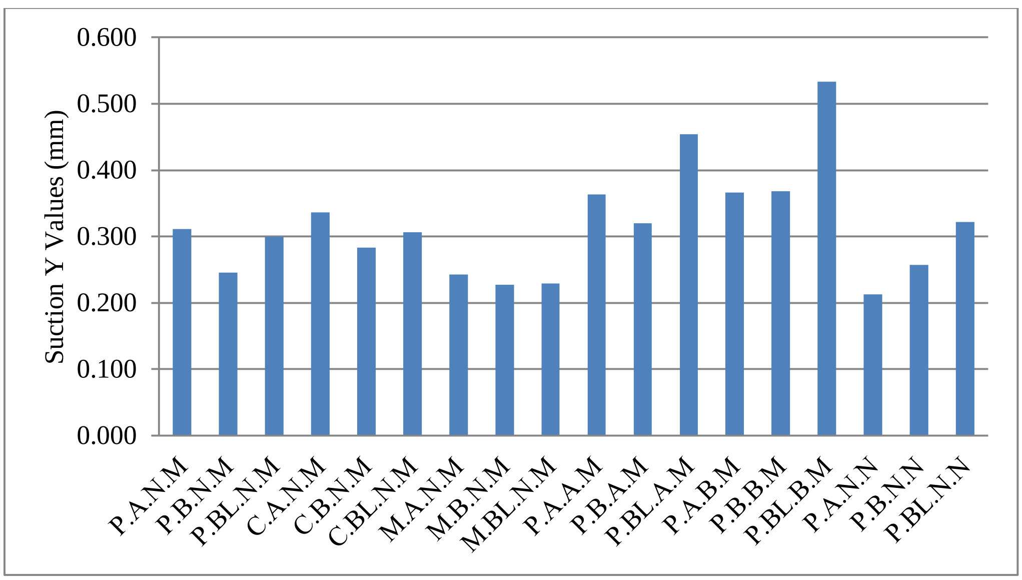

Figure 4.3: Suction *Y* value of sorptivity nick point

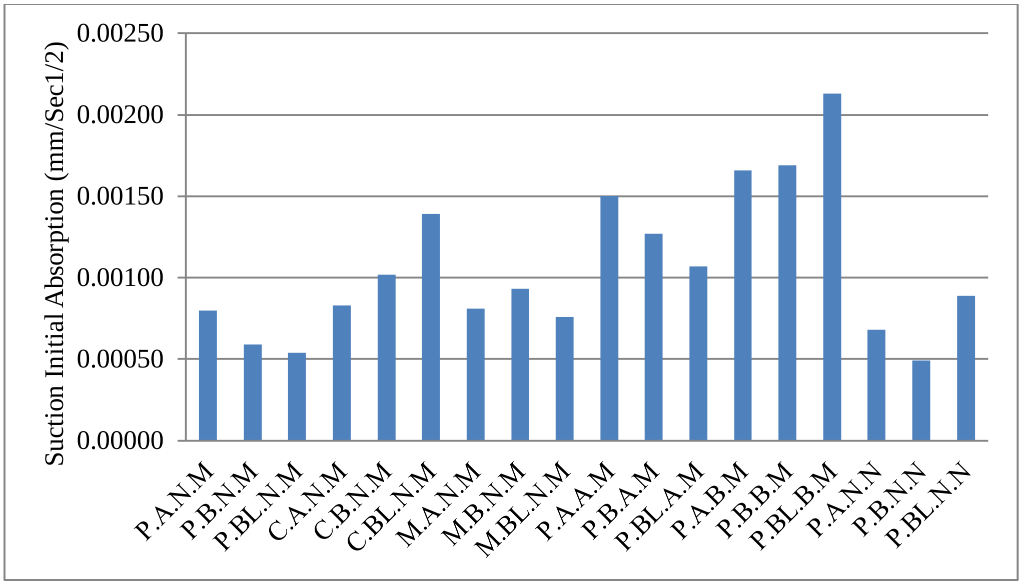

Figure 4.4: Suction initial sorptivity

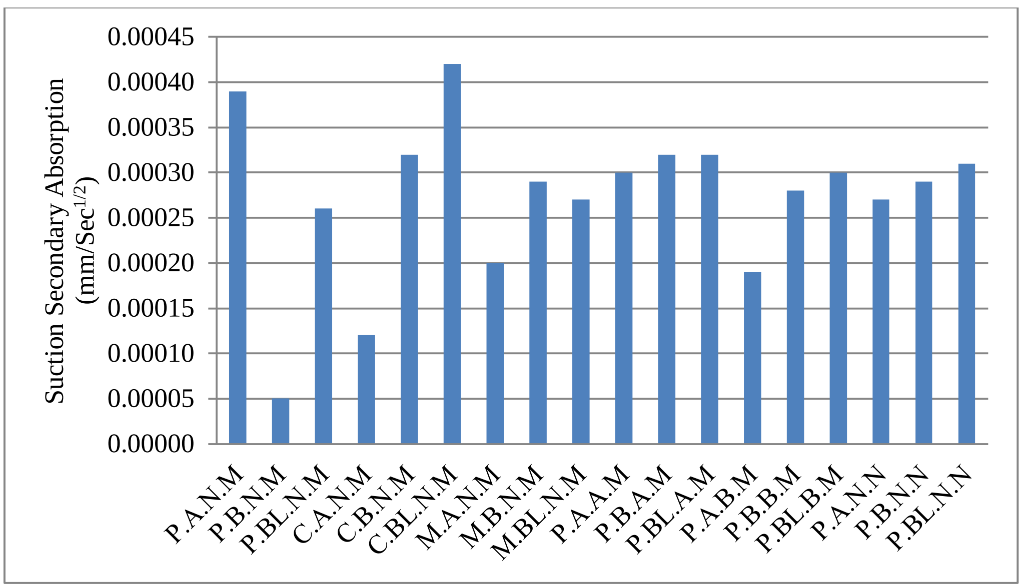

Figure 4.5: Suction secondary sorptivity

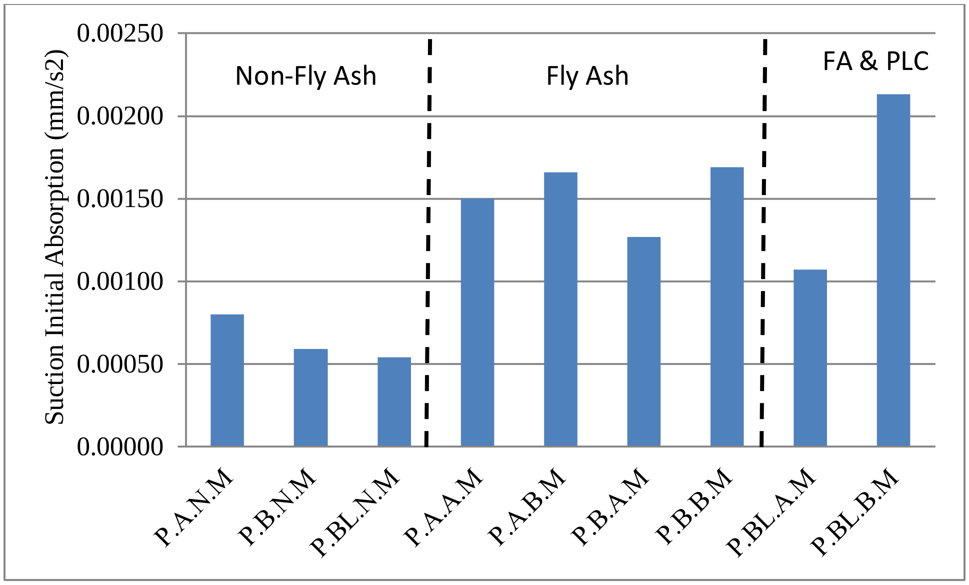

Figure 4.6: Select initial sorptivity

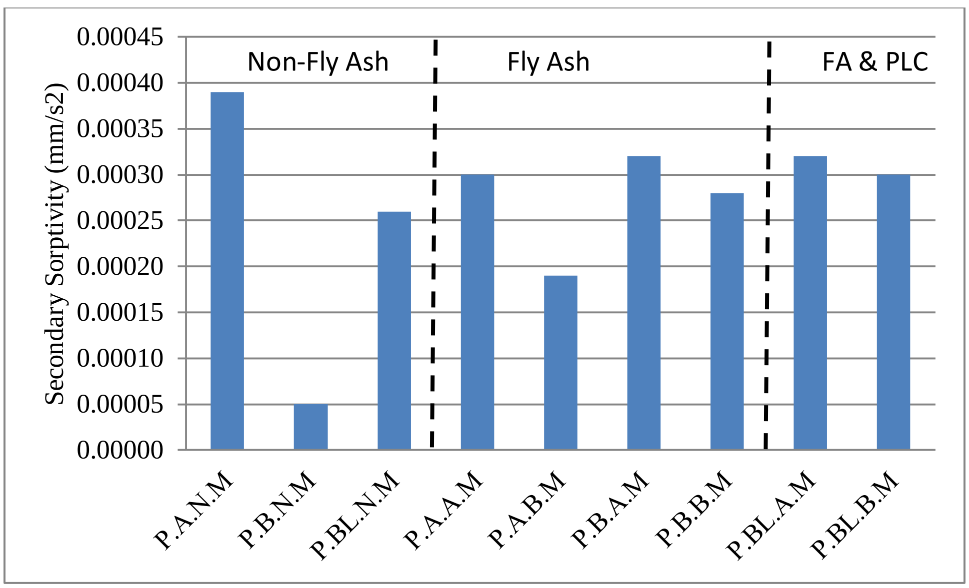

Figure 4.7: Select secondary sorptivity

4.2 Rapid Chloride Permeability Test Results

Seventy-two samples were tested using the rapid chloride penetration test (RCPT). Thirty-six were tested on the 28^{th} and 90^{th} day of each mix. Two samples for each mix were used, and then the results were averaged together. However, only the concrete mixtures containing the Piedmont aggregate are comparable and were used to help demonstrate the impact of chloride permeability of using portland limestone cement with fly ash as a combination (Table 4.4). The results from all mixtures tested are shown in Figure 4.8. The mixtures that only include the same piedmont aggregate, the manufactured sand, two different sources of Type F fly ash or none present, and three different cements can be seen in Figure 4.9. The permeability was reduced with the later age of the concrete, which is most likely due to the effect of the fly ash delayed reaction (Yoshitake et al., 2013). The mixtures containing fly ash have a lower coulomb count compared to the ones without fly ash, and the mixtures containing limestone have an even more noticeable reduction in permeability when compared to the mixtures that only contain fly ash. These results were expected based on the literature (Mohr et al., 2000; Langan and Ward 1990).

Table 4.4: RCPT test results

Designation	RCPT (coulombs)	
	28 Day	90 Day
P.A.N.M	7,170	5,300
P.B.N.M	6,860	5,120
P.BL.N.M	6,550	4,540
C.A.N.M	6,720	4,782
C.B.N.M	6,021	4,629
C.BL.N.M	6,769	5,433
M.A.N.M	6,828	5,240
M.B.N.M	6,056	5,286
M.BL.N.M	6,504	4,985
P.A.A.M	6,401	1,773
P.B.A.M	4,591	1,980
P.BL.A.M	3,682	1,331
P.A.B.M	6,134	1,562
P.B.B.M	5,225	1,651
P.BL.B.M	4,337	1,323
P.A.N.N	4,881	3,471
P.B.N.N	4,394	3,227
P.BL.N.N	4,330	3,449

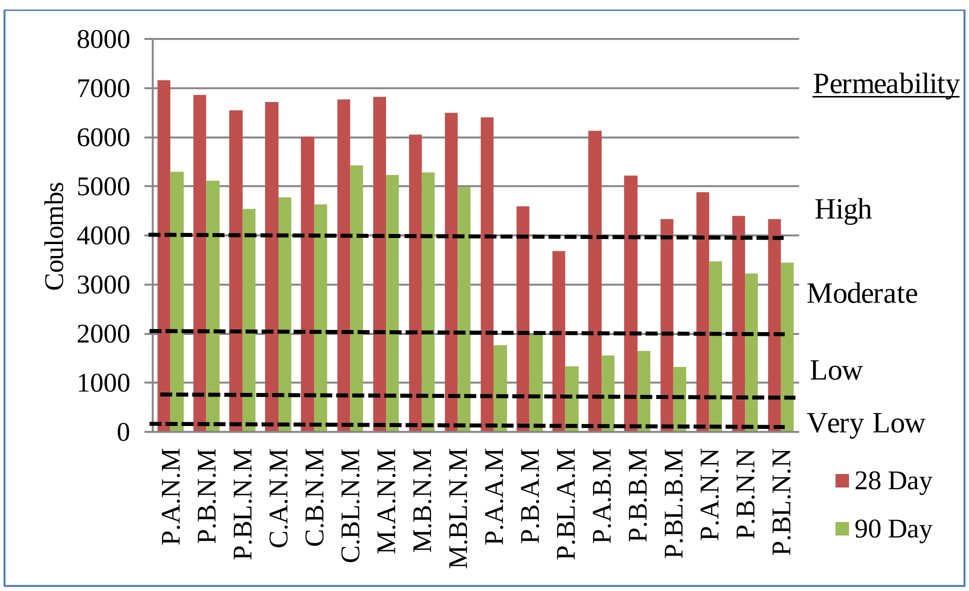

Figure 4.8: RCPT results

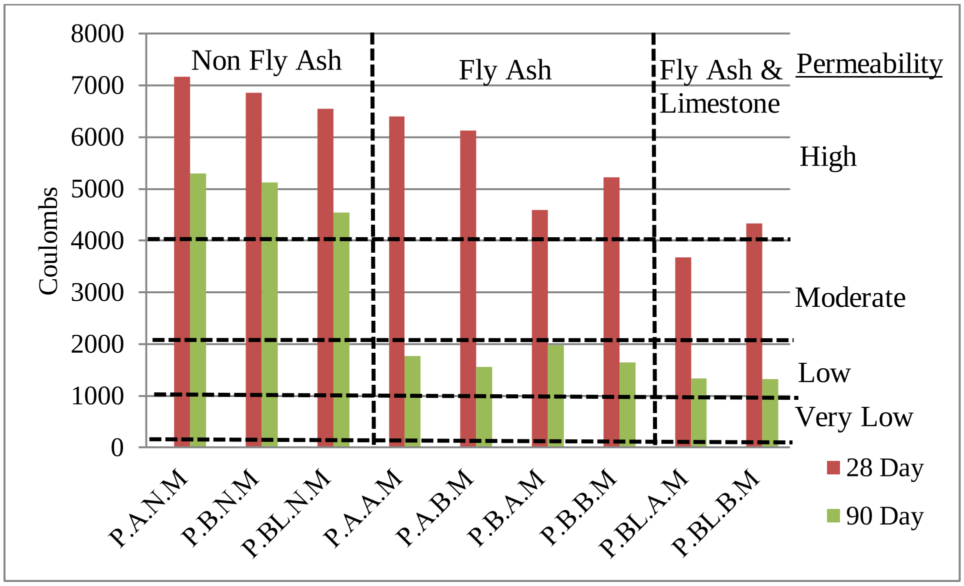

Figure 4.9: Select RCPT results

4.3 Air Permeability Test Results

The air permeability test results were given from the Torrent system as a *Kt*, which is a coefficient of air permeability, and the depth of which the permeability reached, *L* (Table 4.5). This test evaluated the air permeability of the cover concrete for each mix. The permeability was not able to be obtained for the PANM because of damage to the sample. The trend that is visible is that the fly ash mixtures are less permeable than the non-fly ash mixtures (Figure 4.10). There is also a trend that the mixtures that combine limestone and fly ash have a lower permeability than the fly ash non-limestone mixtures. These results are similar to others reported in the literature (Neville 2012).

Table 4.5: Air permeability test results

MIX	*Kt* (E-16m^2)	*L* (mm)
P.A.N.M	NA	NA
P.B.N.M	0.2225	32.4
P.BL.N.M	0.5435	45.6
P.A.B.M	0.0535	15.9
P.B.B.M	0.034	7.8
P.BL.B.M	0.016	5.25
P.A.A.M	0.1785	29.1
P.B.A.M	0.019	6.2
P.BL.A.M	0.0265	11.2

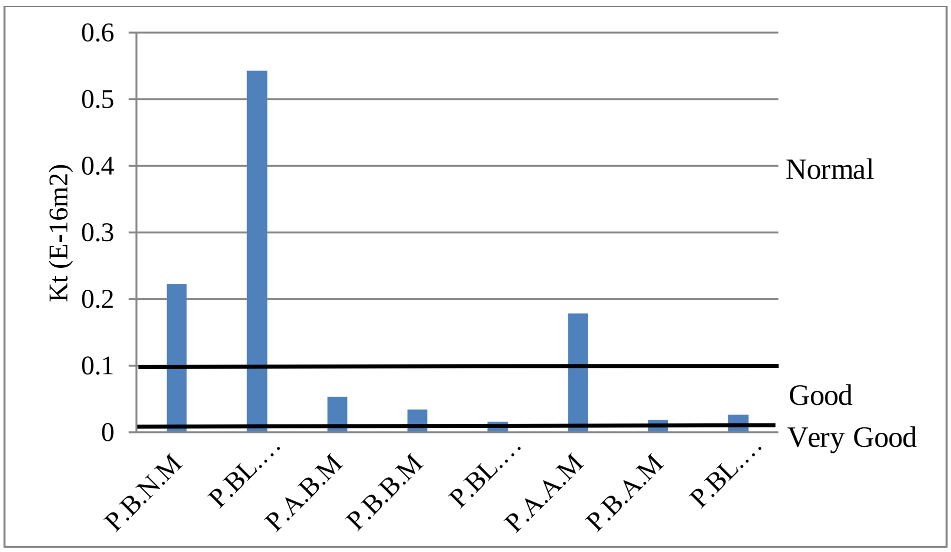

Figure 4.10: Air permeability results

4.4 Surface Resistivity Test Results

The surface resistivity results indicate some of the more distinctive differences between the mixtures. The trend shows that surface resistivity values are higher for the fly ash mixtures and even higher for the fly ash-Portland limestone cement mixtures (Table 4.6). The trend amplifies as the age of the concrete increases. Figure 4.11-Figure 4.16 shows a graphical comparison of the different mixtures by curing age. The trend can be clearly seen as early as the 28th day of curing. These results were taken from averaging four different measurement points per cylinder, and then averaging the total resistivity of three cylinders. The higher the surface resistivity the lower the permeability can be expected. These trends are also supported by the literature (Polder 2001).

Table 4.6: Surface resistivity results

Mix	Instrument (Proceq)	3 Day	7 Day	28 Day	90 Day
P.A.N.M	Set AVG	3.58	4.27	6.91	8.91
P.B.N.M	Set AVG	4.81	5.24	7.33	7.33
P.BL.N.M	Set AVG	4.99	5.36	7.59	9.13
C.A.N.M	Set AVG	4.06	4.85	6.73	9.80
C.B.N.M	Set AVG	4.53	5.21	7.03	8.72
C.BL.N.M	Set AVG	4.84	5.54	6.60	8.09
M.A.N.M	Set AVG	3.05	3.70	5.98	7.76
M.B.N.M	Set AVG	4.48	4.71	6.65	7.78
M.BL.N.M	Set AVG	5.85	6.15	7.60	8.54
P.A.A.M	Set AVG	3.45	3.63	7.51	24.29
P.B.A.M	Set AVG	5.01	5.39	9.84	26.60
P.BL.A.M	Set AVG	4.84	5.57	12.55	35.25
P.A.B.M	Set AVG	3.12	3.63	7.77	26.62
P.B.B.M	Set AVG	4.99	5.36	10.45	32.86
P.BL.B.M	Set AVG	4.60	5.57	12.62	37.35
P.A.N.N	Set AVG	4.57	5.42	7.46	9.64
P.B.N.N	Set AVG	7.99	8.74	10.68	10.81
P.BL.N.N	Set AVG	7.05	7.96	9.46	10.34

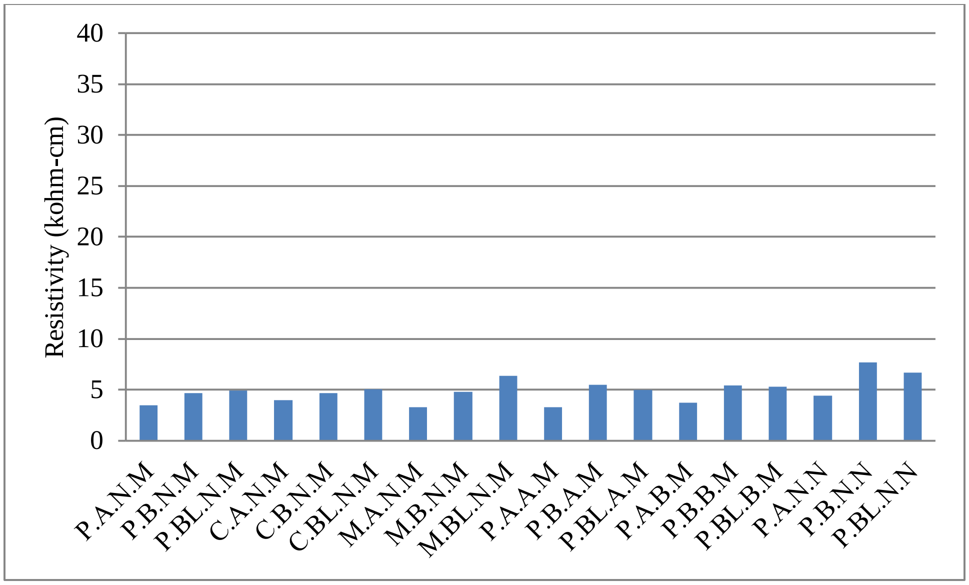

Figure 4.11: 3 Day surface resistivity results

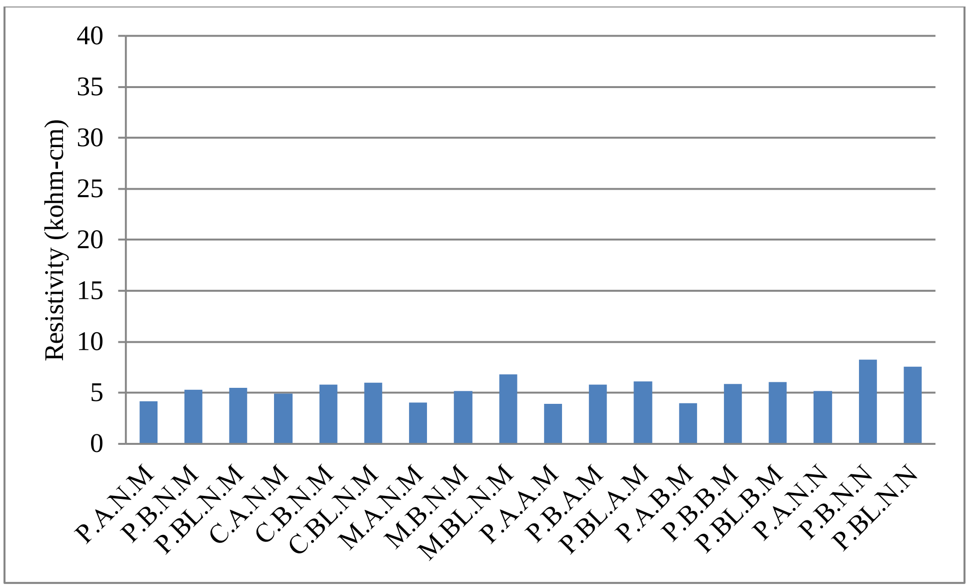

Figure 4.12: 7 Day surface resistivity results

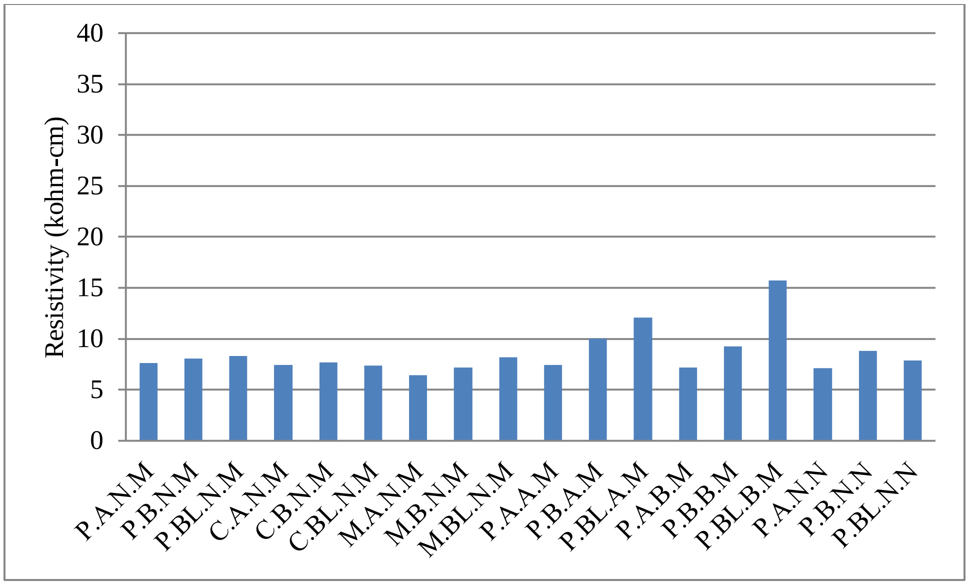

Figure 4.13: 28 Day surface resistivity results

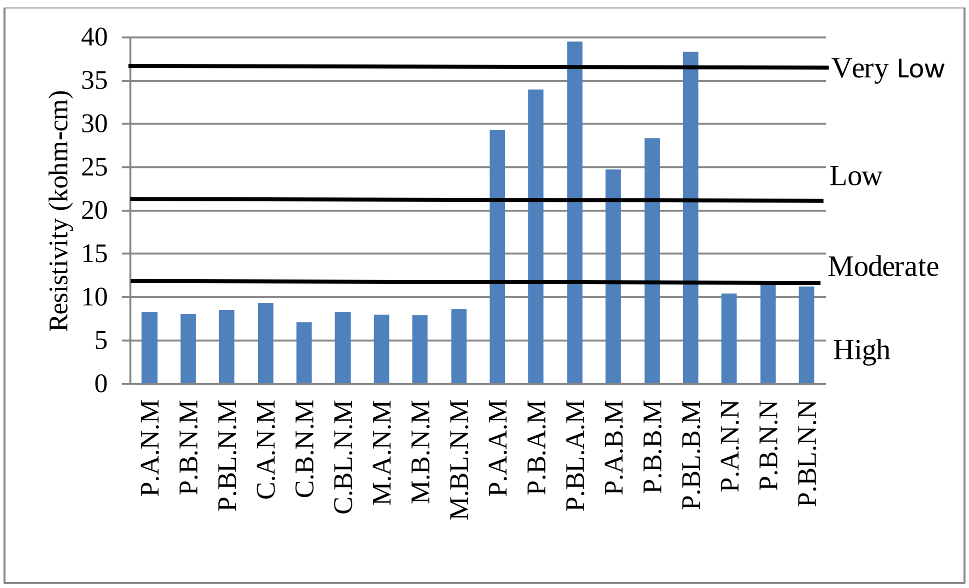

Figure 4.14: 90 Day surface resistivity results

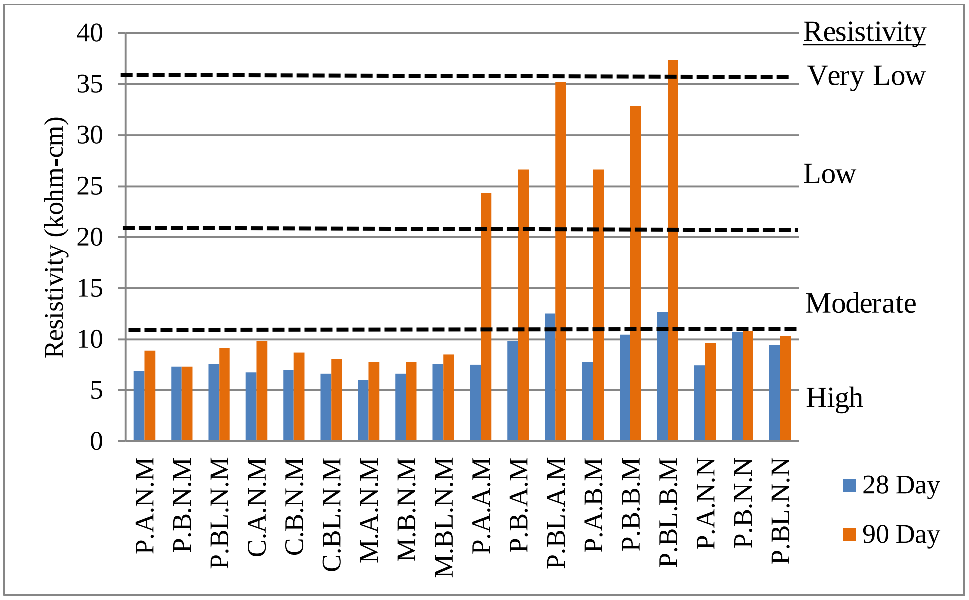

Figure 4.15: 28 day & 90 day surface resistivity results

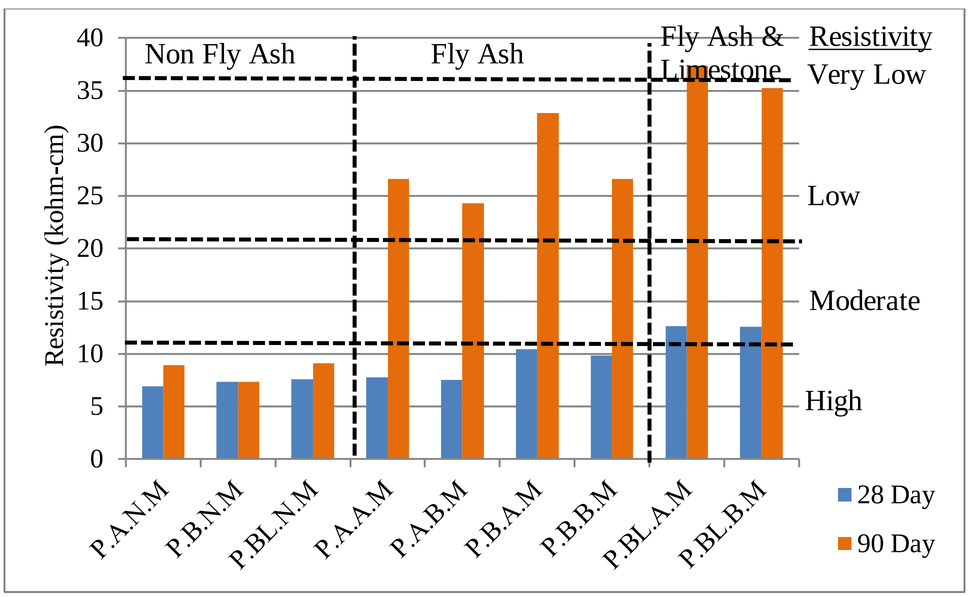

Figure 4.16: Select 28 day & 90 day surface resistivity results

CHAPTER 5: DISCUSSION OF RESULTS

5.1 Comparative Analysis

In order to better understand the durability of the concrete samples, different testing methods were used to ensure the general trend of portland limestone cement (PLC) mixtures with fly ash having lower permeability compared to the other mixtures, can be seen from many different tests. The tests are then compared to one another to determine how well two different test results correlate. The correlation can give a better indication of factors that could confound the test method. For example, if the rapid chloride penetration test (RCPT) and surface resistivity (SR) test correlated very well, but the air permeability test did not, then more analysis would need to be done to determine if there is something in the concrete mixtures that would make electrical resistance methods unsuitable for these types of concrete. To begin, the comparative analysis the air permeability results of the coefficient of permeability *Kt*, and the depth of the permeability *L* were plotted together to illustrate their potential correlation. The correlation between the two is shown to fit a logarithmic trend line very well. This can be expected as for the more permeable the concrete is the deeper the penetration.

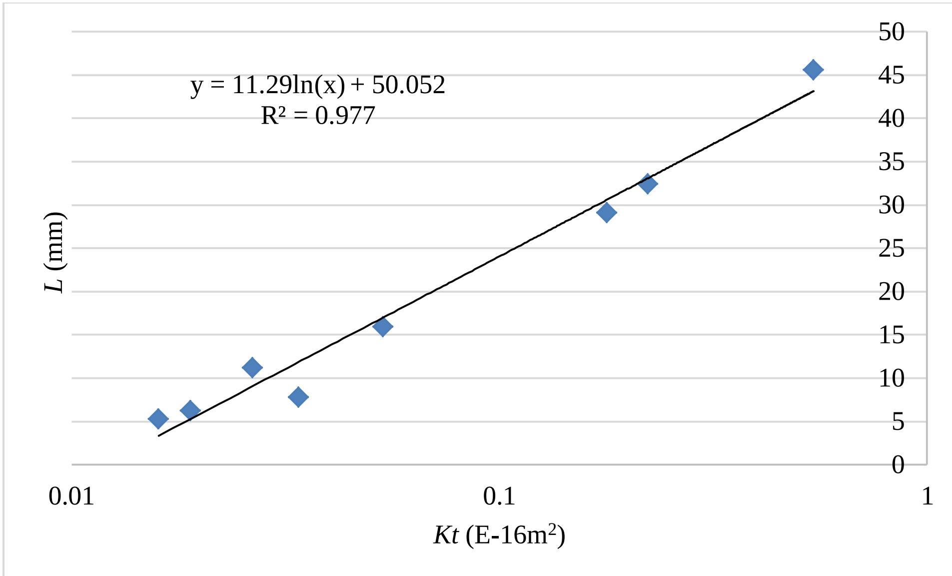

Figure 5.1: Air permeability *Kt* vs. *L*

The next comparative analysis is the plotting of the air permeability coefficient of the samples against other permeability tests to establish correlations between the two different permeability tests. The air permeability plotted with surface resistivity (SR) and the rapid chloride penetration test (RCPT) can be seen in Figure **5.5**. This data shows that there is some correlation between the two tests; both of the limestone and fly ash mixtures tend to stand out from the rest of the concrete mixtures. The portland limestone cement (PLC) and fly ash (FA) mixtures are circled to better show the trend of these mixtures being towards the less permeable side of the graphs. The designation of circling the PLC and FA mixtures can be seen in most of the comparative graphs in chapter 5. The air permeability comparison has a better correlation to both the 28 day RCPT and 28 day SR tests. The SR and air correlation, at 28 days, had a correlation of R^2= 0.68 versus the 90-day correlation of R^2=0.58 (Figure 5.4 & Figure 5.5). The RCPT had correlations of R^2=0.69 at 28 days and R^2=0.63 at 90 days (Figure 5.2 & Figure 5.3). Due to this difference in correlation, the air permeability test used may not represent the improvement in durability that the mixtures gain from the late age reactions. Due to the lack of literature found on the air permeability, this result was not expected.

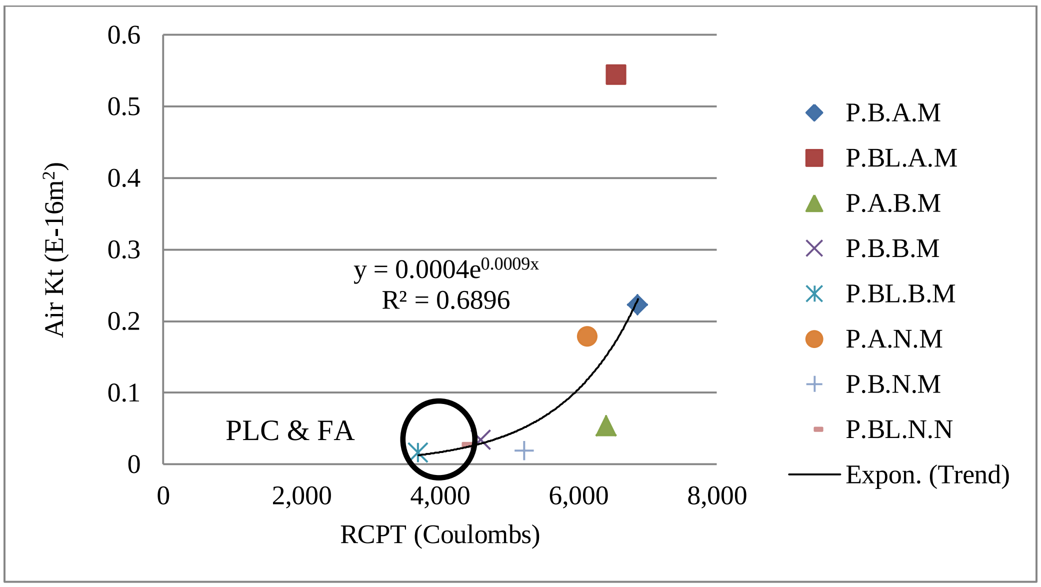

Figure 5.2: Air permeability vs. 28 day RCPT results

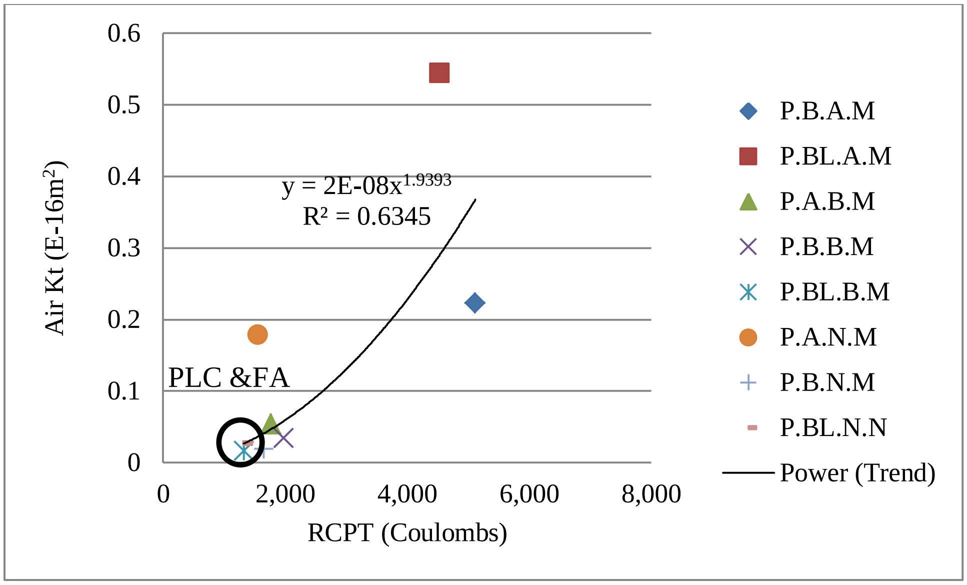

Figure 5.3: Air permeability vs. 90 day RCPT results

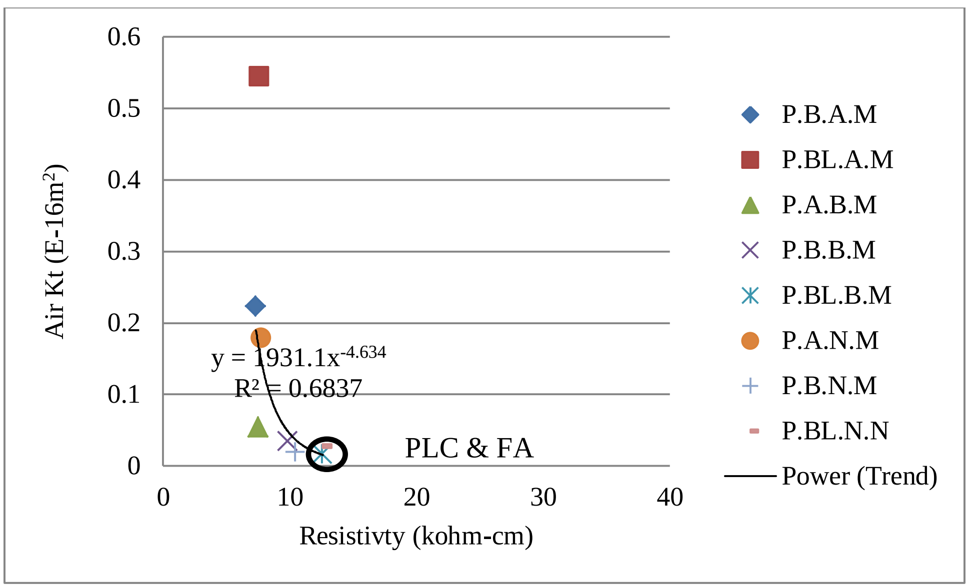

Figure 5.4: Air permeability vs. 28 day surface resistivity results

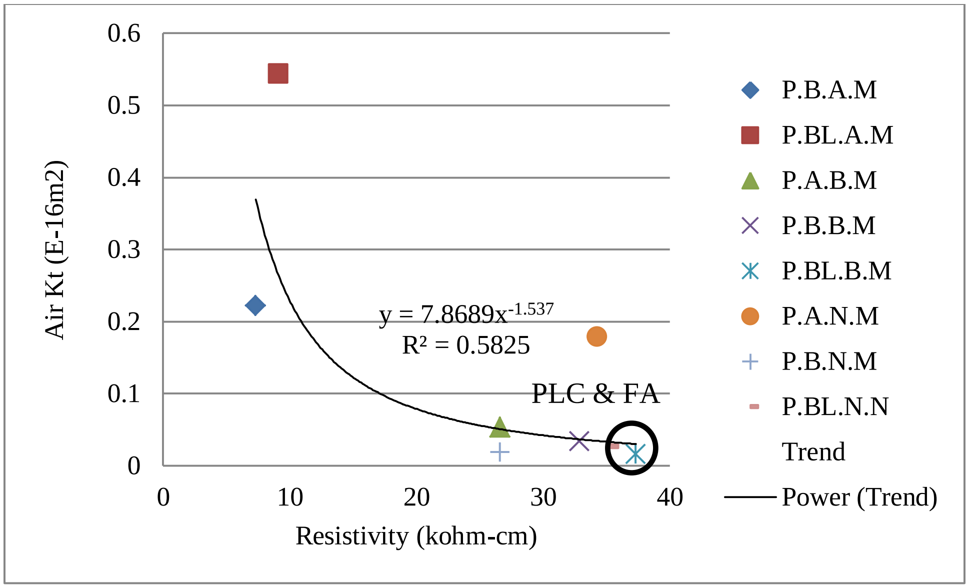

Figure 5.5: Air permeability vs. 90 day surface resistivity results

Two other tests that were compared using a comparative analysis are the rapid chloride penetration test (RCPT) and surface resistivity (SR) test (Figure 5.6 - Figure 5.10). The SR and RCPT test results were judged to be very well correlated for both 90-day curing and 28-day curing. Again, the fly ash and limestone mixtures are notable as the least permeable mixtures. These results were expected based on the literature but not to this extent of this tight of correlation (Morriset al., 1996; Rupnow and Icenogle 2011). The SR test is very strongly correlated with the RCPT; thus, it can be used to obtain similar durability measurement as the RCPT, while being greatly more economical, due to its speed of measurement.

When compared separately the SR correlates better with the RCPT on the later age of the concrete mixtures. The 28-day correlation (Figure 5.8) for all of the mixtures made in the project is R^2 = 0.79 and the 90-day correlation (Figure 5.9) R^2 = 0.94. When the two graphs are combined (Figure 5.10), the correlation was R^2 = 0.93. These correlations suggest that the SR test better represents the later age permeability characteristics. However, when the mixtures containing fly ash are examined separately the 28-day correlation (Figure 5.6) is 0.92, and the 90-day correlation (Figure 5.7) is 0.96. After comparing all of the trend and correlations, it is determined that the lower the permeability the better representative the SR test is of the RCPT. Even at the higher permeability readings, the SR test gives a very good representation of the RCPT.

For completeness the SR, RCPT, and Index results were plotted against the compressive strengths (Figure 5.11Figure 5.15). The RCPT and SR results were compared to their corresponding ages and the index was compared to the 90-day compressive strength because of the many late age tests used in the index. The compressive strength did not vary with the change in cement type as much as the permeability of the concrete did. Due to the lack of change in compressive strength, there was not any significant correlation between compressive strength and any of the permeability results.

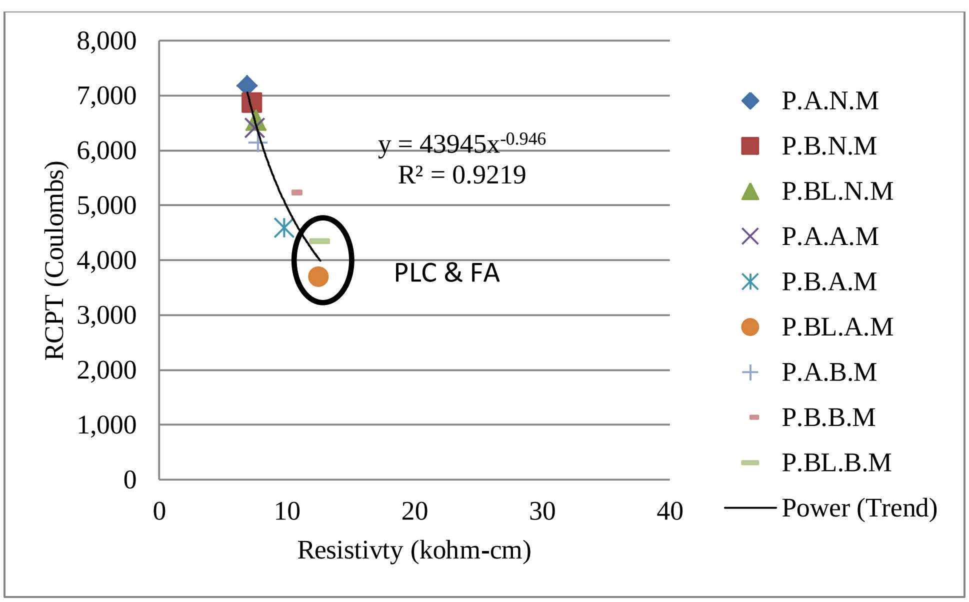

Figure 5.6: Select 28 day RCPT vs. surface resistivity

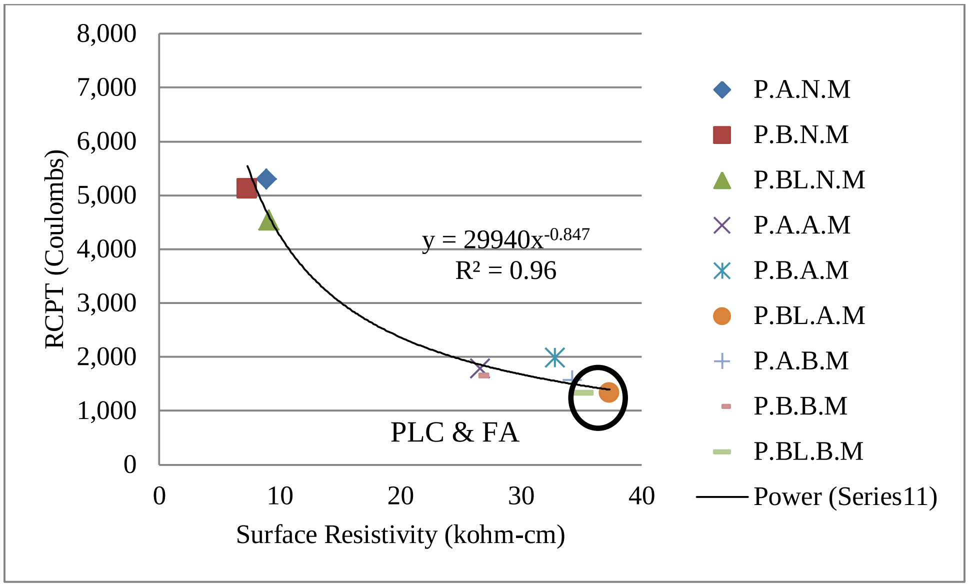

Figure 5.7: Select 90 day RCPT vs. surface resistivity

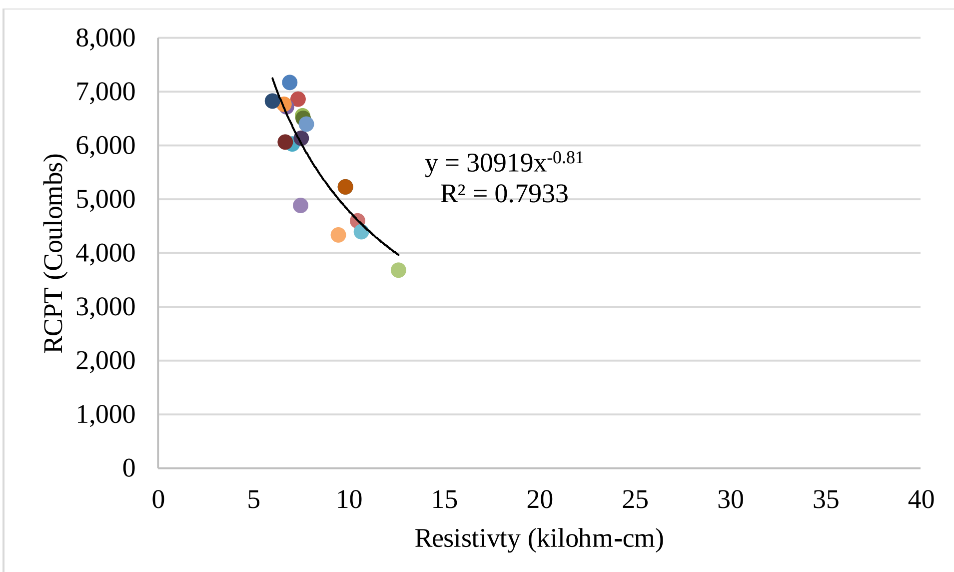

Figure 5.8: 28 day RCPT vs. surface resistivity

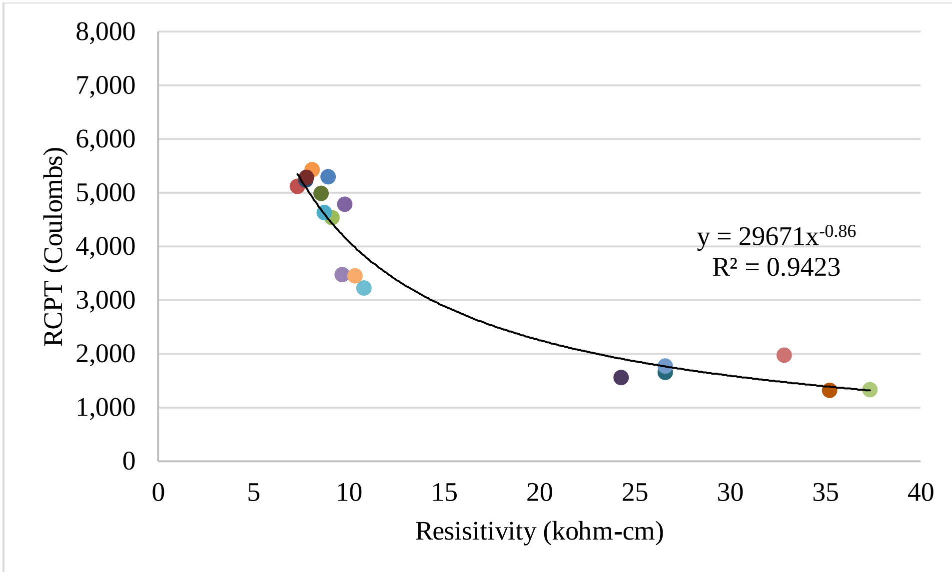

Figure 5.9: 90 Day RCPT vs. surface resistivity

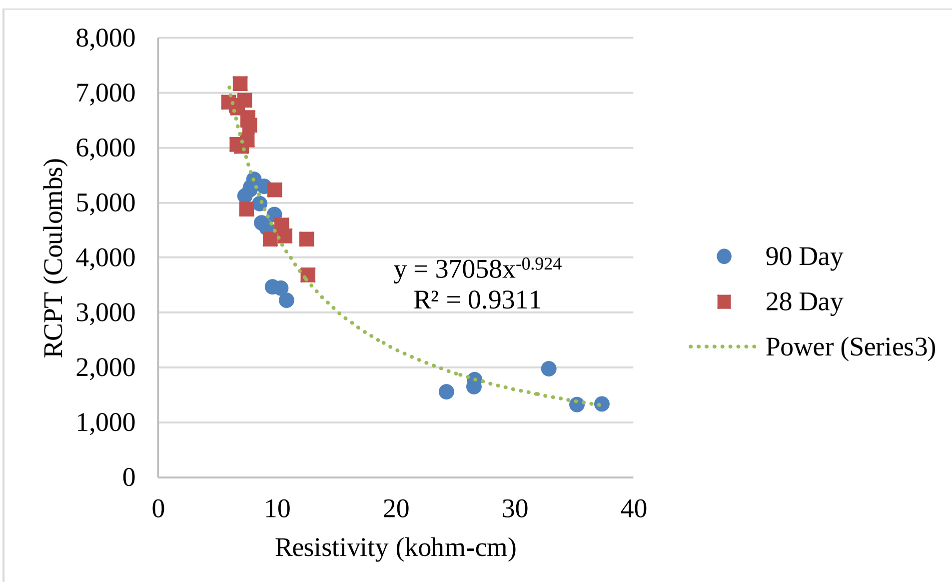

Figure 5.10: Combined RCPT vs. surface resistivity

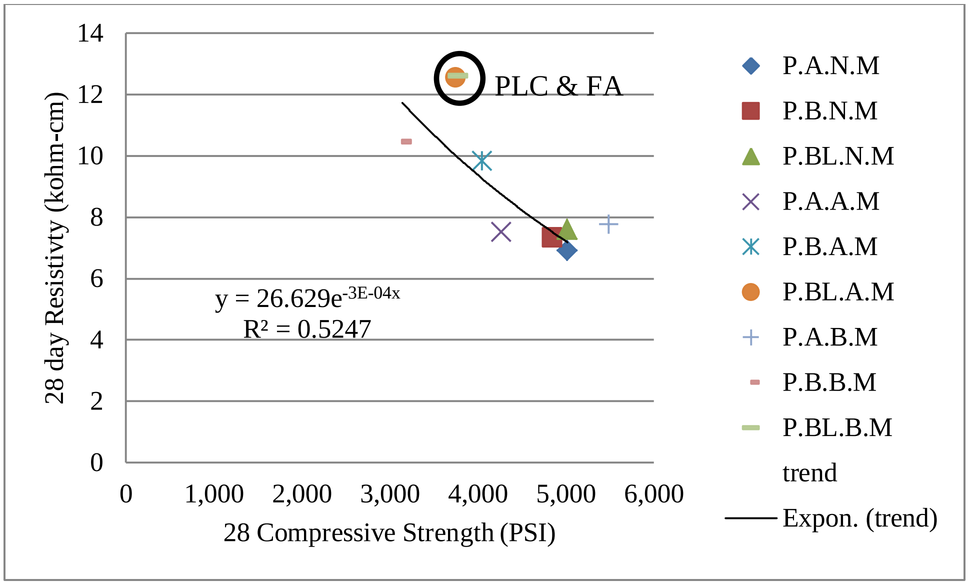

Figure 5.11: 28 day resistivity vs. 28 day compressive strength

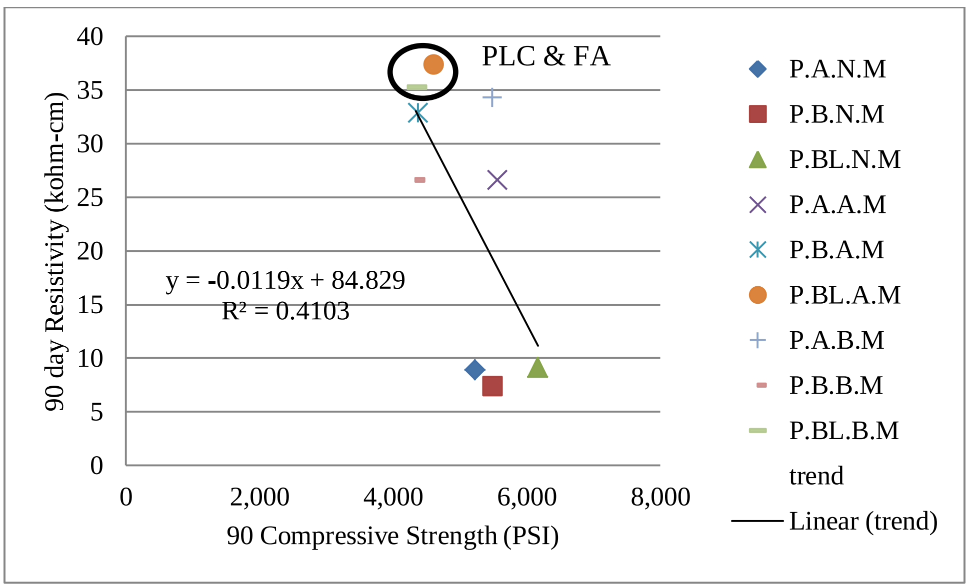

Figure 5.12: 90 day resistivity vs 90 day compressive strength

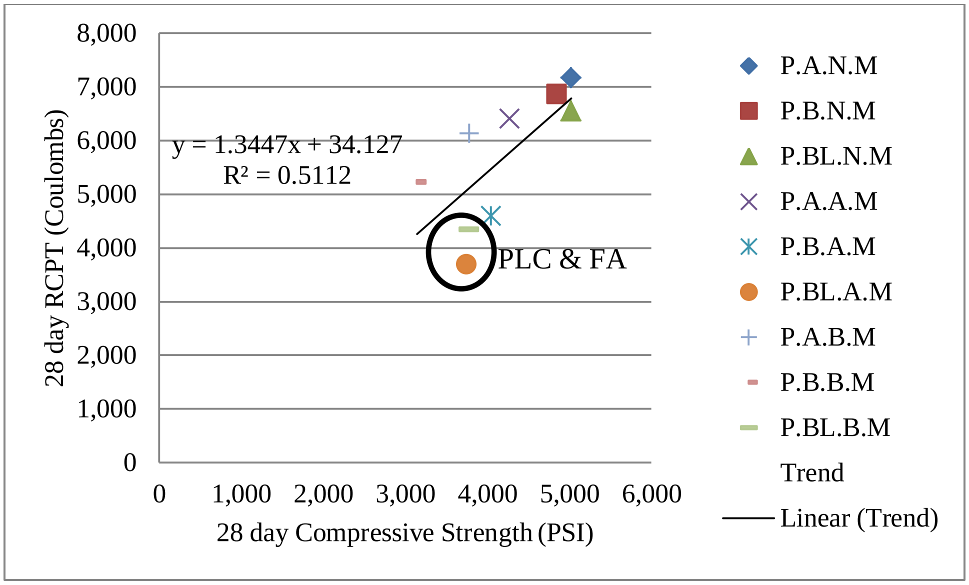

Figure 5.13: 28 day RCPT vs 28 day compressive strength

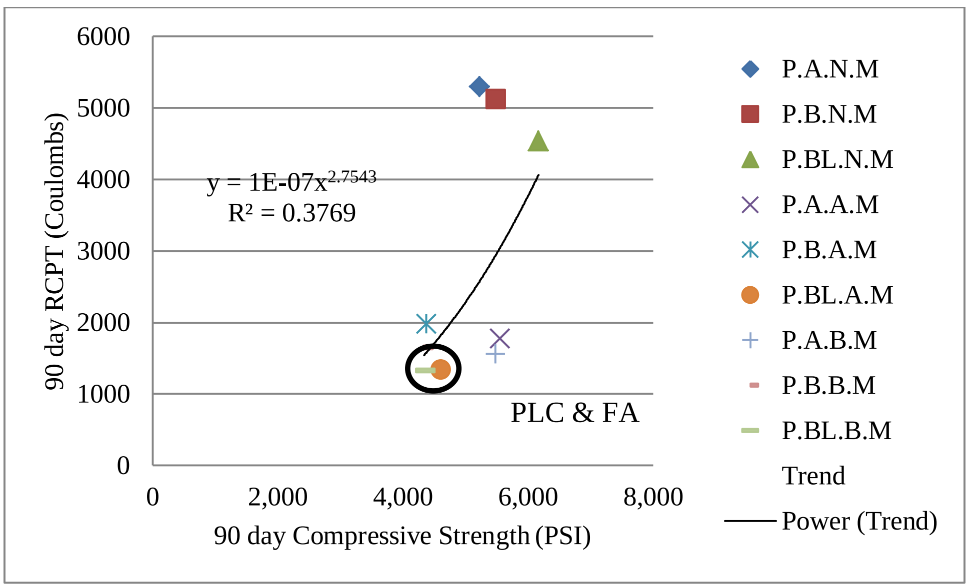

Figure 5.14: 90 day RCPT vs compressive strength

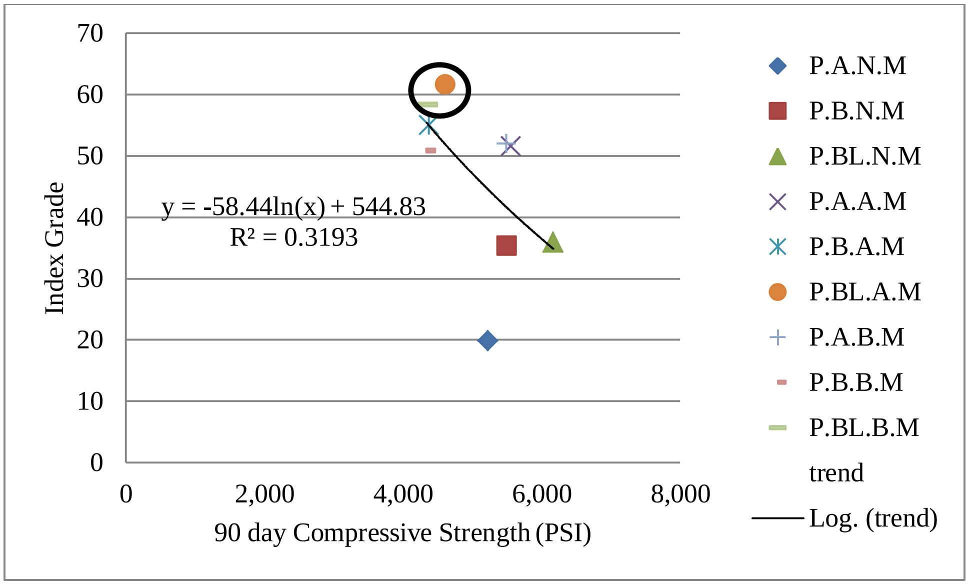

Figure 5.15 Index grade vs 90 day compressive strength

5.2 Permeability Index

In order to better understand the permeability of the concrete, a permeability index (Table 5.4) was created to relate each concrete mixture to an overall permeability grade. These results are also summarized in Figure 5.16. The grade was compromised of individual index scores for each permeability test performed on the concrete mixture. The individual index scores can be seen in Table 5.1 through Table 5.3. It should be noted that the air permeability index is different from the given Torrent index. The individual tests used in this index were the Torrent air permeability test, 28 day surface resistivity, 90 day surface resistivity, 28 day RCPT, and 90 day RCPT. Each mix received a score for each based on interpolation in the range the result met. Once each mix had an individual test score, the individual tests scores were summed to give an overall grade. There was not a specific weighting of one test over another. However the RCPT and SR results for both 28 day and 90 day were used in this index. Due to using both of these curing ages the indexes are weighted towards these two tests. The scoring system gave higher points to mixtures that had lower permeability.

Table 5.1: RCPT index

Charge Passed (Coulombs)	Chloride Ion Permeability	Index Range
>4,000	High	0-1
2,000-4,000	Moderate	1-2
1,000-2,000	Low	2-3
100-1,000	Very Low	3-4
<100	Negligible	4-5

Table 5.2: Surface resistivity index

4”x8” Cylinder (kilohm-cm)	Chloride Ion Permeability	Index Range
<12	High	0-1
12-21	Moderate	1-2
21-37	Low	2-3
37-254	Very Low	3-4
>254	Negligible	4-5

Table 5.3: Air permeability index

Quality of Cover Concrete	Kt ($10^{-16}m^2$)	Index Range
Very Bad	>10	0-1
Bad	1.0-10	1-2
Normal	0.1-1.0	2-3
Good	0.01-0.1	3-4
Very Good	<0.01	4-5

Table 5.4: Permeability index

Test	Air	SR 28	SR 90	RCPT 28	RCPT 90	Overall Score	Grade
Range	0-5	0-5	0- 5	0-5	0-5	0-30	0-100
Info	5 Best	5 Best	5 Best	5 Best	5 Best	30 Best	100 Best
Mix							
P.A.N.M	NA	0.57	0.74	0.47	0.78	2.56	10.24
P.B.N.M	3.86	0.61	0.61	0.52	0.81	6.41	25.64
P.BL.N.M	3.51	0.63	0.76	0.57	0.91	6.38	25.52
P.A.A.M	4.52	0.63	2.35	0.60	2.12	10.22	40.88
P.B.A.M	4.73	0.82	2.74	0.90	2.01	11.20	44.80
P.BL.A.M	4.93	1.06	3.00	1.16	2.35	12.50	50.00
P.A.B.M	3.91	0.65	2.83	0.64	2.23	10.26	41.04
P.B.B.M	4.90	0.87	2.35	0.80	2.18	11.10	44.40
P.BL.B.M	4.82	1.07	2.89	0.94	2.35	12.07	48.28

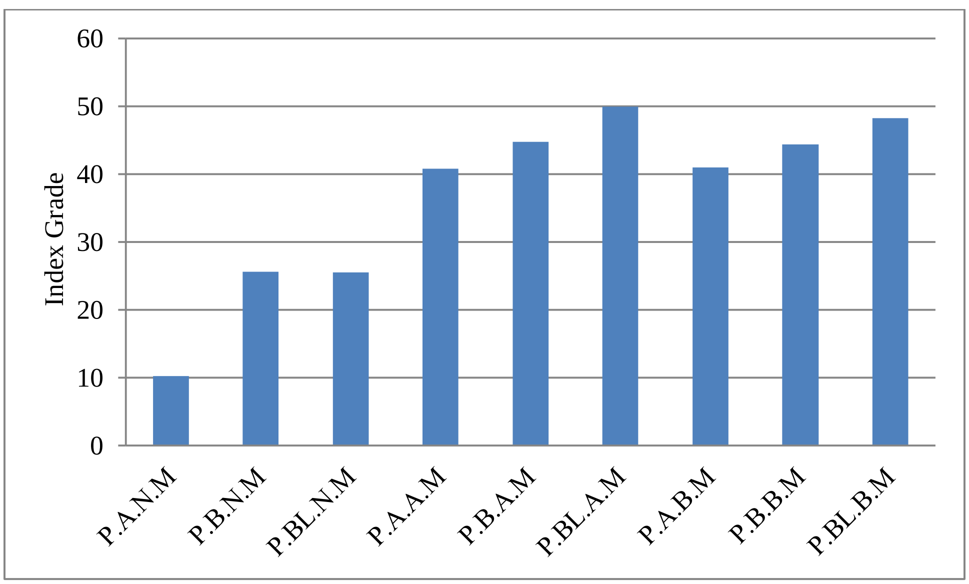

Figure 5.16: Index grade comparison

It can be seen in Figure 5.16 that the mixtures containing fly ash had a much higher index grade which relates to a lower permeability. The mixtures containing limestone had an even higher index grade showing that the limestone reduced the permeability of the concrete even more than a mix that had fly ash alone.

5.3 Comparative Analysis Using the Permeability Index

To start the comparison using the permeability index, the surface resistivity (SR) and rapid chloride penetration test (RCPT) results were used to see how well the index correlated with actual permeability measurements. The index has a much stronger correlation with both the 90 day SR and 90 day RCPT results verses the 28 day results. The similar trend can still be found in all of the graphs that the limestone and fly ash mixtures are less permeable than any other mixture.

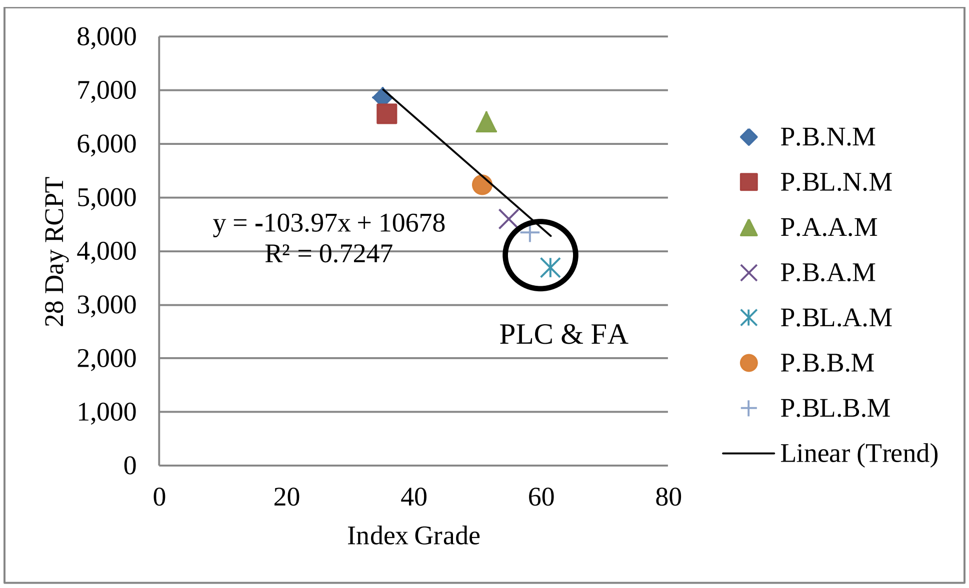

Figure 5.17: 28 day RCPT vs index grade

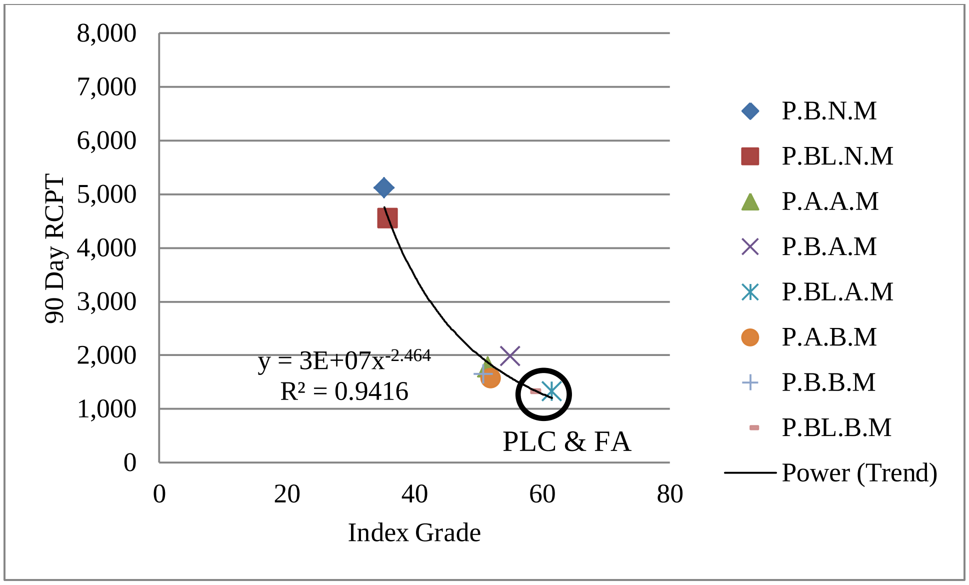

Figure 5.18: 90 day RCPT vs index grade

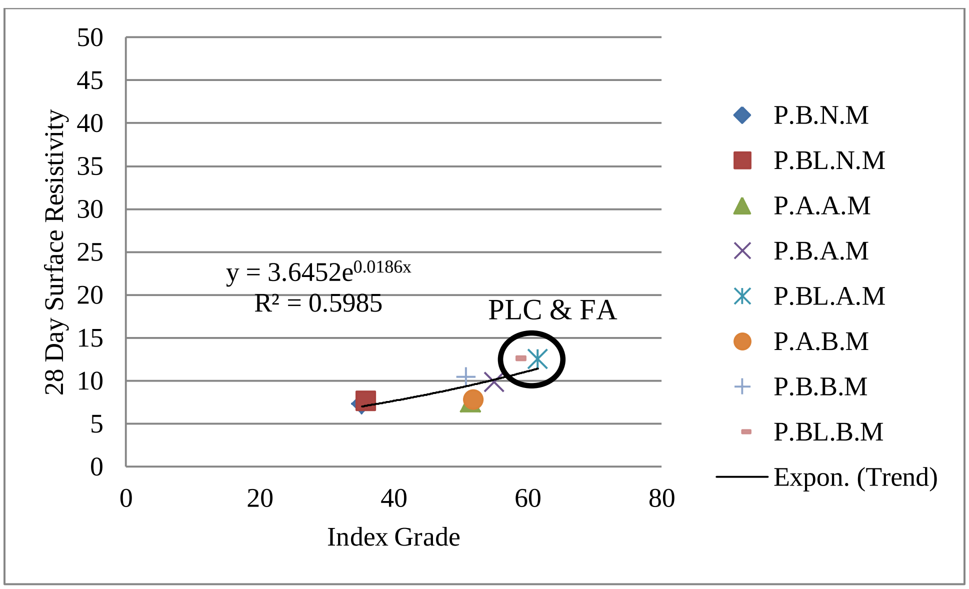

Figure 5.19: 28 day surface resistivity vs index grade

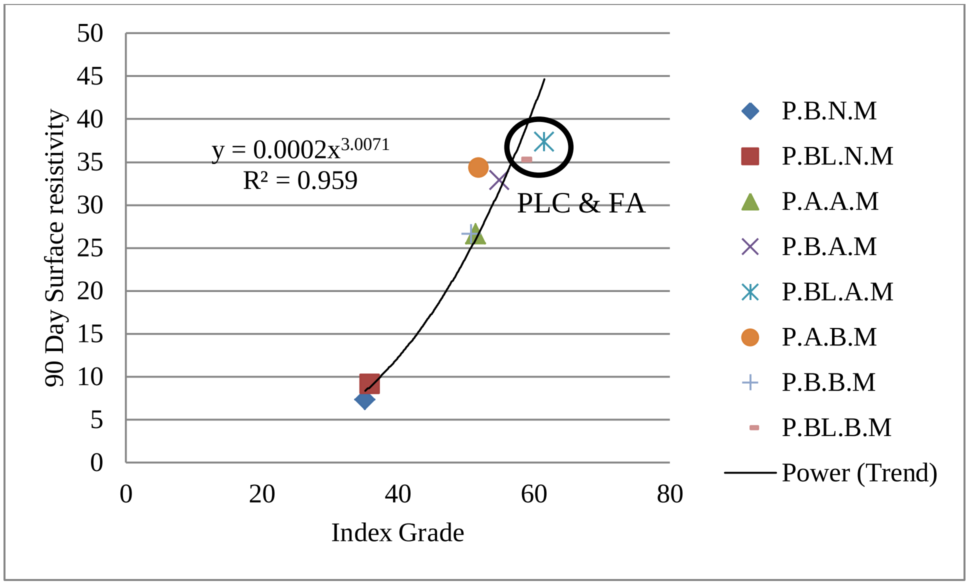

Figure 5.20: 90 day surface resistivity vs index grade

The air permeability versus index comparison shows the similar trend that the fly ash and limestone stand out as the least permeable mixture. When examining Figure 5.21, the lower permeability data points fall much closer to the trend line which could show that the air permeability test better represents the permeability of the mixtures when they have lower permeability. Only the air permeability test was performed on the fly ash mixtures, and in order to get a better representation of the test non-fly ash mixtures should be examined to observe more of the permeability spectrum.

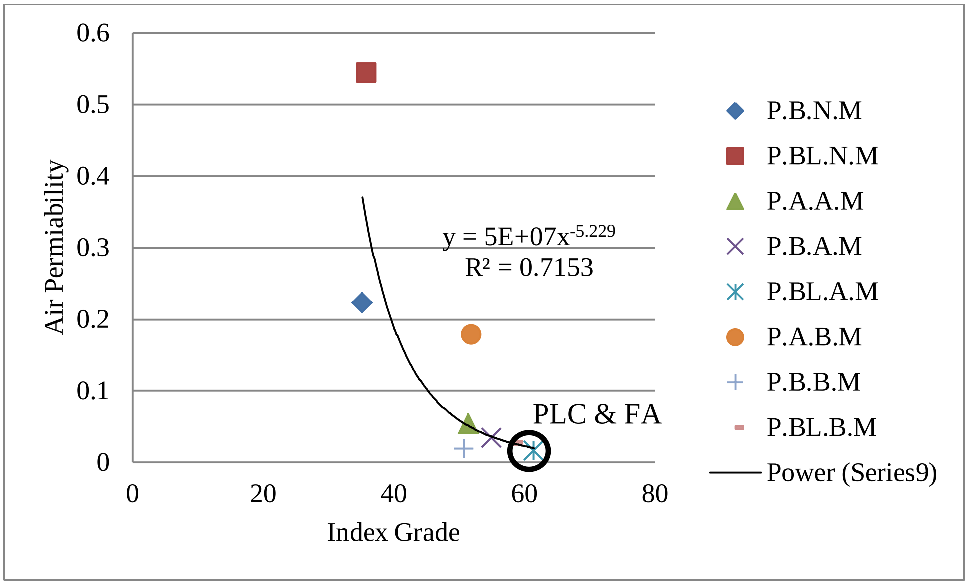

Figure 5.21: Air permeability vs index grade

The initial intent for the permeability index was only to better describe the permeability of the concrete mixtures that incorporated many different permeability tests. Once the literature was examined for the sorptivity test, it was determined that there was no established guidance to qualitatively categorize the permeability based on the results of the test. A secondary intent was formed to use the index to try to better understand the sorptivity results. The index was then modified to exclude the sortivity data.

When comparing the index and many different sorptivity data points, correlations can be seen. Figure 5.22, all seem to exhibit a general correlational trend, but some have better correlations than others. The initial and secondary absorption rates gave a good indication into how the concrete allowed water to penetrate into the pore structure. Another method to analyze the sorptivity of the concrete sample is using the Snick point (Weiss 2015). The Snick point is the intersection point of the best fit trends between the initial and secondary absorption time periods. This point can give us indication into how the concrete is absorbing the water based on the location of the Snick point (Weiss 2015).

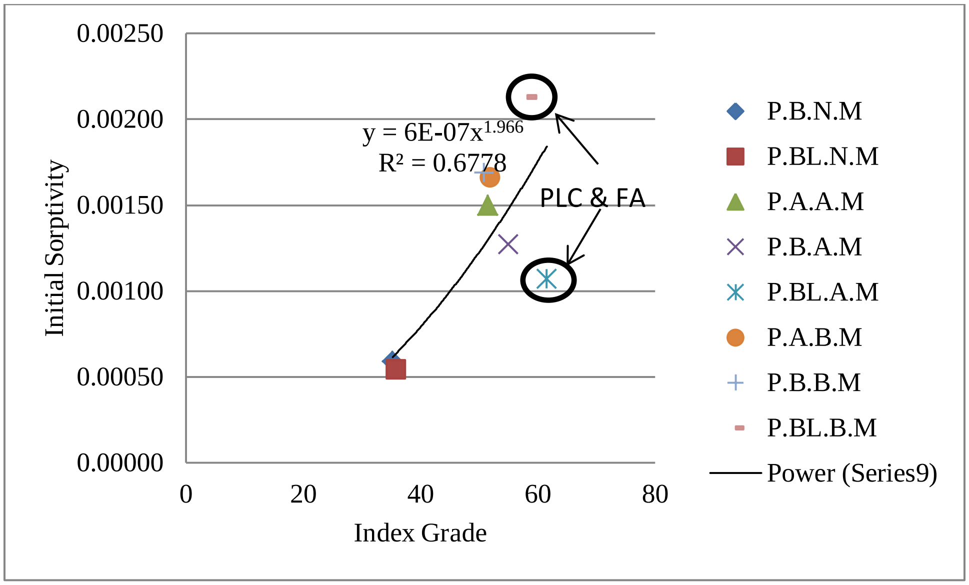

Figure 5.22: Initial sorptivity vs. index grade

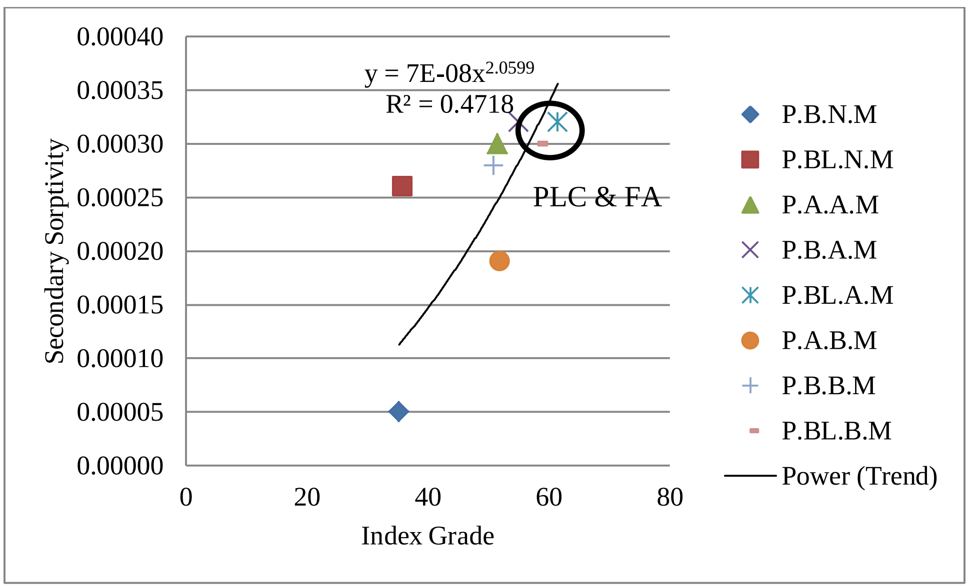

Figure 5.23: Secondary sorptivity vs. index grade

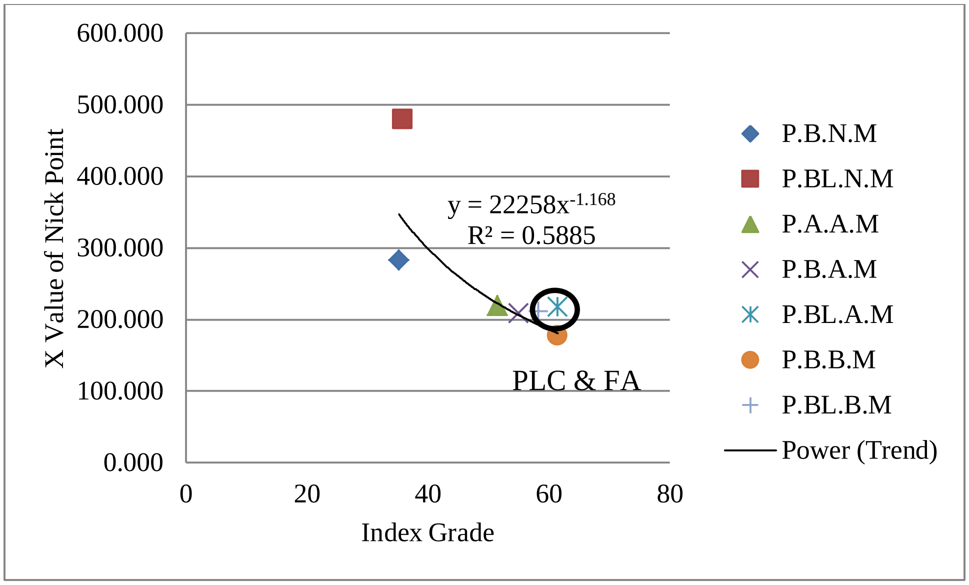

Figure 5.24: *X* coordinate of nick point vs. index grade

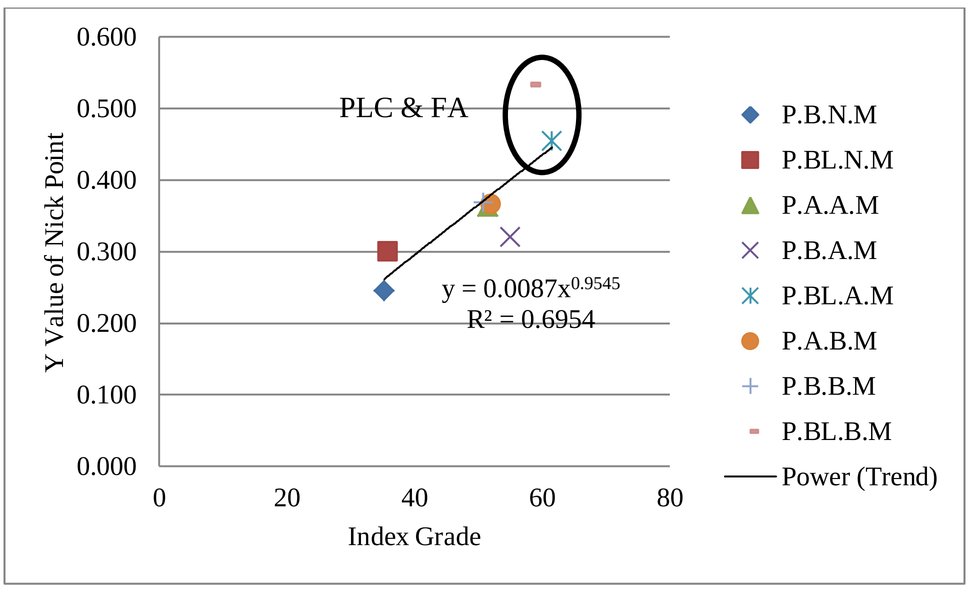

Figure 5.25: *Y* coordinate of nick point vs. index grade

In Figure 5.16 it can be seen that the same trend is held true from many of the pervious individual test results. This trend is that the mixtures containing fly ash have a reduction in permeability when compared to mixtures that do not. For this index the lower the permeability of the concrete the higher grade the mixture received. The index also still shows an even greater reduction in permeability with the mixtures that contain fly ash and limestone by giving those mixtures an even higher score. This makes sense because the index was built based on the how the mixtures performed in the air permeability, RCPT, and SR tests.

The index created had very strong correlation with the 90 day RCPT and SR testing with R^2 values over 0.95 (Figure 5.18 & Figure 5.20). The index did not correlate as well with the air permeability, the early age RCPT, and SR, although here is still a noticeable correlation for these tests (Figure 5.17, Figure 5.19. & Figure 5.21). All of these test mentioned were used in the construction of the index and the correlations within the dataset should be expected. Another aspect that should be noted is in the air, SR, and RCPT graphs the mixtures with the limestone and fly ash are located at the ends of the trends that translate out to having less permeability.

After the index was created the sorptivity test results were plotted against the index grades (Figure 5.22). The index seemed to correlate fairly well with the sorptivity results. However the results do not follow the same trend as the other test results when it comes to order of which the mixtures are on the trend line. For example, the fly ash and limestone mixtures are normally on one distinct end of the trend line in other results, but in sorptivity they are in the middle of the data group., The mixtures that contained fly ash and limestone are more random and do not point to a specific mixture or set of mixtures falling at similar place on the graphs as it has in other tests when compared to the index.

The index does have some limitations. Due to this being an experimental index, the amount of data examined for the use in the index is very limited in itself. There were only nine different concrete mixtures used in the index. All of the mixtures were held at the same water to cement ration and air content. These factors could be changed to verify that the index is valid for a much wider range of data. Not only more concrete mixtures could be used in this index, but more permeability tests could be used to again widen the range of which this index covers. The correlations of the index may be slightly affected based on the air permeability measurement for the first mixture not being available. This cause the score for that mixture to decrease some which would cause the correlation to be shifted slightly.

This index could be utilized to help better summarize how a mixture is going to perform in a real world application. The addition of tests used in the index will only help this index to better predict how the permeability of the concrete compares to other mixtures. The index can also be used to give a better indication into how it may perform in another test that wasn’t actually used to evaluate that specific concrete. For example, because multiple test methods were used, and if more can be added then a concrete sample can is tested using a few of the tests used in the index. Then using the index, the tests that were not performed can be predicted for that concrete. Weighing the tests can also offer a better alternative to the index. This was attempted below.

5.4 Alternative Permeability Index

In order to better understand the correlations of the index developed as part of this work and other conventional test methods, an alternative index was developed. In this index, the 28 day tests were taken out of the index to help better understand the permeability of the concrete at a later age. The index was also weighted 40% towards RCPT, 40% towards SR, and 20% towards air permeability. The primary motivation to create a permeability index was because of the fly ash addition in some of the mixtures. The fly ash does not cause as significant of a reduction of permeability at the 28 day testing as it does in the 90 day testing. Due to this late age reaction, the true permeability characteristics of the concrete may not be represented if the earlier age tests are included in the index. The weighing was determined due to the fact that the RCPT test is more established and has been proven to have good correlations with actual field results (Hooton et al., 2006). The alternative index can be seen in Table 5.5. The total score is out of 25 points. To achieve the desired weighting of the test methods, the 90 day RCPT and SR were double counted. The scores on the relevant mixtures can be seen summarized in Figure 5.26.

Table 5.5: Alternative Permeability Index

Test	Air	SR 90	RCPT 90	Overal Score	Grade
Range	0-5	0- 5	0-5	0-25	0-100
Info	5 Best	5 Best	5 Best	30 Best	100 Best
Mix					Grade
P.A.N.M	NA	0.74	0.78	3.04	12.16
P.B.N.M	3.86	0.61	0.81	6.70	26.8
P.BL.N.M	3.51	0.76	0.91	6.85	27.4
P.A.A.M	4.52	2.35	2.12	13.46	53.84
P.B.A.M	4.73	2.74	2.01	14.23	56.92
P.BL.A.M	4.93	3	2.35	15.63	62.52
P.A.B.M	3.91	2.83	2.23	14.03	56.12
P.B.B.M	4.9	2.35	2.18	13.96	55.84
P.BL.B.M	4.82	2.89	2.35	15.30	61.2

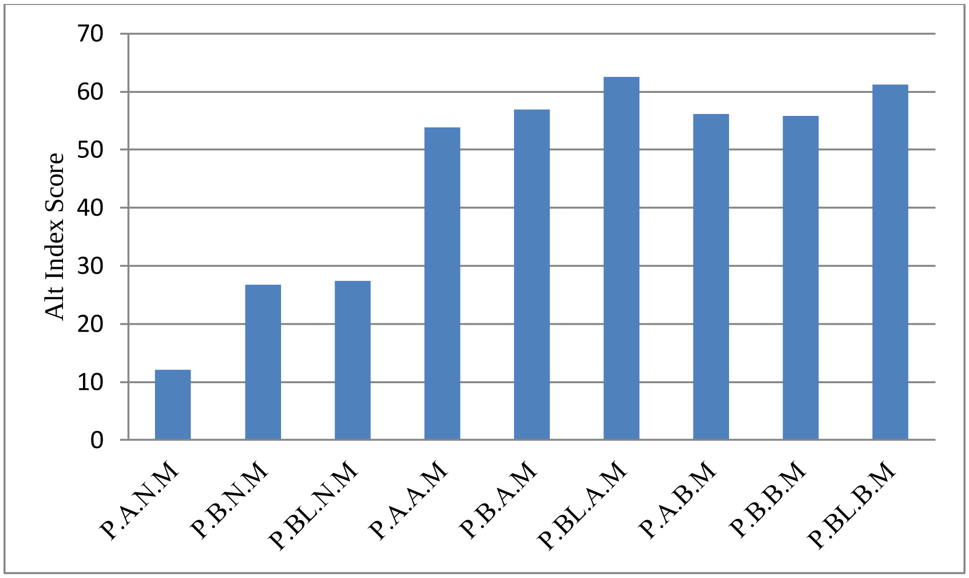

Figure 5.26**:** Alt Index Scores

The alternative index was compared against the individual test results in a similar manner to the original index. It can be seen in Figure 5.27 and Figure 5.29 that the correlation R^2 value for the 28 day tests decreased. This is to be expected due to the fact that no 28 day tests were used in the alternative index. The air permeability correlation also went down slightly. This is likely due to the weighting of the RCPT and SR tests in the alternative index. The correlation was not changed enough to show significance. The 90 day tests correlation went up slightly. This again was expected and likely due to the weighting of the tests in the index. The alternative index has a better or equivalent correlation to the later day tests which is useful in determining the concretes actual permeability after the fly ash has its later age reaction.

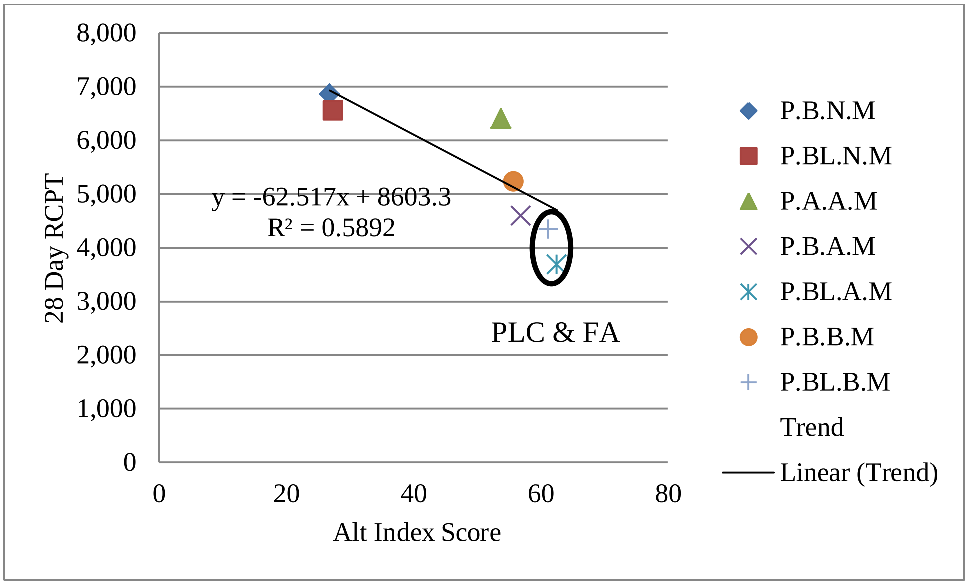

Figure 5.27: Alternative Index vs. 28 Day RCPT

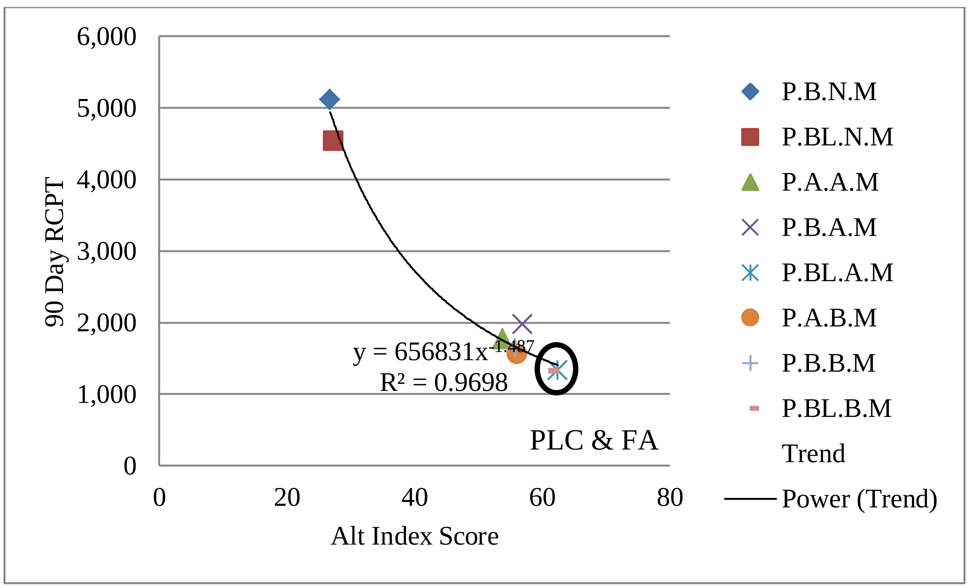

Figure 5.28: Alternative Index Score vs. 90 Day RCPT

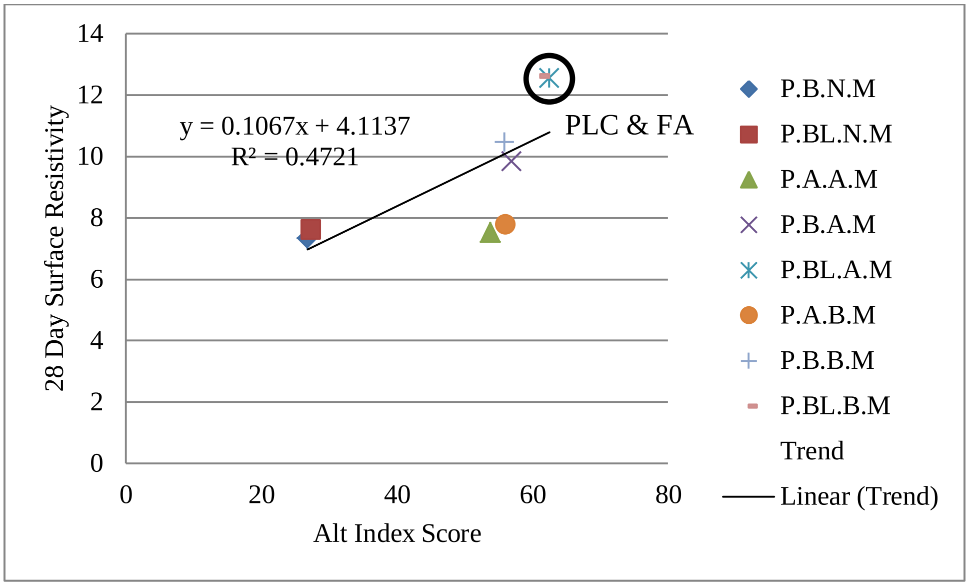

Figure 5.29: Alternative Index Score vs. 28 Day Surface Resistivity

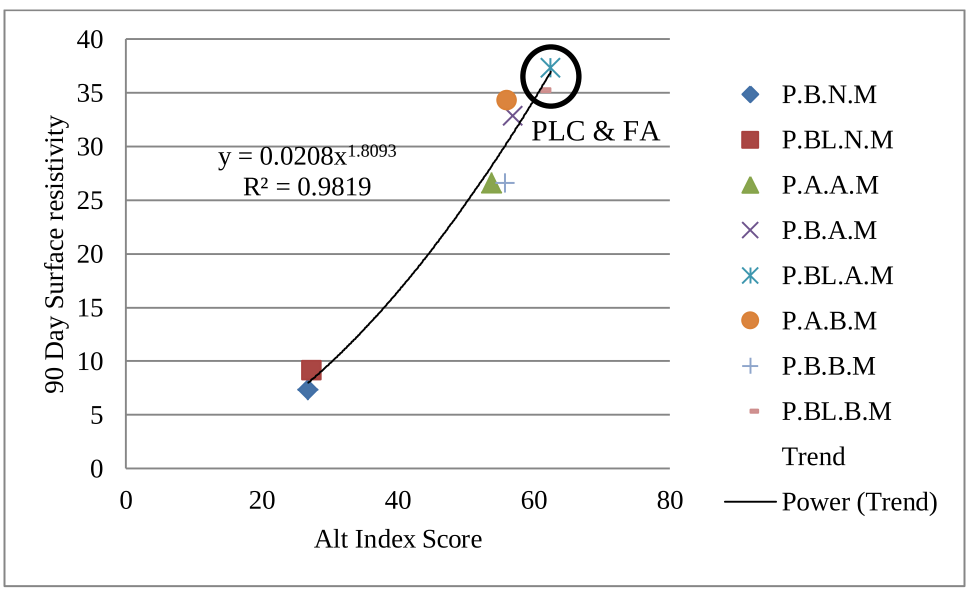

Figure 5.30: Alternative Index Score vs. 90 Day Surface Resistivity

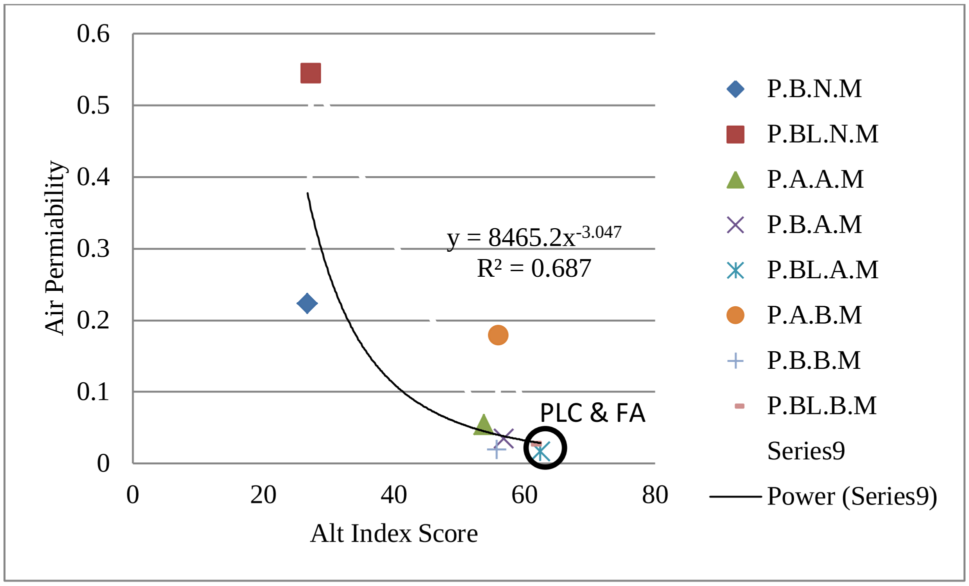

Figure 5.31: Alternative Index Score vs. Air Permeability

CHAPTER 6: CONCLUSION

6.1 Conclusion

In the previous study, durability of pavement concrete mixtures was analyzed using permeability test. The tests that were used were the rapid chloride penetration test (RCPT), surface resistivity test (SR), air permeability test, and sorptivity. The mixtures analyzed were each typical pavement mixtures for the North Carolina Department of Transportation (NCDOT). The mixtures were held to a constant water cement ratio (*w/cm*), air content, and slump. The parameters that were varied include the cement type, fine and coarse aggregate, and supplementary cementitious materials (SCM), which in the study was fly ash. After the initial analysis, the data from each test was placed into a permeability index to better help understand the effects of each change. The change in aggregate was not focused on for this study with the main focus being the change in cement and fly ash.

The overall conclusion of the results is that the inter-ground limestone addition to the ordinary portland cement combined with the fly ash replacement of the cement produces a much less permeable concrete, which correlated to a much more durable concrete when compared to the other mixtures. For these results, permeability of the concrete was used as a surrogate measure to represent the potential durability of the concrete. All mixtures with cement replacement by fly ash exhibited a significant increase in durability, and the fly ash mixtures paired with PLC have a higher durability over the other fly ash mixtures. These results were expected from the literature and are mainly contributed from the increased particle packing from the wide range of particle sizes in the mixture (Yilmaz and Olgun 2008; Yoshitake et al., 2013).These results were found by way of the results from several different permeability tests combined to form a permeability index. The less permeable the concrete is can be linked directly to the higher durability of the concrete (Mindess et al., 2003; Neville 2012).

Based on the RCPT, the mixtures containing fly ash gave an average of 218% reduction in permeability from 28 days to 90 days; the non-fly as mixtures gave a 32% average reduction. When comparing the reduction from the addition of fly ash, it was found that at the 28^{th} day the permeability was reduced 35% with the addition of the fly ash to the mixtures. At the 90^{th} day, the addition of the fly ash was found to reduce the permeability by 211% when compared against the mixtures that did not contain fly ash. The fly ash made the most substantial increase in the reduction of permeability, but, limestone had some effect on the permeability of the concrete as well. With such a high reduction in permeability, the use of fly ash and limestone in the concrete could be used to help increase the concrete’s reinforcement corrosion resistance from the chloride ion. This reduction in permeability would slow the chloride ion and many other intrusive agents down which would help increase the durability of the concrete.

The addition of limestone did not have any noticeable effect on the durability of the concrete when the fly ash was not present. When the limestone and fly ash were both present, there was a reduction in permeability of around 30% for both the 28^{th} and 90^{th} day when compared to the mixtures that contained fly ash but did not contain limestone.

Within the data, many conclusions can be made about the test methods and their ability to represent the durability of the concrete mixture. The test indirectly measured the durability of the concrete by measuring the permeability of the concrete. The tests examined were the rapid chloride penetration test (RCPT), surface resistivity (SR), air permeability using the torrent system, the ponding method of sorptivity and the suction method.

The most significant results were found in the RCPT and SR results and comparison. The RCPT test is a proven test to measure the chloride permeability of a concrete sample. The SR test is a new method to try to link the resistivity of the cover concrete to the actual chloride permeability in which the total resistivity of the sample is measured (Morris et al., 1996). The results found in the comparison of the two tests showed a very tight correlation of the two results. Both tests were affected by changes in the concrete in very similar ways. The fly ash addition showed a very similar reduction in permeability in both tests. The higher surface resistivity correlated directly to lower chloride permeability. These results of permeability will provide the ability to evaluate concretes for better reinforcement corrosion resistance, better freeze thaw resistance, and other concrete durability aspects that can be seen through the concrete permeability.

With these findings, the SR test is a much more effective way of determining the permeability of the concrete over the RCPT because of the time it takes to perform the SR test over the RCPT. The SR test can be performed in just a few seconds on almost any concrete sample and even in place concrete without having to take cores or any other type of sample. The RCPT takes 6 hours to perform with at least a 24 hour preparation time before the actual test. The RCPT would have to be performed that would need to be taken from an in-place concrete that needs to be examined. Both test results showed that the PLC mixtures that include fly ash had the least permeability. Neither the SR nor RCPT had a better correlation than the other to the air permeability test. This makes sense because of how well the SR and RCPT are correlated to each to other.

The Torrent air permeability system was used to determine the permeability of the cover concrete. This test proved to be effective in representing the permeability of the concrete when compared to the SR and RCPT. This test is limited by the fact that it only measures conditions at the surface concrete, but it can be used to take a quick and effective measurement. The permeability differences between mixture types were not as noticeable with the air permeability system when compared to other test but the differences were present.

The sorptivity testing is the final test method that was utilized in this evaluation. The correlation restrictions from the ASTM standards proved hard to meet, and many tests did not quite achieve the specified R^2 value of 0.96. However, particularly with the suction method, the results were still useful and could be compared with other tests to help identify trends. When using the ponding method, however, it was difficult to prevent the samples from leaking even after trying many different sealing techniques. Due to the difficulties encountered in execution of the ponding method, it was not utilized in this analysis. The sorptivity testing did not provide clear indications of change between the different mixtures. The results of the suction method sorptivity testing showed that the mixtures containing fly ash had higher sorptivity than those that didn't contain fly ash. This finding is contradictory to the literature (Hooton and Beal 1993). The only conclusion that could be made as to why the sorptivity results seemed abnormal is due to inconsistency's of the test method. Both the ponding and suction method relied on a seal surface from duct tape which can be inconsistent on the effectiveness of sealing the surface.

6.2 Recommendations

One of the most significant recommendations that can be made is that there should be a use of fly ash in the concrete mixtures if more durable concrete is desired. The high reduction of permeability from the fly ash addition will lead to a more durable concrete.

The limestone addition was found to only be beneficial to durability when the fly ash is present. Without fly ash, the limestone addition did not have a positive or negative effect on the concrete's permeability. The limestone addition did, however, have a reduction of the permeability of the concrete which gives us an increase in durability. This increase in durability from the limestone was not as great as the increase in durability from the addition of the fly ash. The gain from addition of limestone at the 28th day was proportionally the same as the gain at the 90th day.

More research can be done to determine the effects from changing the replacement amounts and ratios for the fly ash and inter-ground limestone additions in the mixtures. The replacement amount and ratio were held constant for this study for both the fly ash and limestone. Higher dosage of limestone up to about 50% by weight should be focused on due to the 12% replaced by weight used in this study being a very accepted dosage amount (Hooton et al., 2007). The ratio of inter-ground limestone to fly ash seems to be another area with very limited research that could be explored further.

The surface resistivity (SR) test and rapid chloride penetration test (RCPT) results are very promising, and more data could be gathered on different concrete mixtures to help prove the effectiveness of using the SR test as a standard over the RCPT. The mixtures in this study were kept to a very tight air content and water to cement ratio. Varying parameters, such as those, could help build confidence in this correlation. Literature shows that this correlation has been proven by others as well as this study (Morriset al., 1996).

The air permeability test was done with the Torrent system on a very select set of samples. This test could also be performed on a more wide range of samples to have a better data set.

The sorptivity testing was the most problematic of the tests performed, and because of that the recommendation for it is to find better ways to control the test samples in order to eliminate errors. The ponding method specifically needs to be adjusted to come close to meeting the ASTM tight tolerances. This test also could be performed on a wider set of data to give a better representation of the results.

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APPENDIX A: MATERIAL INFORMATION

April 23, 2014

- ASTM C29 – Bulk Density ("Unit Weight") and Voids in Aggregate
- ASTM C40 – Organic Impurities in Fine Aggregates for Concrete
- ASTM C88 – Soundness of Aggregates by Use of Sodium Sulfate or magnesium Sulfate
- ASTM C117 – Materials finer than # 200 Sieve in Mineral Aggregates by Washing
- ASTM C123 – Lightweight Particles in Aggregate
- ASTM C128 – Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregates
- ASTM C136 – Sieve Analysis of Fine and Coarse Aggregates (Gradation Requirements for NCDOT)
- ASTM C142 – Clay Lumps and Friable Particles in Aggregates
- ASTM C289 – Potential Alkali-Silica Reactivity of Aggregates (Chemical method)
- ASTM C1218 – Water Soluble Chloride in Mortar and Concrete
- ASTM C1260 – Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
- ASTM D2419 – Sand Equivalent Value of Soils and Fine Aggregate

Upon completion of our testing, it appears that the samples obtained and provided, which are understood to be representative of the fine aggregates that are currently being produced for both of the above referenced sand pits, meet all of the specified limits of the respective test methods, and therefore should be considered as meeting ASTM C33 – Standard Specification for Concrete Aggregates.

Once again we appreciate the opportunity to provide our services for your project needs. If you have any questions, or if additional information becomes available, please contact us a

Sincerely,

Attachments: Laboratory Testing Summary Report

APPENDIX A (continued)

Soil Summary Analysis of Fine Aggregates for Use in Concrete Mixes
ASTM Test Procedures :
C29 - C40 - C88 - C117 - C123 - C128 - C136 - C142 - C289 - C1218 - C1260 - D2419

Project Name: ______ ______ Aggregate Type: _ ___
Project Number: ______ ______ Sample Location: _ ___
Date of Tests: ______ ______ Test No.: _ ___
Laboratory ID: ______ ______ Sample No.: _ ___

ARD SEIVE SIZE	NCDOT PERMISSIBLE LIMITS PERCENT BY WEIGHT, PASSING (Std. Size 2S for Year 2012)
3/8 in.	100
# 4	95 - 100
# 8	80 - 100
# 16	45 - 95
# 30	25 - 75
# 50	5 - 30
# 100	0 - 10
# 200	0 - 3

ASTM C136 - GRADATION TEST DATA

Sieve Size	Individual		Cumulative		Permissible Limits
(inches)	Retained (grams)	% Retained	% Retained	% Passing	% by Weight, Passing
3/8 in	0.00	0.0	0.0	100	100
# 4	1.40	0.6	0.6	99	95 - 100
# 8	3.10	1.2	1.8	98	80 - 100
# 16	47.20	18.9	20.7	79	45 - 95
# 30	103.60	41.4	62.1	38	25 - 75
# 50	70.60	28.2	90.4	10	5 - 30
# 100	17.90	7.2	97.5	2	0 - 10
# 200	1.80	0.7	98.2	1.8	0 - 3

Test Weight: 250.00 grams
Weight Retained: 245.60 grams

Fineness Modulus for Concrete Mixes	
2.73	2.3 - 3.1 O.K.

ASTM C123 Lightweight Particles	
Result = 0.2%	C33 Limits - < 1.0 % OK

ASTM C40 Organic Impurities	
Result = Color Plate 1	< or = to 3 okay

ASTM C142 - Clay Lumps/Friable	
Result = 0.6%	C33 Limits - 3 % Max

ASTM C128 - Specific Gravity	
BSG	2.64
SSD Gravity	2.66
Apparent	2.69
% Absorption	0.74%

ASTM C117	
% Passing # 200	NCDOT Size 2S Limit
Result = 1.5%	< 3.0 % OK

ASTM C29 - Bulk Density	
96.9 lb/ft3	Bulk Density (Dry Basis)
40%	Voids Content

ASTM D2419 Sand Equivalency	
SE =	75

ASTM C1260 - Alkali Reactivity	
Result = 0.04 % @ 16 days	< 0.10 % Ok @ 16 days

ASTM C1218 - Water Soluable Chloride Ion Content
Result = < 0.002

ASTM C289 - Alkali-Silica Reactivity
Result = Potentially Deleterious

ASTM C88 - Soundness (Magnesium Sulfate Used in Test)	
Result = 4 %	15 % Weighted Average Loss Limit with the use of Magnesium Sulfate - 5 Cycles Performed -

Tests Performed by : ______ ______
Tests Checked by : ______ ______

Figure A.1: Fine Aggregate Information

Table A.1: Cement B & BL Mill Sheet

Samples for UNC Charlotte			
UNCC		UNCC	
Sample Type	I-II		IL
Date Tested at	1/20/2015		1/13/2015
% Limestone	3.4		10.2
Blaine	406		530
SiO2	20.33		19.83
Al2O3	4.93		4.29
Fe2O3	3.46		3.45
CaO	64.46		64.32
MgO	1.56		1.38
SO3	3.29		3.46
Na2O	0.18		0.15
K2O	0.59		0.47
NaEq	0.57		0.46
C3S		60.5	
C2S		12.7	
C3A		7.2	
C4AF		10.5	
1 Day psi	2580		2690
3 Day psi	4340		4520
7 Day psi	5250		5610
28 Day psi	6400		6590

Please Note: The Bogue phase calculations are not corrected for Limestone addition.

CEMENT MILL TEST REPORT

Cement Identified as: **Type I LA, Type II LA** Date: **10/1/2014**

Plant:

Location:

Production Dates:

Beginning: **10/1/2014**

Ending: **Silos: 14**

CHEMICAL REQUIREMENTS (ASTM C 114)	ASTM C 150 & AASHTO M85 SPEC'S	TYPE I (ASTM, AASHTO)	TYPE II (ASTM, AASHTO)	TYPE I LA (ASTM, AASHTO)	TEST RESULTS
Silicon Dioxide (SiO2), %	Minimum	----	----	----	20.3
Aluminum Oxide (Al2O3), %	Maximum	----	6.0	----	4.7
Ferric Oxide (Fe2O3), %	Maximum	----	6.0	----	3.3
Calcium Oxide (CaO), %		----	----	----	64.1
Magnesium Oxide (MgO), %	Maximum	6.0	6.0	6.0	1.2
Sulfur Trioxide (SO3), % **	Maximum	3.5	3.0	3.5	3.0
Loss on Ignition (LOI), %	Maximum	3.0	3.0	3.0	1.6
Insoluble Residue, %	Maximum	0.75	0.75	0.75	0.30
Alkalies (Na2O equivalent), %	Maximum			0.60	0.54
Tricalcium Silicate (C3S), %	Maximum	----	----	----	58
Tricalcium Aluminate (C3A), %	Maximum	----	8	----	7
C3S + 4.75(C3A), %	Maximum	----	100	----	92
PHYSICAL REQUIREMENTS					
(ASTM C 204) Blaine Fineness, M2/Kg	Minimum	280	280	280	4074
(ASTM C 191) Time of Setting (Vicat)					
Initial Set, minutes	Minimum	45	45	45	115
Final Set, minutes	Maximum	375	375	375	210
(ASTM C 451) False Set, %	Minimum	50	50	50	85
(ASTM C 185) Air Content, %	Maximum	12	12	12	6
(ASTM C 151) Autoclave Expansion, %	Maximum	0.80	0.80	0.80	-0.01
(ASTM C 1038) Expansion in Water, %at 3.6 SO3	Maximum	0.02	0.02	0.02	0.001
(ASTM C186) 7 day Heat of Hydration, (cal/g)					73
(ASTM C 109) Compressive Strength, psi (MPa)					
1 Day		----	----	----	2530 (17.4)
3 Day	Minimum	1740(12.0)	1450(10.0)	1740(12.0)	3560(24.5)
7 Day	Minimum	2760(19.0)	2470(17.0)	2760(19.0)	4530 (31.2)
*28 Day	Minimum	----	----	----	6370 (43.9)

*** The performance of Type I/II has proven to be improved with sulfur trioxide levels in excess of the 3.0% limit for Type II.*
Note D in ASTM C-150 allows for additional sulfate, provided expansion as measured by ASTM C-1038 does not exceed 0.020%.
Satisfies the requirements of VDOT Standard Road & Bridge specification section 214
(*) Tests results for this period not available. Most recent test results provided

hereby certifies that this cement meets or exceeds the chemical and physical Specifications of:

Physical testing completed by:
Chemical testing completed by:

x ASTM C-150 for Type I
x ASTM C-150 for Type II
x ASTM C-150 for Type II M.H.
x ASTM C-150 for Type I L.A.
x AASHTO M85 for SCDOT Type I LA
x AASHTO M85 for Type I
x AASHTO M85 for Type II
x ASTM C-1157 for Type GU

By
Quality Control Manager

is not responsible for the improper use or workmanship associated with the use of this cement.

Figure A.2: Cement A Mill Sheet

Table A.2: Mountain Coarse Aggregate Sieve Analysis

Sieve Size	Percent Passing	ASTM C 33 Specification, % Passing
1"	98.8%	100
3/4"	81.8%	90-100
1/2"	27.9%	---
3/8"	11.9%	20-55
No.4	3.5%	0-10
No.8	0.8%	0-5
No.200 Decant, %:	0.4%	1.0/1.5[1]

Table A.3: Piedmont Coarse Aggregate Sieve Analysis

Sieve Size	Percent Passing	ASTM C 33 Specification, % Passing
1"	100	100
3/4"	96	90-100
1/2"	55	---
3/8"	33	20-55
No.4	5	0-10
No.8	2	0-5
No.200 Decant, %:	0.3	1.0/1.5[1]

Table A.4: Coastal Coarse Aggregate Sieve Analysis

Sieve Size	Percent Passing	ASTM C 33 Specification, % Passing
1"	97.8%	100
3/4"	76.9%	90-100
1/2"	38.3%	---
3/8"	24.0%	20-55
No.4	5.6%	0-10
No.8	1.4%	0-5
No.200 Decant, %:	0.3%	1.0/1.5[1]

Table A.5: Manufactured Sand Sieve Analysis

Sieve Size	Percent Passing	NCDOT 2MS Specification Percent Passing (%)
3/8	100.0%	100.0%
No. 4	100.0%	95-100%
No. 8	85.0%	80-100%
No. 16	64.0%	45-95%
No. 30	47.0%	25-75%
No. 50	30.0%	5-35%
No. 100	14.0%	0-20%
No. 200	5.2%	0-10%

Table A.6: Natural Sand Sieve Analysis

Sieve Size	Percent Passing	ASTM C 33 Specification, % Passing
3/8	100.0%	100.0%
No. 4	99.9%	95-100%
No. 8	98.8%	80-100%
No. 16	79.5%	50-85%
No. 30	34.9%	25-60%
No. 50	5.6%	5-30%
No. 100	0.9%	0-10%
No. 200	0.3%	0-3%

Client:

Date: February 10, 2016
TEC Services I.D.: _
Lab No.: 15-1333

REPORT OF FLY ASH TESTS			
Date Sampled: DS 11/23-12/11	Start Date:	November 23, 2015	
Manufacturer:	End Date:	December 11, 2015	
	Date Received:	December 16, 2015	
Chemical Analysis**	**Results (wt%)**	**Specification (Class F)**	
		ASTM C618-15	**AASHTO M295-11**
Silicon Dioxide (SiO_2)	53.8	----	----
Aluminum Oxide (Al_2O_3)	27.5	----	----
Iron Oxide (Fe_2O_3)	8.05	----	----
Sum of Silicon Dioxide, Iron Oxide & Aluminum Oxide ($SiO_2+Al_2O_3+Fe_2O_3$)	89.3	70 % min.	70 % min.
Calcium Oxide (CaO)	2.3	----	----
Magnesium Oxide (MgO)	1.0	----	----
Sodium Oxide (Na_2O)	0.45	----	----
Potassium Oxide (K_2O)	2.44	----	----
"Sodium Oxide Equivalent ($Na_2O+0.658K_2O$)"	2.05	----	----
Sulfur Trioxide (SO_3)	0.62	5 % max.	5 % max.
Loss on Ignition	2.1	6 % max.	5 % max.
Moisture Content	0.18	3 % max.	3 % max.
Available Alkalies**			
Sodium Oxide (Na_2O) as Available Alkalies	0.16	----	----
Potassium Oxide (K_2O) as Available Alkalies	0.71	----	----
Available Alkalies as "Sodium Oxide Equivalent ($Na_2O+0.658K_2O$)"	0.63	----	1.5 % max.*
Physical Analysis			
Fineness (Amount Retained on #325 Sieve)	21.9%	34 % max.	34 % max.
Strength Activity Index with Portland Cement			
At 7 Days: Control Average, psi: 4820 / Test Average, psi: 3780	78%	75 % min.† (of control)	75 % min.† (of control)
At 28 Days: Control Average, psi: 6100 / Test Average, psi: 5190	85%	75 % min.† (of control)	75 % min.† (of control)
Water Requirements (Test H_2O/Control H_2O) Control, mls: 242 / Test, mls: 236	98%	105 % max. (of control)	105 % max. (of control)
Autoclave Expansion:	-0.03%	± 0.8 % max.	± 0.8 % max.
Specific Gravity:	2.21	----	----

† Meeting the 7 day or 28 day strength activity index will indicate specification compliance

* Optional

**Chemical Analysis performed by

Figure A.3: Fly Ash A Mill Sheet

Client

Date:	January 30, 2015
TEC Services Project No:	[illegible]
TEC Laboratory No:	14-1090

REPORT OF FLY ASH TESTS

Date Sampled:	DS 12/11-12/16	Start Date:	December 11, 2014
Manufacturer:		End Date:	December 16, 2014
		Date Received:	December 22, 2014

		Specification (Class F)	
Chemical Analysis**	**Results**	**ASTM C618-12a**	**AASHTO M295-11**
Silicon Dioxide	53.21	----	----
Aluminum Oxide	28.74	----	----
Iron Oxide	7.64	----	----
Sum of Silicon Dioxide, Iron Oxide & Aluminum Oxide	89.59	70 % min.	70 % min.
Calcium Oxide	1.74	----	----
Magnesium Oxide	0.92		
Sulfur Trioxide	0.38	5 % max.	5 % max.
Loss on Ignition	2.61	6 % max.	5 % max.
Moisture Content	0.10	3 % max.	3 % max.
Available Alkalies as Na_2O	0.42	----	1.5 % max.*
Sodium Oxide	0.11	----	----
Potassium Oxide	0.47	----	----
Physical Analysis			
Fineness (Amount Retained on #325 Sieve)	13.3%	34 % max.	34 % max.
Strength Activity Index with Portland Cement			
At 7 Days: Control Average, psi: 4930; Test Average, psi: 3840	78%	75 % min.† (of control)	75 % min.† (of control)
At 28 Days: Control Average, psi: 6150; Test Average, psi: 5540	90%	75 % min.† (of control)	75 % min.† (of control)
Water Requirements (Test H_2O/Control H_2O): Control, mls: 242; Test, mls: 236	98%	105 % max. (of control)	105 % max. (of control)
Autoclave Expansion	0.03%	± 0.8 % max.	± 0.8 % max.
Specific Gravity:	2.29	----	----

† Meeting the 7 day or 28 day strength activity index will indicate specification compliance
* Optional Requirement
**Chemical Analysis performed by

Figure A.4: Fly Ash B Mill Sheet

APPENDIX B: PONDING METHOD DATA

Table B.1: Ponding Results

	Ponding			
Mix	X	y	Initial	Secondary
P.A.N.M	205.000	0.311	0.00066	0.00049
P.B.N.M	341.000	0.227	0.00023	0.00013
P.BL.N.M	245.500	0.310	0.00056	0.00040
C.A.N.M	190.500	0.338	0.00067	0.00012
C.B.N.M	82.250	0.262	0.00099	0.00023
C.BL.N.M	121.000	0.261	0.00107	0.00018
M.A.N.M	265.833	0.512	0.00154	0.00028
M.B.N.M	111.163	0.173	0.00086	0.00004
M.BL.N.M	98.733	0.198	0.00159	0.00010
P.A.A.M	283.000	0.337	0.00210	0.00130
P.B.A.M	366.000	0.397	0.00267	-0.00017
P.BL.A.M	675.450	0.383	0.00077	-0.00016
P.A.B.M	1517.000	0.503	0.00067	-0.00037
P.B.B.M	178.000	0.469	0.00063	0.00039
P.BL.B.M	220.800	0.389	0.00030	0.00008
P.A.N.N	42.250	0.228	0.00024	0.00064
P.B.N.N	281.000	0.377	0.00061	0.00035
P.BL.N.N	435.350	0.104	-0.00007	-0.00049

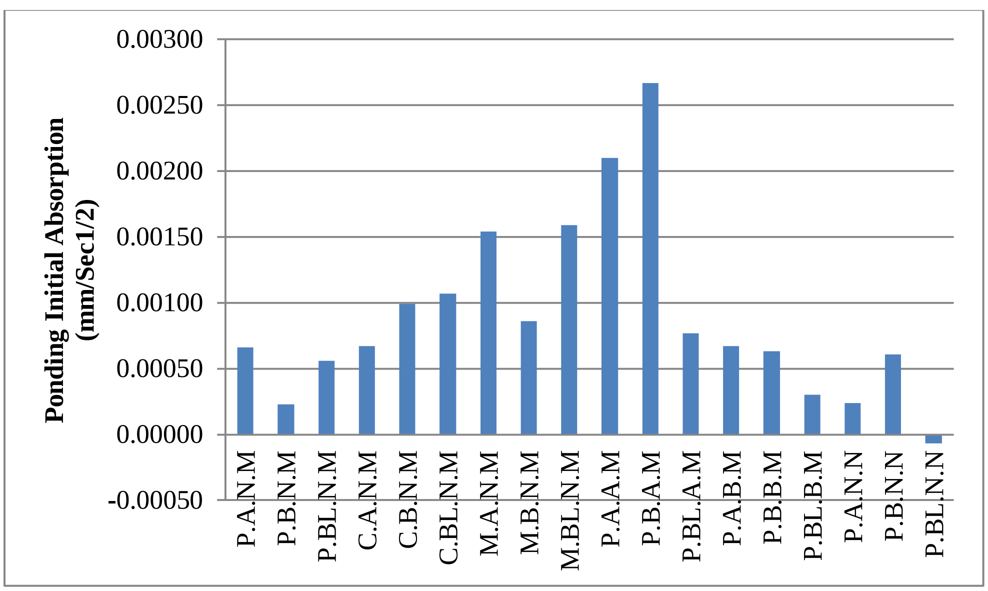

Figure B.1: Ponding Initial Absorption

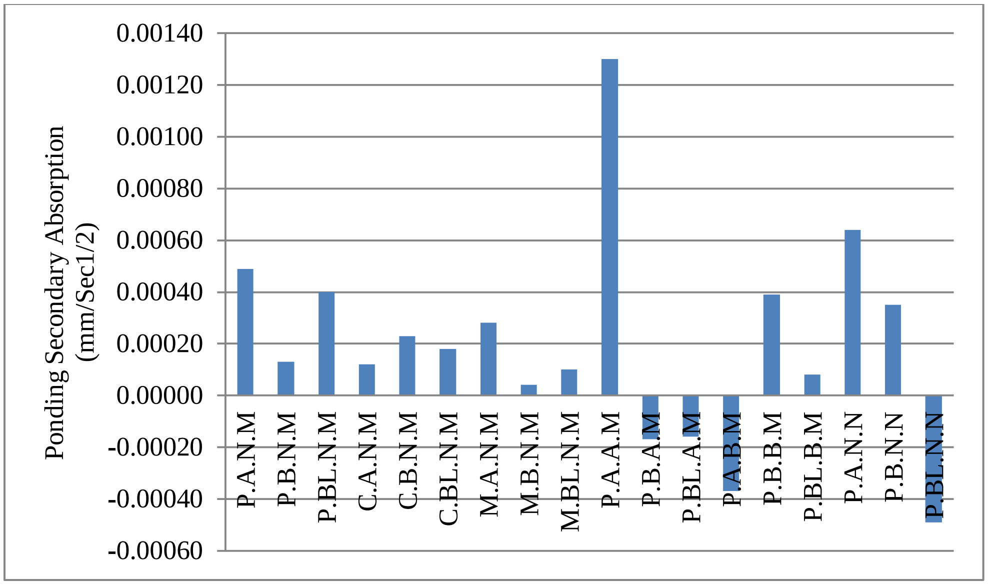

Figure B.2: Ponding Secondary Absorption

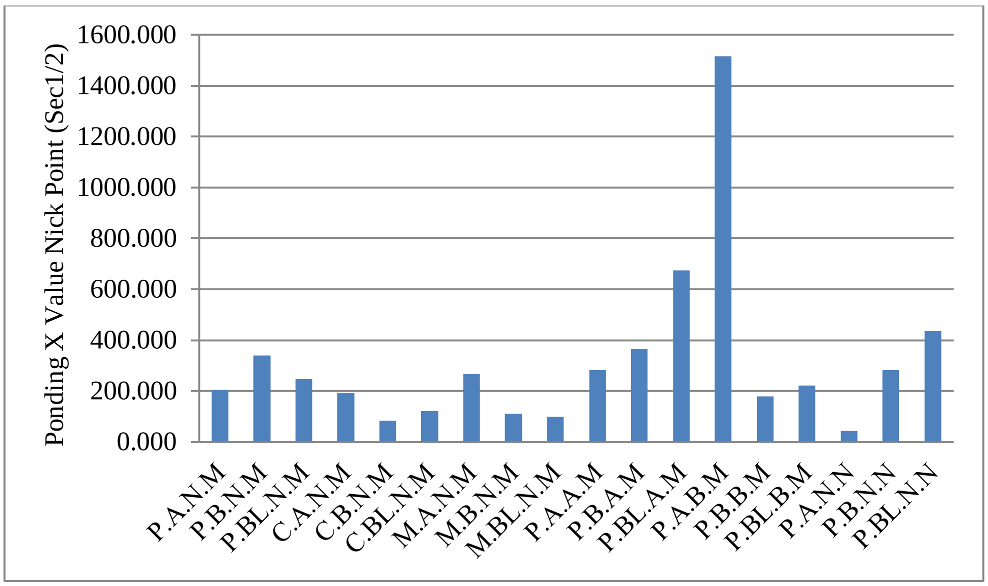

Figure B.3: Ponding Nick Point X Value

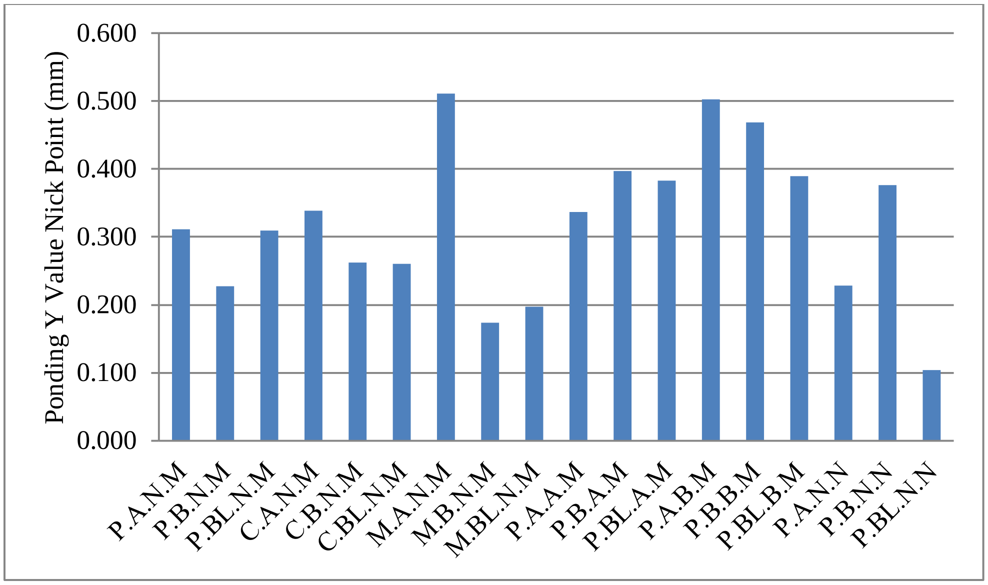

Figure B.4: Ponding Nick Point Y Value

APPENDIX C: SORPTIVITY RAW GRAPHS

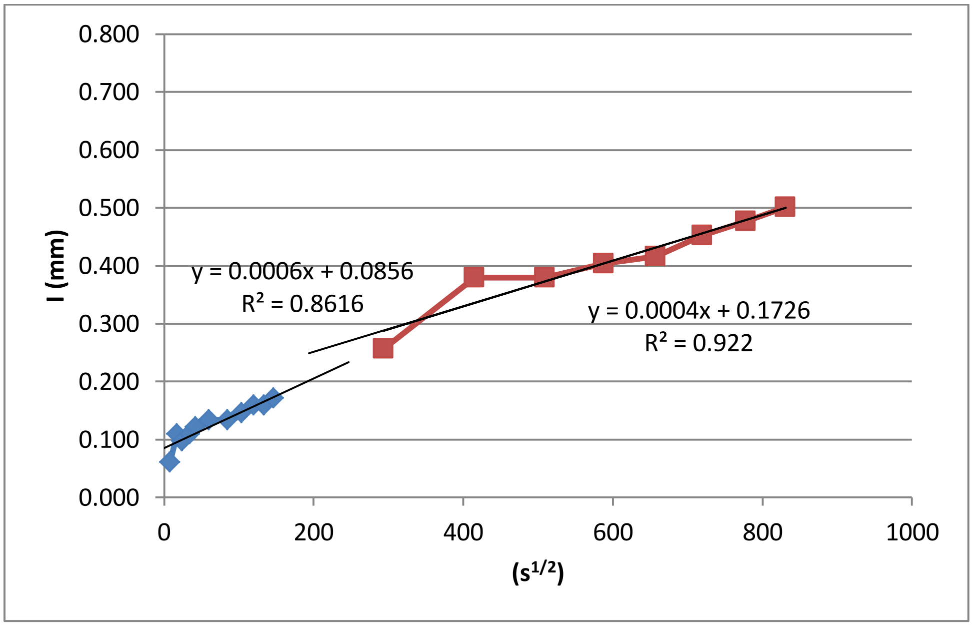

Figure C.1: P.BL.N.M Suction 1

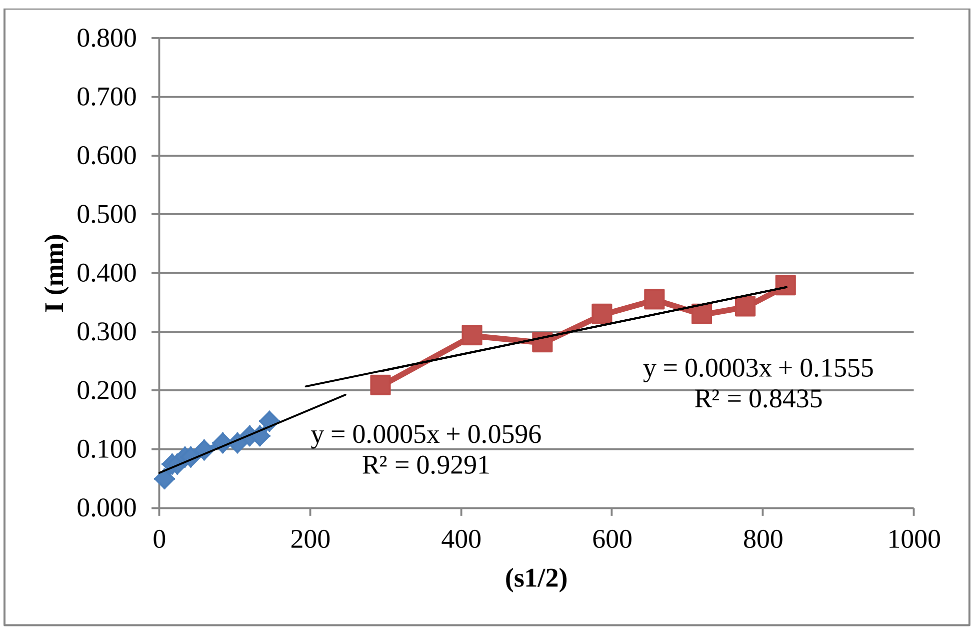

Figure C.2: P.BL.N.M Suction 2

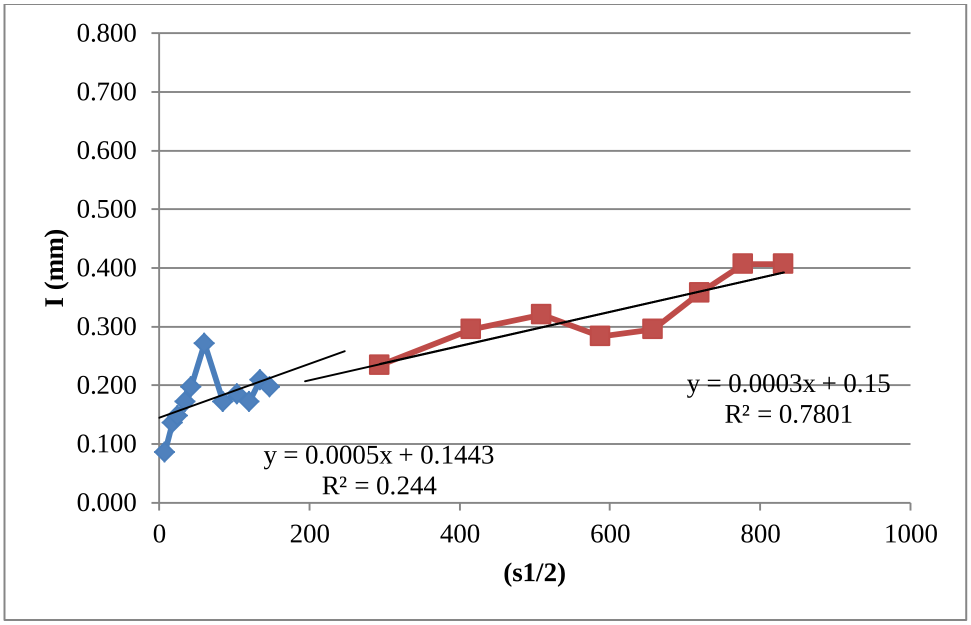

Figure C.3: P.B.N.M Suction 1

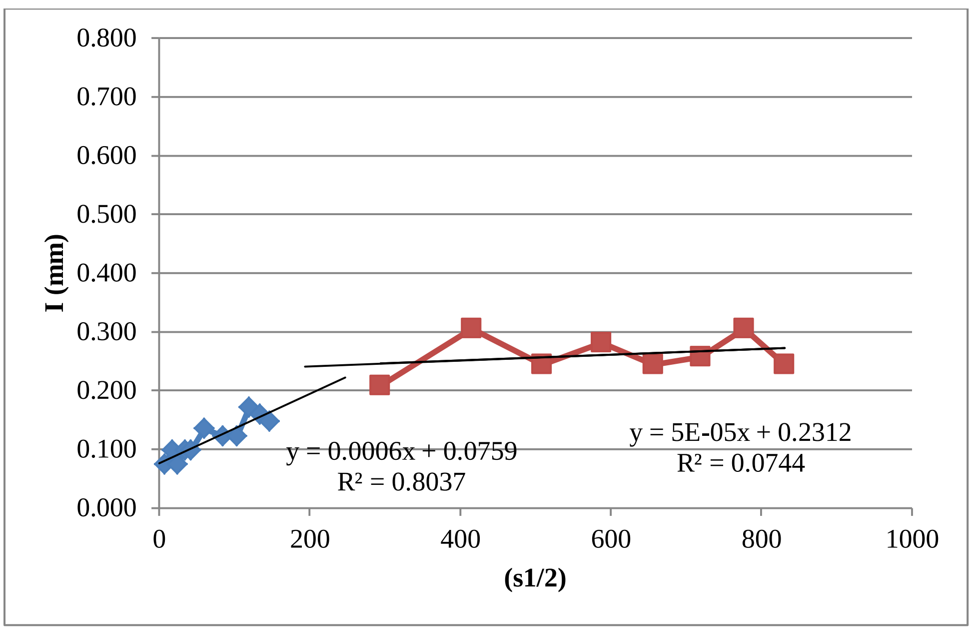

Figure C.4: P.B.N.M Suction 2

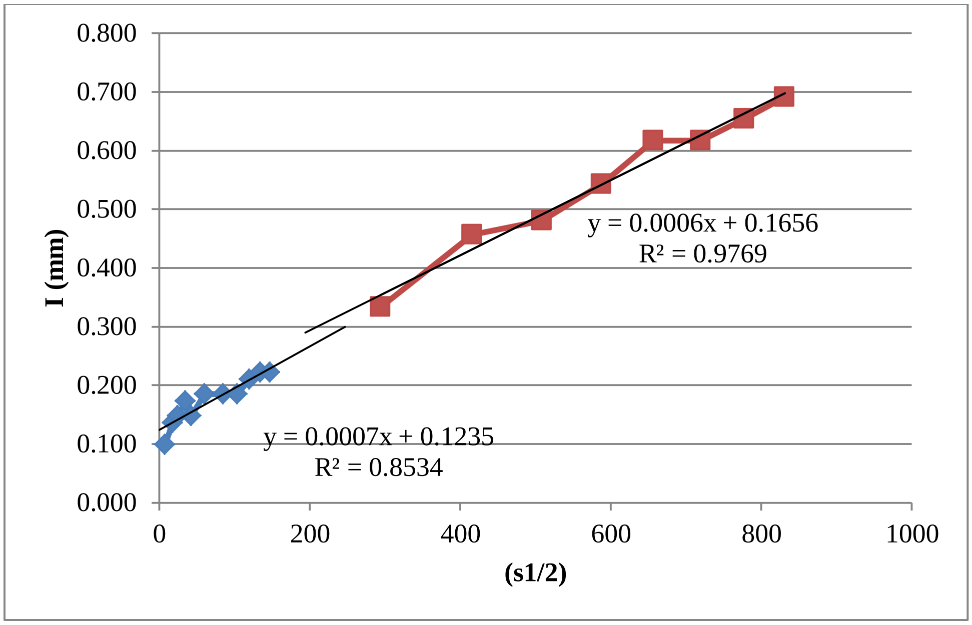

Figure C.5: P.A.N.M Suction 1

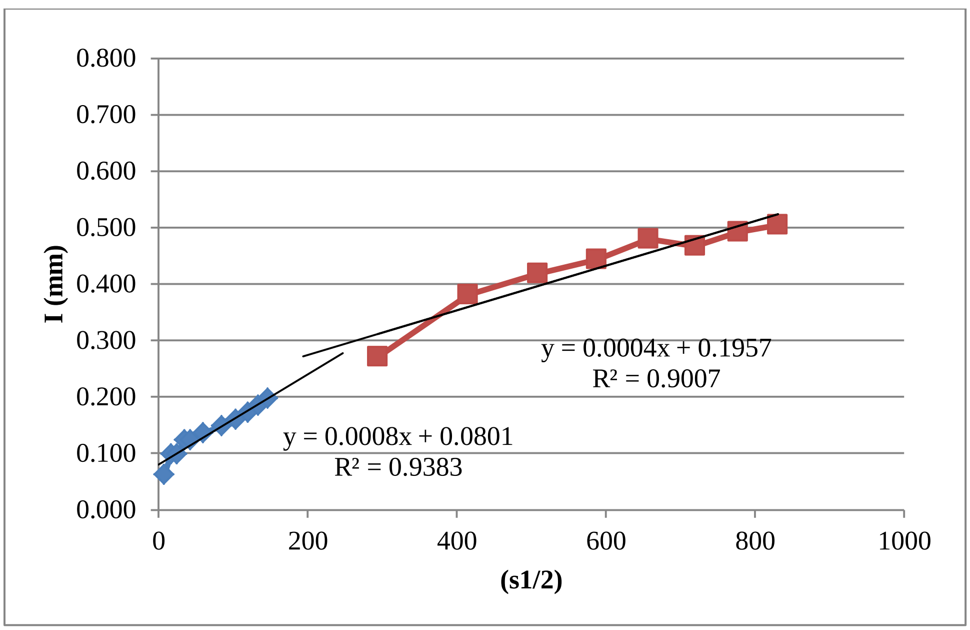

Figure C.6: P.A.N.M Suction 2

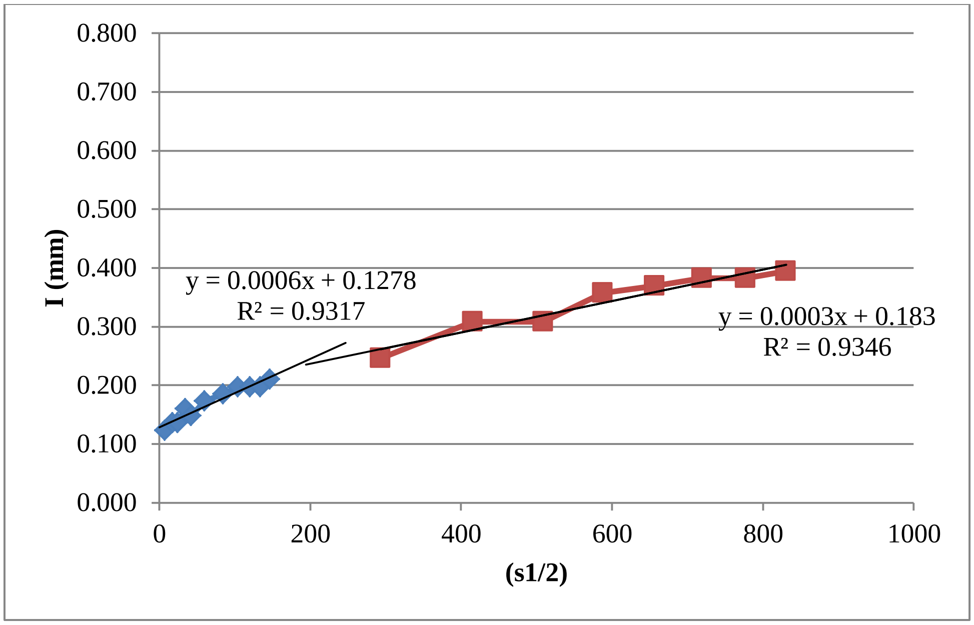

Figure C.7: C.A.N.M Suction 1

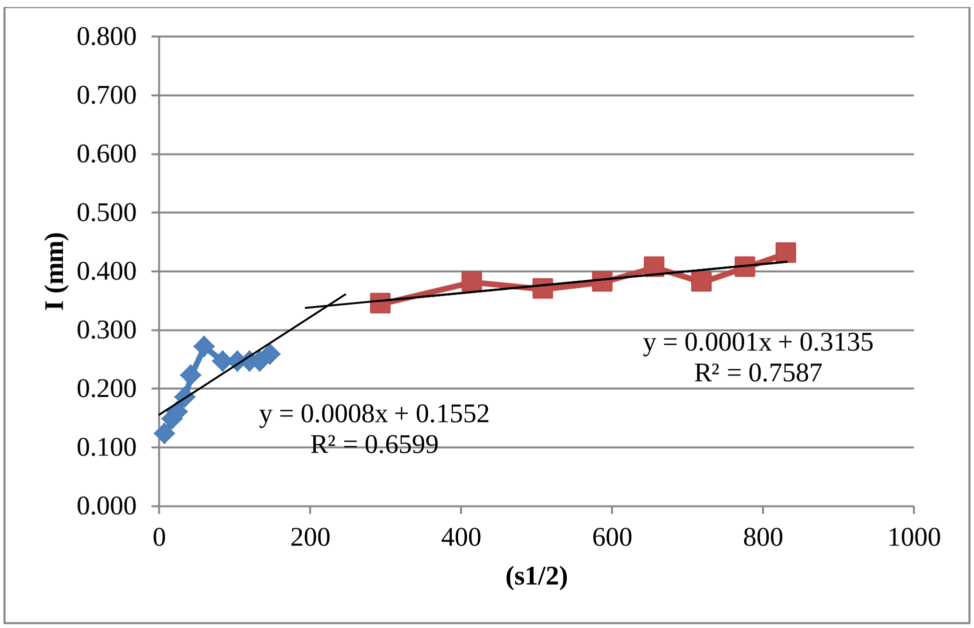

Figure C.8: C.A.N.M Suction 2

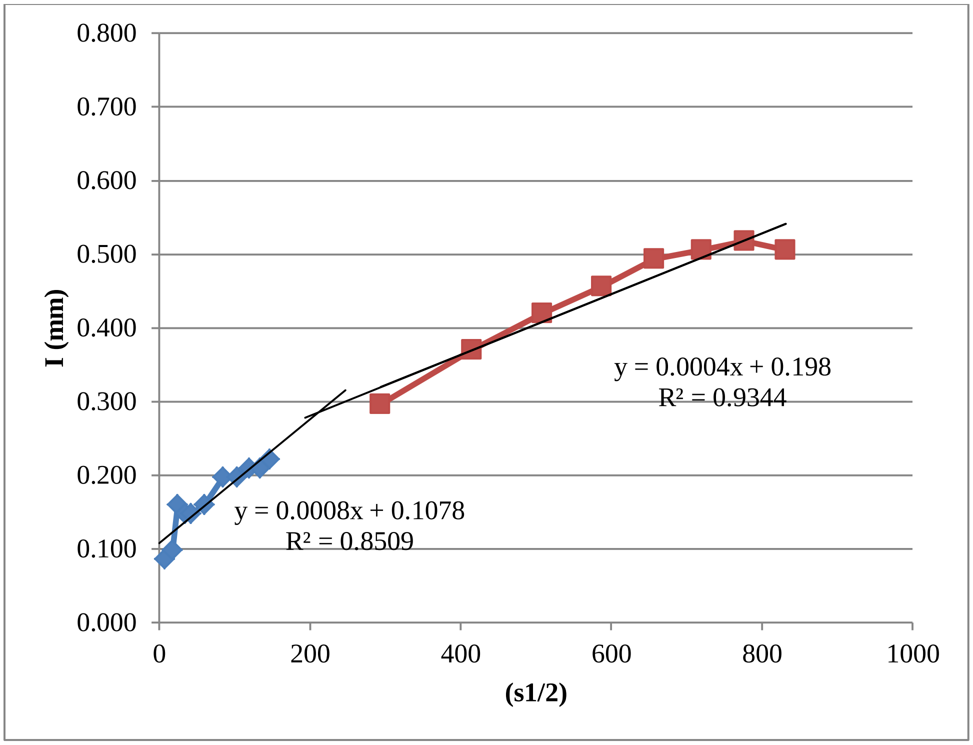

Figure C.9: M.A.N.M Suction 1

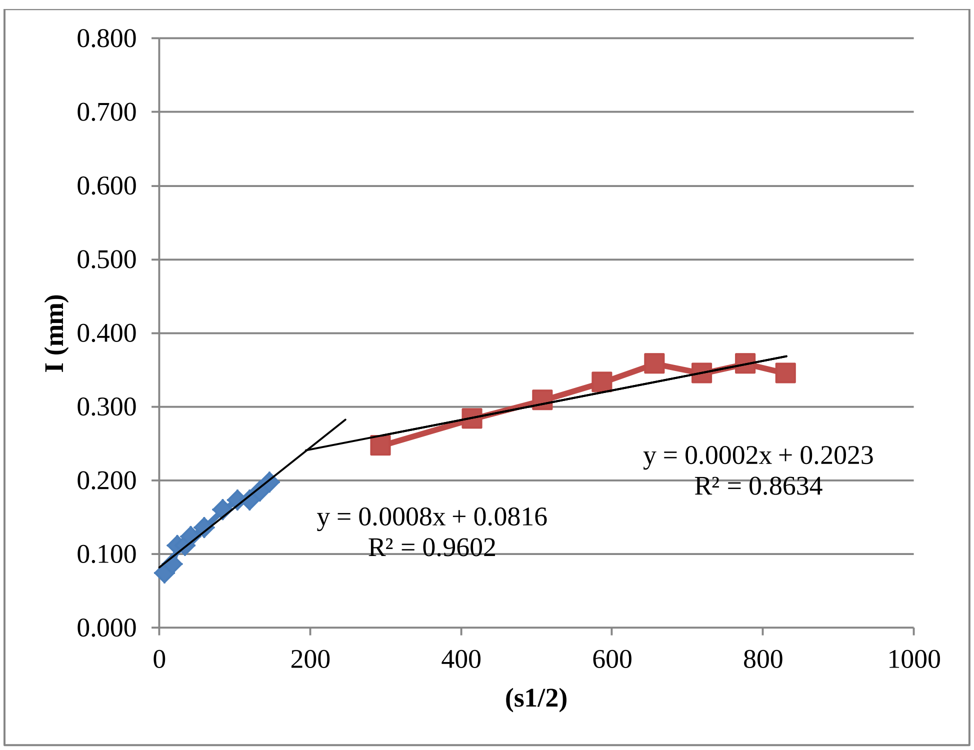

Figure C.10: M.A.N.M Suction 2

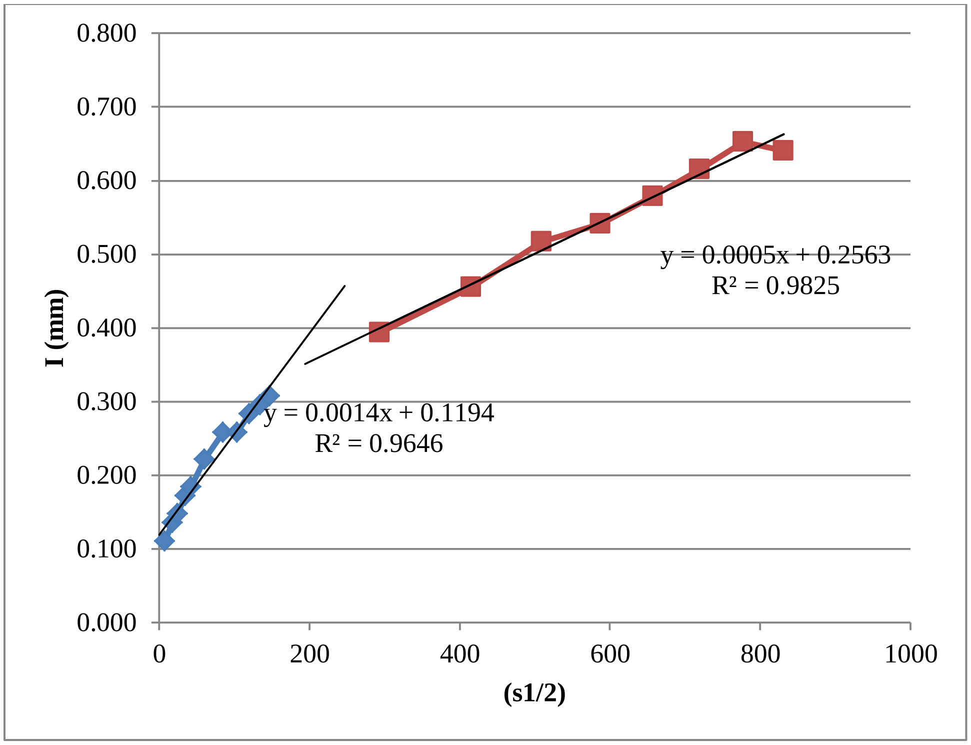

Figure C.11: C.BL.N.M Suction 1

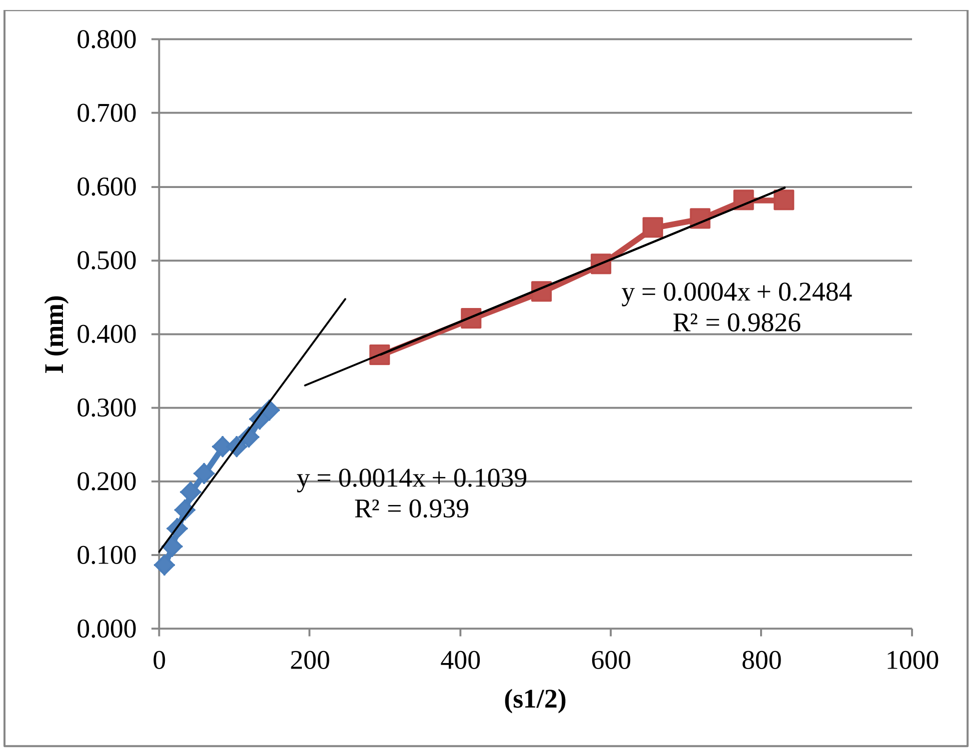

Figure C.12: C.BL.N.M Suction 2

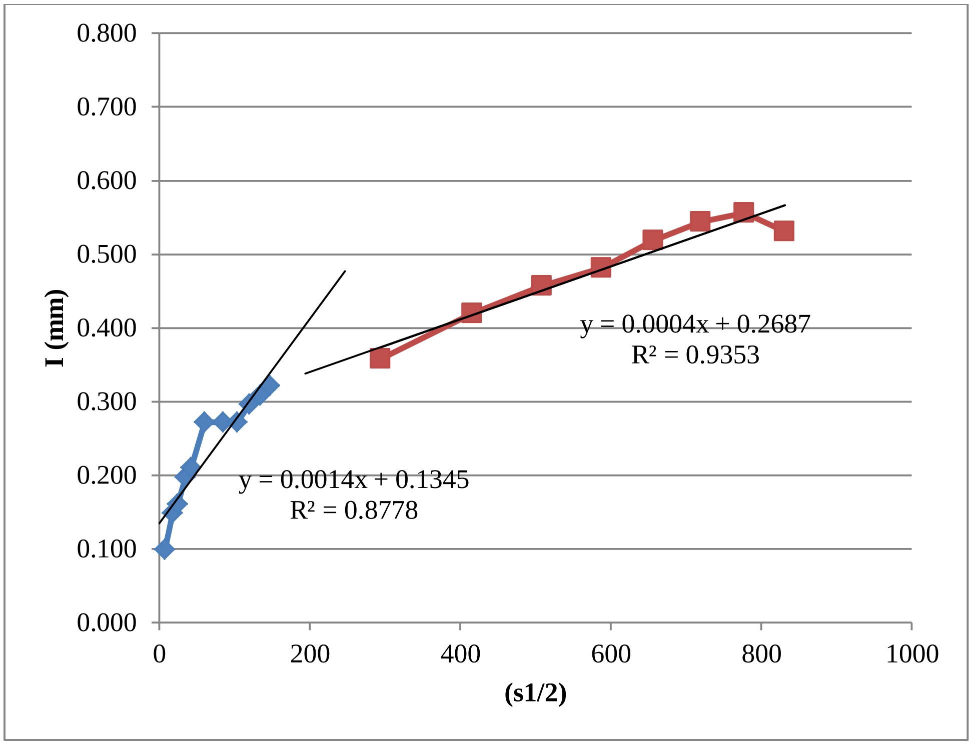

Figure C.13: C.B.N.M Suction 1

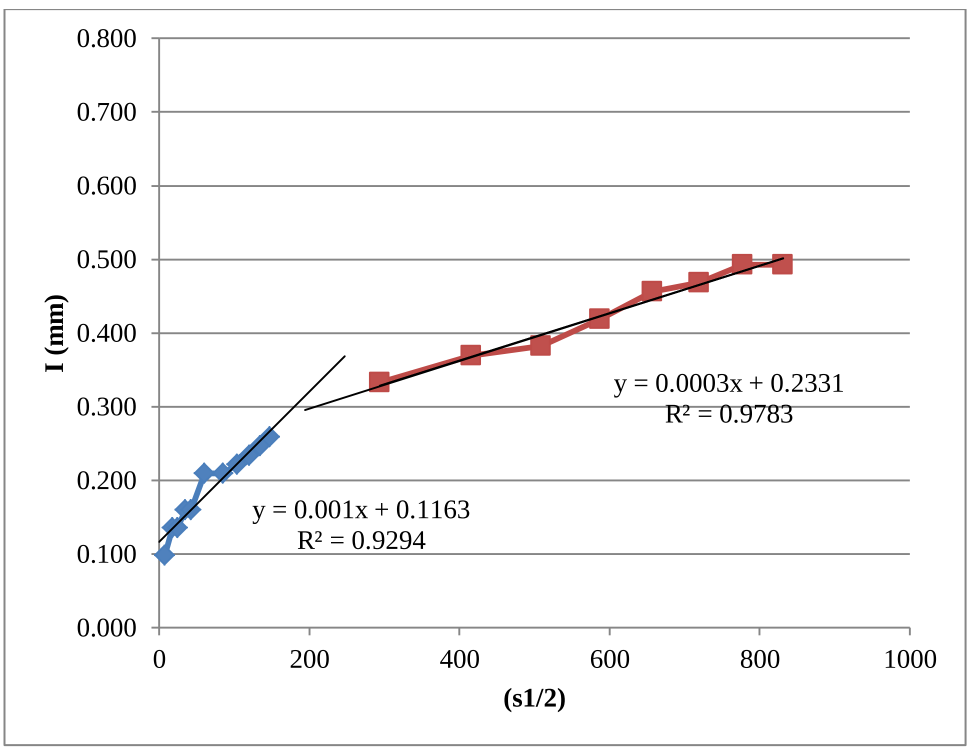

Figure C.14: C.B.N.M Suction 2

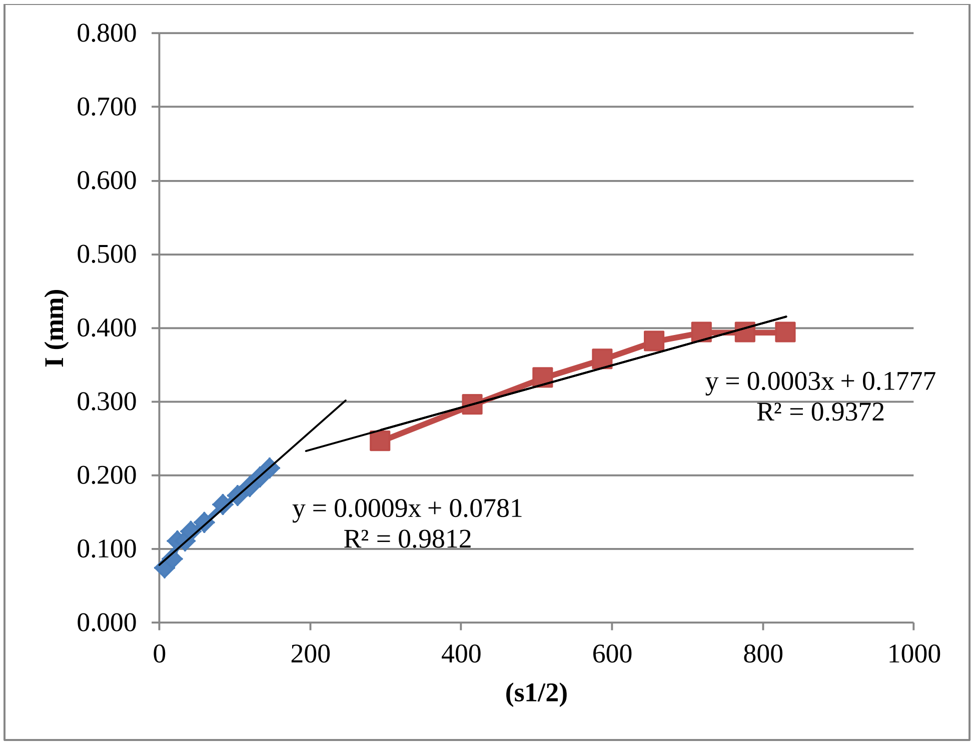

Figure C.15: M.B.N.M Suction 1

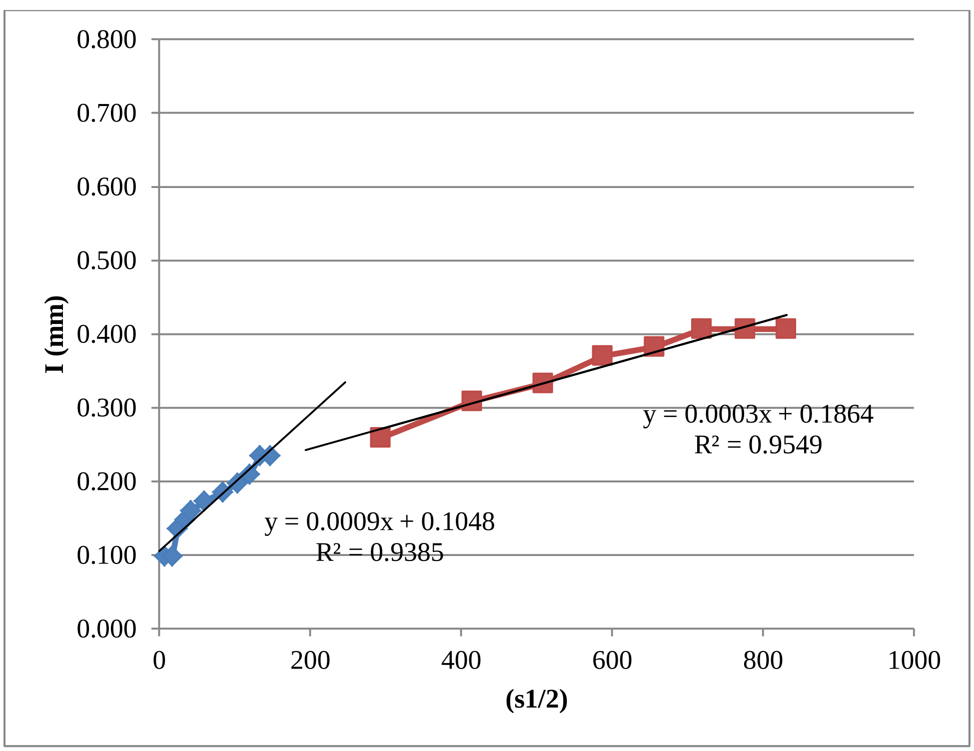

Figure C.16: M.B.N.M Suction 2

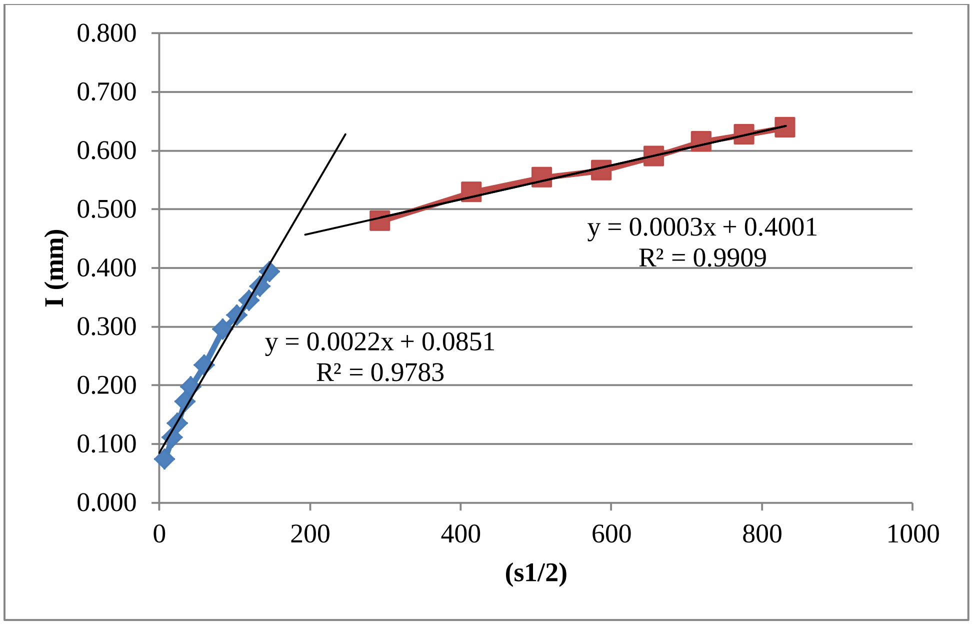

Figure C.17: P.B.B.M Suction 1

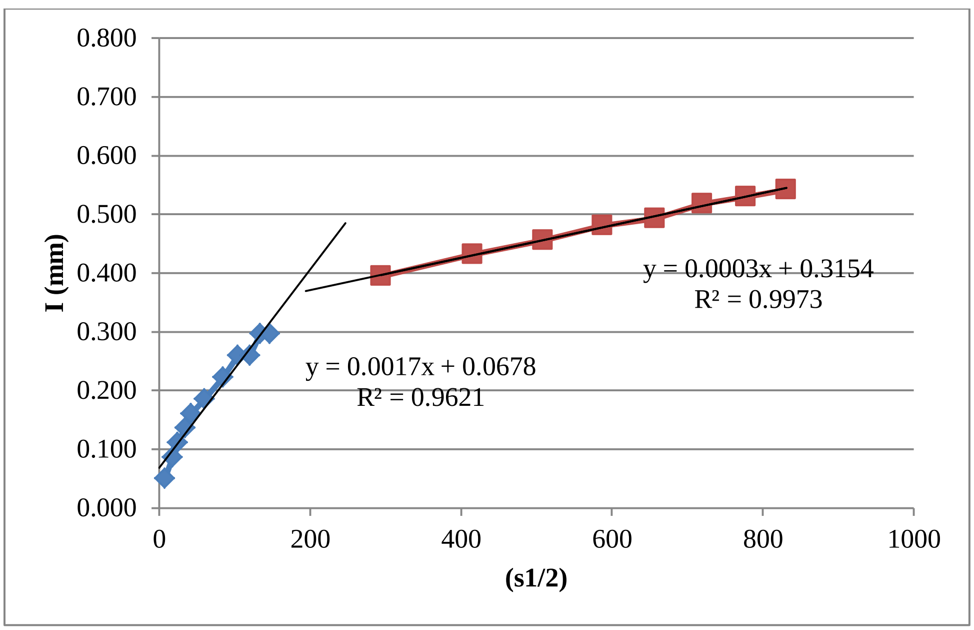

Figure C.18: P.B.B.M Suction 2

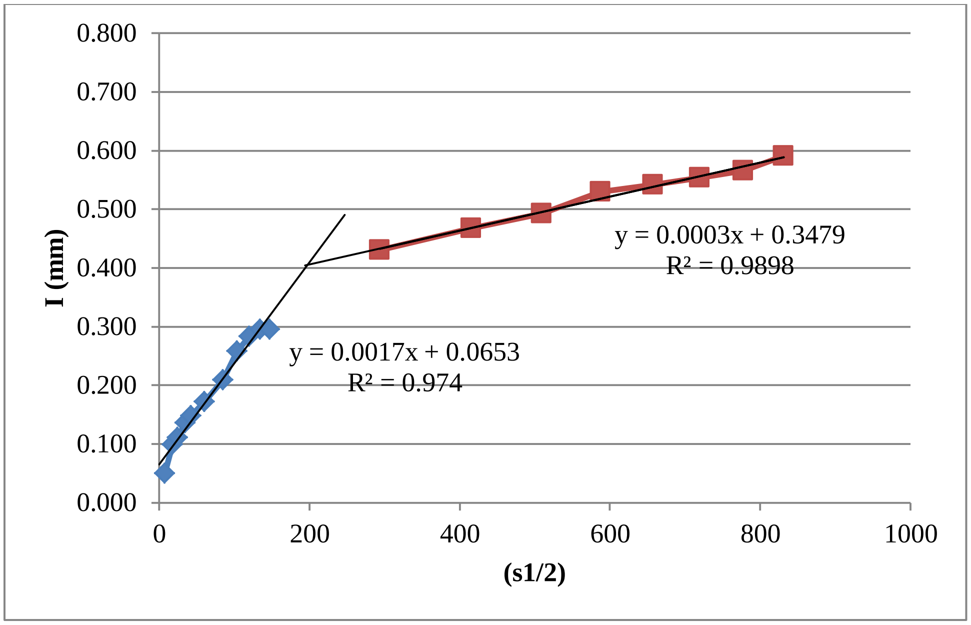

Figure C.19: P.A.B.M Suction 1

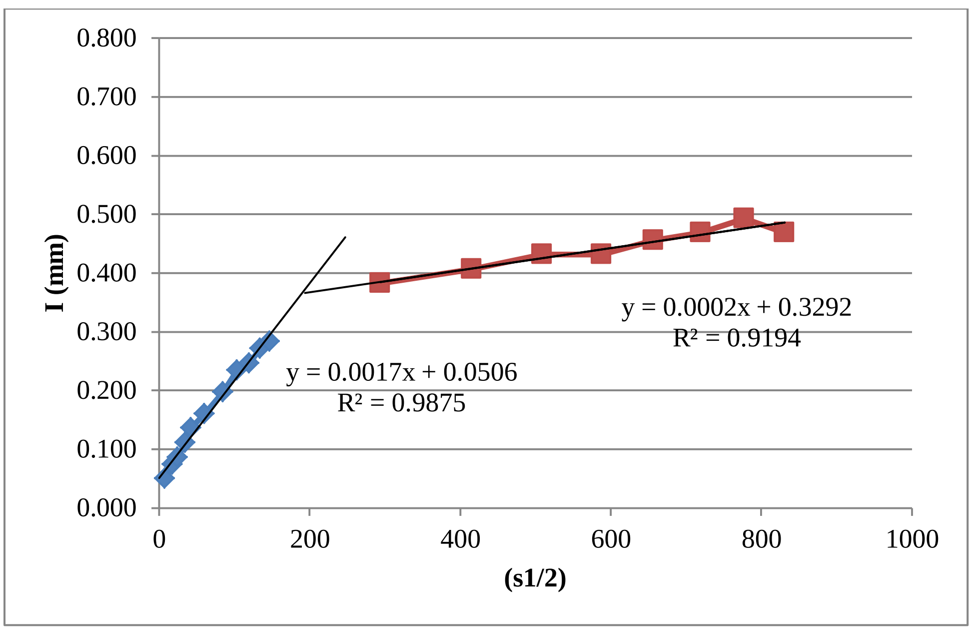

Figure C.20: P.A.B.M Suction 2

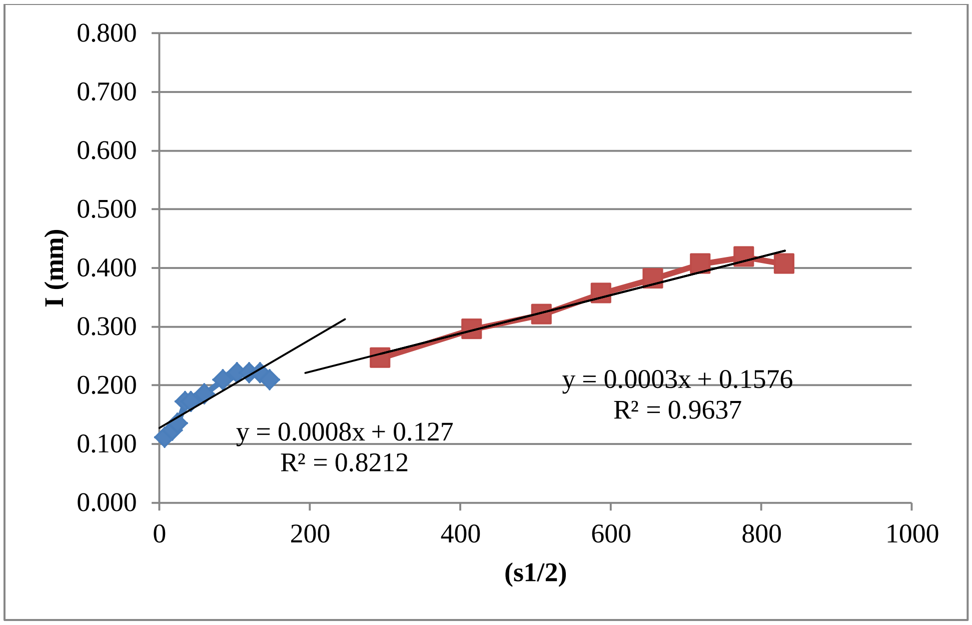

Figure C.21: M.BL.N.M Suction 1

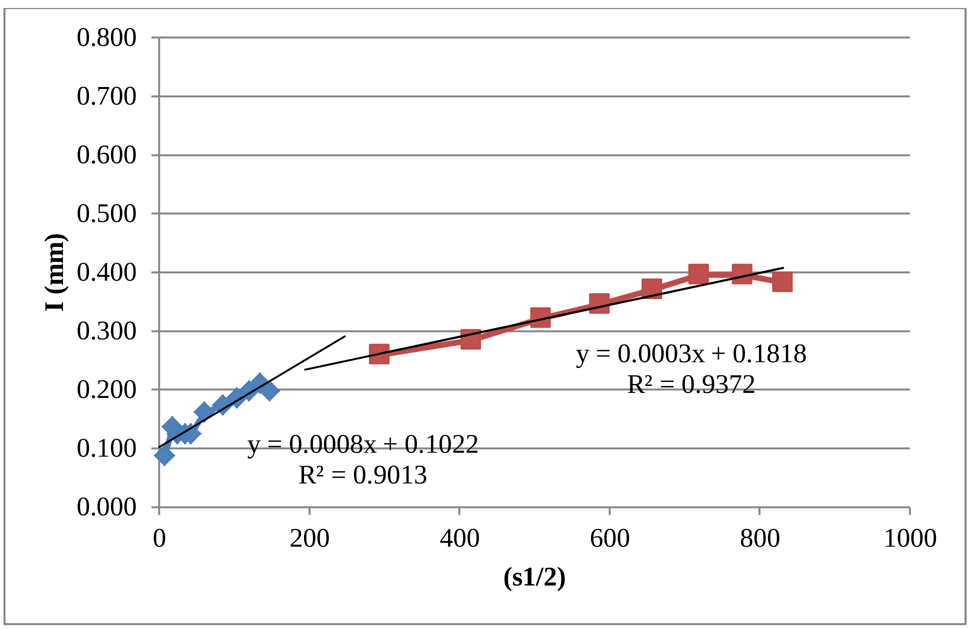

Figure C.22: M.BL.N.M Suction 2

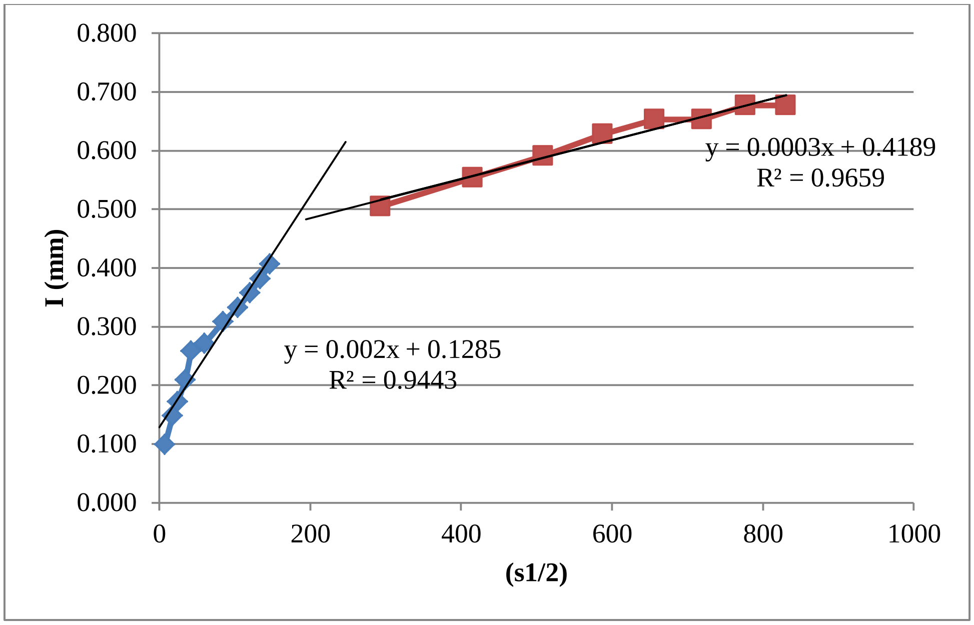

Figure C.23: P.BL.B.M Suction 1

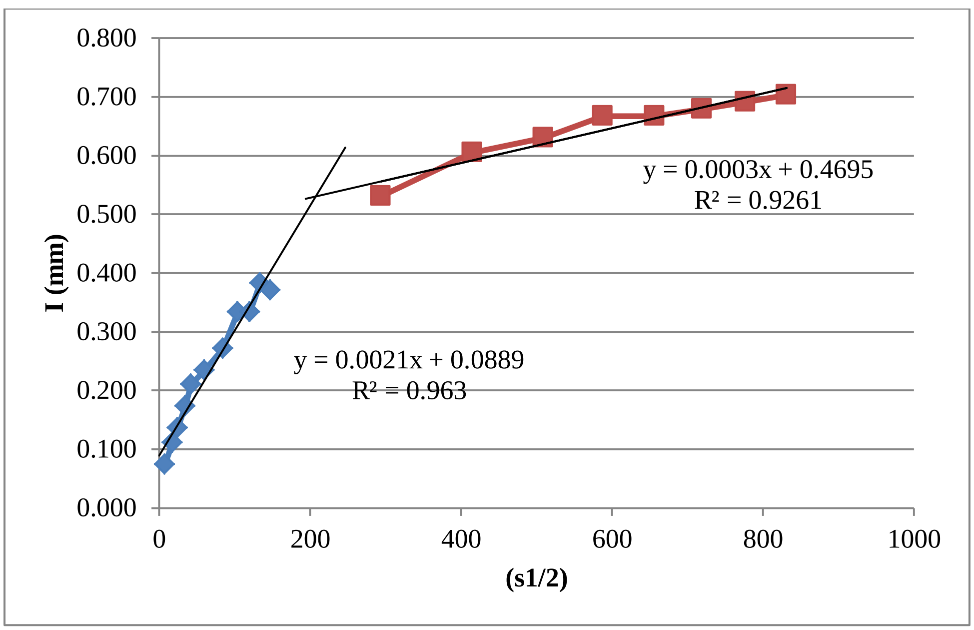

Figure C.24: P.BL.B.M Suction 2

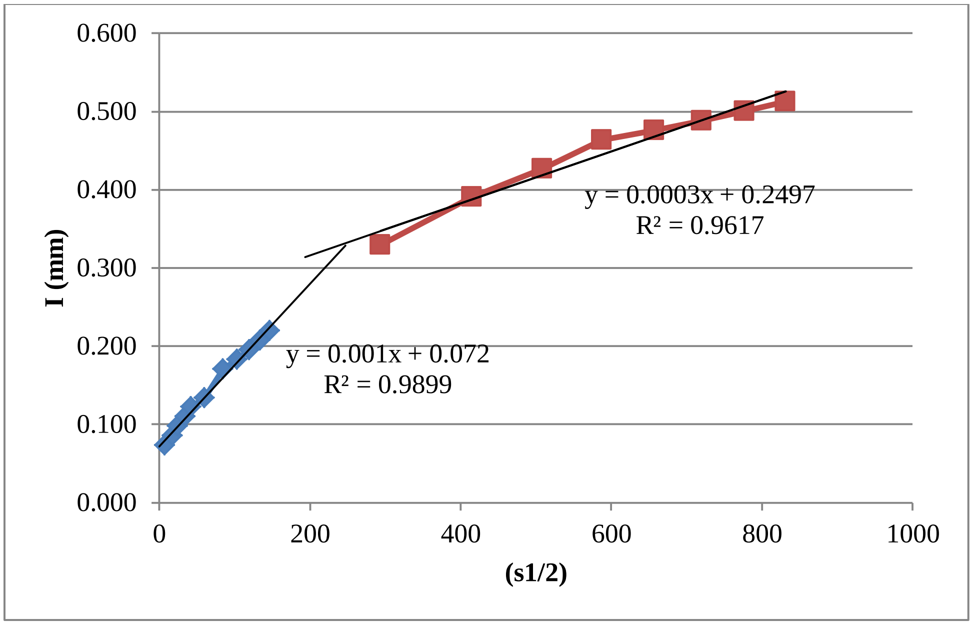

Figure C.25: P.BL.R.M Suction 1

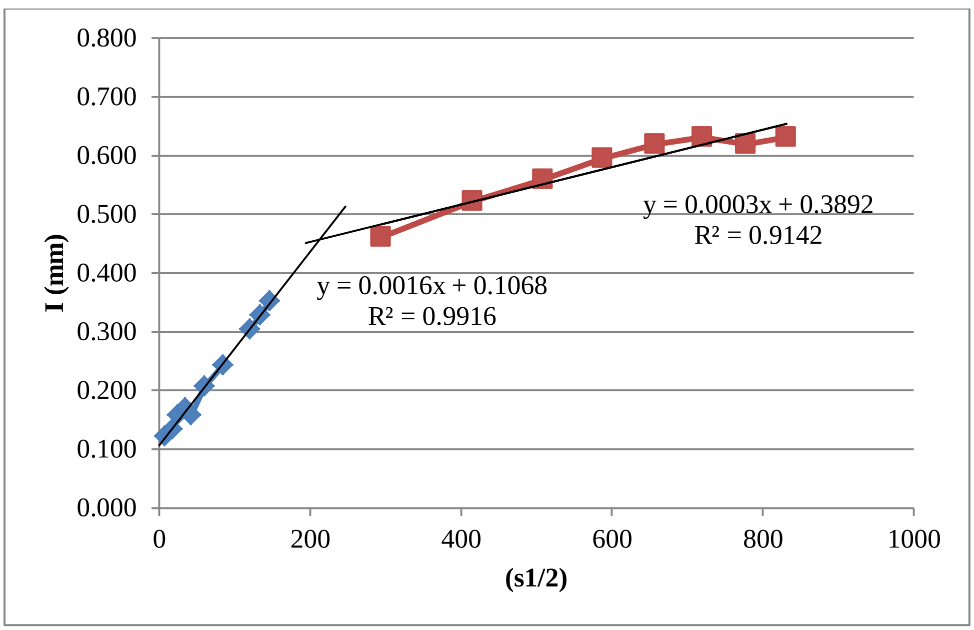

Figure C.26: P.BL.R.M Suction 2

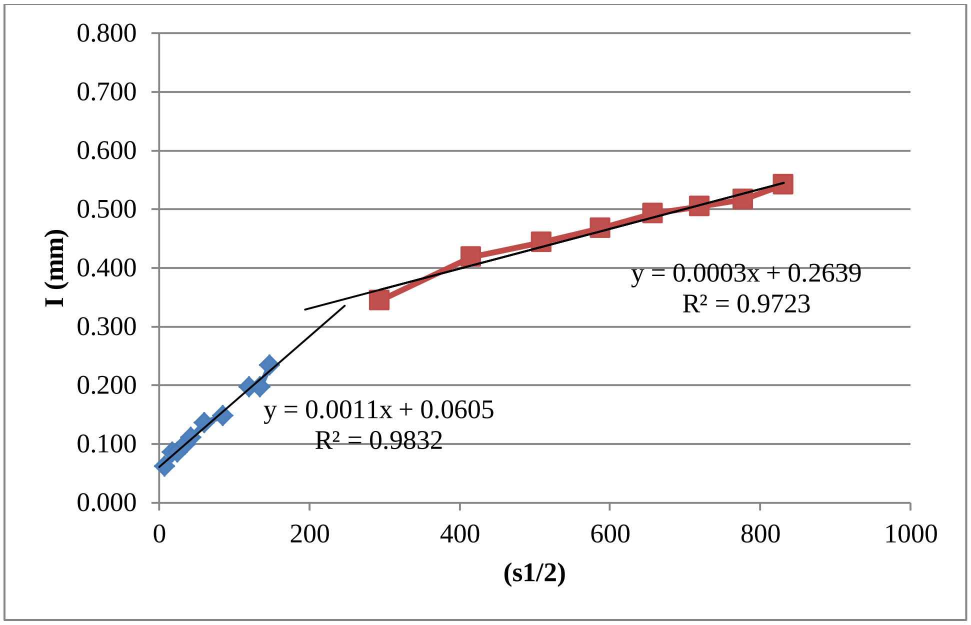

Figure C.27: P.B.R.M Suction 1

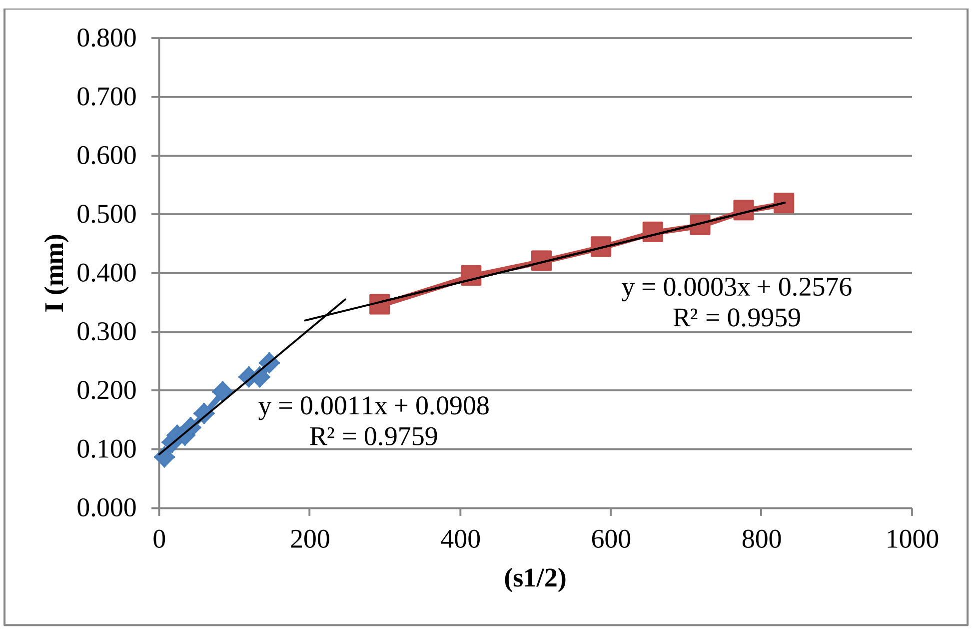

Figure C.28: P.B.R.M Suction 2

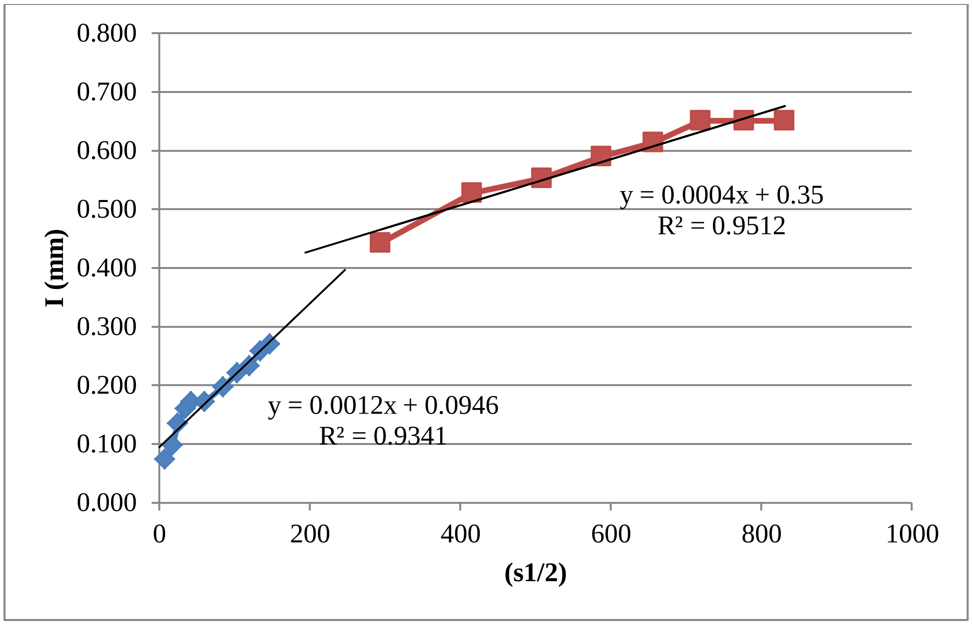

Figure C.29: P.A.R.M Suction 1

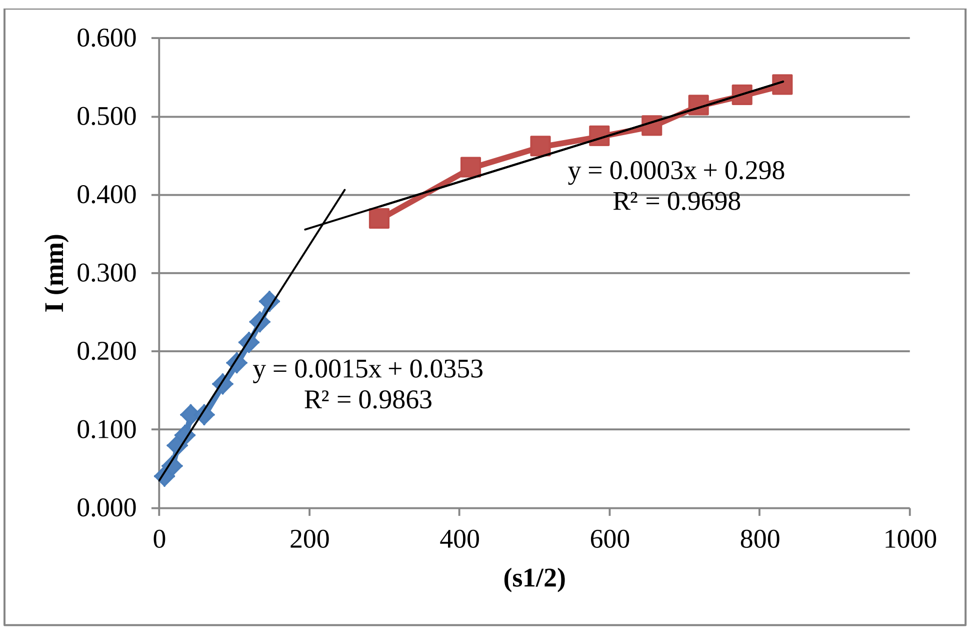

Figure C.30: P.A.R.M Suction 2

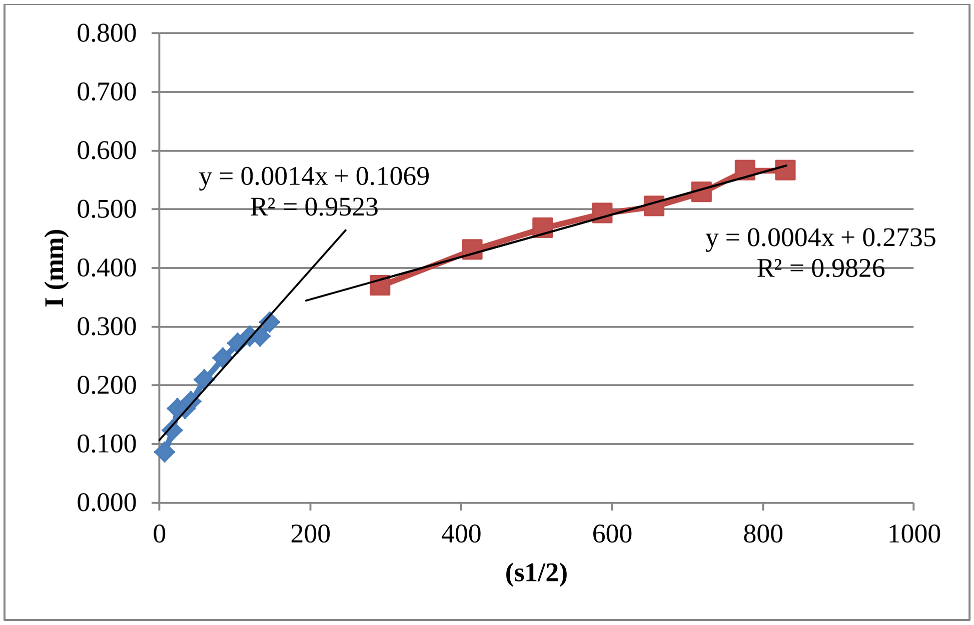

Figure C.31: P.A.N.N Suction 1

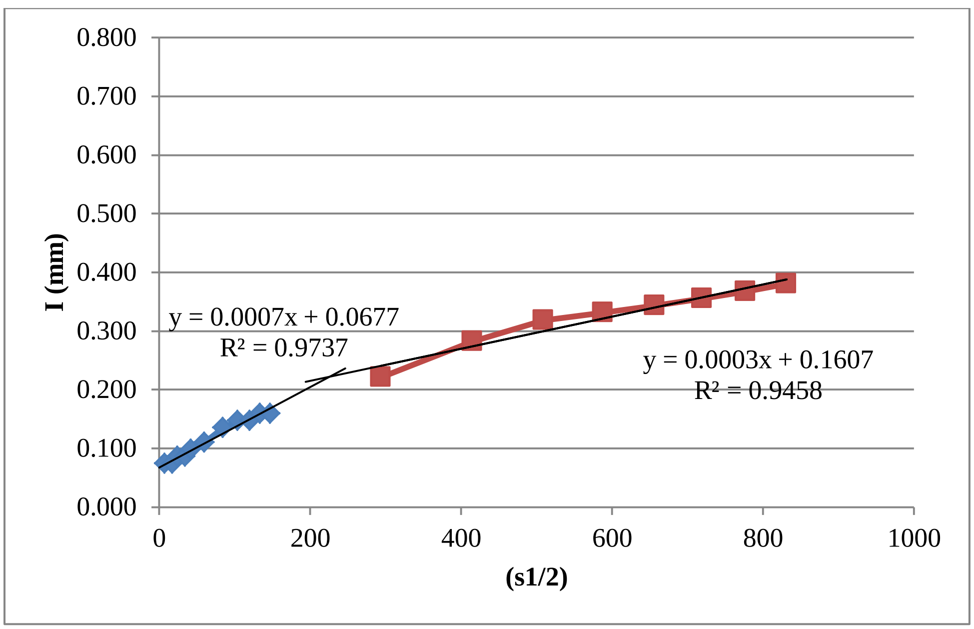

Figure C.32: P.A.N.N Suction 2

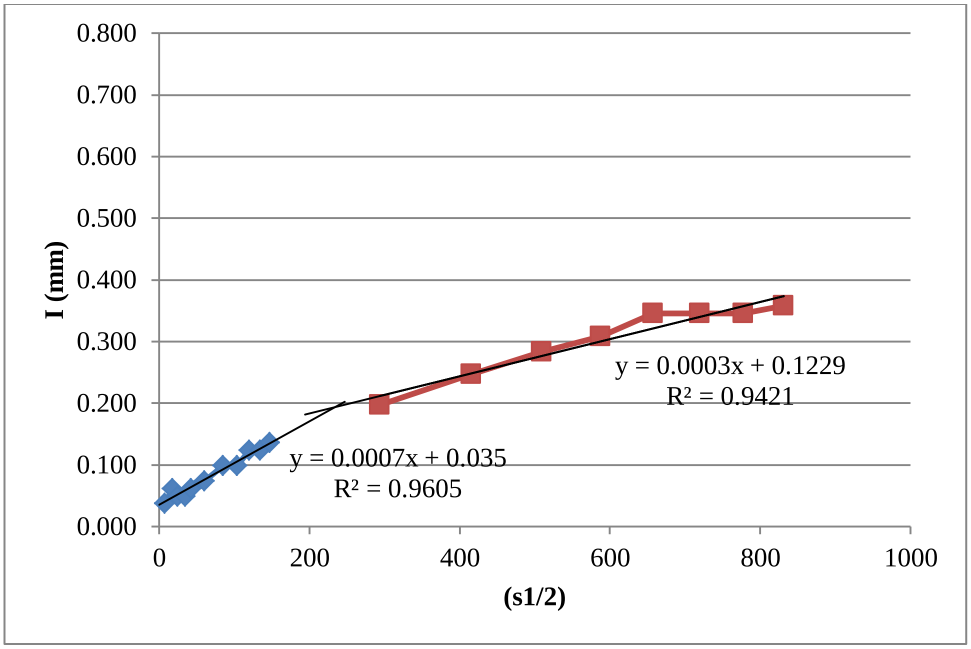

Figure C.33: P.BL.N.N Suction 1

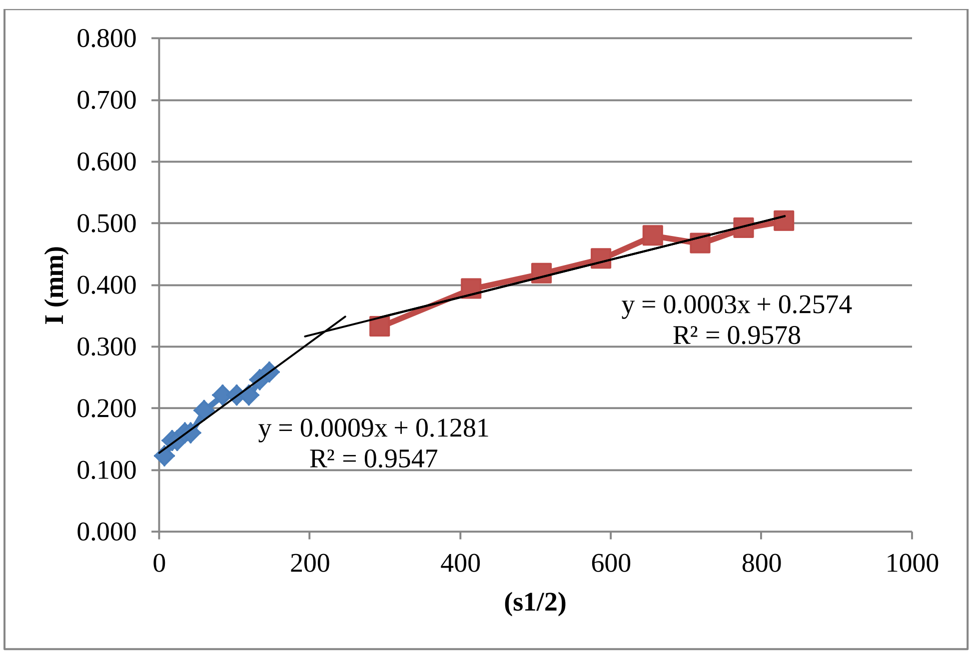

Figure C.34: P.BL.N.N Suction 2

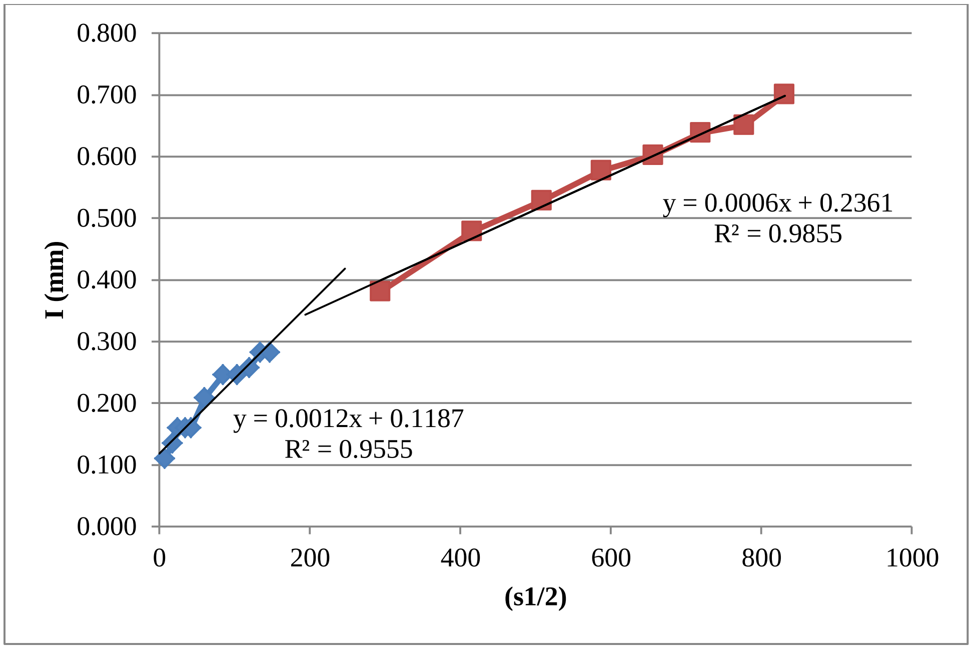

Figure C.35: P.B.N.N Suction 1

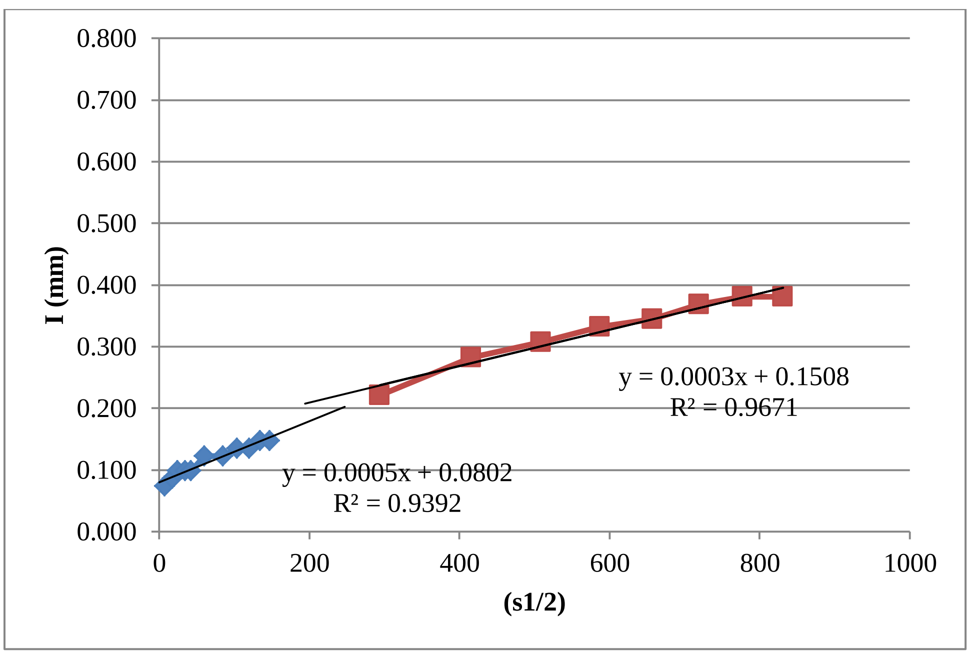

Figure C.36: P.B.N.N Suction 2

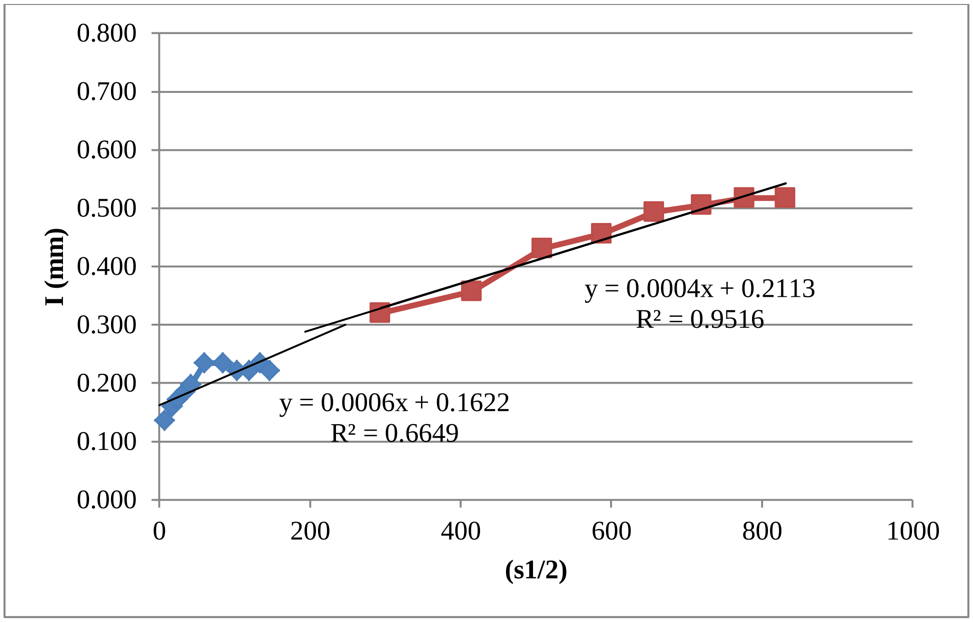

Figure C.37: P.B.N.M Ponding 1

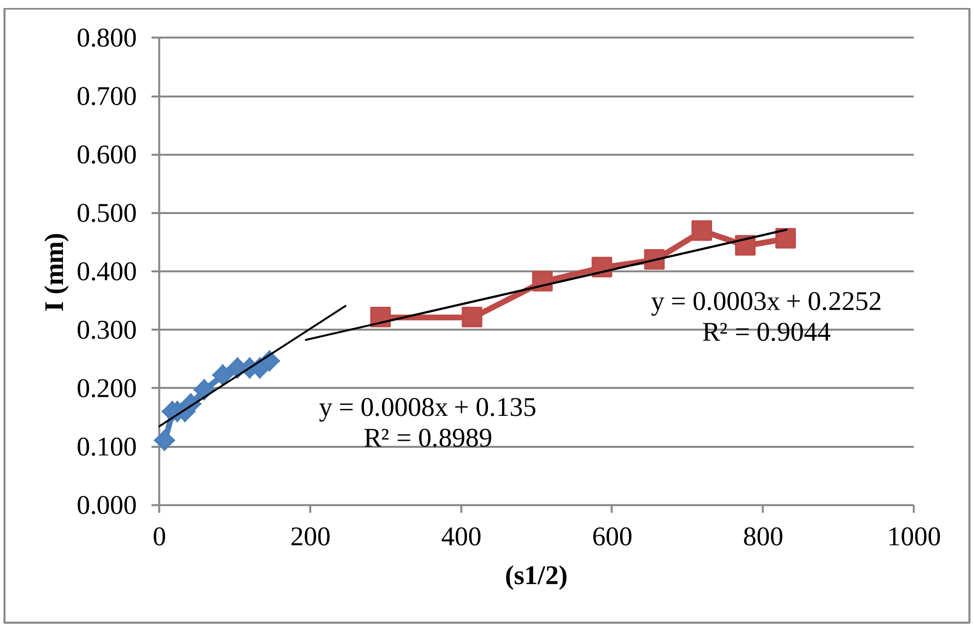

Figure C.38: P.B.N.M Ponding 2

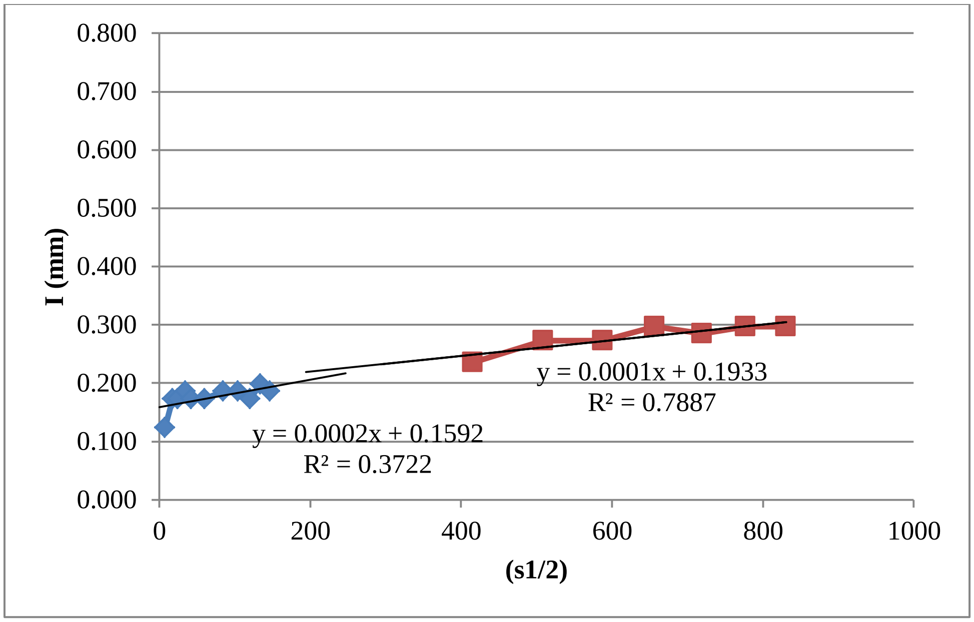

Figure C.39: P.B.N.M Ponding 1

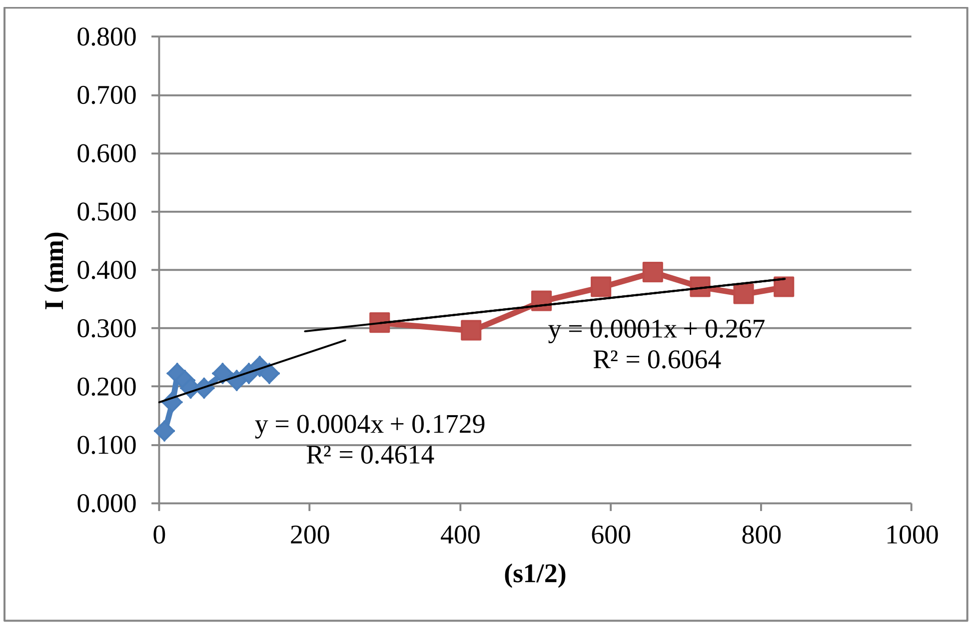

Figure C.40: P.B.N.M Ponding 2

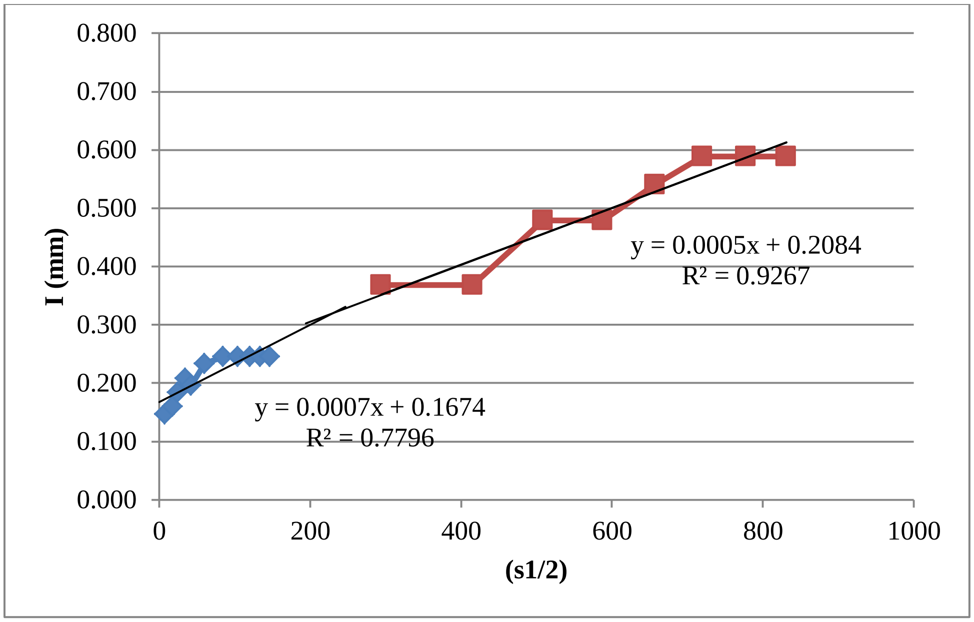

Figure C.41: P.A.N.M Ponding 1

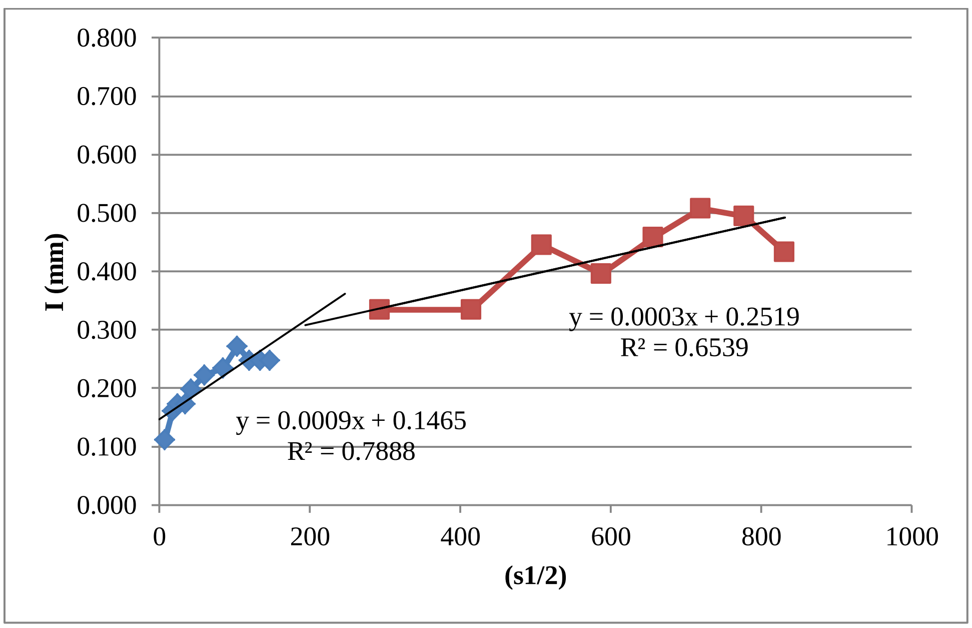

Figure C.42: P.A.N.M Ponding 2

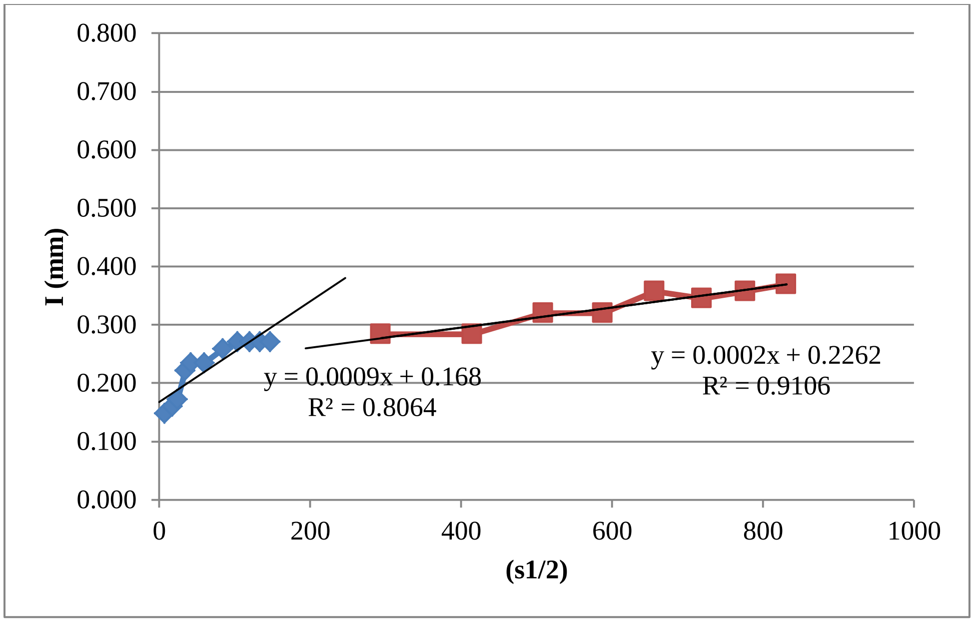

Figure C.43: C.A.N.M Ponding 1

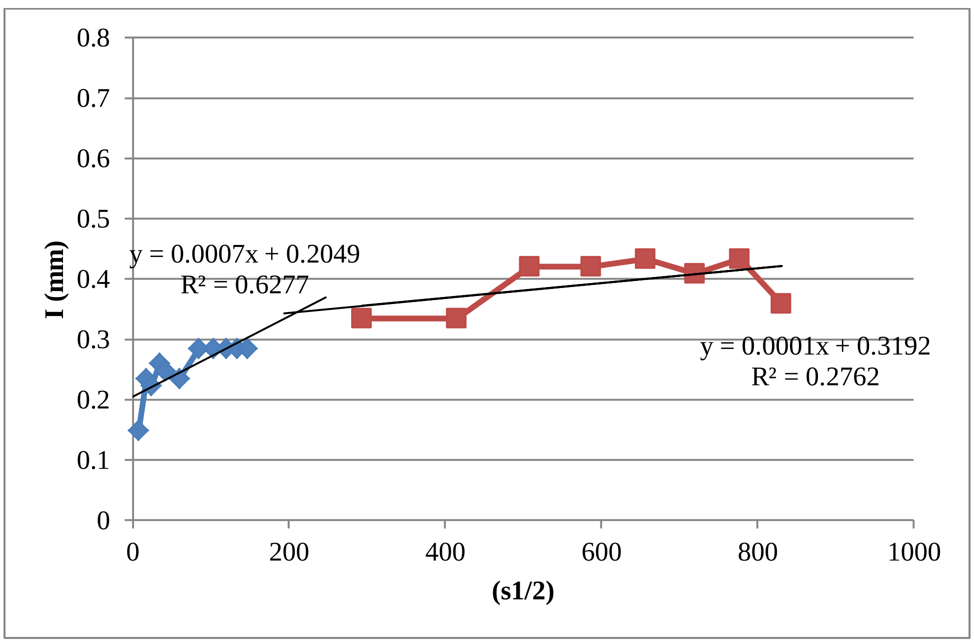

Figure C.44: C.A.N.M Ponding 2

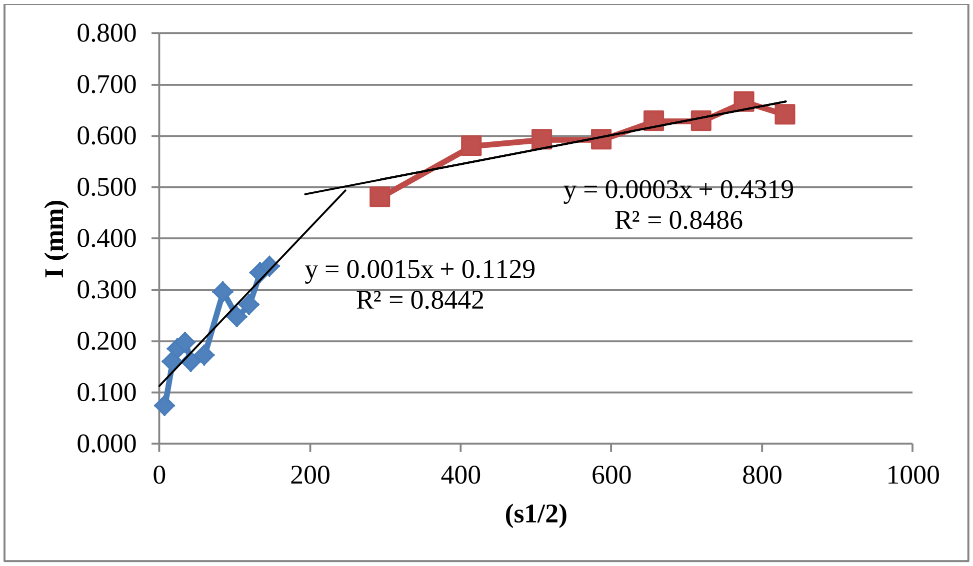

Figure C.45: M.A.N.M Ponding 1

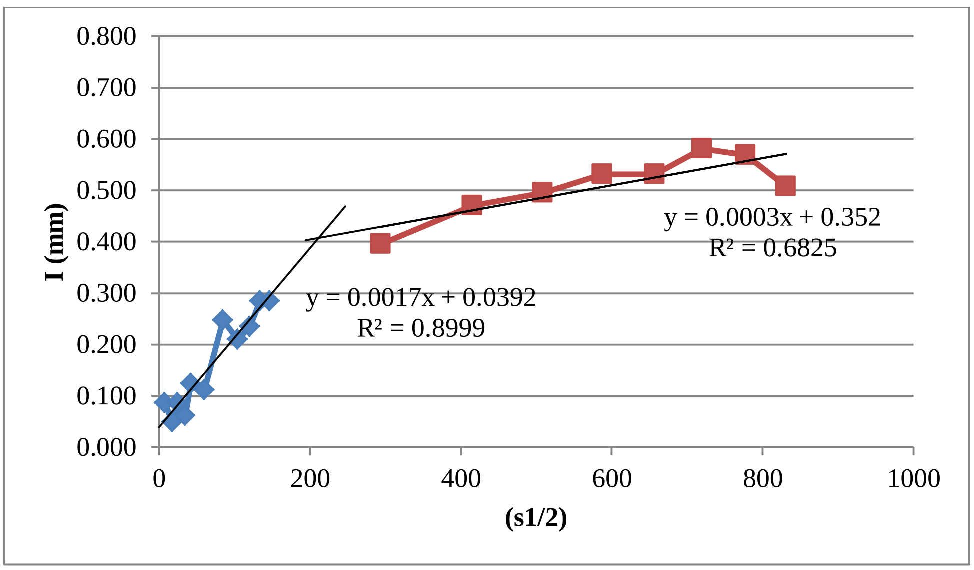

Figure C.46: M.A.N.M Ponding 2

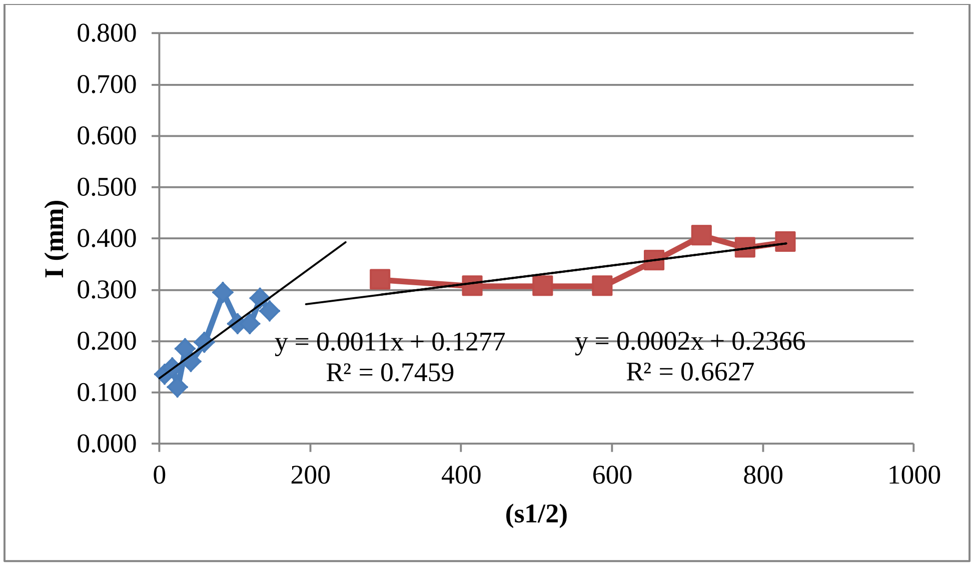

Figure C.47: C.BL.N.M Ponding 1

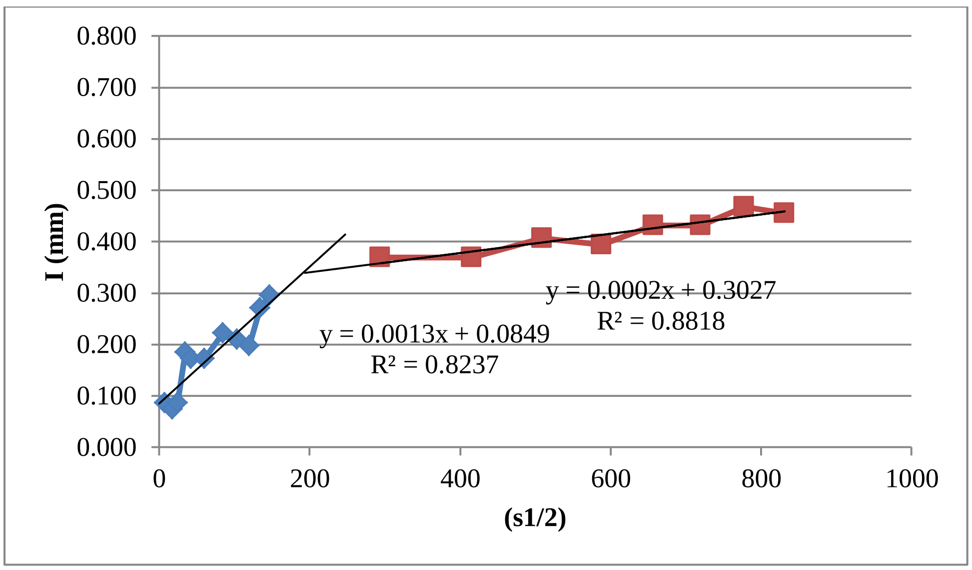

Figure C.48: C.BL.N.M Ponding 2

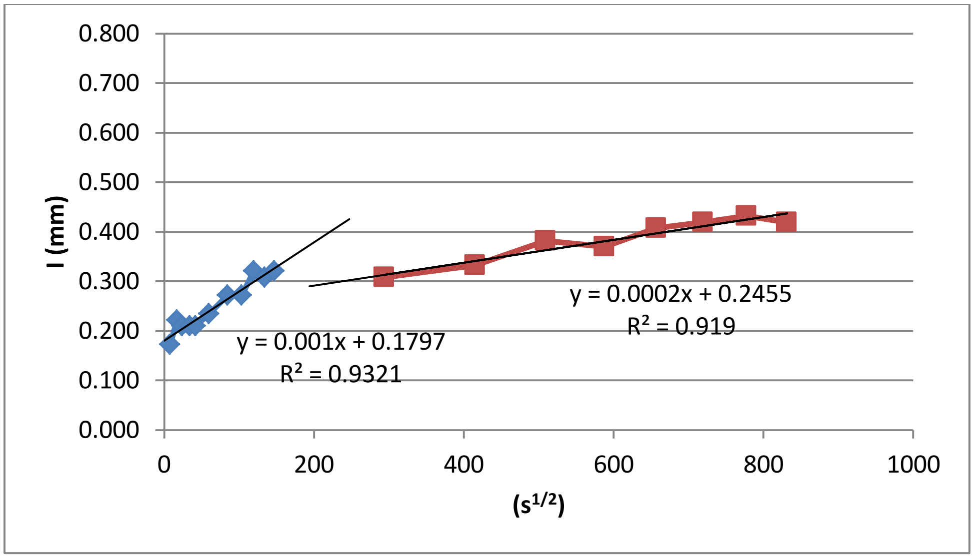

Figure C.49: C.B.N.M Ponding 1

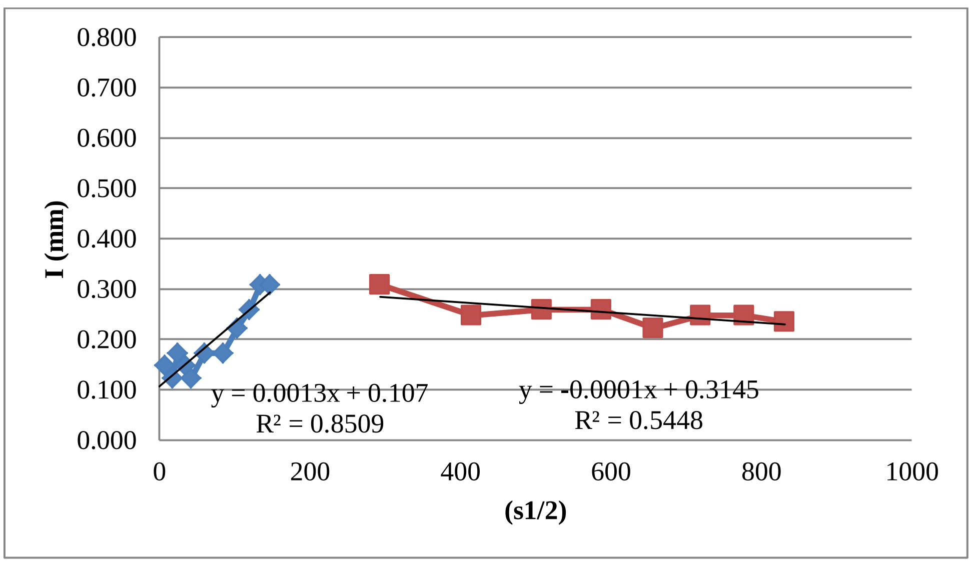

Figure C.50: C.B.N.M Ponding 2

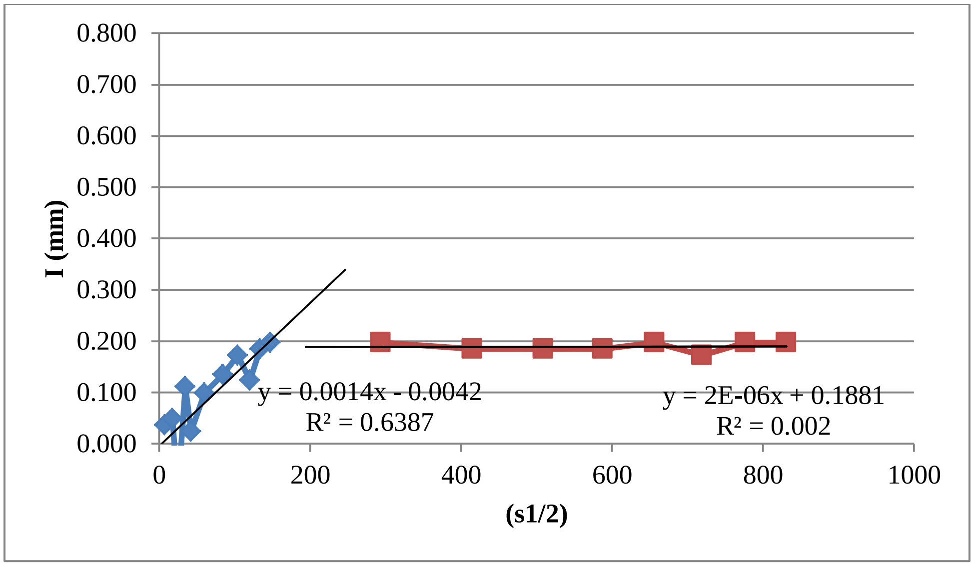

Figure C.51: M.B.N.M Ponding 1

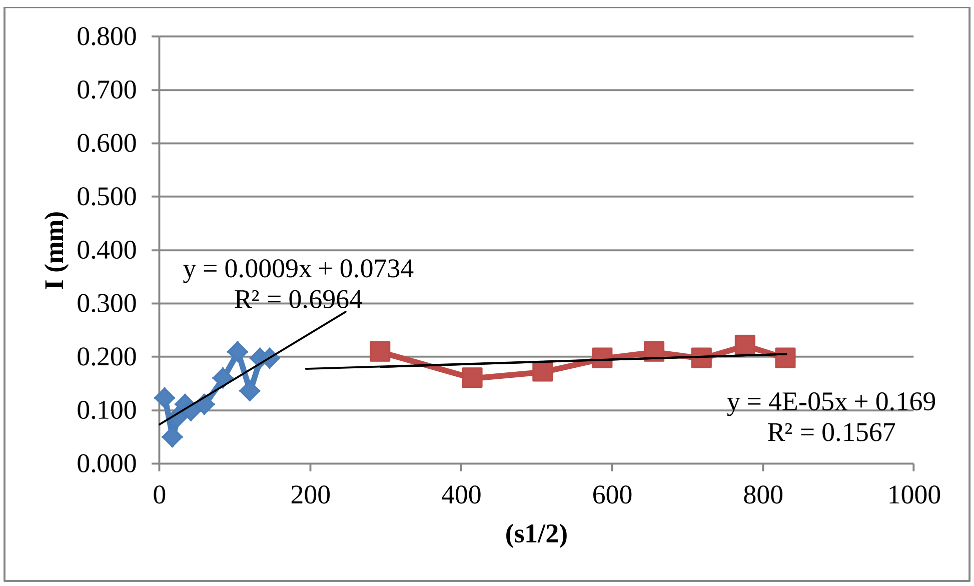

Figure C.52: M.B.N.M Ponding 2

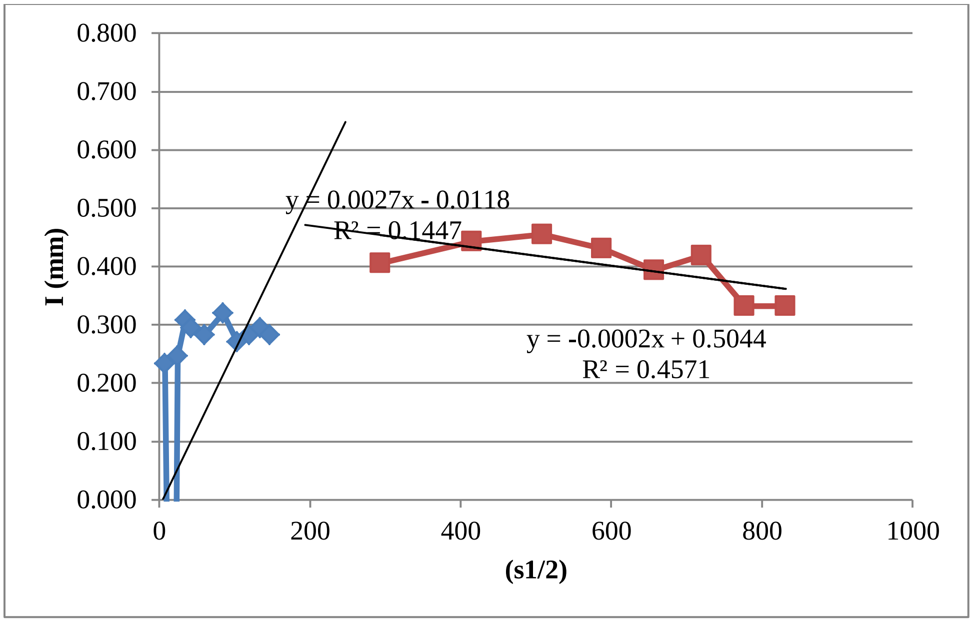

Figure C.53: P.B.B.M Ponding 1

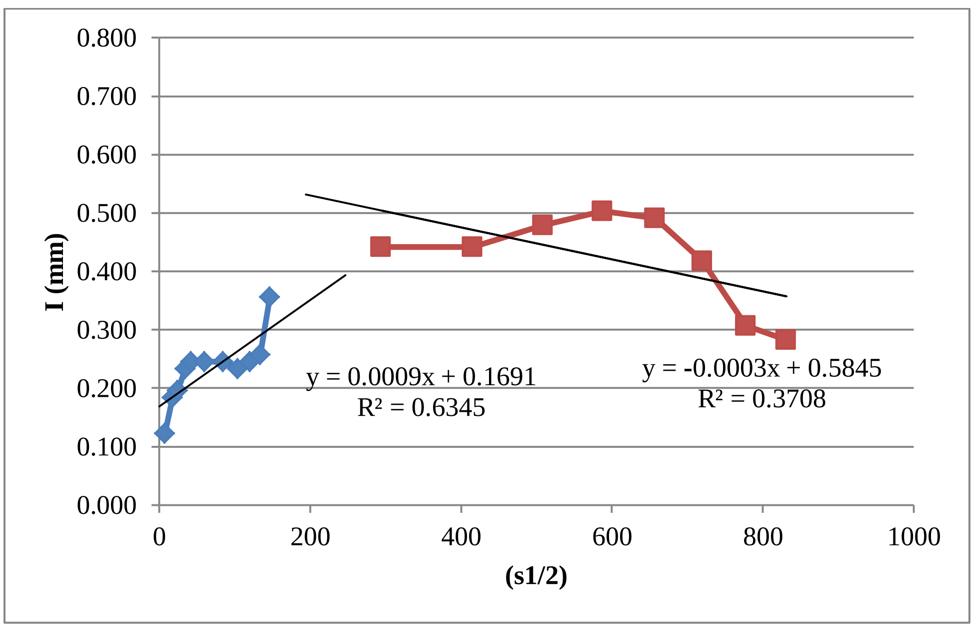

Figure C.54: P.B.B.M Ponding 2

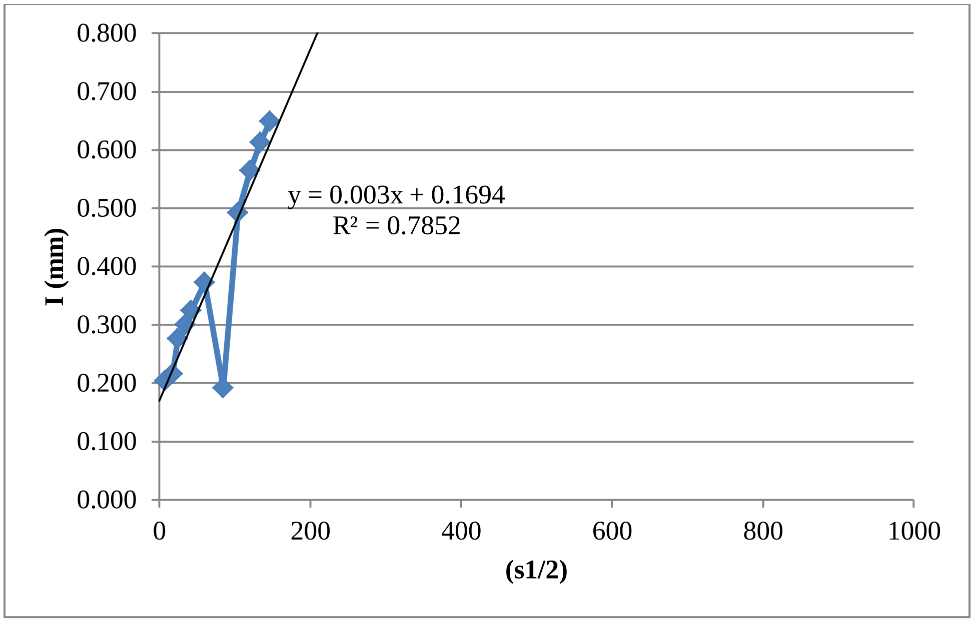

Figure C.55: P.A.B.M Ponding 1

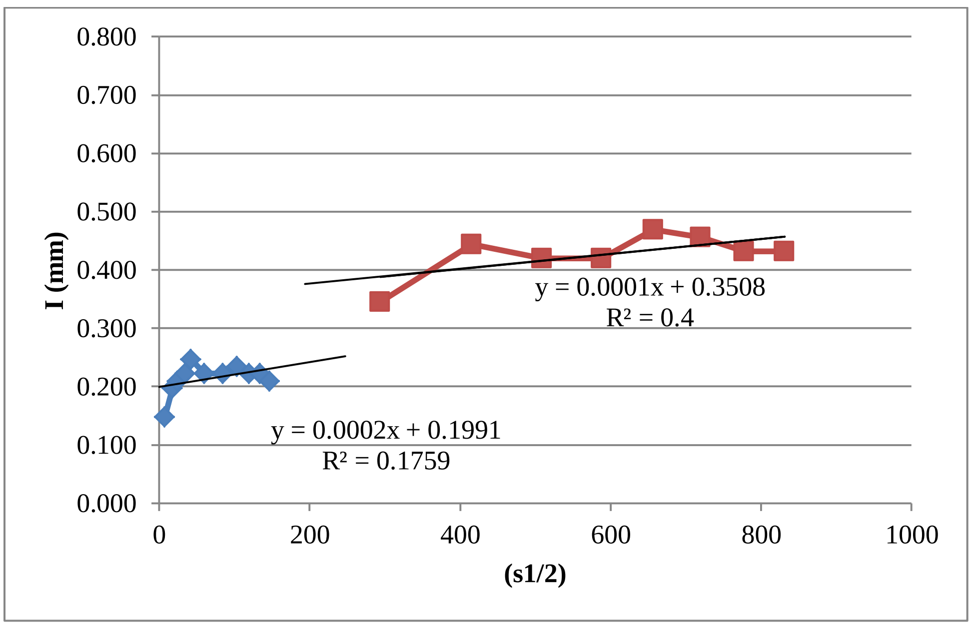

Figure C.56: P.A.B.M Ponding 2

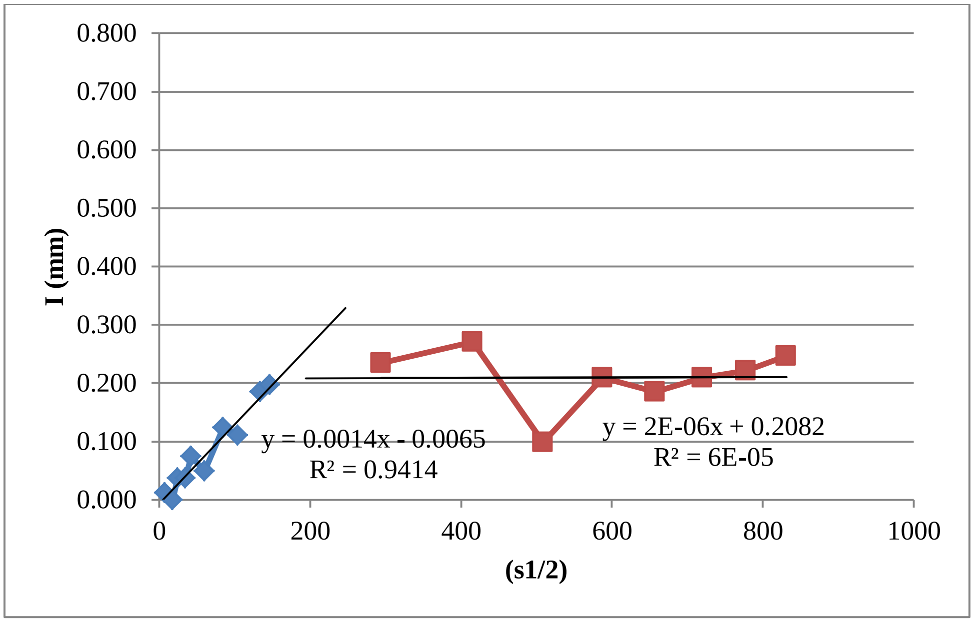

Figure C.57: M.BL.N.M Ponding 1

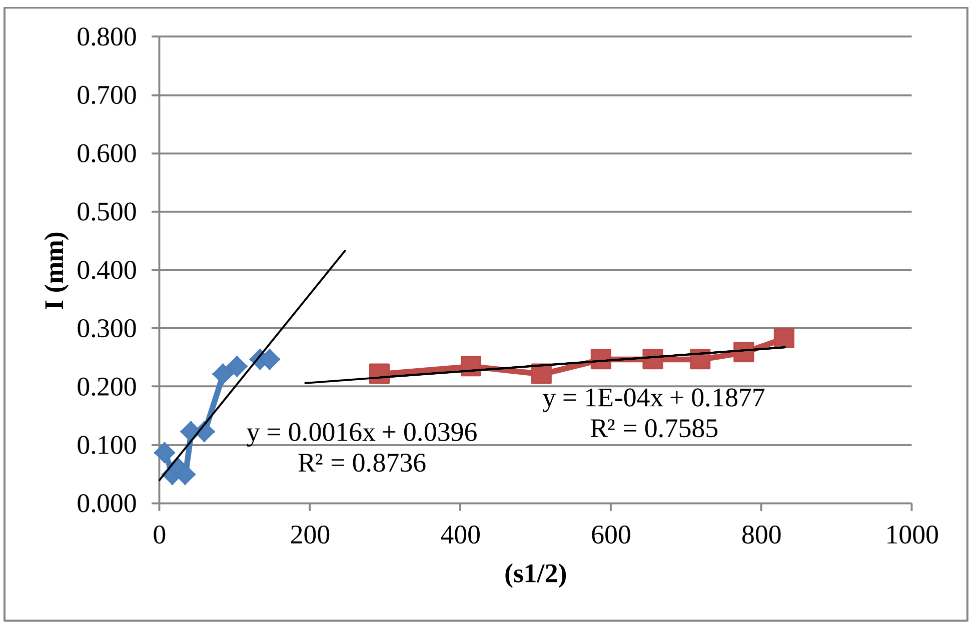

Figure C.58: M.BL.N.M Ponding 2

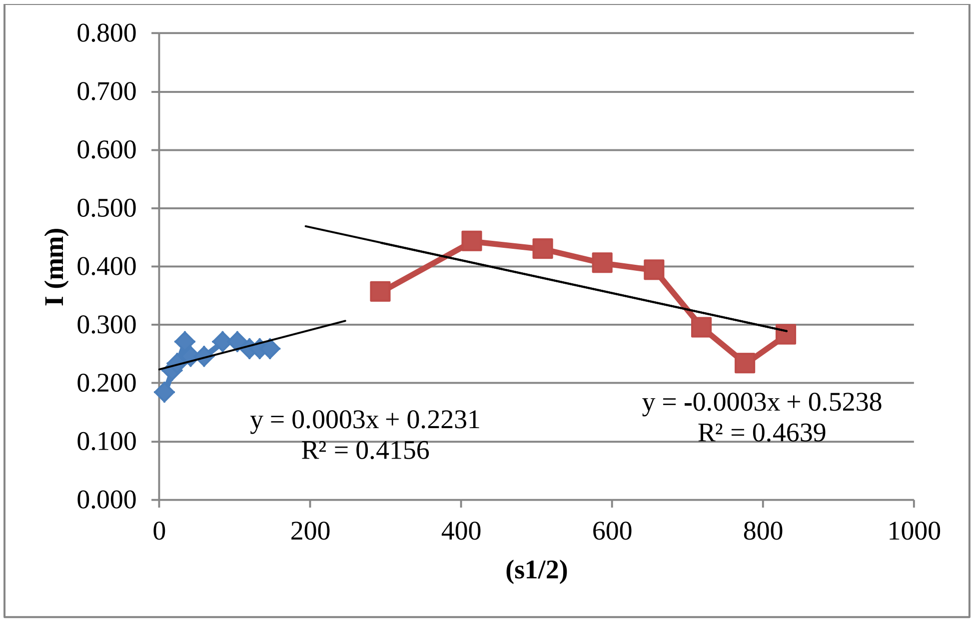

Figure C.59: P.BL.B.M Ponding 1

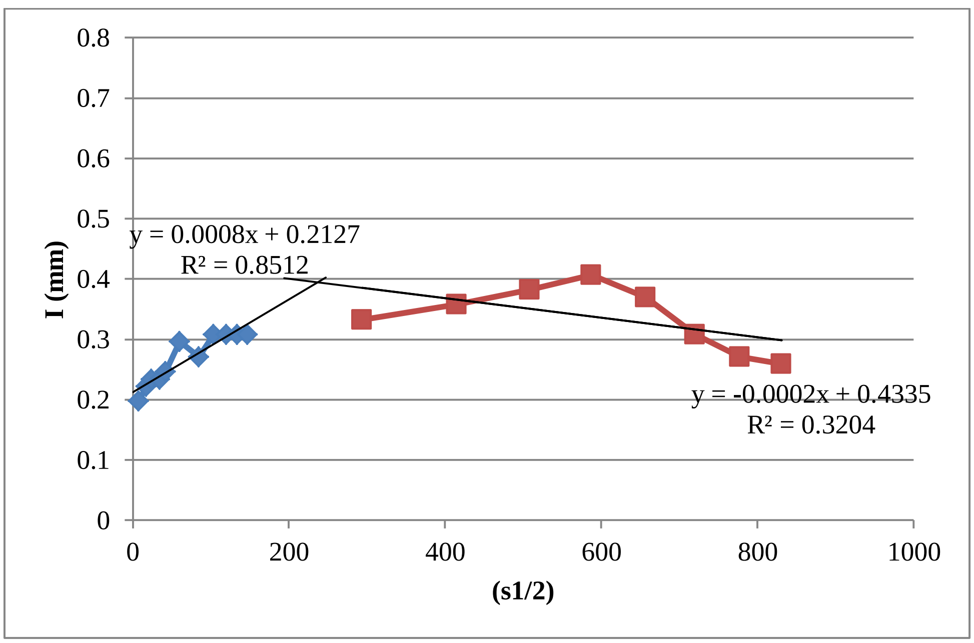

Figure C.60: P.BL.B.M Ponding 2

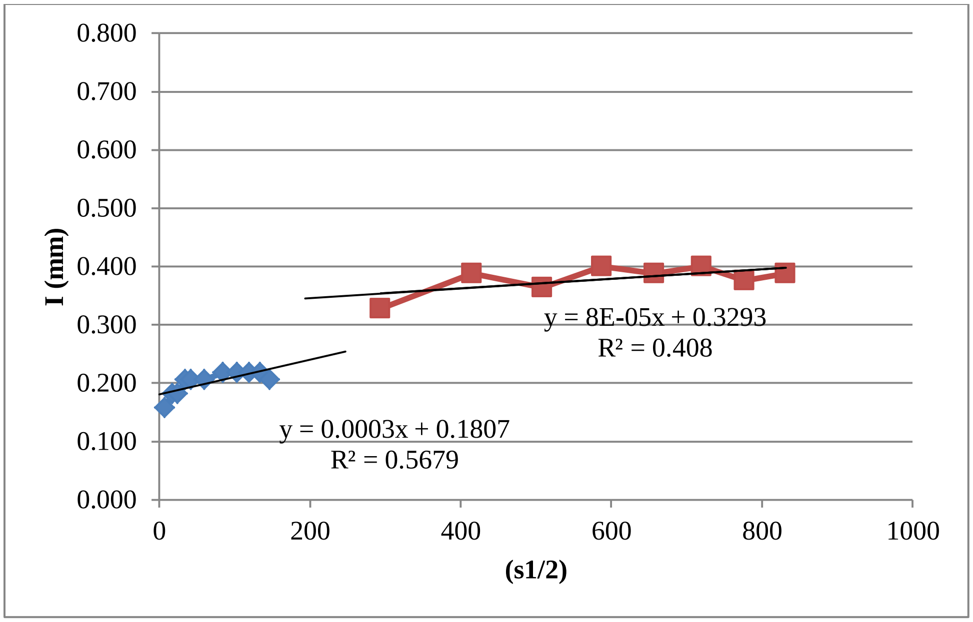

Figure C.61: P.BL.R.M Ponding 1

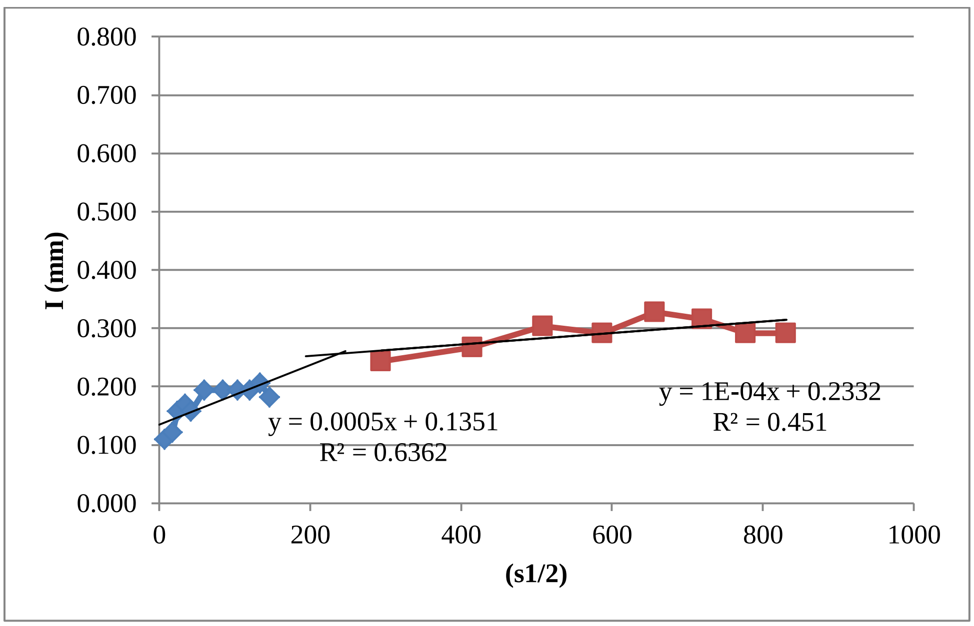

Figure C.62: P.BL.R.M Ponding 2

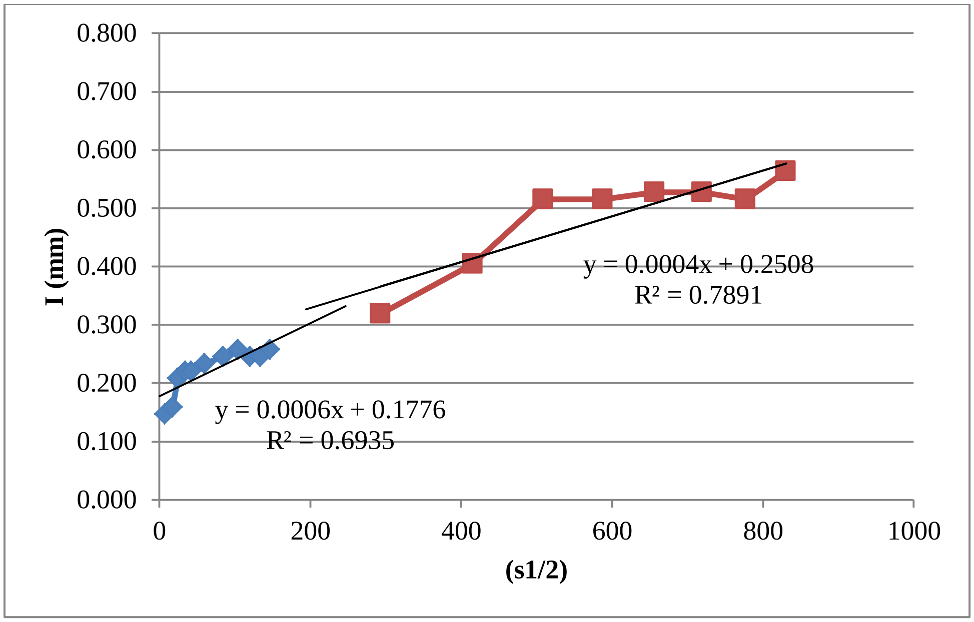

Figure C.63: P.B.R.M Ponding 1

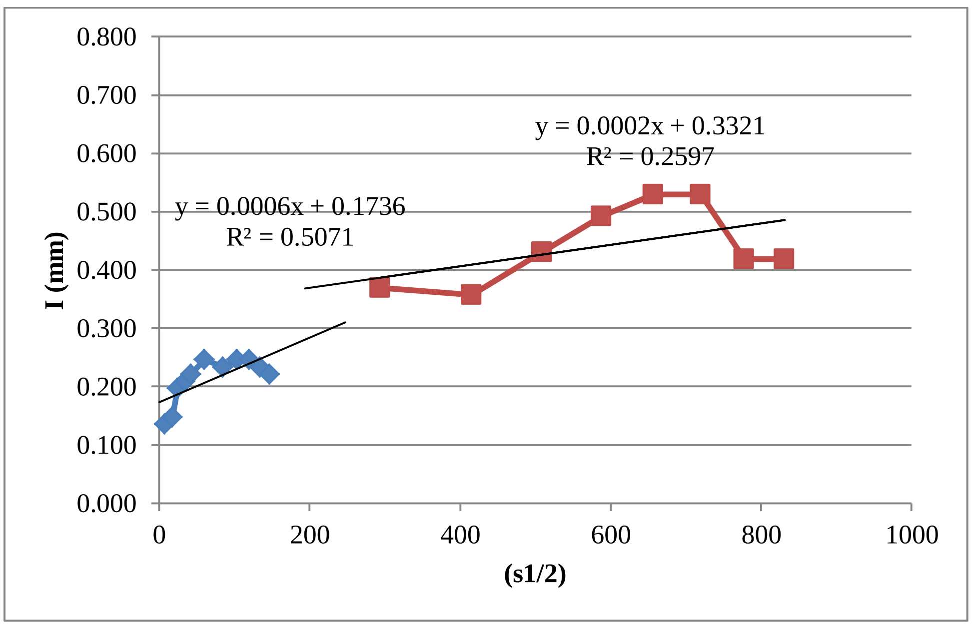

Figure C.64: P.B.R.M Ponding 2

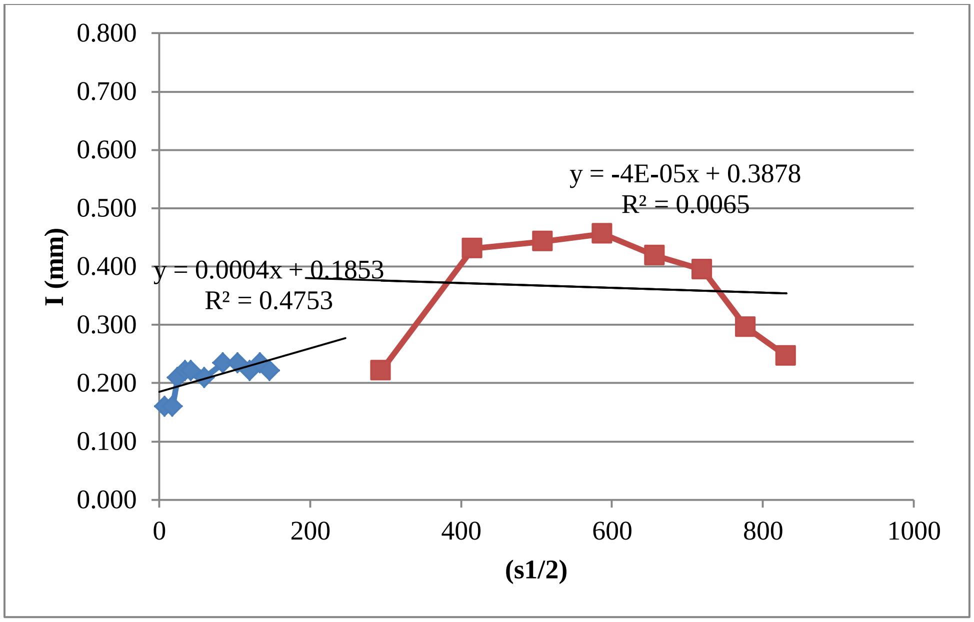

Figure C.65: P.A.R.M Ponding 1

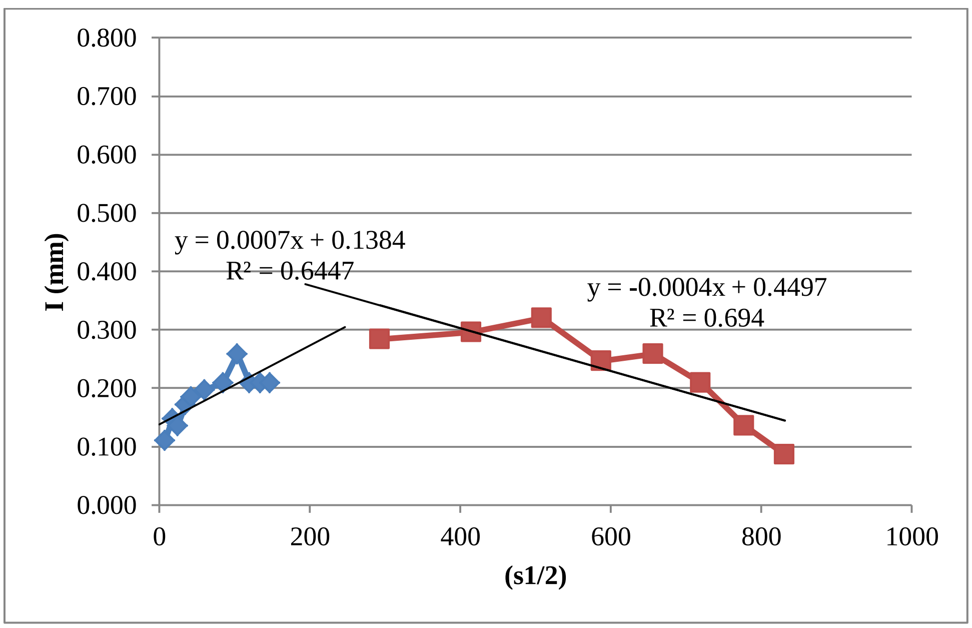

Figure C.66: P.A.R.M Ponding 2

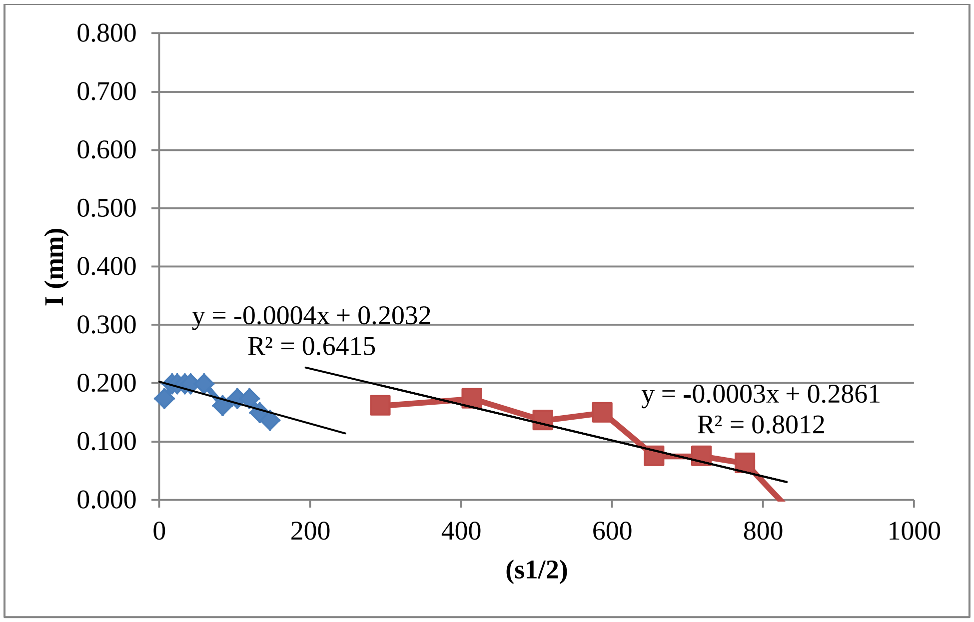

Figure C.67: P.A.N.N Ponding 1

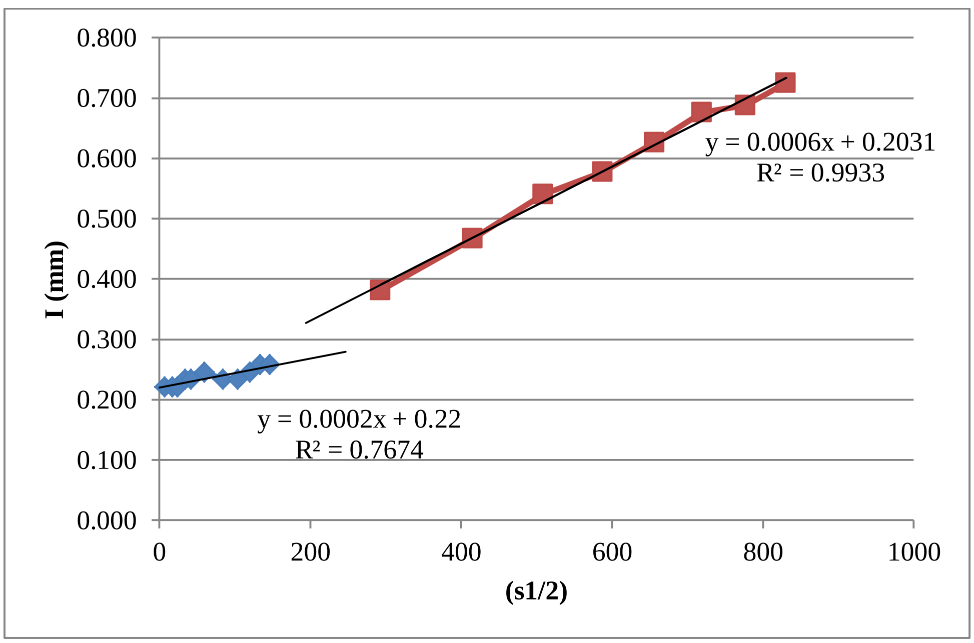

Figure C.68: P.A.N.N Ponding 2

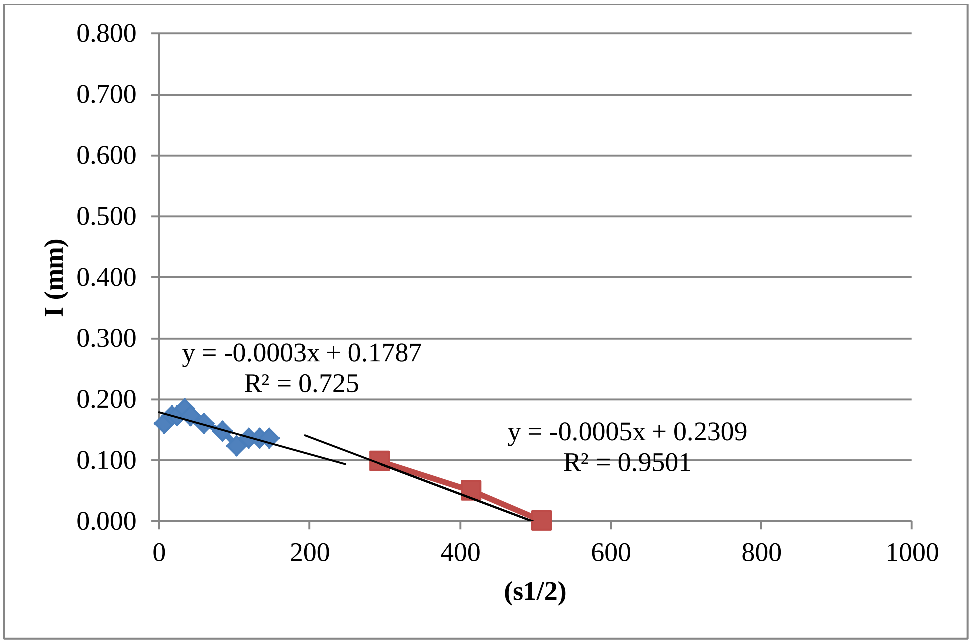

Figure C.69: P.BL.N.N Ponding 1

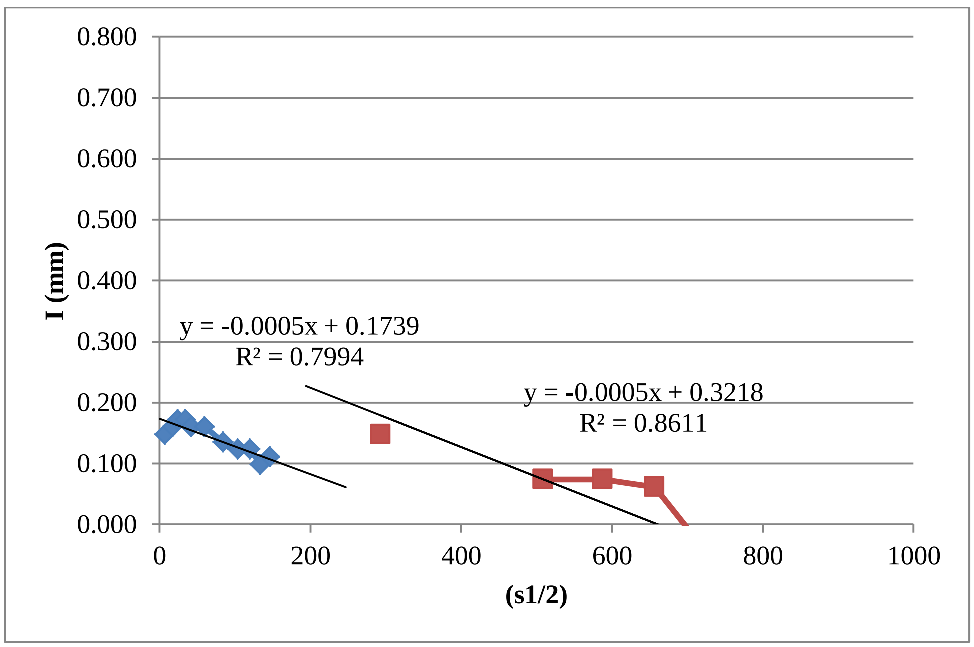

Figure C.70: P.BL.N.N Ponding 2

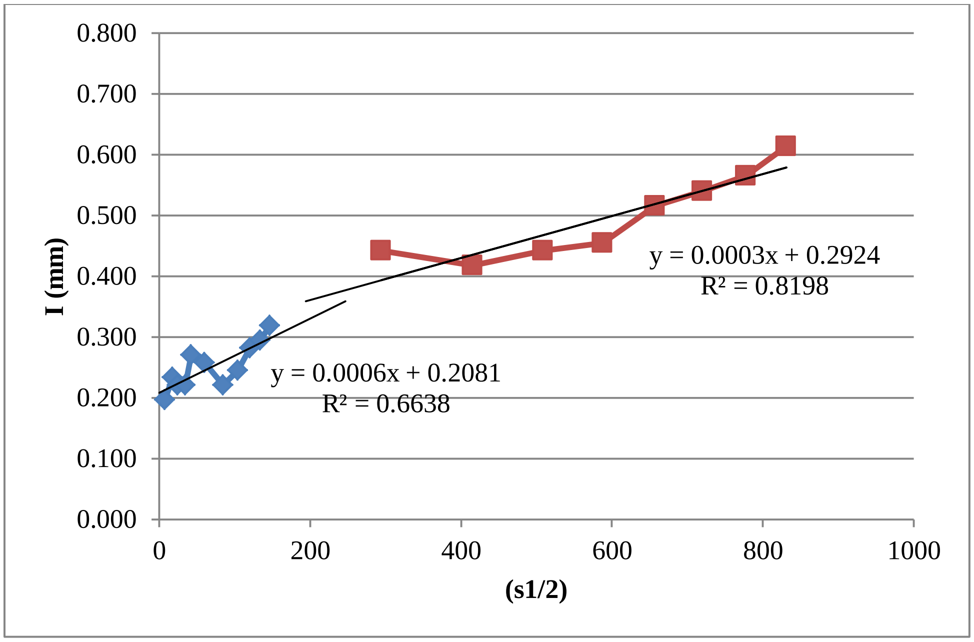

Figure C.71: P.B.N.N Ponding 1

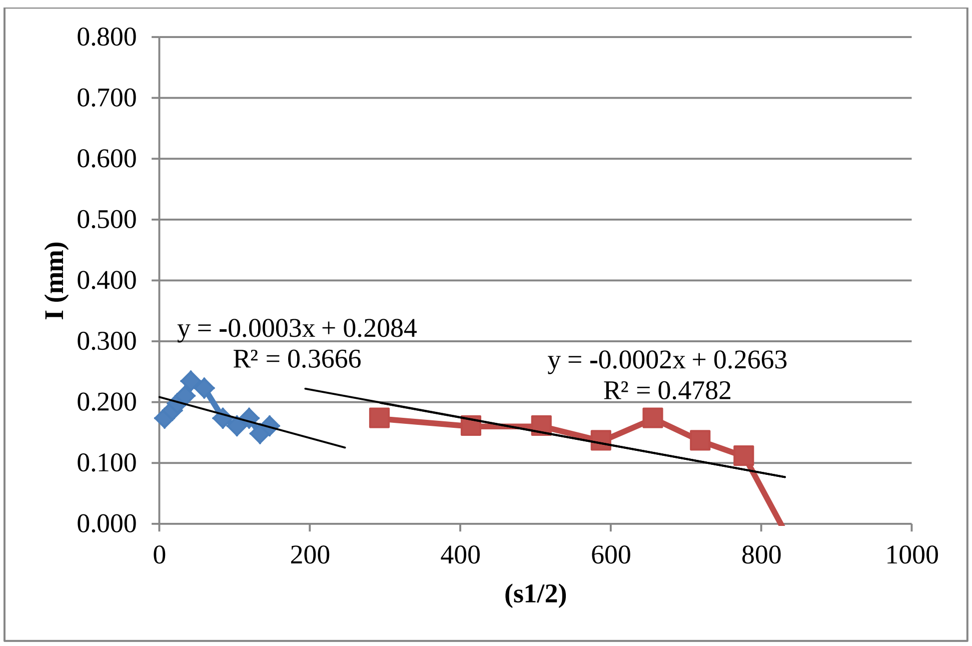

Figure C.72:P.B.N.N Ponding 2

APPENDIX D: MIXTURE INFORMATION

Table D.1: Compiled Results of Slump Values for Each Batch

Designation	Individual Batch Slump (in)				Average Slump (in)
	1	2	3	4	
P.A.N.M	1.5	1.25	1.25	1.75	1.4
P.B.N.M	2	2	1.75	2	1.9
P.BL.N.M	2	2	2.25	2.5	2.2
C.A.N.M	-	0.75	1	1.5	1.1
C.B.N.M	-	1	1.5	1.75	1.4
C.BL.N.M	-	1	1	1.25	1.1
M.A.N.M	2.75	-	1.75	1.5	2.0
M.B.N.M	3.25	-	2.25	1.75	2.4
M.BL.N.M	2.25	-	2.5	2	2.3
P.A.A.M	2.5	3.5	2.25	2.5	2.7
P.B.A.M	2.5	2.5	2.25	1.75	2.3
P.BL.A.M	2.5	3.25	2	2.25	2.5
P.A.B.M	-	3	2.25	2	2.4
P.B.B.M	-	2.75	2	2	2.3
P.BL.B.M	-	2.755	2.25	2	2.3
P.A.N.N	-	1.5	2	2.25	1.9
P.B.N.N	-	2.5	3.75	3.75	3.3
P.BL.N.N	-	2.75	3	2.75	2.8

Table D.2: Compiled Results of Air Content Values for Each Batch

Designation	Individual Batch Air Content (%)				Average Air Content (%)
	1	2	3	4	
P.A.N.M	5.6	5.5	5.1	5.5	5.4
P.B.N.M	5.9	6.0	6.0	6.0	6.0
P.BL.N.M	5.0	5.8	5.6	6.0	5.6
C.A.N.M	-	5.7	5.8	6.0	5.8
C.B.N.M	-	5.4	5.7	5.8	5.6
C.BL.N.M	-	5.6	5.0	6.0	5.5
M.A.N.M	5.4	-	5.4	5.2	5.3
M.B.N.M	5.7	-	5.2	5.2	5.4
M.BL.N.M	5.0	-	5.4	5.0	5.1
P.A.A.M	5.5	5.9	5.6	5.6	5.7
P.B.A.M	5.1	5.3	5.3	5.0	5.2
P.BL.A.M	5.1	5.3	5.1	5.3	5.2
P.A.B.M	-	5.4	5.6	5.8	5.6
P.B.B.M	-	6.0	5.6	5.6	5.7
P.BL.B.M	-	5.9	5.6	5.3	5.6
P.A.N.N	-	5.0	5.3	5.5	5.3
P.B.N.N	-	5.1	5.6	5.6	5.4
P.BL.N.N	-	5.9	5.3	5.4	5.5

Table D.3: Compiled Admixture Dosages

Designation	Air Entraing Admixture (fluid oz/cwt)	Midrange Water Reducer (fluid oz/cwt)
P.A.N.M	3.8	13.8
P.B.N.M	2.8	13.8
P.BL.N.M	2.4	13.8
C.A.N.M	2.8	17.3
C.B.N.M	1.0	17.3
C.BL.N.M	1.4	17.3
M.A.N.M	3.8	13.8
M.B.N.M	1.4	10.4
M.BL.N.M	2.1	10.4
P.A.A.M	4.3	13.8
P.B.A.M	5.1	3.9
P.BL.A.M	7.5	3.9
P.A.B.M	4.3	13.8
P.B.B.M	10.2	3.9
P.BL.B.M	12.6	3.9
P.A.N.N	0.5	0.0
P.B.N.N	0.7	0.0
P.BL.N.N	0.8	0.0

Table D.4: Compiled Results of Unit Weight Values for Each Batch

Designation	Individual Batch Unit Weight (pcf)				Average Unit Weight (pcf)
	1	2	3	4	
P.A.N.M	144	144	146	145	145
P.B.N.M	143	143	143	143	143
P.BL.N.M	146	143	144	142	144
C.A.N.M	-	138	138	137	138
C.B.N.M	-	138	139	138	139
C.BL.N.M	-	137	139	139	139
M.A.N.M	145	-	145	146	145
M.B.N.M	143	-	145	145	144
M.BL.N.M	146	-	144	146	145
P.A.A.M	141	139	142	142	141
P.B.A.M	142	142	142	143	142
P.BL.A.M	143	141	142	142	142
P.A.B.M	-	141	142	142	142
P.B.B.M	-	139	141	142	141
P.BL.B.M	-	140	141	142	141
P.A.N.N	-	144	142	142	143
P.B.N.N	-	143	142	142	142
P.BL.N.N	-	147	142	141	143