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The influence of superabsorbent polymer (cassava starch) on the rheological behavior of cement pastes.

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INFLUENCE OF SUPERABSORBENT POLYMER (CASSAVA STARCH) ON THE
RHEOLOGICAL BEHAVIOR OF CEMENT PASTES

By

James Wong
B.S., University of Louisville, 2015

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INFLUENCE OF SUPERABSORBENT POLYMER (CASSAVA STARCH) ON THE
RHEOLOGICAL BEHAVIOR OF CEMENT PASTES

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ABSTRACT

Rheological properties are the properties typically reference flow properties of concrete and are related to processing, construction, and setting. The purpose of this research was to investigate the influence of superabsorbent polymers (SAP) and superplasticizer (SP) on rheological properties, specifically of cement pastes with 0.35, 0.45 and 0.55 water-to-cement ratios (w/c), SAP water replacement dosages of 0%, 5%, 10%, 15%, 20% and 25% were tested. Tests included rheological measurements of yield stress, viscosity using the Bingham equation and the flow behavior index using Herschel-Bulkley equation. Slump diameter tests were used to measure flow of the cement pastes. Comparisons of slump diameters were made with regular cement pastes, pastes with SAP and SP using 0.45 w/c as a reference paste. Heat of hydration tests were also conducted to measure heat and energy produced during the hydration of cement pastes containing SAP.

The research from this study found high water-to-cement ratios in plain pastes produced lower yield stress, viscosity and flow behavior index values compared to low water-to-cement ratio plain pastes. Adding SAP was found to increase the viscosity of the paste, however, the influences of SAP on yield stress was found to depend on the w/c ratio. It was also found that when superplasticizer is used, the yield stress is reduced significantly, however, it only has slight influence on viscosity. The slump diameter measurements decreased with increasing SAP dosage. The calorimetric measurements indicate that the addition of SAP does not change the hydration mechanism of the pastes.

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I. INTRODUCTION

The objective of this thesis is to investigate the influence of superabsorbent polymer, and with addition of superplasticizer on rheological properties such as yield stress, viscosity and flow behavior index of cement paste. Since cement paste is the only liquid phase in fresh concrete, it is important to analyze and understand the paste's rheological properties so that the on-site performance of concrete, such as pumpability, stability, and flowability can be improved.

A. Background

When concrete is placed, it needs to be cured. Curing requires adequate moisture, temperature and time to achieve and develop the desired properties of strength and durability of a designed system of concrete. If not cured properly, concrete will shrink causing it to crack, leading to loss of strength and durability.

Concrete shrinkage is a phenomenon that the volume of the material decreases even though it is not subjected to any external load. The main forms of shrinkage are drying and autogenous shrinkage. The former is caused by moisture evaporation on the surface of the concrete specimen, while the latter is caused by the consumption of water during cement hydration, a process known as self-desiccation. Research has found that moisture condition is a critical factor for concrete curing. Variation in relative humidity during concrete curing greatly affects strength development. Figure 1 depicts various strengths of cured concrete vs amount of days curing.

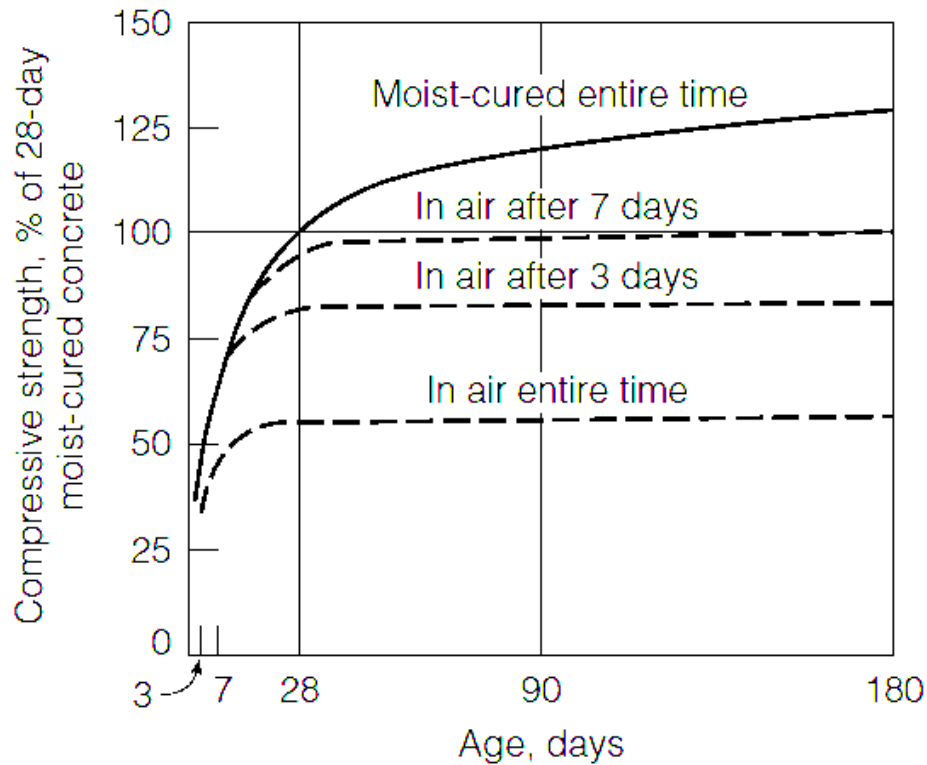


FIGURE 1 – COMPRESSIVE STRENGTH VS AGE (Mamlouk and Zaniewski 2011)

The conventional method to cure concrete is through external control of moisture such as spraying or ponding the concrete surface with water, or using wet burlap and plastic sheeting covering. This prevents the loss of moisture from the concrete surface and provides additional water to compensate for the internal loss of moisture due to chemical reaction. Although external control of moisture is a common method for curing, the applications provides difficulties in uniform cure of the concrete.

Taking concrete as a composite material, as the cement particles react to the water in the mixture, the system becomes smaller due to chemical shrinkage with time. As the concrete begins to set, the particles will contract and the system transitions from a fluid to

a solid. When the particles cannot contract, vapor filled pockets begin to open up. This leads to problems such as self-desiccation. Self-desiccation leads to an increase amount of autogenous shrinkage occurring without moisture loss and temperature change, this leads to an increase potential for cracking to develop. As the concrete ages after placement, vapor spaces are formed in it and relative humidity and pore pressure are reduced. This reduction leads to less chemical activity in the water and less likely to hydrate the cement. When this occurs, strength is limited. Therefore, besides external curing, other curing methods are needed to prevent internal cracking caused by self-desiccation.

1. Internal Curing and Superabsorbent Polymer

Internal curing is a practical way of supplying additional curing water throughout the concrete mixture. This is done by water absorbed in pre-wet light weight aggregate (LWA) or superabsorbent polymers (SAP) holding/absorbing water, which is then added the mix design. When the hydration process occurs, water is consumed. Once this water is used up, the system will require additional water to hydrate. At this time water is released from the LWA or SAP to further extend the hydration process. The optimum use of these materials in the concrete system is the key to providing a uniform cure in the concrete system compared to external curing methods.

Pre-wet LWA releases water in a suction type process in voids created from chemical shrinkage and self-desiccation. The use of pre-wet LWA have been used commonly in internal curing but issues arise regarding difficulties in controlling consistency of the application are common. These issues are minimized when SAP is used for internal curing due to the fineness of the material and the ease of dispersion when mixed

with water and added to the mix, compared to placement of pre-wet LWA during the mixing process. SAP are polymeric materials that can absorb and retain a large amount of liquid from its surroundings. SAP absorbs water at a high rate, sometimes 5000 times their own weight. Standard SAPs typically have an absorption of 100 to 400 grams per gram of dry weight. Fine SAP is normally mixed into the concrete and absorbs the water in the mix. The water is released when self-desiccation occurs similarly to pre-wet LWA.

2. Rheology

Rheology is the study of flow of a material, usually of a liquid or plastic flow of solids. Fluid behaviors in rheology are categorized as Newtonian or Non-Newtonian (Björn, Annika, et al., 2012). Newtonian fluids such as water, oil or air produce a linearly proportional relationship between shear stress and shear rate. This relationship is known as dynamic viscosity or apparent viscosity which describes a fluid's resistance of deformation. Different flow behaviors such as Newtonian, Bingham, Shear thinning and thickening is shown in Figure 2.

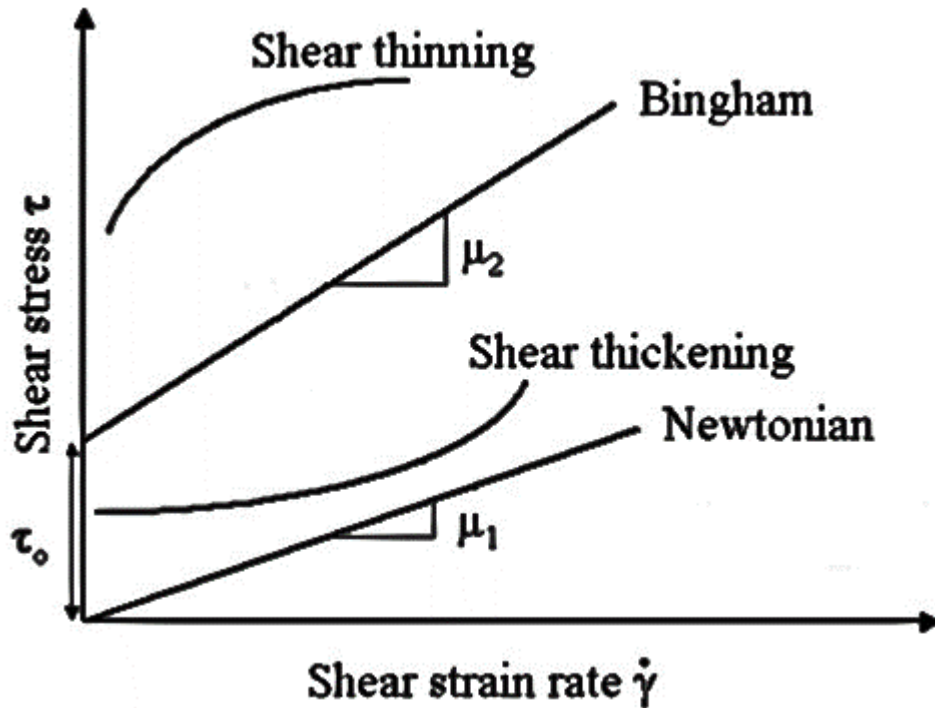


FIGURE 2 – FLOW BEHAVIORS (<http://www.theconcreteportal.com/rheology.html>)

When measuring the dynamic viscosity, the fluid is subjected to a force impact caused by moving a body in the fluid. Resistance to this movement measures the fluid's viscosity. Shear strain is applied to the fluid and a shear stress is measured to characterize rheological properties and flow behaviors. Newtonian fluids exhibit Newtonian behaviors, characterized by a linear relationship between shear stress and shear rate and flow due to gravity. Fluids not observing this behavior are characterized as Non-Newtonian fluids. Flow behaviors such as Bingham, Shear thinning and thickening exhibit this fluid. Bingham fluids are similar to Newtonian fluids, the linear relationship between shear stress and shear rate occur after a finite yield stress range, a stress that initiates flow of the fluid. Shear thinning fluids describe a type of fluid which becomes thinner as the shear rate increases until a limit viscosity has been reached. This type of thinning behavior is caused by an increase in shear rate and the fluid will flow in the direction of the current. Fluid

structures will deform at a certain shear rate, thus breaking aggregates causing a reduction in the fluid's viscosity. Shear thickening fluids exhibits the opposite effect of shear thinning fluids. As shear rates increase, the fluid becomes thicker. The behavior occurs when colloidal suspension transitions from a stable state to a state of flocculation when a shear rate is applied. The particles in the liquid possess attractive charges and when flocculated, begin to draw to each other, resulting in the fluid becoming thicker,

3. Rheological Models

When testing fluids, rheological models are applied to characterize the behavior of these fluids. Models such as the Newtonian, Bingham and Herschel-Bulkley Models are popular models used in the field of rheology. In the Newtonian Model, shear stress τ (Pa) and shear rate $\dot{\gamma}$ (s^{-1}) are proportional. Viscosity η (Pa·s), characterizes the slope of the linear line when plotting shear rate versus shear stress. The model is represented in the following equation.

$$\tau = \eta\dot{\gamma} \quad (1)$$

$\tau =$ *shear stress*

$\dot{\gamma} =$ *shear rate*

$\eta =$ *viscosity*

In the Bingham Model, Bingham plastic fluids exhibits a yield stress τ_0 (Pa). When plotting shear rate vs shear stress, the plot is linear and is similar to the Newtonian Model but the difference in this model, is that the Bingham plastic fluid will produce a shear rate once a certain stress is achieved, this stress is called the yield stress τ_0 (Pa). The parameters that describe this type of flow are the yield stress and Bingham plastic viscosity η' (Pa·s), the slope of the line.

$$\tau = \tau_0 + \eta' \dot{\gamma} \quad (2)$$

$\tau = \text{shear stress}$

$\dot{\gamma} = \text{shear rate}$

$\eta' = \text{Bingham plastic viscosity}$

$\tau_0 = \text{yield stress}$

The Herschel-Bulkley model is applied when a material behaves non-linearly. Stress τ (Pa), shear rate $\dot{\gamma}$ (s^{-1}), flow behavior index n , yield stress τ_0 (Pa) and consistency index K (Pa·s) are represented in this rheological model. The flow index measures the degree of shear-thinning ($n < 1$) or shear-thickening ($n > 1$) of the fluid.

$$\tau = \tau_0 + K\dot{\gamma}^n \quad (3)$$

$\tau =$ shear stress

$\dot{\gamma} =$ shear rate

$n =$ flow behavior index

$K =$ consistency index

$\tau_0 =$ yield stress

4. Connection between Rheology, Concrete and Cement Paste

Workability, strength and durability are three important properties of concrete representing its processing, mechanical and long-term performance. Strength and durability can be related to the mix design and curing of concrete. The workability property is an important factor regarding processes such as transporting, pumping, pouring, spraying, compaction and finishing of the concrete. Poor workability leads to issues on job sites and many of these issues can affect cost and potentially strength and durability as well. Rheological properties, as one of the most important fresh properties, govern workability and processing of concrete. The rheological properties of pastes, as the matrix of concrete controls the concrete flow, segregation of coarse aggregates, bleeding of paste matrix, ect. Therefore, the rheology of paste is essential to the uniformity, flowability, and workability of concrete. Previous research showed that the factors that can control and

affect cement paste rheology are determined by mix design, including the water-to-cement ratio (w/c ratio), types and amount of admixtures, and other supplementary powder (Vikan, H. 2007). Rheological properties such as yield stress, viscosity and flow behavior index of cement pastes should be determined and analyzed to better understand workability of concrete, thus assisting in the understanding of concrete flowability.

B. Literature Review

Ferraris et al. (1992) analyzed and discussed the connection between concrete rheology and cement paste rheology by using a parameter call the gap, which is the spacing between aggregates present in concrete. Variables such as water-to-cement ratio, aggregate gradation, admixture type and dosages affect the workability. The flow of concrete is very sensitive to the volume fraction of paste and higher paste volume fractions can lead to segregation. Slump tests for pastes, such as a mini-slump test have limited usefulness in connecting flow to concrete rheology because concrete slump depends on more than just the cement paste fraction. This can be observed when squeezing a drop of cement paste between microscope sliders. The paste will act like a lubricant and as the drop is squeezed thinner and thinner, the graininess of the suspension becomes evident and finally the surfaces lock up and will not slide with finger pressure. The fluid thickness, which the authors referred to as “gap” is related to the spacing of the aggregates. This value can potentially be the parameter that permits shear stress and viscosity measurements at various shear rates.

In this study, Type I cement was used, with water-to-cement ratios from 0.4 to 0.55.

In addition, admixtures of naphthalene sulfonate formaldehyde condensate, sodium salt,

melamine sulfonate formaldehyde condensate, sodium salt and sodium polyacrylate were used in this study. The admixture dosages were between 0.4 to 0.6 percent of solids based on cement weight and were pre-dissolved and mixed in water. A rheometer was used with flat 50 mm parallel plates. The distance of the plates simulated the gap between aggregates. Gaps varied from 0.07 to 0.6 mm. Average paste thickness is considered to be 0.2 mm. The bottom plate is rotated at a controlled speed, while the gap between the plates are measured by a micrometer. A shear rate of 10 s^{-1} was applied for 30 seconds to evenly distribute the paste. The shear rate of 0.1 s^{-1} to 100 s^{-1} with 15 points where torque were measured. The curves of average points were compared to determine the influence of gap, or composition, on torque. Based on the study, the authors found that the thickness of the cement paste between the parallel plate surfaces is larger than two to three times the diameter of an average particle. Addition of superplasticizers reduces flocculation of cement grains and has a large effect at small separations by reducing effective particle size and particle-wall interactions. Measurement of paste thickness is a more refined approach predicting concrete flow, due to the combined observation of the volume fraction of paste and its properties. The properties of paste or its volume fraction alone can indicate concrete flow reliably.

Rheological properties of cement pastes from self compacting concrete were analyzed and studied by Schwartzentruber et al. (2004). Self compacting concrete (SCC) is high flow concrete that does not require vibration during the placement process. The rheological properties of SCC and previous findings, the authors determined improvements can be made regarding placing concrete without vibration.

Some problems such as bleeding, settlement or segregation can occur simultaneously on construction sites for SCC. Segregation can occur during placement and afterwards. Dynamic segregation occurs when placing the concrete and static segregation (segregation after concrete has been placed) occurs, due to the sedimentation of the coarsest aggregates by gravity. To avoid segregation, cement paste rheology must be analyzed. Cement paste needs to be fluid enough to ensure the concrete is viscous enough to support coarse aggregates. Non-zero yield stress helps avoid initiation of segregations, while the viscosity and shear thinning properties limits the segregation effect.

The SCC mixture in this study consisted of: Portland cement, limestone filler, superplasticizer and viscosity enhancing admixture (VEA). Twelve mixtures were made in this study. Cement pastes were characterized by viscosity and yield stress. Empirical tests such as spread and flow time tests were also performed on all twelve cement pastes. Spread tests were conducted using a mini cone placed on a glass plate and filled with paste and then lifted. The diameter of the resulting spreading sample was measured from two perpendicular directions and the average is found from these values. The flow time test consisted of a specific time required for a given volume of paste flowing through the cone nozzle. The apparent viscosity and shear yield stress is measured in this study using a viscometer. A concentric cylinder geometry is used for the rheological measurements, the inner and outer cylinders are covered with rough paper to prevent slippage on the surface. A gap of 1.5 mm between the cylinders were used. The viscosity was measured at the end of a pre-shearing of 120 s^{-1} , shear rate of 100 s^{-1} for 40 seconds and the Herschel-Bulkley model was used to determine shear yield stress. A second shear test method consisting of a mold filled with paste and rotational vane rotated at a constant slow speed was used to

measure the yield stress as well. The values obtained by the vane were twice as much as values determined from the Herschel-Bulkley model, the author determined that this could be due to the fact shearing conditions using the vane method are different than the concentric cylinder method, the vanes start at rest but the concentric cylinders are at steady shear flow. The rheological properties quantify the influence of mixing parameters such as type of mixer, mixing times and addition of superplasticizer. A standard mixer leads to lower values of yield stress compared to a portable mixer. Lumps were also produced using the standard mixer as well. The portable mixer produces more efficient in mixing due to the unpacking of extremely small particles. Regarding mixing time, using the vane geometry, two additional minutes were needed to measure yield stress. Superplasticizer addition at the end of the mixing procedure produces a more flowable paste due to the molecules not interacting with the calcium sulphate. The results from this study determined that admixture contents produced an increase of yield stress with time of static rest. With VEA, static rest time and superplasticizer dosages produce lower rheological values. This is due to the VEA affecting the values of viscosity and shear yield stress. Regarding superplasticizer dosage, the influence of VEA is more important compared to time of rest. Linear correlation regarding flow time and viscosity were also found. These results indicate pastes must be produced with the same mixer, superplasticizer should be added in the same step of the mixing procedure and the duration and volume of the batch must not be changed. VEA affects both viscosity and yield stress, increasing the dosage increase the previous properties. Saturation of superplasticizer dosage is not modified by VEA dosage. Correlations from spread diameters, yield stress, flow time and viscosity produce accurate values compared to more complex tests.

Mansour et al. (2010) observed the effects of rheological behavior of cement pastes that incorporated Metakaolin, a clay mineral. The authors analyzed rheological behaviors using Algerian Metakaolin (MK. Metakaolin is a thermally activated aluminosilicate material produces from kaolinite lay through a calcining process. In their tests, different dosages of MK on cement pastes were tested and rheological behaviors were analyzed through flow, creep/recovery and oscillatory tests. Rheological properties of fresh cement paste and concrete are important regarding their connection to workability of fresh concrete in previous studies. Cement pastes containing 0%, 5%, 10%, 15% and 20% of MK were prepared with deionized water and 2% superplasticizer. The rheological parameters analyzed in this study were: stress, viscosity, loss and storage of moduli. In the dynamic test, a monitor of viscoelastic properties was completed by an oscillating rheometric method consisting of applying an oscillating shear stress and measuring shear strain. By controlling the value of shear stress and frequency within the linear viscoelastic region of the material, the microstructure of the cement paste will not be destroyed during the test, this allows an observation of the material properties. The creep/recovery technique measures the strain when stress is applied (creep) or removed (recovery). The strain divided by the stress is the compliance. Using this technique provides information regarding the material's behavior. The rheometer used in this study was an AR2000 and a vane geometry was used to test the cement pastes, the radius of the vane rotor is 14 mm and rotates inside a fixed hollow 15 mm radius cylinder. The space between the outer cylinder and vane is 1mm. Rheological testing was done immediately after mixing of the cement pastes in the rheometer. A pre-shearing of 500 s^{-1} was applied for 60 seconds followed by 60 seconds of rest. The paste was pre-sheared to create irreversible structural breakdown. The resting

of the sample allowed the cement particles to achieve structural equilibrium, returning to the same strain status before the test. The cement paste was then sheared by applying a sweep stress from 0 to 200 Pa, with a frequency of 1 Hz within 2 minutes to produce the curve of the flow test. Shear stress was swept from 0.01 Pa to 20 Pa, during this the shear moduli was measured during the stress sweep tests and the critical stress values were determined as values where the shear moduli started to decrease. The next step in the authors' process was to apply a frequency sweep to determine critical value of applied frequency, this is defined as the frequency at which the shear modulus begins to decrease. During this frequency sweep, the cement paste is subjected to an oscillatory stress with a constant amplitude at a value smaller than the critical strain determined by the previous stress sweep. For the oscillatory test, a stress-control mode was used. 0.1 to 110 Hz frequency sweep was applied with a 0.03 Pa of constant stress after determining the limits of linear viscoelastic region from the previous step when using the stress sweep experiments from 0.01 to 20 Pa of stress at 1 Hz constant frequency. The oscillatory test began 1 minute after the paste was placed in the rheometer. The temperature of the specimens were maintained at 20 degrees Celsius by circulating water in the water cup in which the outer cylinder is embedded. For the creep/recovery test after pre-shearing and the equilibrium period, a constant stress of 0.03 Pa was applied while the strain was measured for 40 seconds. After that the stress was removed and the strain is measured for an additional 40s. Regarding the rheological model in this study, the Herschel-Bulkley equation were for data analysis. The author's determined that MK improved the cement pastes' flowability from the flow test. The shear stresses increase with the increase of shear rate. The pastes initially had a shear thinning behavior until a certain limit of shear rate was

applied due to the decreased viscosity. The viscosity was observed to increase with an increase of shear rate, this might be due to the superplasticizer. The oscillatory test observed that the addition of MK improved the flowability of cement paste and their behavior during oscillation. In the creep/recover test, the MK improves the paste rheological behavior due to the particles in the microstructure not elastically recovering to their equilibrium status.

Bey et al. (2014) observed the consequences of competitive adsorption between polymers on rheological behavior of cement paste. Rheological measurements of yield stress and plastic viscosity regarding the use of water absorptive polymers were used to study their effects on the cement paste behavior. The materials used in this study are Portland cement CEM 1 52 PMES CP2, superplasticizer and a cellulose derived viscosity enhancing agent. The mixing procedure consisted of water and cement homogenized by hand for 1 minute and then allowed to mix using a high speed mixer at 840 rpm. The paste then was allowed to rest for 18 minutes before addition of the polymer, resting allows the chemical reaction of the hydration products without interference from the organic molecules. After the addition of the polymer, the mixture underwent another high speed mixing phase for 1 minute, then the mixture was allowed to mix at a low speed for 18 minutes. In the rheological analysis, the equipment used a Bohlin C-VOR shear rheometer equipped with a Vane geometry. The diameter of the Vane was 25 mm, the outer cup 50 mm and a depth of 60 mm. The cup was filled with testing cement paste placed in a reference structural state by pre-shears at a shear stress of 90 Pa for 120 seconds, then a decreased shear rate applied from 100 s^{-1} to 1 s^{-1} (logarithmic distribution of shear rate)

for 200 seconds. Rheological changes from the two polymers were analyzed based on changing the proportions of the polymers in the mix design. The data from the tests was analyzed using a Bingham model to compute the value of yield stress and plastic viscosity. Figures were created to analyze the dependence of yield stress and plastic viscosity on the polymer type and dosage. The authors determined that the two rheological characteristics decreased with an addition of superplasticizer. These rheological properties had an increase when the viscosity enhancing agent was added. The superplasticizer created a decrease in the attractive colloidal forces between particles, thus lowering the yield stress and increased the fluidity of the concrete. Due to the decrease in yield stress, a decrease in flocculation state of cement pastes was also observed and a decreased plastic viscosity. The viscosity enhancing agent produced an increase in yield stress from polymer bridging, while also increasing the viscosity due to the polymer that remained in the solution being slightly absorbed at the surface of cement particles.

Effects of superabsorbent polymers (SAP) on rheological properties of fresh cement-based mortars were studied by Mechtcherine et al. (2015). The authors state that water absorption and release SAP governs the rheological properties of fresh concrete. This key connection between SAP and rheological properties of the cement pastes help determine the influences it has on pumping, placement, compatibility, durability and the performance of concrete. There have been few studies regarding the influence SAP on the rheology of concrete. In previous studies, addition of SAP produced a decreased amount of water in the concrete system. This decrease in water, produces an increase in yield stress and plastic viscosity. Reduction of slump and increase flow time are occur due to the

increase in the previous two rheological properties. In this study two types of SAP each with different water absorption and desorption rates were used. Three reference mortar mixtures with varying water-to-binder ratio, amount of SAP and additions of silica fume were also incorporated in the mix designs as well. The two SAPs are labeled SAP-B (acrylic acid) and SAP-D with three grading categories: DS (very fine), DC (fine) and DN (coarse). SAP-D is synthesized from two primary monomers acrylic acid and acrylamide. The SAPs were chosen due to the different absorption and desorption behavior in extracted cement pore solution. The SAPs were used in a teabag test to determine the different absorption and desorption behaviors. The test was conducted by preparing a cement pore solution from a suspension of ordinary Portland cement used for mortar preparation with water-to-cement ratio of 4.3 after 24 hours of immersion. 0.2 to 0.3 grams of SAP were put into a teabag which had been pre-wetted with the cement pore solution. The teabag was then hung in a beaker filled with cement pore solution and was sealed to avoid carbonation. The weights of the teabag and SAP were measured at time intervals. SAP-B continuously released the majority of the stored liquid within 10 minutes of removing the SAP. SAP-D released any store liquid after 90 minutes. The particle sizes SAP-DN, SAP-B, SAP-DC and SAP-DS from large to small and the finer particles absorbed the cement pore solution more rapidly than the coarse particles.

Two of the three reference mortars had a water-to-binder ratio of 0.3 which used the SAP for internal curing. The difference between the two reference mortars is that one used silica fume as a partial replacement for cement. The third reference mortar had water-to-cement ratio of 0.45, lower content of superplasticizer compared to the previous two and use the SAP to increase resistance against frost-thaw cycles. Rheological testing was

conducted with a HAAKE MARS II rheometer for 10, 20, 30, 45, 60 and 90 minutes after water addition to the dry, pre-blended components of the mortars. The unit cell had a volume of 550 ml and a 77 mm diameter, a vane rotor with radius of 26 mm was used in the test. The mortar was kept in the unit cell for the entire testing period and was agitated before each measurement to reduce possible sedimentation. The unit cell was equipped with protruding lamellas 2mm thick to reduce slippage or formation of lubrication layer, the lateral gap between the vane rotor and the lamellas was 9mm. An applied shear rate between 0 and 15s^{-1} , in shear rate range from 0.96 s^{-1} to 9.61 s^{-1} were performed for six segments. An oscillatory test was used to determine the viscoelastic behavior of the mortar and a continuous shear rate controlled test was used to measure the changes in shear stress as a function of shear rate and to derive the yield stress and plastic viscosity values from a Bingham model. Based on the results from the tests, the authors were able to show that sorptivity - measure of the capacity of a medium to absorb or desorb liquid by capillarity, of the SAP affects the yield stress and plastic viscosity of fresh mortars. Initial release of liquid from SAP-B caused a slower increase in plastic viscosity over time. Mortars containing SAP-D showed a steady increase in plastic viscosity because of negligible desorption of liquid or from addition absorption. The addition of the SAP counteracted the effect of superplasticizer on the yield stress.

Finer SAPs provided higher values of yield stress and plastic viscosity due to a greater total absorption surface but larger particles continued to absorb water over the entire time of the test which results in larger increase of rheological values. The availability of free water in a mix resulted in higher water absorption rates and higher changes in rheological values as well.

II. MATERIALS

A. Cement

Type I ordinary Portland cement was used for all samples tested. Table I lists the chemical compounds including the loss of ignition of the cement which was determined with XRF (X-ray fluorescence) analysis. Table II lists the mineral composition of the cement (calculated from Bogue's equation). Figure 3 shows the particle size distribution of the cement provided by CEMEX Technical Center in Riverview, Florida. The medium size of the cement is 13 μm , and the specific surface area is 400.8 m^2/kg .

TABLE I

CHEMICAL COMPOSITION OF TYPE I ORDINARY PORTLAND CEMENT

Chemical Composition	% Mass
SiO_2	19.70
Al_2O_3	4.84
Fe_2O_3	3.05
CaO	62.62
MgO	4.00
SO_3	3.23
Na_2O	0.15
K_2O	0.49
LOI (ASTM C-114)	1.21

TABLE II

MINERAL COMPOSITION

Mineral Composition	% Mass
C_3S	59.1
C_2S	11.9
C_3A	7.67
C_4AF	9.3

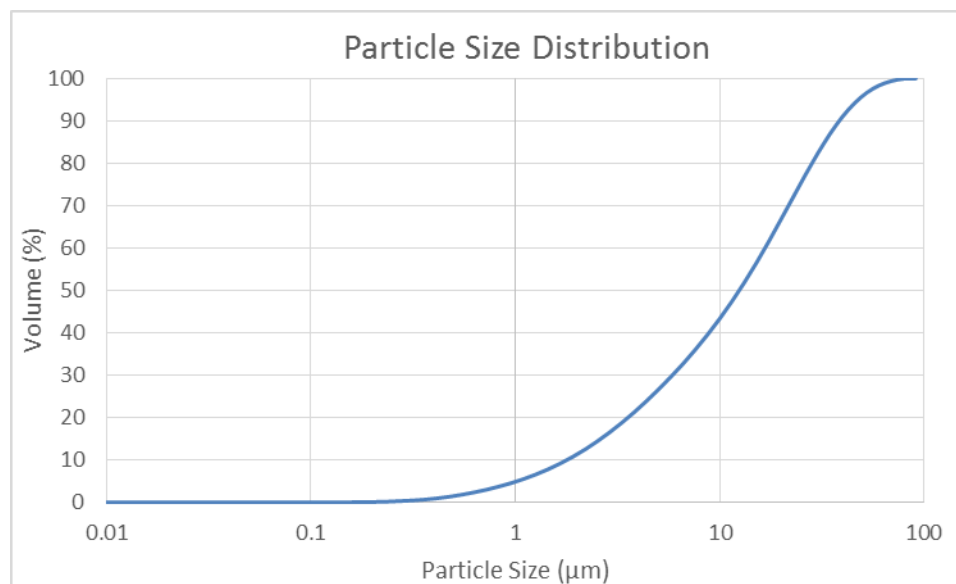


FIGURE 3 – PARTICLE SIZE DISTRIBUTION

B. Cassava Starch Graft (Superabsorbent Polymer)

The superabsorbent polymer (SAP) used in this study is a cassava starch, named after a starch graft acrylamide-2-acrylamido-2-methyl propyl sulfonic acid (STAGAA). When producing the SAP, the cassava starch was mixed and dissolved with distilled water and heated to gelatinize for 30 minutes, the temperature was then lowered and ammonium persulfate was added for 30 minutes. Americium, 2-acrylamido-2-methyl propyl sulfonic acid and N,N'-methylenebisacrylamide were dissolved in distilled water and added slowly, grafted and copolymerized for 2 hours until a transparent gel substance is produced as shown in Figure 4. The product was precipitated in alcohol, filtered and washed with distilled water repeatedly, and dried in a vacuum oven to constant weight at 105 °C. The product is then crushed and ground to required powder fineness. The absorbency of the SAP is 14 g/g_{gel}. The STAGAA is then mixed with water to a mass ratio of 1:14. The

mixture is blended for 15 minutes using a blender with speeds of 150-200 rpm to achieve an even dispersion. It is allowed to rest for 15 minutes and blended for an additional 5 minutes. The liquid STAGAA gel is given an additional resting period of 25 minutes to allow water absorption to reach saturation. Figure 5 shows the saturated STAGAA gel ready for concrete application.

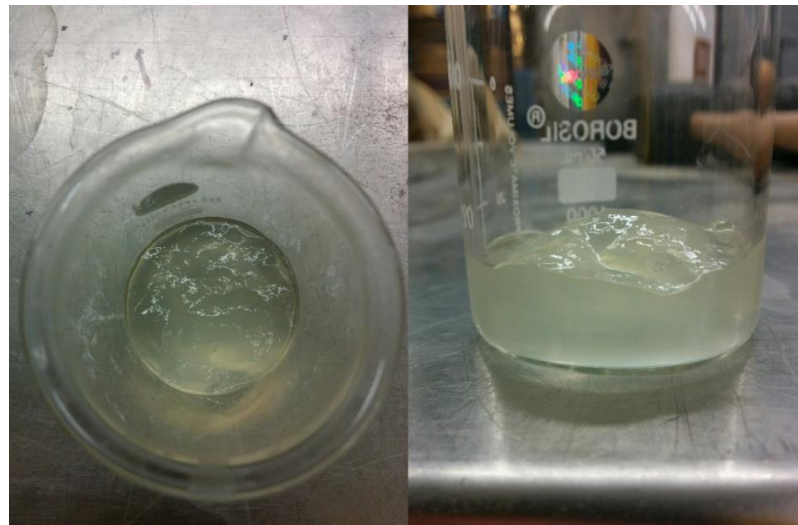


FIGURE 4 – STARCH GRAFT ACRYLAMIDE-2-ACRYLAMIDE-2-METHYL
PROPYL SULFONIC ACID (STAGAA) GEL

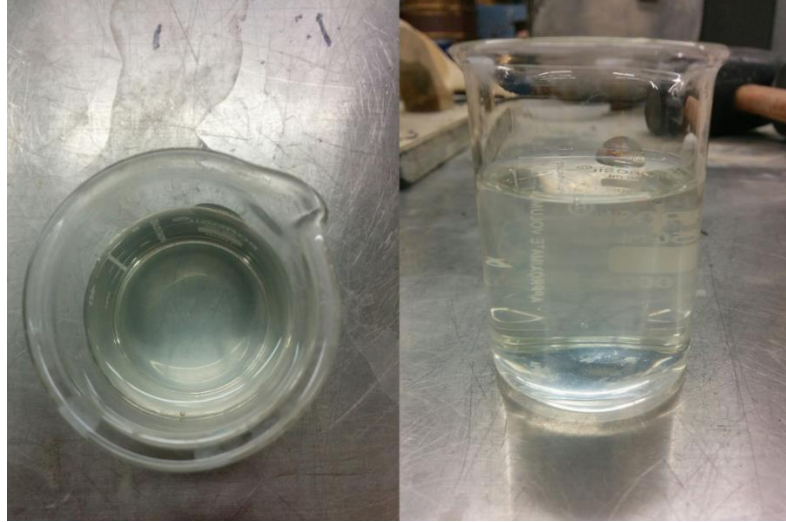


FIGURE 5 – STARCH GRAFT ACRYLAMIDE-2-ACRYLAMIDE-2-METHYL
PROPYL SULFONIC ACID (STAGAA) SATURATED LIQUID GEL

C. Superplasticizer

Superplasticizer (SP), a commonly used admixture, is often added to concrete to improve its flowability. In this study, Polycarboxylate based Superplasticizer with a density of 1.1 kg/L was used for low water-to-cement ratio pastes. 0.35 w/c ratio pastes involving SP, slump diameters were produced with ± 2.54 cm (1 inch) in comparison to reference average slump diameter of 0.45 w/c of plain paste. Superplasticizer is shown in Figure 6.

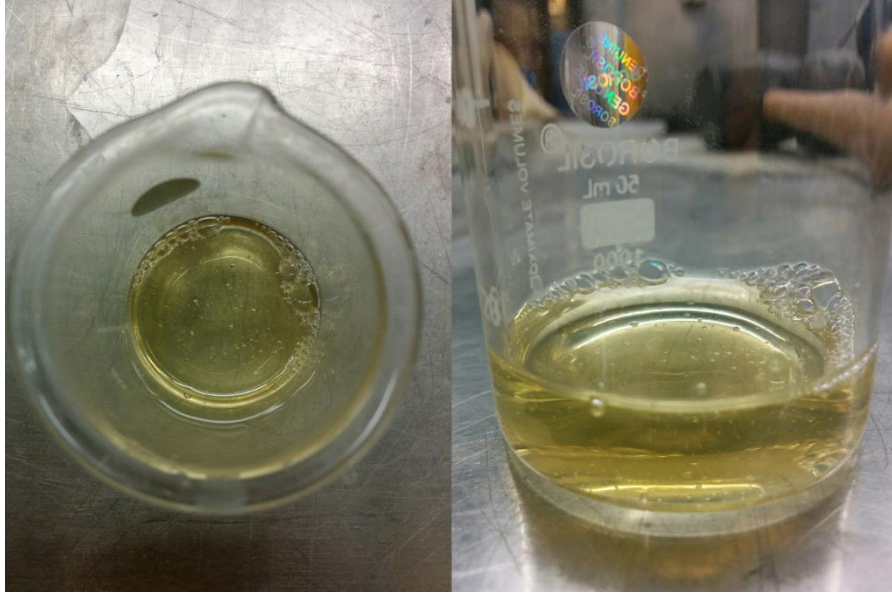


FIGURE 6 – SUPERPLASTICIZER (SP)

III. TESTING EQUIPMENT AND EXPERIMENTAL PROCEDURE

A. Testing Matrix

Table III lists the mix design used in this study. Three water-to-cement (w/c) ratios of 0.35, 0.45 and 0.55 were evaluated. For each w/c ratio, mixing water was replaced by SAP with variable percentages by weight (5% to 25%). The purpose of this was to study the influence of SAP dosage on the fresh properties of pastes including early hydration and flowability.

The specimen names are labeled according to mix designs. For example, in specimen P35-5-0, “P35” represents the water-to-cement ratio of the paste, “5” represents the SAP replacement of water and “0” represents no use of SP in the mix design. P35-0-SP through P35-25-SP are pastes with SAP and SP. The SP dosage were determined based on ± 2.54 cm (1 inch) in slump diameter using the average slump diameter of P45-0-0 as a reference. All pastes were produced in three batches and tested with the rheometer and slump mini-cone according to the following experimental procedures in this section and heat of hydration tests were conducted by CEMEX Technical Center.

TABLE III
MIX DESIGN

Specimen	w/c	cement wt (g)	water wt (g)	SAP wt (g)	SP wt (g)	
P35-0-0	0.35	764.16	267.46	0.00	0.00	
P35-5-0		764.16	254.08	13.37	0.00	
P35-10-0		764.16	240.71	26.75	0.00	
P35-15-0		764.16	227.34	40.12	0.00	
P35-20-0		764.16	213.97	53.49	0.00	
P35-25-0		764.16	200.59	66.86	0.00	
P35-0-SP		764.16	267.46	0.00	1.53	
P35-5-SP		764.16	254.08	13.37	1.73	
P35-10-SP		764.16	240.71	26.75	1.93	
P35-15-SP		764.16	227.34	40.12	2.13	
P35-20-SP		764.16	213.97	53.49	2.33	
P35-25-SP		764.16	200.59	66.86	2.53	
P45-0-0		0.45	664.59	299.07	0.00	0.00
P45-5-0			664.59	284.11	14.95	0.00
P45-10-0	664.59		269.16	29.91	0.00	
P45-15-0	664.59		254.21	44.86	0.00	
P45-20-0	664.59		239.25	59.81	0.00	
P45-25-0	664.59		224.30	74.77	0.00	
P55-0-0	0.55	587.98	323.39	0.00	0.00	
P55-5-0		587.98	307.22	16.17	0.00	
P55-10-0		587.98	291.05	32.34	0.00	
P55-15-0		587.98	274.88	48.51	0.00	
P55-20-0		587.98	258.71	64.68	0.00	
P55-25-0		587.98	242.54	80.85	0.00	

B. Mixing

1. Pre-mixing Preparation

Cement pastes tested were mixed using a KitchenAid Heavy Duty Stand Mixer (as shown in Figure 7). The mixing paddle and spatula are shown in Figures 8. Mixing speeds of 136 rpm and 195 rpm were used during mixing phases. Pre-mixing procedures consist of weighing cement, SAP and water for each respective mix design. Cement was weighed in a mixing bowl. Water and SAP were combined in a 500 mL beaker and stirred with a rigid plastic spoon to produce a well-mixed solution. For mix designs incorporating SP the materials were weighed out separately in a 100 mL beaker, the solution of SAP and water were poured until the volume of 100 mL was reached and then mixed.



FIGURE 7 – KITCHENAID HEAVY DUTY STAND MIXER AND BOWL



FIGURE 8 – MIXING PADDLE AND SPATULA

2. Mixing Procedures

a. Mixing Procedure A (plain pastes)

For all of the plain pastes (consisting of water and cement only) small amounts of water were poured around the perimeter of the cement in the mixing bowl before mixing to reduce sticking of cement paste to the sides of the bowl during mixing. While water is gradually added to the cement, the paste is mixed with a mixing speed of 136 rpm for three minutes. After that, a spatula was used to scrape cement paste from the sides and bottom of the mixing bowl for one minute, to ensure a homogenous mixture. The cement paste is then allowed to rest for an additional minute before it is mixed again with a speed of 195 rpm for an additional 3 minutes.

b. Mixing Procedure B (pastes with SAP)

For those pastes with SAPs, the mixing protocol follows a similar procedure as described in the previous section. Before mixing, the weighted SAP and water were premixed in a beaker with a capacity of 500mL and poured around the perimeter of the cement similar to the plain paste mixing procedure. The SAP and water mixture was gradually added during mixing and the procedures for mixing plain pastes were followed exactly for all the pastes with SAP.

c. Mixing Procedure C (pastes with SAP and SP)

Mixing Procedure C was similar to the process used in Mixing Procedure A and B, with differences such as the following: The 100 mL beaker containing premixed water, SAP and SP was added to the cement. Residual solution of mixed water and SAP in the 500mL beaker was used to rinse potential SP residual in the 100 mL beaker and added to

the cement. This process was repeated until all of the solution has been added to the cement. The procedures for mixing plain pastes were follow exactly for pastes with SP.

C. Rheometer

An Anton Paar MCR 502 rheometer with a co-cylindrical cup configuration consisting of a gap size of 1.6 mm was used to measure the rheological properties of each cement paste. The rheometer and co-cylindrical cup configuration are shown in Figure 9 and Figure 10. Paste samples were placed in the co-cylindrical cup after the final mixing phase and transferred to the rheometer for testing. Figure 11 shows the co-cylindrical cup placed into the rheometer and the measuring bob lowering to perform the test. Rheological testing was conducted 13 minutes after initial mixing. During the test, the samples were pre-sheared at a shear rate of 60 s^{-1} for a duration of 10 seconds and followed with a 3 minute period of rest. Samples were then sheared at shear rates of 300, 250, 200, 150, 100 and 10 s^{-1} for 10 seconds each. Each shear rate interval consisted of 60 data acquisition points at 0.166667 second intervals each. Values recorded from the rheological test included of shear rate, shear stress, viscosity and torque. These values were recorded in a table, exported from the data collection program and were used for data analysis.

Regarding the procedure used in analyzing data from the rheological test results, the first step was to determine values of yield stress, viscosity and flow behavior index of the samples. The following is an example of determining these values for P45-0-0. The last ten shear stress values (of the sixty total collected) were averaged at each shear rate to determine consistent values. These values are shown in Table IV. Yield stress, viscosity and flow behavior index were computed using the Genetic Algorithms method, (Kelessidis

2006) (A flow chart describing this process is shown in Figure 12), using the Herschel-Bulkley equation. These values were also shown in Table IV. The process begins with an estimation of shear stresses produced using the Herschel-Bulkley equation and approximate yield stress, viscosity and flow behavior index (initial values set to 1.0). Sum of square error (SSE) and sum of square total (SST) were produced for each shear rate and the summation of SSE and SST values were also computed. The correlation coefficient was also computed to determine quality of SSE and SST values. An optimization program was used to repeat the calculations of the values minimizing the sum of SSE, and produce shear stress values with lowest possible errors. This approximation produces values of yield stress, viscosity and flow behavior indices from the Herschel-Bulkley equation. Yield stress and viscosity were also computed using the Bingham equation by plotting the original Shear stress vs Shear rates from the data. Linear regression was used to determine the two values. Figure 13 is an example for P45-0-0, the equation $y = 0.2332x + 26.636$ represents the Bingham equation, where $y =$ shear stress τ , $x =$ shear rate $\dot{\gamma}$, $26.636 =$ yield stress τ_0 in units of Pa and $0.2332 =$ viscosity K in units of Pa·s. These two processes repeated for all collected rheological data in this thesis.



FIGURE 9 – ANTON PAAR MCR 502 RHEOMETER



FIGURE 10 – CO-CYLINDRICAL CUP



FIGURE 11 – BOB LOWERING INTO CO-CYLINDRICAL CUP

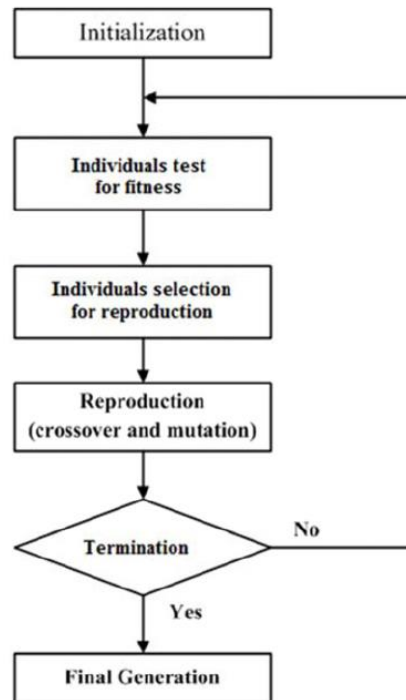


FIGURE 12 – GENETIC ALGORITHMS METHOD FLOW CHART (Rooki, Reza, et al. 2012)

TABLE IV

CALCULATION DATA TABLE

Shear Rate (s ⁻¹)	Shear Stress (Pa)	Estimated Shear Stress (Pa)	Sum of square error	Sum of square total	Correlation coefficient
$\dot{\gamma}$	τ	τ'	SSE	SST	R ²
			($\tau - \tau'$) ²	($\tau - \Sigma\tau$) ²	1 - [(Σ SSE)/(Σ SST)]
300	95.0210	94.3844	0.4052	760.8228	0.9994
250	84.3576	85.0518	0.4819	286.2734	
200	74.4541	74.9540	0.2499	49.2259	
150	64.0398	63.8059	0.0547	11.5476	
100	51.6033	51.0679	0.2866	250.7372	
50	35.1521	35.4089	0.0660	1042.3783	
Σ	67.4380	Σ	1.5444	2400.9852	

Herschel-Bulkley		
Yield Stress (Pa)	Viscosity (Pa's)	Flow behavior index
τ_0	K	n
5.6045	2.7498	0.6092

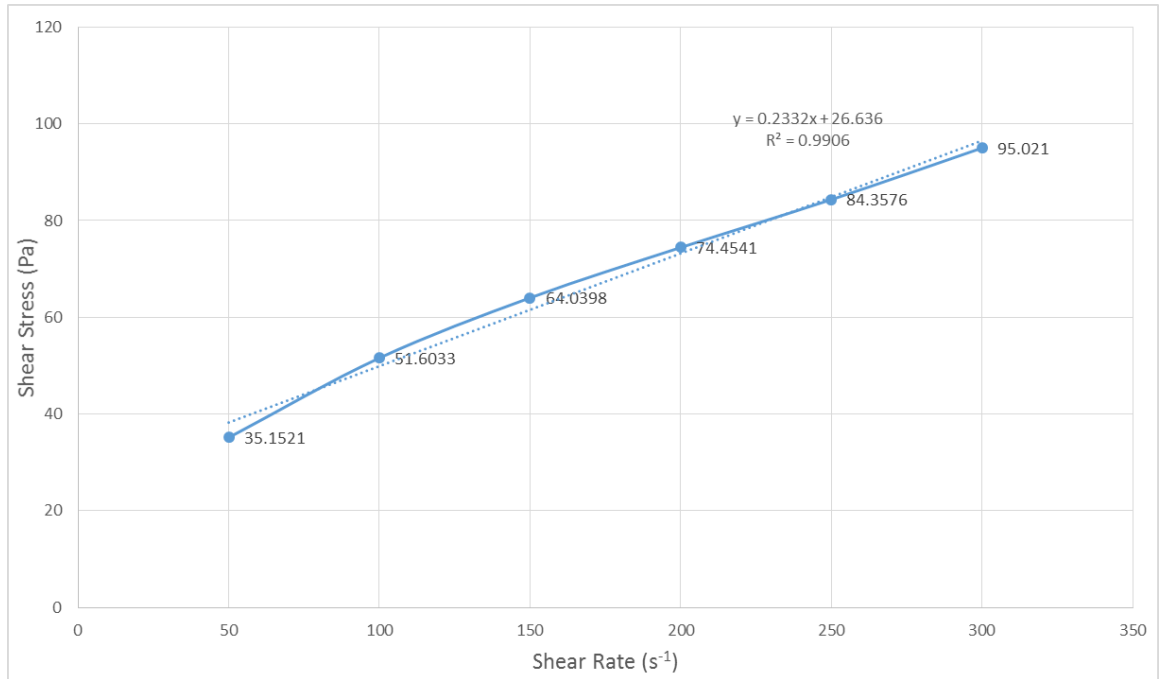


FIGURE 13 – SHEAR STRESS VS SHEAR RATE FOR P45-0-0 BINGHAM

EQUATION PARAMETERS

D. Slump Diameter

A Slump Diameter test was conducted simultaneously with the rheological test. The test was performed to determine the slump diameter of a sample resulting in a measure of flowability. A slump mini-cone was used to perform this test along with a flow table, steel rod and straight edge shown in Figure 14, Figure 15 and Figure 16. During the test, the cone is placed in the middle of the table and a layer of cement paste is poured inside the cone. The layer is rodded 25 times to ensure a uniform filling of the mold. A second layer is poured, rodded 25 times and a straightedge is used to cut the cement surface flush with the top surface of the cone. The cone is vertically lifted 13 minutes after initial mixing and the slump diameter is observed. A tape was used to measure the diameter to the nearest hundredth in two perpendicular directions, the average of the two slump diameter represents the slump diameter of the corresponding sample. An example of the measurements is shown in Figure 17.

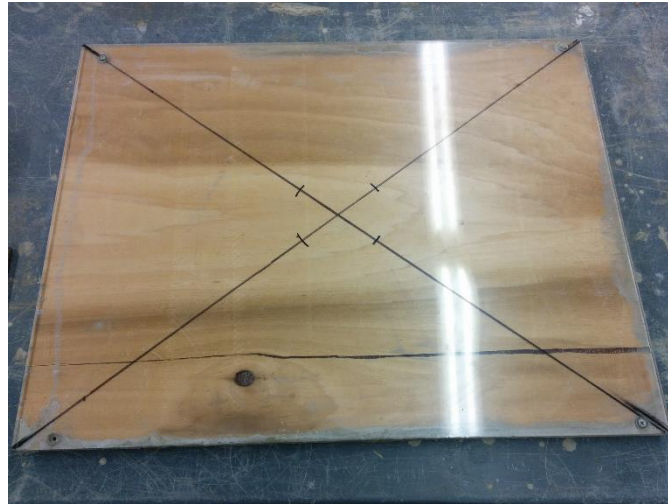


FIGURE 14 – FLOW TABLE

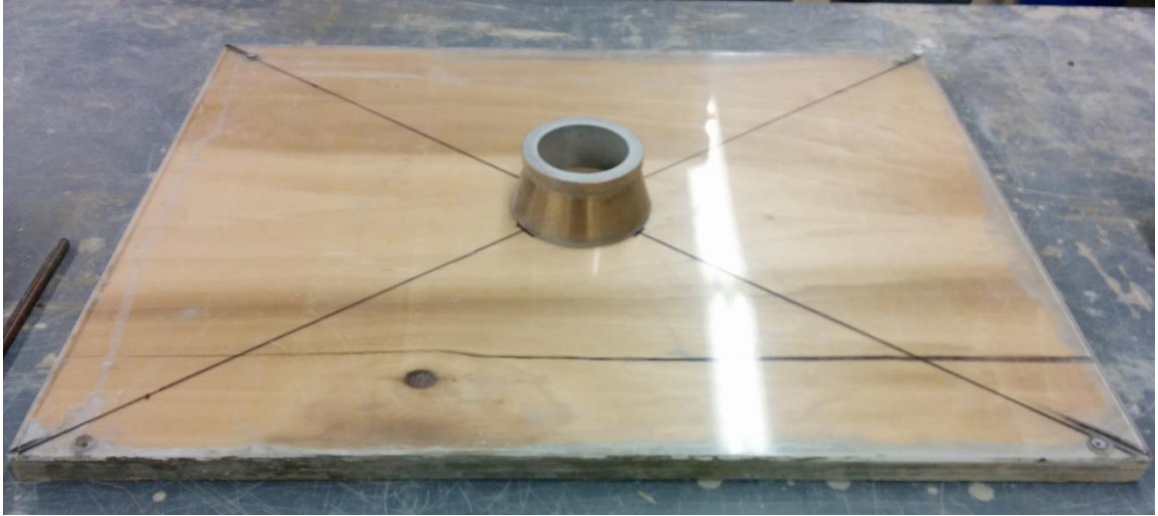


FIGURE 15 – SLUMP MINI-CONE



FIGURE 16 – STEEL ROD AND STRAIGHT EDGE



FIGURE 17 – MEASUREMENT EXAMPLE

E. Heat of Hydration

The heat of hydration test for this study was performed by CEMEX Technical Center located in Riverview, Florida using testing methods defined in ASTM C1702-09a Standard Test Method for Measurement of Heat of Hydration of Hydraulic Cementitious Materials Using Isothermal Conduction Calorimetry. TAM Air, a commercial calorimeter shown in Figure 18, is an eight-channel isothermal heat conduction calorimeter. The calorimeter measures the heat flow which represents the rate of reaction of the cement pastes and the heat evolved representing the extent of the reaction of the cement pastes during the hydration process. Before testing, the calorimeter was calibrated based on the manufacturers' specification. The heat flow was measured by heat detectors when heat is produced by the samples and exchanged with the surroundings. The energy recorded is

determined based on unit weight of cementitious material mass. Samples using the three water-to-cement ratios along with SAP dosage were tested for a total of 30 hours.



FIGURE 18 – TAM AIR CALORIMETER (Black)

IV. RESULTS, ANALYSIS AND DISCUSSION

This section presents an analyzes and discussion of the results from the rheological tests, slump diameter tests measuring flowability, the influences of addition of superplasticizer and the heat of hydration of the mix designs conducted and evaluated in this investigation.

Each figure in the following section presents the average and range plus and minus the standard deviation of the measured rheological values of yield stress, viscosity and flow behavior index for plain pastes, pastes involving SAP and SP.

A. Effect of Water-to-Cement Ratio on Rheological Properties

To better understand the effect of water-to-cement (w/c) ratios on rheological properties, the yield stress, viscosity and flow behavior index, of pastes P35-0-0, P45-0-0 and P55-0-0 were investigated. In Figure 19, the yield stress, determined using the Bingham equation, is shown for each w/c ratio. It is clear from the figure that the greater the w/c the lower the yield stress. This is also noticeable in Figure 20 which presents yield stress vs w/c ratios determined from the Herschel-Bulkley equation. However, an important difference is that the yield stress decreases exponentially in the Herschel-Bulkley equation, while it decreases constantly in the Bingham model. It should also be noticed that the yield stress of P55-0-0 in Figure 20 is 0 and there were no range of standard deviation due to all three samples producing 0 values. This was obtained purely from the data fitting and regression method utilizing the Herschel-Bulkley equation. It does not reflect the true characteristics of paste P55-0-0. Since the yield stress is the minimum stress needed to initiate flow, for cement paste a zero yield stress is not reasonable. This implied that when

the w/c ratio is high, the Herschel-Bulkley model is not a good option to obtain the yield stress.

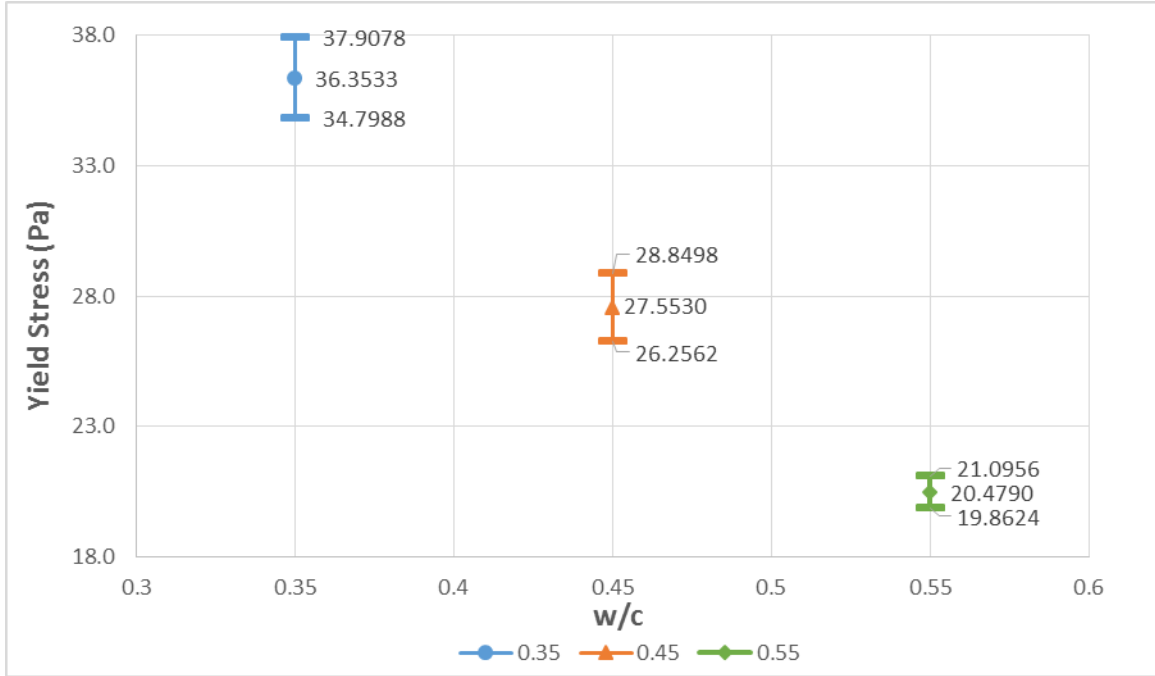


FIGURE 19 - BINGHAM YIELD STRESS VS W/C

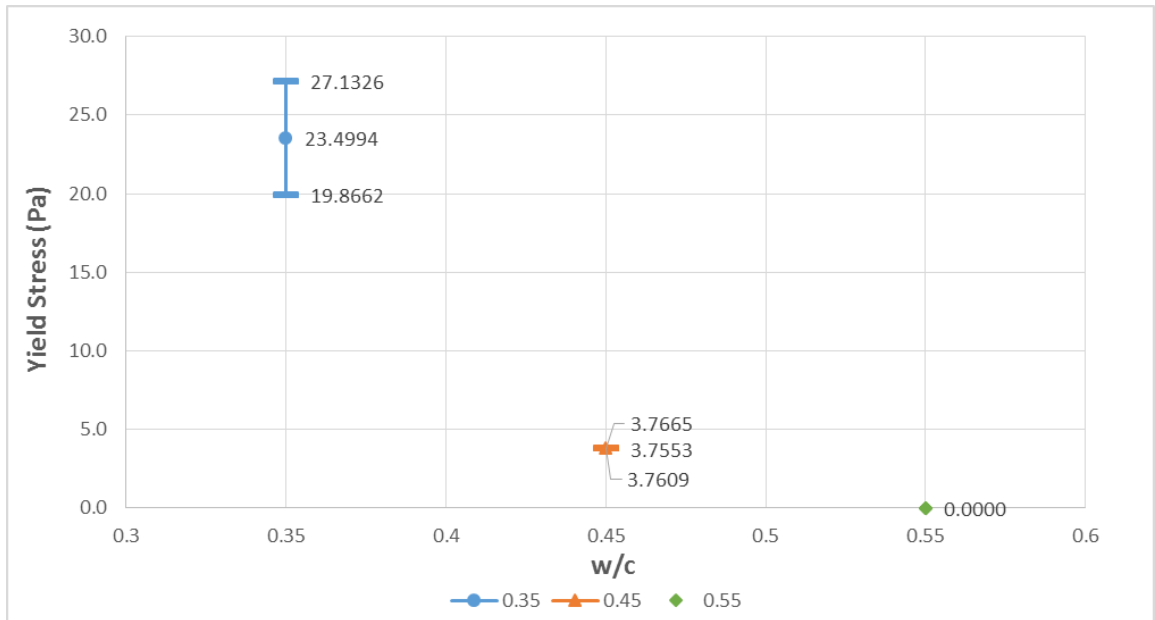


FIGURE 20 - HERSCHEL-BULKLEY YIELD STRESS VS W/C

For the same control samples, the viscosities calculated from Bingham model are plotted in Figure 21. Similar to yield stress, viscosity also reduces when w/c ratios is increased. For viscosities determined from the Herschel-Bulkley equation, one can see in Figure 22 that they increases with higher w/c ratio. This result contradicts the findings in Figure 21. The discrepancy can be attributed to the different flow behavior of each paste. Figure 23 plots the flow index “n” for each paste, showing that when w/c ratio is increased from 0.35 to 0.55, shear thinning characteristics of the paste becomes more dominate. The regression values of both yield stress and viscosity depend profoundly on flow index of the material. Therefore, in later analysis in this thesis uses the Bingham model is used to investigate yield stress and viscosity, and the Herschel-Bulkley model to investigate the flow behavior of the paste via the flow index.

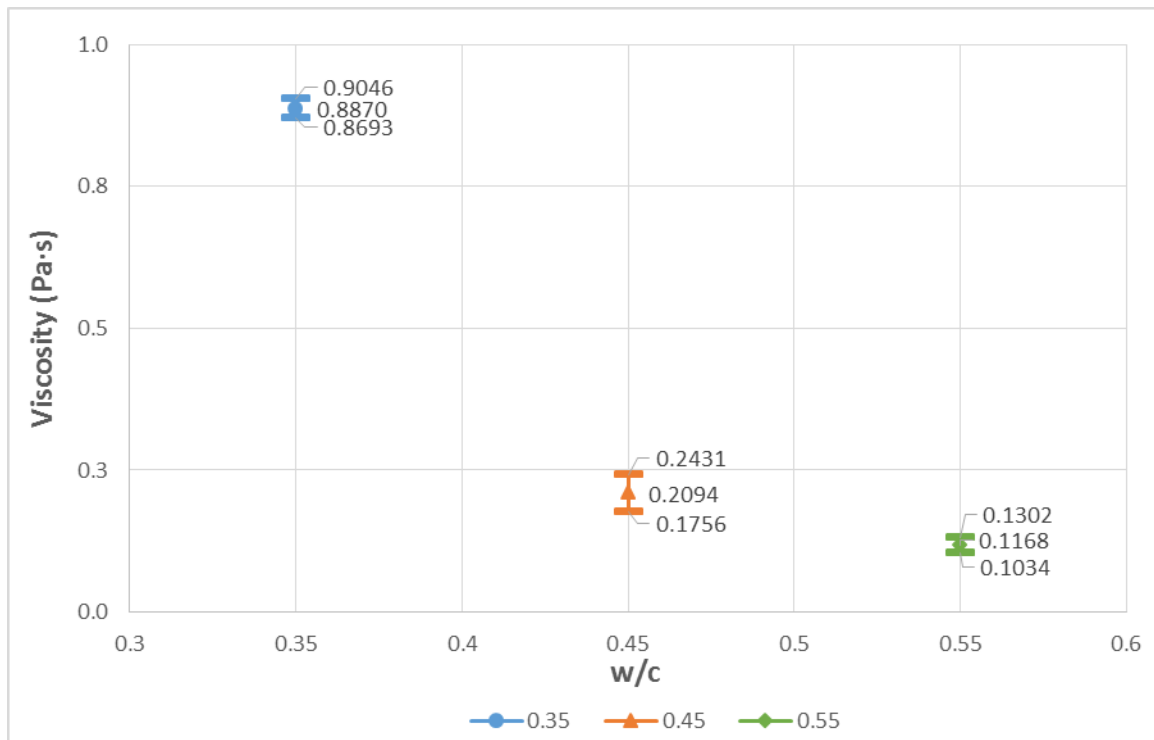


FIGURE 21 - BINGHAM VISCOSITY VS W/C

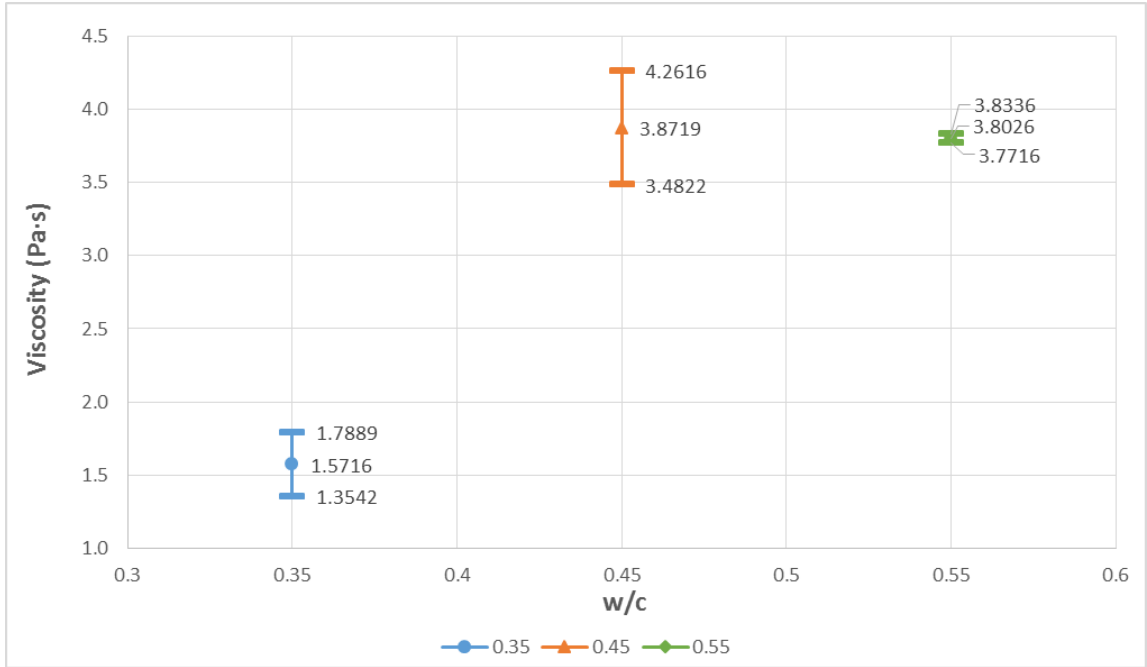


FIGURE 22 - HERSCHEL-BULKLEY VISCOSITY VS W/C

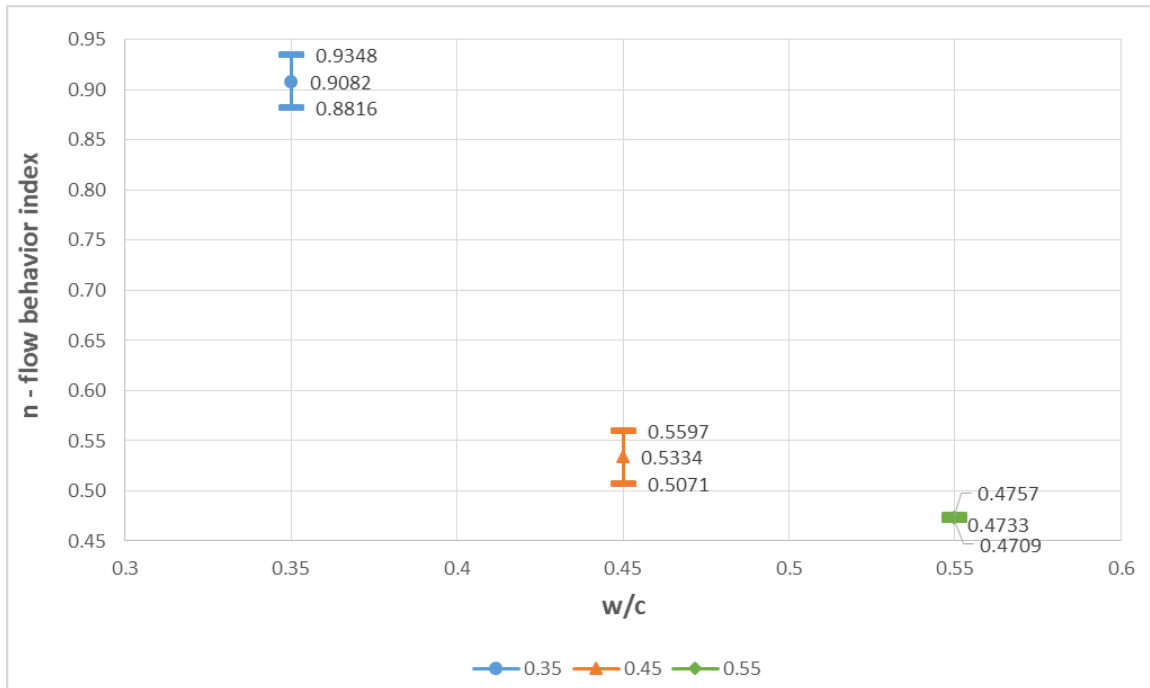


FIGURE 23 - HERSCHEL-BULKLEY FLOW BEHAVIOR INDEX VS W/C

B. Effect of SAP Dosages on Rheological Properties

Effect of SAP dosage on yield stress was analyzed in this study. Bingham Yield Stress vs SAP % are plotted in Figure 24. For the pastes with w/c ratio of 0.35, increasing SAP dosage in the mix design produced increasing yield stress up to a point where the values appear to level off. For 0.45 pastes the opposite effect is found, as SAP dosages increase, yield stress decreased. For 0.55 w/c, increasing SAP dosage produced little effect on yield stress values. Similarities can be seen for pastes P45-10-0 and P55-10-0 where there is an increase in yield stress, compared to lower SAP dosages yield stress values. P35-15-0, P45-15-0 and P55-15-0 also produce reductions in yield stress compared to the 10% dosages, this could potentially indicate a threshold or optimum dosage for these pastes at this percent dosage for all three w/c ratios. However, the yield stress of P35- 20-0 can contradict this theory due to its high yield stress value. But it could be that the actual value is lower if the yield stress interval is taken into consideration. Another remark can be made regarding high dosages of 25% or more: potential yield stresses for 0.45 w/c will be very similar to those of 0.55 w/c. This is seen between the changes of yield stress from 20 % to 25% dosage, as the values approaches those of 0.55 w/c values. Overall SAP dosages affect yield stress greatly for 0.35 w/c and 0.45 w/c, changes of 10.0664 Pa for 0.35 w/c and 5.9393 Pa for the latter between reference pastes and 25% dosages.

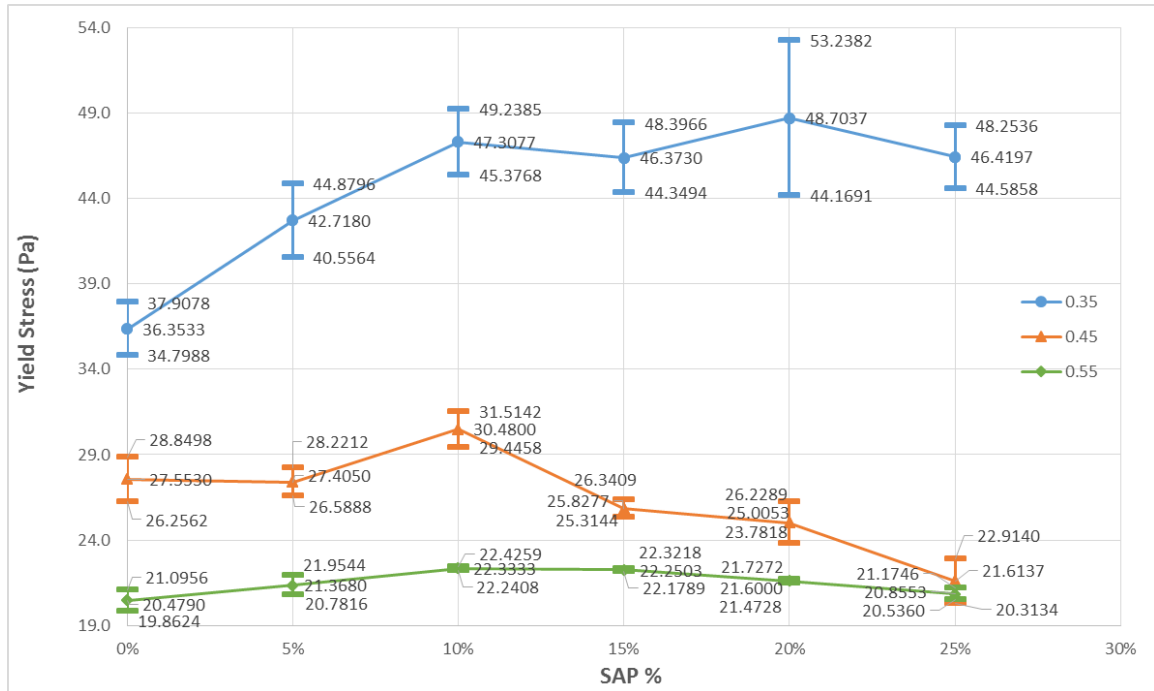


FIGURE 24 – BINGHAM YIELD STRESS VS SAP %

The influence of SAP dosage on viscosity, for all three w/c ratios can be seen in Figure 25. This trend shows as SAP dosage increases, the viscosity also increases. The SAP material is more viscous compared to water and when mixed and applied to cement pastes, the more SAP used, the more viscous the paste would be. This was verified by visual inspection. SAP pastes appear more viscous compared to the reference pastes. For w/c ratios of 0.45 and 0.55 the viscosity trend lines in Figure 25 are very similar and show little change in viscosity for different dosages of SAP. For 0.35 w/c ratio, there is more variation in viscosity for different dosages of SAP. The variation and large transitions in values of 0.35 w/c ratio pastes could potentially be due to the low w/c ratio with combination of SAP. High w/c ratios such as 0.45 and 0.55 produce smaller changes due to the amount of free water in the cement paste. Thus the addition of SAP had a less impact on viscosity values. Overall, viscosity does not change much when adding SAP to cement pastes.

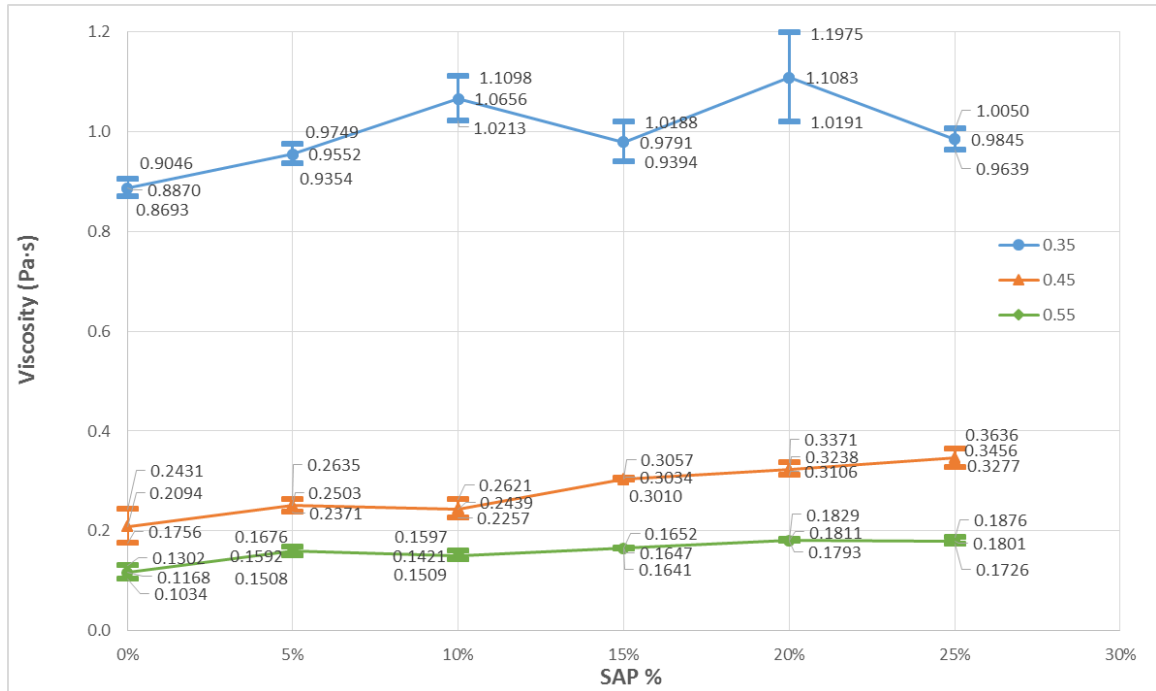


FIGURE 25 – BINGHAM VISCOSITY VS SAP %

Concerning the flow behavior index, Figure 26 plots the calculated values vs SAP dosage. For all of the three w/c ratios, although there are some large drops in flow indices, the overall trends show that the flow behavior index value increases with increased SAP dosage. This indicates that the material moves from a shear thinning behavior towards a shear thickening behavior when more water is replaced by SAP. For all the pastes with 0.55 w/c, the changes in the flow behavior index values are small and the overall behavior can still be considered shear thinning.

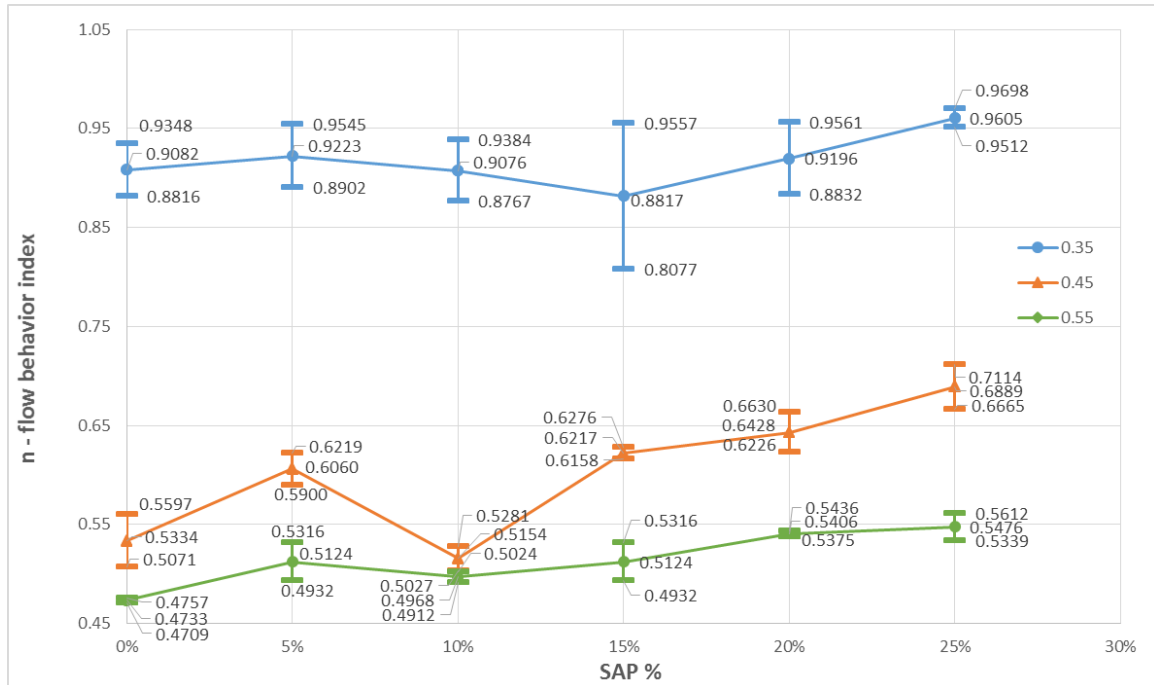


FIGURE 26 – HERSCHEL-BULKLEY FLOW BEHAVIOR INDEX VS SAP%

C. Slump Diameter (plain pastes and pastes with SAP)

Slump diameter for plain pastes and pastes with SAP test measurements are listed in Table V. For the reference pastes, P35-0-0 had the smallest average diameter compared to P45-0-0 and P55-0-0. When lifting the slump mini-cone during the test, for all 0.35 w/c ratio the cement paste kept the shape of the cone, this is observed in Figure 27. For 0.45 w/c ratio and 0.55 w/c ratio, the paste would spread across the table when the cone was lifted. Examples are shown in Figure 28 and Figure 29. Regarding the differences in average diameter between w/c ratios, the measurements are consistent with the expectation that the lower w/c ratio, the smaller the flow. For all of the pastes with SAP replacements, the larger the SAP dosage, the smaller the flow diameter. This is because when water is replaced by SAP, the amount of the free water at the fresh state that can be used to flow

the material is reduced. The reduction in slump diameter can easily be observed in the 0.45 w/c pastes, where each addition of 5% more SAP to the paste results in about 0.87 cm reduction in slump diameter. A similar reduction is seen in 0.35 w/c pastes as well but the reduction averages are much less due to the low amount of water in the cement pastes. However, one should noticed that for 0.55 w/c pastes, the change in the flow diameter between the different percentages of SAP replacement is not significant. And for the flow diameter of the 0.55 w/c ratio paste with 25% SAP replacement is slightly larger than that of the 20% replacement. This hints that for the pastes with high w/c ratio, even though water is replaced with SAP, it still has enough free water left to flow the material.

TABLE V

SLUMP DIAMETER MEASUREMENTS

	0.35 w/c	0.45 w/c	0.55 w/c
SAP %	Average Diameter (cm)	Average Diameter (cm)	Average Diameter (cm)
0	11.38	20.62	22.68
5	10.82	18.48	21.72
10	10.73	17.90	21.47
15	10.78	17.82	21.13
20	10.78	16.57	20.28
25	10.77	16.28	20.73



FIGURE 27 – SLUMP DIAMETER TEST P35-0-0



FIGURE 28 – SLUMP DIAMETER TEST P45-0-0



FIGURE 29 – SLUMP DIAMETER TEST P55-0-0

D. Influence of Addition of Superplasticizer

For all of the pastes with 0.35 w/c ratio, superplasticizer was also used to increase the flowability. The dosage of superplasticizer was controlled so that the pastes produced similar flow diameters to P45-0-0 (see Table IV). This paste was chosen as a reference due to the average slump diameter being the largest of all 0.45 w/c ratio pastes. The Bingham yield stress vs SAP dosage for P35-0-SP though P35-25-SP samples are plotted in Figure 30. From the figure, one can see that the yield stresses of the superplasticizer samples are greatly reduced compared to yield stress of 0.35 w/c pastes without superplasticizer and P45-0-0 SP. SP addition for 25% SAP dosage produced a rise in yield stress slightly lower than the value at 10% SAP dosage, this indicates that once a threshold value of

superplasticizer dosage is reached, the increase of superplasticizer will not reduce the yield stress.

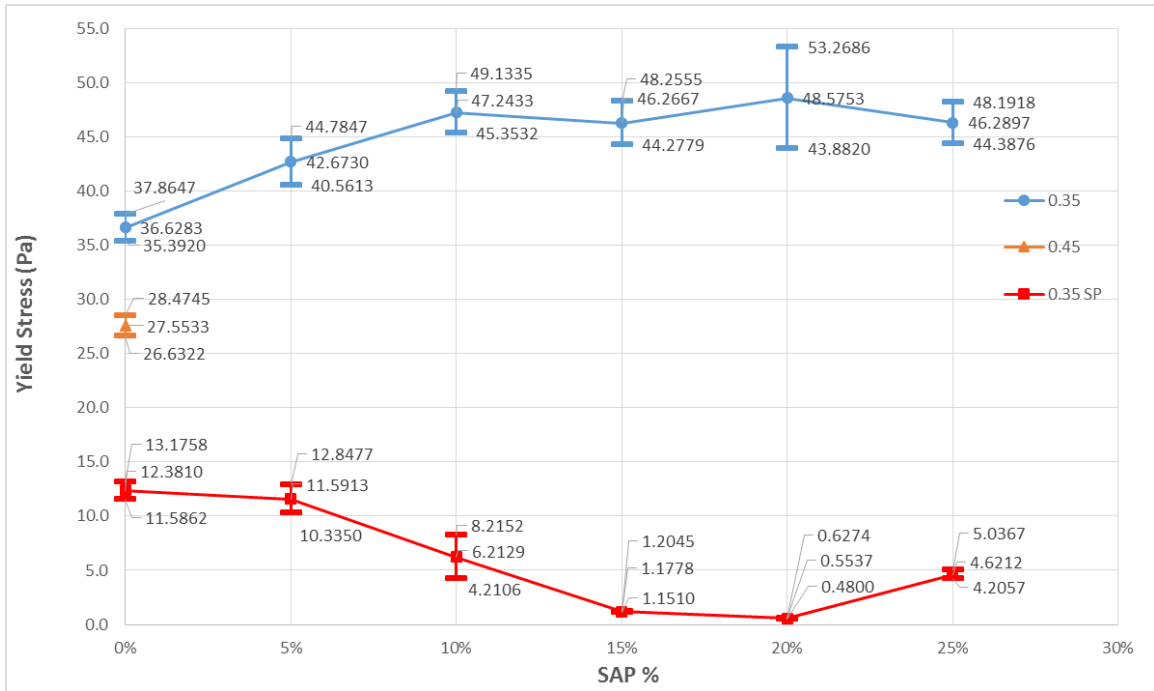


FIGURE 30 – ADDITION OF SP: BINGHAM YIELD STRESS VS SAP %

Influence of superplasticizer on Bingham viscosity also produced reductions. This can be observed in Figure 31. One can see that the viscosity values for all of the pastes with superplasticizer are higher than that of that P45-0-0. It increases steadily with the increase of superplasticizer and SAP. Comparing this result with Figure 30, it can be concluded that the superplasticizer has more impact on the yield stress than the viscosity.

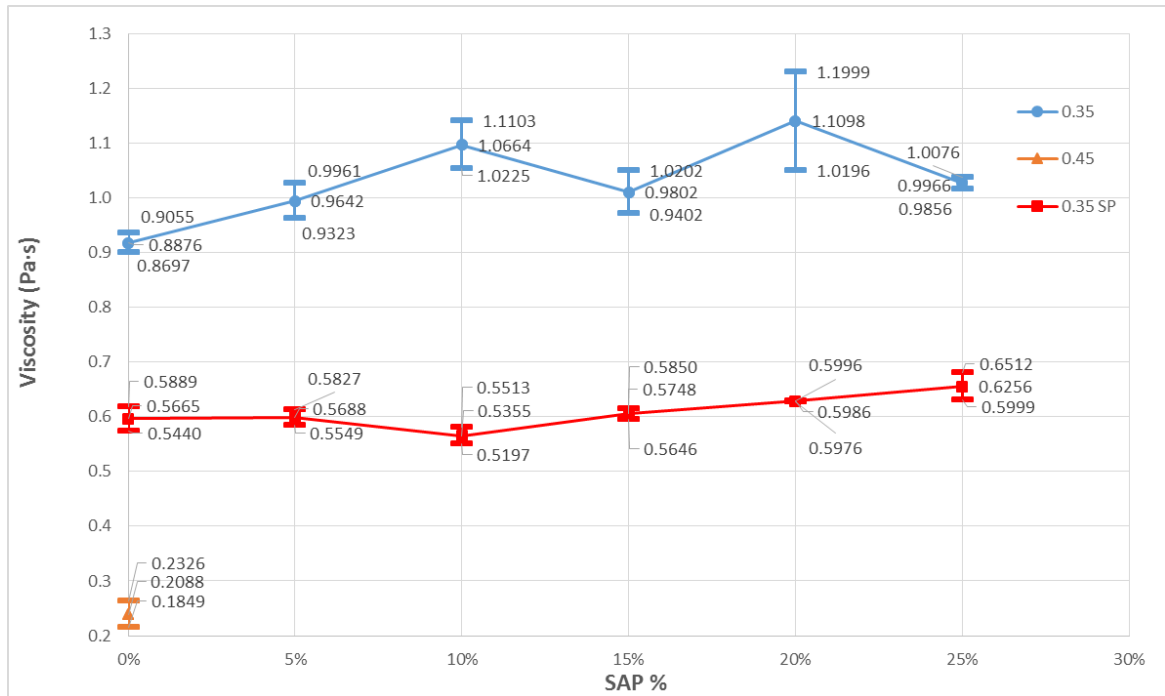


FIGURE 31 – ADDITION OF SP: VISCOSITY VS SAP %

When the flow behavior index is considered, the superplasticizer changes the material behavior quite significantly. This can be observed in Figure 32. It shows that all of the pastes with superplasticizer have indexes bigger than 1, indicating shear thickening behavior. With superplasticizer, flow behavior index value increases with the increment of the SAP and superplasticizer dosages. Although similar trends can be seen for the pastes without superplasticizer, the superplasticizer samples show more significant changes with the “n” increased from 1.175 to 1.349 with 0 to 25% SAP replacement. While the “n” value only increases slightly from 0.911 to 0.964 for the pastes without superplasticizer. This hints that the addition of superplasticizer makes the material be more sensitive to the shear conditions.

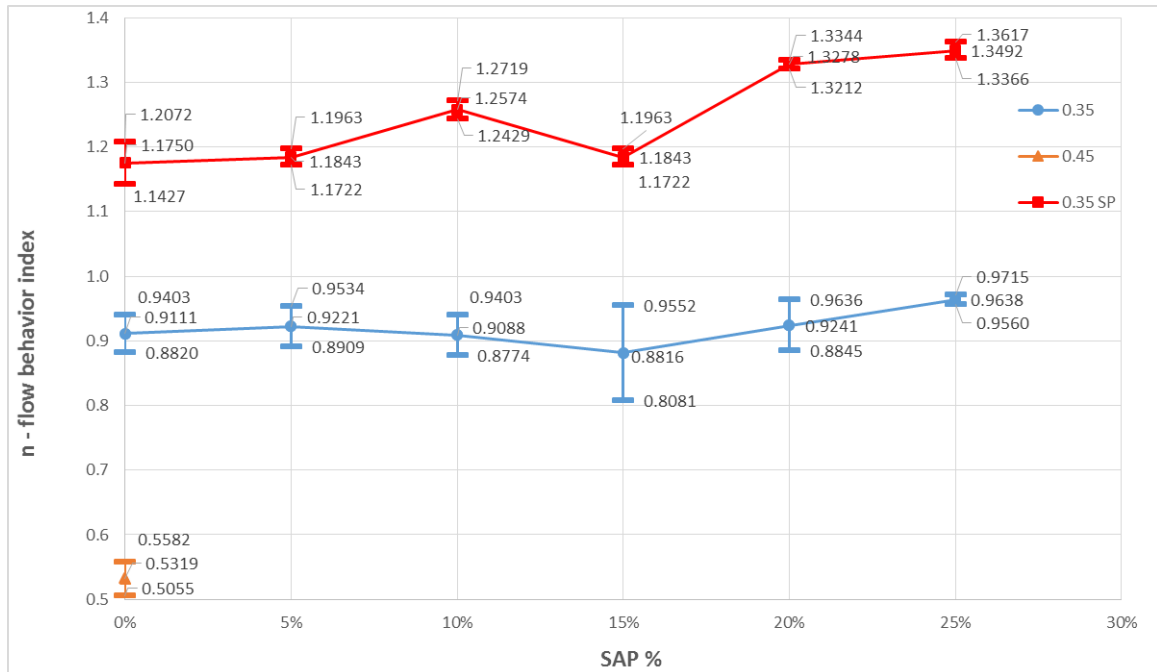


FIGURE 32 – ADDITION OF SP: FLOW BEHAVIOR INDEX VS SAP %

E. Heat of Hydration

Figures 33, 34 and 35 plots the heat of hydration for 0.35 w/c, 0.45 w/c and 0.55 w/c vs a period of time of 30 hours. For all three w/c ratios, there are no large differences regarding heat produced from the addition of SAP. To better analyze the heat production produced in the hydration process of the samples, power or rate of energy transfer per unit mass vs time are plotted in Figures 36, 27 and 38 from 0.5 hours to 30 hours. The plots began at 0.5 hours because the large rate of energy produced in the first two minutes makes it difficult to observe the data. In Figure 36, 5% SAP replacement dosage produced the largest amount of power for 0.35 w/c ratio samples. For samples involving 0.45 w/c and 0.55 w/c ratios, 0% SAP replacement dosages produced the highest power in Figure 37 and 38. Even though 0 or 5% SAP dosages produced maximum values in hydration power,

there is very little difference to other measured dosages, thus the addition of SAP does not greatly affect the hydration of cement pastes. Another interesting factor that can be observed the power vs time figures, are two peaks that represent the two main hydration reactions in cement paste. The first peak represents C_3S (tri-calcium silicates) and the second peak represents C_3A (Tri-calcium aluminate). The reactions for all samples seem to occur at similar times and higher w/c ratios produce less defined peaks in the power.

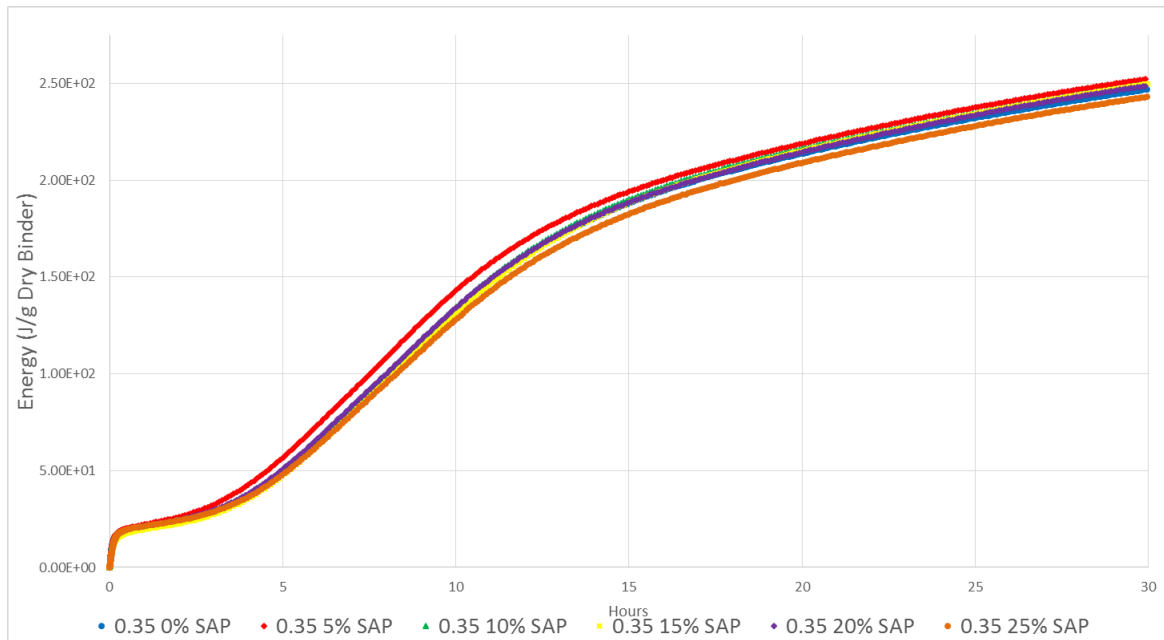


FIGURE 33 – ENERGY 0.35 W/C 0-30 HRS

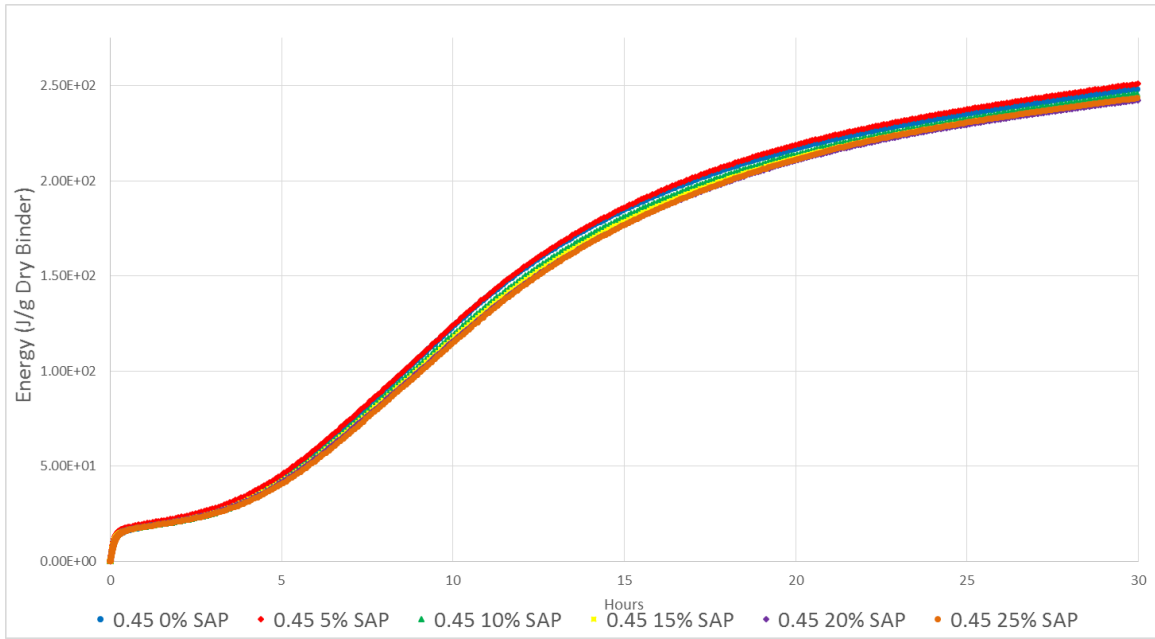


FIGURE 34 – ENERGY 0.45 W/C 0-30 HRS

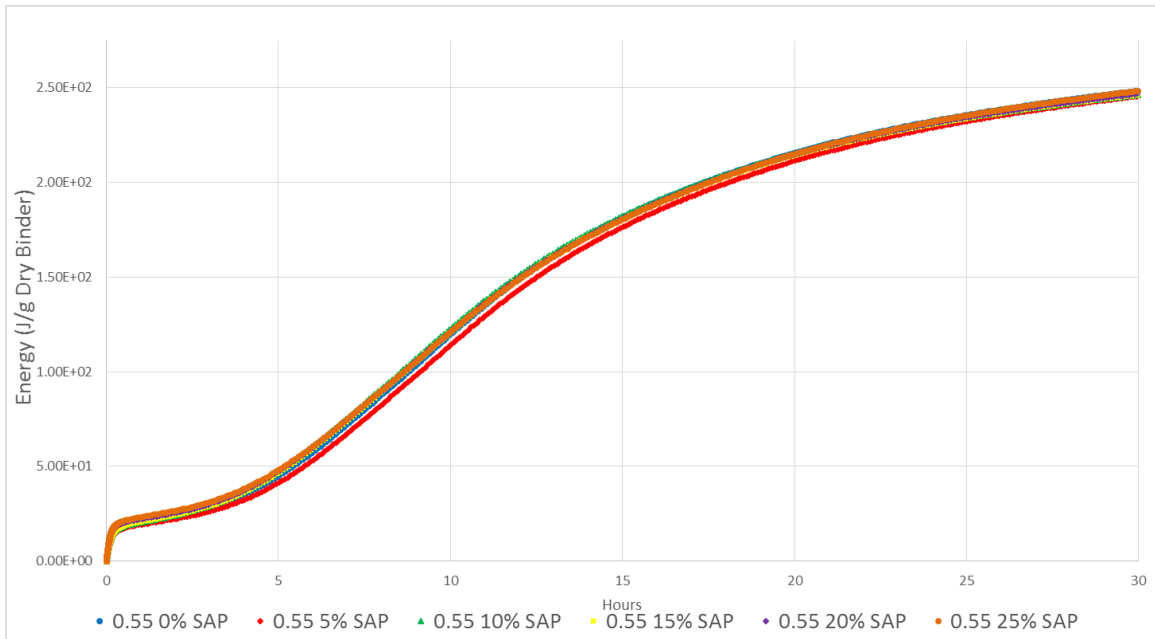


FIGURE 35 – ENERGY 0.55 W/C 0-30 HRS

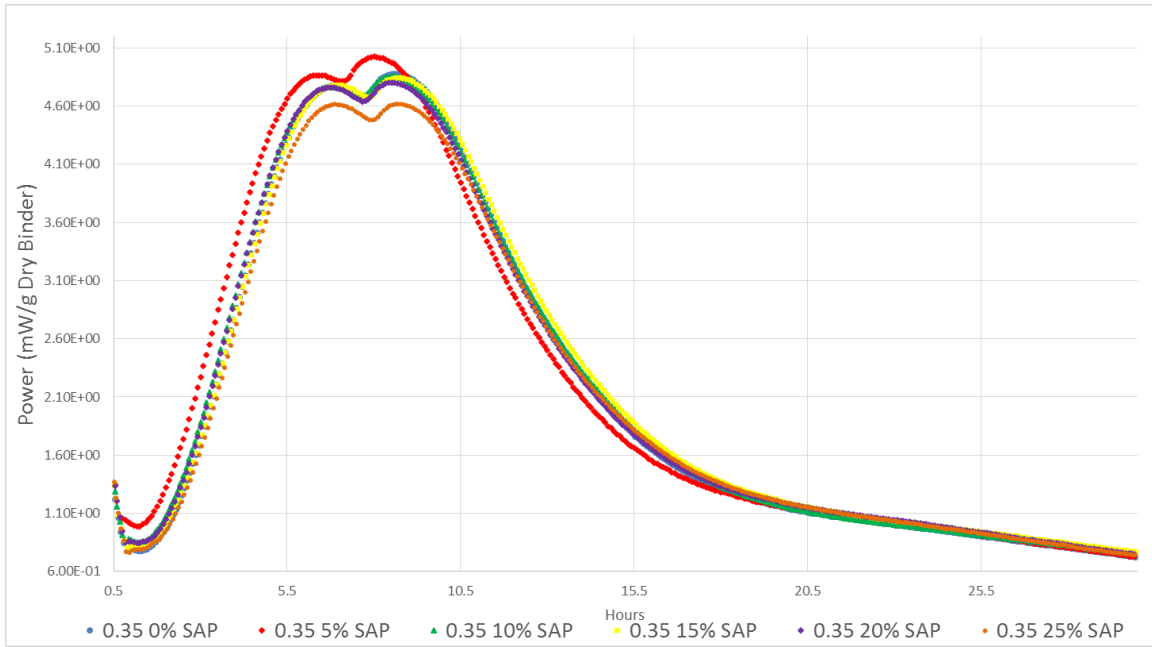


FIGURE 36 – POWER 0.35 W/C 0.5-30 HRS

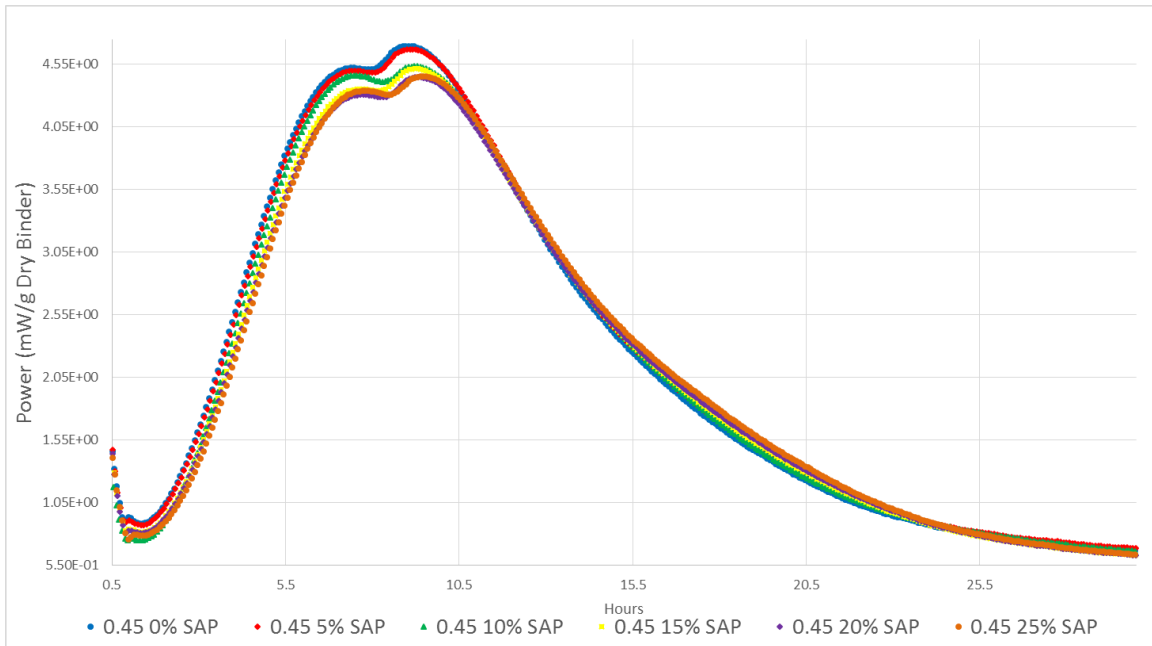


FIGURE 37 – POWER 0.45 W/C 0.5-30 HRS

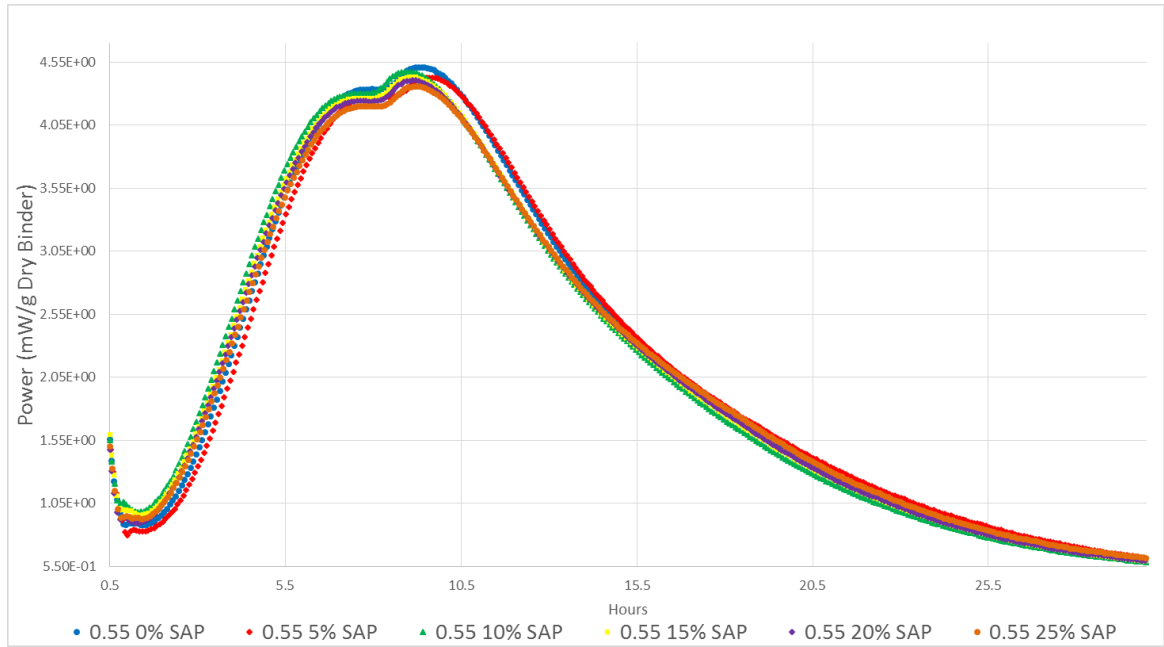


FIGURE 38 – POWER 0.55 W/C 0.5-30 HRS

V. CONCLUSIONS

Rheological properties such as yield stress, viscosity and flow behavior index were determined and analyzed for cement pastes containing SAP in this study. Slump Diameter measurements were also conducted to measure flowability of the pastes and heat of hydration measurements were determined to analyze the effects of SAP on hydration as well. The following conclusions can be made from the research in this investigation:

High w/c ratios in cement pastes without admixtures produce lower yield stress, viscosity and flow behavior index values indicating shear thinning tendency compared to lower w/c ratios.

Regarding the addition of SAP, 0.35 w/c pastes observed an increase yield stress, viscosity and flow behavior index, while 0.45 w/c pastes produced a decrease in yield stress, an increase in viscosity and flow behavior index. For 0.55 w/c pastes, SAP additions produced increases in viscosities and flow behavior index values. However, the yield stress increased with SAP additions up to 10% and a slight decrease with further addition of SAP.

Addition of SP produced large reductions in yield stress to points well below both the 0.35 w/c pastes without SP and the reference paste (P45-0-0). Reductions in viscosity was also observed compared to 0.35 w/c pastes without SP, however viscosities were compared to the reference paste. SP seems to reduce yield stress more than viscosity in cement pastes. It appears that adding SP converts the materials' flow behavior from shear thinning to shear thickening.

For the slump diameter test, increasing SAP dosages produced smaller average diameters for all w/c ratios, as expected due to the reduced amount of water being replaced.

For the Heat of hydration tests, 0.35 and 0.45 w/c pastes produced lower heat values during the initial and acceleration hydration stages as SAP dosage increased. However, 0.55 w/c pastes produced the opposite effect. Higher SAP dosages 20% and 25% produced higher energy values during the initial hydration stage. During the acceleration stage, higher SAP dosages produced lower values. An interesting observation was made regarding the maximum heat of hydration values for 0.55 w/c pastes, the value occurs at different times for lower w/c ratios and may be the result of water being released for SAP at different times. Also energy produced during hydration produced similar energy release responses for all pastes tested.

VI. RECOMMENDATIONS

The following recommendation can be made based on the results from this investigation:

This test in this study should be extended to:

- different types of cements and supplementary powders
- different types of superabsorbent polymers
- various superplasticizers and other chemical additives
- testing using different rheology geometries
- bleeding tests can be used in future studies

Different types of cements and powders such as fly ash and silica fume are composed of different chemical characteristics, which can potentially produce various rheological properties. Different types of superabsorbent polymers can also be investigated, other materials can potentially improve rheological properties compared to the Cassava Starch Graft SAP used in this study. Other chemical admixtures, such as viscosity modifying agent, could also be tested. The compatibility among all different chemical and mineral admixtures could be studied. Alternative rheological testing geometries can also be used to conduct rheological tests, such as the double gap cylinder which increase the low stress measurement capability of the concentric cylinder or vane which eliminates wall slippage. Including tests such as the bleeding test can also be useful for high w/c ratio pastes. The test can help compare self-consolidating concrete paste with ordinary pastes and pastes involving superabsorbent polymers. The influences of curing temperature on

rheological properties can also be investigated. These new testing methods and materials can provide further information on this current study, and provide a deep understanding on the topic.

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APPENDIX I

TABLE VI

P35-0-0 RHEOLOGICAL CALCULATIONS

0.35 wc 0% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	310.9872727	306.7976788	17.55269726	13503.96825			Yield Stress	to 26.63362896
250	258.8945455	263.0279157	17.08474971	4110.585568			Viscosity	eta 1.37850302
200	213.4781818	218.6521617	26.77006758	349.5959397			Flow Index	n 0.931728586
150	176.8481818	173.5039873	11.1836373	321.5750997				
100	131.7154545	127.2954759	19.53621137	3977.224802			Bingham	
50	76.76054545	79.40357404	6.985600111	13928.75616			Yield Stress	35.851
			99.11296333	36191.70582			Viscosity	0.9082
	194.780697						R2=	0.997261445
							R2=1-SSE/SST	
0.35 wc 0% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	300.2618182	298.2473512	4.058077121	11767.345			Yield Stress	to 15.31988641
250	255.6090909	257.9349998	5.409852254	4073.588075			Viscosity	eta 2.307960165
200	215.4454545	216.3279927	0.778873575	559.844355			Flow Index	n 0.843094296
150	172.2609091	173.0368604	0.602100407	381.1676439				
100	130.8163636	127.3711865	11.86924544	3717.104414			Bingham	
50	76.31290909	77.78251086	2.159729356	13333.67081			Yield Stress	38.054
			24.87787815	33832.7203			Viscosity	0.8785
	191.7844242						R2=	0.99926468
							R2=1-SSE/SST	
0.35 wc 0% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	298.9509091	296.490517	6.053529401	12022.71713			Yield Stress	to 21.0477621
250	251.7281818	255.2091309	12.11700666	3896.933592			Viscosity	eta 1.713925827
200	212.5790909	213.0076601	0.183671533	541.7876934			Flow Index	n 0.890565743
150	169.8481818	169.6222875	0.051028237	378.4805179				
100	127.0554545	124.5914213	6.07145981	3874.726735			Bingham	
50	75.65472727	76.89947631	1.549400166	12915.87479			Yield Stress	35.98
			26.0260958	33630.52046			Viscosity	0.8761
	189.3027576						R2=	0.999226117
							R2=1-SSE/SST	

TABLE VII

P35-5-0 RHEOLOGICAL CALCULATIONS

0.35 wc 5% SAP sample 1								
[1/s]	[Pa]	tao'	(tao-tao')^2	(yi-ybar)^2			Herschel-Bulkley	
300	330.4245455	328.4614618	3.853697252	14119.16458		Yield Stress	to	7.678638411
250	282.0245455	284.8905439	8.213947144	4959.55258		Viscosity	eta	3.332863596
200	239.0818182	239.5341876	0.204638122	755.2253473		Flow Index	n	0.800684893
150	192.8354545	191.8325448	1.005827941	352.125225				
100	141.7881818	140.7814793	1.013449949	4873.753423			Bingham	
50	83.44818182	84.08986218	0.411753689	16423.00501			Yield Stress	41.417
			14.7033141	41482.82616			Viscosity	0.9974
	211.6004545			R2=	0.999645557			
				R2=1-SSE/SST				
0.35 wc 5% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	335.8409091	331.1564812	21.94386505	15008.60358		Yield Stress	to	30.29703364
250	279.76	285.6256811	34.40621495	4412.771781		Viscosity	eta	1.773877523
200	236.9136364	239.1686004	5.084862699	556.1264454		Flow Index	n	0.900012472
150	192.0272727	191.5222258	0.255072394	453.8617072				
100	148.03	142.2275672	33.66822649	4264.260177			Bingham	
50	87.416	90.27860287	8.194495215	15854.66354			Yield Stress	45.111
			103.5527368	40550.28723			Viscosity	0.9613
	213.331303			R2=	0.997446313			
				R2=1-SSE/SST				
0.35 wc 5% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	324.1336364	320.3761155	14.11896292	14214.09483		Yield Stress	to	33.85374295
250	271.0663636	275.0627902	15.97142505	4376.564213		Viscosity	eta	1.312797302
200	225.6081818	229.2376074	13.17273031	428.3833703		Flow Index	n	0.944225422
150	184.4172727	182.7618572	2.740400497	419.9829212				
100	140.1690909	135.3963993	22.77858501	4191.483403			Bingham	
50	84.07	86.62632522	6.534798633	14602.48869			Yield Stress	41.491
			75.31690242	38232.99743			Viscosity	0.9338
	204.9107576			R2=	0.998030055			
				R2=1-SSE/SST				

TABLE VIII

P35-10-0 RHEOLOGICAL CALCULATIONS

0.35 wc 10% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	370.8763636	363.2433205	58.26334767	18724.56361		Yield Stress	to	30.30994387
250	304.2172727	313.5518559	87.1344435	4925.041002		Viscosity	eta	2.119399347
200	256.7127273	262.7119561	35.99074681	514.1143986		Flow Index	n	0.886571271
150	216.2636364	210.392974	34.46467686	315.950625				
100	161.46	156.0157502	29.63985564	5267.658456			Bingham	
50	94.70181818	98.30397541	12.97553669	19414.7489			Yield Stress	49.079
			258.4686072	49162.07699			Viscosity	1.0569
	234.0386364			R2=	0.994742521			
				R2=1-SSE/SST				
0.35 wc 10% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	359.4190909	354.0287541	29.05573045	17468.92893		Yield Stress	to	36.8132051
250	297.98	304.5020184	42.53672353	5002.872218		Viscosity	eta	1.566574618
200	250.3872727	254.2830472	15.17705893	535.3789636		Flow Index	n	0.931082149
150	205.8118182	203.1815943	6.918077531	459.5534139				
100	156.4409091	150.8684822	31.0519417	5013.787884			Bingham	
50	93.455	96.63118309	10.08813902	17900.83849			Yield Stress	47.348
			134.8276712	46381.3599			Viscosity	1.028
	227.2490152			R2=	0.997093063			
				R2=1-SSE/SST				
0.35 wc 10% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	380.4290909	375.8742487	20.74658731	19634.10695		Yield Stress	to	20.56382958
250	318.2909091	324.1855523	34.74681824	6081.438088		Viscosity	eta	2.598223804
200	268.9436364	271.0425681	4.405514607	820.0378512		Flow Index	n	0.862263558
150	217.3409091	216.0161127	1.755085403	527.4566425				
100	162.8081818	158.349379	19.8809222	6006.118486			Bingham	
50	94.03127273	96.35811755	5.41420682	21396.68591			Yield Stress	45.303
			86.94913458	54465.84392			Viscosity	1.1143
	240.3073333			R2=	0.998403603			
				R2=1-SSE/SST				

TABLE IX

P35-15-0 RHEOLOGICAL CALCULATIONS

0.35 wc 15% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2				
300	345.44	340.274392	26.68350644	16328.90167	Yield Stress	to		36.50414312
250	286.6427273	292.1091135	29.88137807	4759.25007	Viscosity	eta		1.370829711
200	238.3563636	243.4259001	25.70020011	428.5295191	Flow Index	n		0.946890155
150	196.4263636	194.0847968	5.482935175	450.6723709				
100	150.4018182	143.8446936	42.99588272	4523.04549			Bingham	
50	88.66518182	92.18699613	12.40317601	16638.47873			Yield Stress	44.203
			143.1470785	43128.87786			Viscosity	0.9912
	217.6554091			R2=				0.996680946
				R2=1-SSE/SST				
0.35 wc 15% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2				
300	353.2981818	349.4160308	15.07109683	16766.75761	Yield Stress	to		39.8920743
250	296.2427273	299.9335386	13.62208842	5246.258541	Viscosity	eta		1.330433274
200	245.7054545	250.0048441	18.4847504	479.3379477	Flow Index	n		0.955424029
150	200.4990909	199.5104829	0.977345711	543.4761885				
100	154.5281818	148.2451282	39.47676234	4800.201273			Bingham	
50	92.59636364	95.76866052	10.06346752	17217.45575			Yield Stress	46.426
			97.69551122	45053.4873			Viscosity	1.0136
	223.8116667			R2=				0.997831566
				R2=1-SSE/SST				
0.35 wc 15% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2				
300	331.0727273	327.5414781	12.46972062	14188.26411	Yield Stress	to		39.61184283
250	278.4454545	282.2792306	14.69783886	4420.55139	Viscosity	eta		1.366641343
200	233.4090909	236.4486087	9.238668441	460.1395507	Flow Index	n		0.93803717
150	190.8854545	189.8945611	0.981869864	444.0617504				
100	147.1636364	142.3493196	23.17764555	4198.339011			Bingham	
50	90.773	93.23489995	6.060951378	14685.85931			Yield Stress	48.171
			66.62669471	38397.21512			Viscosity	0.9359
	211.9582273			R2=				0.998264804
				R2=1-SSE/SST				

TABLE X

P35-20-0 RHEOLOGICAL CALCULATIONS

0.35 wc 20% SAP sample 1							
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			
300	373.4290909	366.8050847	43.87745782	18400.17438	Yield Stress	to	35.27811211
250	310.0781818	317.1097602	49.44309402	5226.759813	Viscosity	eta	2.060975213
200	259.6081818	266.3085009	44.89427536	476.3888268	Flow Index	n	0.890729953
150	218.1027273	214.0842546	16.14812279	387.2678117			
100	166.9636364	159.8823103	50.14517862	5015.219168		Bingham	
50	98.50927273	102.4822851	15.78482724	19396.85036		Yield Stress	53.237
			220.2929559	48902.66036		Viscosity	1.0545
	237.7818485			R2=	0.995495277		
				R2=1-SSE/SST			
0.35 wc 20% SAP sample 2							
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			
300	416.0254545	407.0591179	80.39519276	25520.20773	Yield Stress	to	38.25241638
250	336.4509091	347.4032896	119.9546385	6428.176399	Viscosity	eta	1.477554725
200	280.3481818	287.3588738	49.14980197	579.5180829	Flow Index	n	0.967758532
150	232.7209091	226.8232223	34.78270897	554.7951986			
100	173.8263636	165.6205072	67.33608027	6797.777638		Bingham	
50	98.27818182	103.3757003	25.98469469	24962.99456		Yield Stress	43.851
			377.6031172	64843.4696		Viscosity	1.2138
	256.275			R2=	0.994176698		
				R2=1-SSE/SST			
0.35 wc 20% SAP sample 3							
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			
300	369.6136364	364.7187743	23.95967463	18304.31474	Yield Stress	to	34.76615447
250	309.2436364	314.0882481	23.47026239	5613.521771	Viscosity	eta	1.799518522
200	257.3418182	262.5697542	27.33131552	529.9950432	Flow Index	n	0.913679642
150	211.9736364	209.9147271	4.239107192	499.3687709			
100	162.1990909	155.6910175	42.35501986	5201.453939		Bingham	
50	95.54936364	98.95663481	11.60949682	19257.34418		Yield Stress	48.638
			132.9648764	49405.99845		Viscosity	1.061
	234.320197			R2=	0.99730873		
				R2=1-SSE/SST			

TABLE XI

P35-25-0 RHEOLOGICAL CALCULATIONS

0.35 wc 25% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	336.8290909	333.2916297	12.513632	15167.8855		Yield Stress	to	38.41086611
250	281.9636364	286.1762928	17.74647397	4663.867626		Viscosity	eta	1.27169238
200	236.4018182	238.6305447	4.967221839	516.6845847		Flow Index	n	0.954844002
150	191.0318182	190.5390766	0.242794299	512.5380417				
100	146.5772727	141.7036718	23.75198639	4501.584505			Bingham	
50	89.22309091	91.69935291	6.131873501	15487.31225			Yield Stress	44.715
			65.353982	40849.8725			Viscosity	0.9983
	213.6711212			R2=	0.998400142			
				R2=1-SSE/SST				
0.35 wc 25% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	345.6636364	343.0709354	6.722098364	15605.69536		Yield Stress	to	43.88062228
250	291.4054545	294.6715243	10.66721146	4993.482267		Viscosity	eta	1.198008869
200	245.3890909	245.9577679	0.323393537	607.5343608		Flow Index	n	0.967852296
150	195.21	196.8466383	2.678584876	651.8257717				
100	152.2736364	147.1959187	25.78321637	4687.763285			Bingham	
50	94.50345455	96.70228327	4.834847753	15935.88728			Yield Stress	48.403
			51.00935237	42482.18832			Viscosity	0.9848
	220.7408788			R2=	0.998799277			
				R2=1-SSE/SST				
0.35 wc 25% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	351	347.0024281	15.98058094	16659.9332		Yield Stress	to	41.24294519
250	291.3554545	297.5028864	37.79091791	4820.360794		Viscosity	eta	1.218728794
200	247.0972727	247.6898955	0.351201804	633.560935		Flow Index	n	0.968653778
150	199.4763636	197.4807371	3.982525191	504.0147455				
100	149.1136364	146.7337557	5.663831986	5301.732969			Bingham	
50	93.51709091	95.14691947	2.656341131	16489.01136			Yield Stress	45.751
			66.42539896	44408.61401			Viscosity	1.0067
	221.9266364			R2=	0.998504223			
				R2=1-SSE/SST				

TABLE XII - P35-0-SP

RHEOLOGICAL CALCULATIONS

0.35 wc 0% SAP sample 1									
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley		
300	189.63	188.9746831	0.429440185	5758.025037			Yield Stress	to	23.34286
250	156.3418182	157.1749346	0.694082893	1814.203661			Viscosity	eta	0.210253
200	125.9863636	126.4401087	0.205884615	149.7690148			Flow Index	n	1.169261
150	97.30790909	96.99087369	0.100511446	270.2880475					
100	69.96509091	69.18494201	0.608632308	1916.973644				Bingham	
50	43.25890909	43.72649331	0.218635001	4968.761066				Yield Stress	11.782
			2.257186449	14878.02047				Viscosity	0.5827
	113.7483485				R2=	0.999848287			
					R2=1-SSE/SST				
0.35 wc 0% SAP sample 2									
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley		
300	181.27	180.1919894	1.162106936	5176.704387			Yield Stress	to	22.75451
250	148.8445455	150.4165418	2.471172618	1562.135797			Viscosity	eta	0.223252
200	121.0972727	121.5256338	0.183493241	138.6880934			Flow Index	n	1.149848
150	94.36818182	93.70729989	0.436764925	223.5772563					
100	68.12809091	67.26797011	0.739807788	1696.829546				Bingham	
50	42.216	42.81551774	0.359421519	4503.038322				Yield Stress	12.906
			5.352767027	13300.9734				Viscosity	0.5509
	109.3206818				R2=	0.999597566			
					R2=1-SSE/SST				
0.35 wc 0% SAP sample 3									
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley		
300	164.0218182	163.1102629	0.830933042	4529.805981			Yield Stress	to	19.70269
250	133.32	134.6587724	1.792311582	1339.707513			Viscosity	eta	0.141917
200	107.0545455	107.4004165	0.119626765	106.8444852			Flow Index	n	1.212915
150	82.04527273	81.5681506	0.227645529	215.288481					
100	58.42136364	57.53514255	0.785387816	1466.631196				Bingham	
50	35.44490909	36.02346002	0.334721182	3754.389813				Yield Stress	7.459
			4.090625915	11412.66747				Viscosity	0.5101
	96.71798485				R2=	0.999641571			
					R2=1-SSE/SST				

TABLE XIII

P35-5-SP RHEOLOGICAL CALCULATIONS

0.35 wc 5% SAP sample 1								
[1/s]	[Pa]	tao'	(tao-tao')^2	(yi-ybar)^2			Herschel-Bulkley	
300	186.4581818	185.1954601	1.59446605	5661.675497		Yield Stress	to	22.86095
250	151.9381818	153.8482546	3.648377879	1658.452814		Viscosity	eta	0.197378
200	123.1236364	123.5968065	0.223889953	141.8376338		Flow Index	n	1.176815
150	95.68263636	94.66589408	1.033764872	241.2256096				
100	68.14118182	67.41914344	0.521339422	1855.274192			Bingham	
50	41.94063636	42.57024358	0.396405245	4798.809405			Yield Stress	11.072
			7.418243421	14357.27515			Viscosity	0.5722
	111.2140758			R2=	0.999483311			
				R2=1-SSE/SST				
0.35 wc 5% SAP sample 2								
			SSE	SST			Herschel-Bulkley	
[1/s]	[Pa]	tao'	(tao-tao')^2	(yi-ybar)^2				
300	182.7127273	181.6524745	1.124135895	5298.086327		Yield Stress	to	24.77616
250	149.6027273	151.1893666	2.51742437	1574.340077		Viscosity	eta	0.182893
200	121.5127273	121.8346314	0.10362225	134.2806905		Flow Index	n	1.184181
150	94.35045455	93.81339054	0.288437741	242.5593868				
100	68.43009091	67.48909565	0.885472072	1721.808619			Bingham	
50	42.93990909	43.57302257	0.400832679	4486.971956			Yield Stress	12.97
			5.319925008	13458.04706			Viscosity	0.554
	109.9247727			R2=	0.999604703			
				R2=1-SSE/SST				
0.35 wc 5% SAP sample 3								
			SSE	SST			Herschel-Bulkley	
[1/s]	[Pa]	tao'	(tao-tao')^2	(yi-ybar)^2				
300	188.8809091	187.8343087	1.095372361	5859.16486		Yield Stress	to	23.87447
250	154.1763636	155.6083126	2.050477915	1750.638851		Viscosity	eta	0.174375
200	124.0163636	124.6552354	0.40815713	136.4372659		Flow Index	n	1.200286
150	95.94672727	95.2280009	0.516567603	268.599321				
100	68.71190909	67.73315917	0.957951398	1903.037513			Bingham	
50	42.28209091	42.96129415	0.461317045	4907.511968			Yield Stress	10.59
			5.489843451	14825.38978			Viscosity	0.5814
	112.3357273			R2=	0.9996297			
				R2=1-SSE/SST				

TABLE XIV

P35-10-SP RHEOLOGICAL CALCULATIONS

0.35 wc 10% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	175.0872727	173.9545986	1.282950631	5436.570929		Yield Stress	to	19.79497
250	140.8227273	142.4514056	2.652593035	1557.767276		Viscosity	eta	0.1208
200	111.9690909	112.5165992	0.299765289	112.6766167		Flow Index	n	1.253836
150	85.16609091	84.43898736	0.528679577	262.0537967				
100	59.73181818	58.67608724	1.114567826	1732.419893			Bingham	
50	35.348	36.0990544	0.564082717	4356.814038			Yield Stress	4.477
			6.442639074	13458.30255			Viscosity	0.5536
	101.3541667				R2=	0.999521289		
					R2=1-SSE/SST			
0.35 wc 10% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	169.3945455	168.4449455	0.901740017	4829.721393		Yield Stress	to	22.719
250	137.3763636	138.726266	1.82223636	1404.60162		Viscosity	eta	0.116087
200	109.98	110.4707369	0.240822753	101.6396973		Flow Index	n	1.250949
150	84.52272727	83.9489288	0.329244688	236.4097277				
100	60.58218182	59.58980385	0.984814024	1545.760961			Bingham	
50	37.53427273	38.21107292	0.458058495	3889.277945			Yield Stress	8.3842
			4.736916338	12007.41134			Viscosity	0.5229
	99.89834848				R2=	0.999605501		
					R2=1-SSE/SST			
0.35 wc 10% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	169.7263636	168.5775572	1.319756171	5057.746218		Yield Stress	to	21.38556
250	136.3490909	138.0002606	2.726361507	1424.349915		Viscosity	eta	0.100945
200	108.46	109.0814193	0.386162002	97.05145519		Flow Index	n	1.277208
150	82.94190909	82.1159925	0.682138215	245.4430202				
100	58.66890909	57.56828466	1.211374137	1595.173343			Bingham	
50	35.50490909	36.31431045	0.65513056	3982.06701			Yield Stress	5.6419
			6.980922591	12401.83096			Viscosity	0.5312
	98.6085303				R2=	0.999437105		
					R2=1-SSE/SST			

TABLE XV

P35-15-SP RHEOLOGICAL CALCULATIONS

0.35 wc 15% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	181.4254545	180.2205248	1.451855762	6142.28438		Yield Stress	to	19.84149
250	144.4654545	146.1782974	2.933830527	1715.01398		Viscosity	eta	0.09195
200	113.4772727	114.1850119	0.500894742	108.6711479		Flow Index	n	1.308614
150	85.46945455	84.58786927	0.77719259	309.1714798				
100	59.14709091	57.92877123	1.484302849	1927.704904			Bingham	
50	34.33163636	35.21764852	0.785017532	4722.588336			Yield Stress	1.1095
			7.933094003	14925.43423			Viscosity	0.5825
	103.0527273			R2=	0.999468485			
				R2=1-SSE/SST				
0.35 wc 15% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	176.7118182	175.5388582	1.375835216	5801.481132		Yield Stress	to	18.5892
250	140.9809091	142.6332194	2.73012938	1635.114208		Viscosity	eta	0.09977
200	110.8909091	111.5954333	0.496354378	107.0510028		Flow Index	n	1.290514
150	83.61954545	82.7510398	0.754302071	286.4494705				
100	57.74954545	56.61063385	1.297119652	1831.396463			Bingham	
50	33.31345455	34.13256072	0.670934932	4519.995137			Yield Stress	1.1486
			7.324675628	14181.48741			Viscosity	0.568
	100.5443636			R2=	0.999483504			
				R2=1-SSE/SST				
0.35 wc 15% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	181.6463636	180.3421213	1.701048192	6083.654914		Yield Stress	to	19.85872
250	144.7372727	146.6892982	3.810403332	1688.281019		Viscosity	eta	0.101858
200	114.4181818	114.948481	0.281217261	115.9844147		Flow Index	n	1.290787
150	86.33918182	85.45276551	0.785733878	299.6151185				
100	59.85	58.7245587	1.266618119	1918.315238			Bingham	
50	34.90045455	35.74427165	0.7120273	4726.30417			Yield Stress	2.0015
			8.557048083	14832.15487			Viscosity	0.5808
	103.6485758			R2=	0.999423075			
				R2=1-SSE/SST				

TABLE XVI

P35-20-SP RHEOLOGICAL CALCULATIONS

0.35 wc 20% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	186.2045455	184.8791547	1.756660648	6549.944479		Yield Stress	to	20.84636
250	147.6145455	149.5217859	3.637566145	1792.821868		Viscosity	eta	0.082505
200	115.7327273	116.4453968	0.507897855	109.4096982		Flow Index	n	1.331566
150	86.94745455	86.02260183	0.85535254	335.8189524				
100	60.16481818	58.83136018	1.778110251	2034.731664			Bingham	
50	34.97281818	35.93919057	0.933875596	4942.09			Yield Stress	0.5435
			9.469463035	15764.81666			Viscosity	0.5985
	105.2728182			R2=	0.999399329			
				R2=1-SSE/SST				
0.35 wc 20% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	186.7390909	185.5439617	1.428333818	6597.776301		Yield Stress	to	20.39826
250	148.3745455	150.0398892	2.773369751	1837.164033		Viscosity	eta	0.084954
200	116.0281818	116.7999348	0.595602656	110.5817947		Flow Index	n	1.327622
150	87.08436364	86.19632474	0.788613084	339.5923008				
100	60.07072727	58.80703338	1.596922248	2064.945069			Bingham	
50	34.77745455	35.70125176	0.853401301	5003.431651			Yield Stress	0.146
			8.036242858	15953.49115			Viscosity	0.6021
	105.5123939			R2=	0.999496271			
				R2=1-SSE/SST				
0.35 wc 20% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	192.1463636	190.8725863	1.622508784	7101.169878		Yield Stress	to	20.16157
250	152.0936364	153.9579066	3.47550346	1955.029198		Viscosity	eta	0.083532
200	118.8163636	119.4581485	0.411887797	119.6494564		Flow Index	n	1.336394
150	88.68254545	87.76472059	0.842402474	368.4625668				
100	60.69281818	59.48393989	1.461386714	2226.434234			Bingham	
50	34.83581818	35.73359621	0.806005396	5335.149258			Yield Stress	1.211
			8.619694625	17105.89459			Viscosity	0.6234
	107.8779242			R2=	0.999496098			
				R2=1-SSE/SST				

TABLE XVII

P35-25-SP RHEOLOGICAL CALCULATIONS

0.35 wc 25% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	183.1272727	181.7695176	1.843499118	6730.949431		Yield Stress	to	17.42531
250	143.5872727	145.5962844	4.03612806	1806.450915		Viscosity	eta	0.068891
200	111.3272727	111.9731376	0.417141401	104.9060129		Flow Index	n	1.363514
150	82.23118182	81.29515702	0.876142418	355.4630321				
100	55.51845455	54.16986891	1.818683208	2076.30178			Bingham	
50	30.718	31.7055188	0.975193389	4951.501895			Yield Stress	4.45
			9.966787593	16025.57307			Viscosity	0.6031
	101.0849091			R2=	0.99937807			
				R2=1-SSE/SST				
0.35 wc 25% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	187.5590909	186.268591	1.665390072	7054.238655		Yield Stress	to	16.2513
250	147.5572727	149.4700044	3.658542305	1934.917485		Viscosity	eta	0.082532
200	114.5209091	115.08839	0.322034593	119.9317018		Flow Index	n	1.33779
150	84.35036364	83.51459624	0.698507144	369.3781146				
100	56.60763636	55.35384311	1.57199752	2205.423752			Bingham	
50	30.82218182	31.72129072	0.808396824	5292.183325			Yield Stress	5.1008
			8.724868457	16976.07303			Viscosity	0.621
	103.5695758			R2=	0.999486049			
				R2=1-SSE/SST				
0.35 wc 25% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	198.4763636	197.2716084	1.451435266	7832.89365		Yield Stress	to	18.76233
250	156.5545455	158.2568447	2.897822636	2169.865785		Viscosity	eta	0.079618
200	121.1927273	121.9131869	0.519062146	125.8884		Flow Index	n	1.352639
150	89.50209091	88.66210856	0.705570354	419.0469531				
100	60.44772727	59.15363219	1.674682076	2452.725625			Bingham	
50	33.66290909	34.57855746	0.838411933	5823.188351			Yield Stress	4.4351
			8.086984412	18823.60876			Viscosity	0.6538
	109.9727273			R2=	0.999570381			
				R2=1-SSE/SST				

TABLE XVIII

P45-0-0 RHEOLOGICAL CALCULATIONS

0.45 wc 0% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2				Herschel-Bulkley
300	94.99090909	94.38444292	0.36780122	758.7570744		Yield Stress	to	5.60450238
250	84.41054545	85.05181319	0.411224314	287.8173941		Viscosity	eta	2.749803099
200	74.47590909	74.95403511	0.228604487	49.42856939		Flow Index	n	0.609180213
150	64.03481818	63.80588919	0.052408485	11.6318203				
100	51.60818182	51.06791399	0.291889329	250.8163279			Bingham	
50	35.15181818	35.40891077	0.066096598	1042.873078			Yield Stress	26.641
			1.418024433	2401.324264			Viscosity	0.2332
	67.44536364			R2=	0.999409			
				R2=1-SSE/SST				
0.45 wc 0% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2				Herschel-Bulkley
300	88.071	87.5502836	0.271145568	586.1453756		Yield Stress	to	3.624277354
250	79.06336364	79.53577681	0.22317421	231.12522		Viscosity	eta	3.632874088
200	70.27854545	70.7608183	0.232587101	41.19052952		Flow Index	n	0.550496351
150	61.00672727	60.92771061	0.006243632	8.144364694				
100	50.07272727	49.46411253	0.370411901	190.104348			Bingham	
50	34.671	34.92303746	0.063522879	852.0304484			Yield Stress	27.536
			1.167085292	1908.740286			Viscosity	0.2076
	63.86056061			R2=	0.999389			
				R2=1-SSE/SST				
0.45 wc 0% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2				Herschel-Bulkley
300	82.38045455	81.93798778	0.195776842	459.7853547		Yield Stress	to	3.622870777
250	74.56572727	74.94200146	0.141582263	185.7190803		Viscosity	eta	4.192468632
200	66.81481818	67.2243533	0.167719014	34.53877282		Flow Index	n	0.513247293
150	58.48818182	58.49385757	3.22142E-05	6.000866778				
100	48.75772727	48.1848435	0.328195812	148.3553527			Bingham	
50	34.62018182	34.84493251	0.050512871	692.6195788			Yield Stress	28.483
			0.883819017	1527.019006			Viscosity	0.1855
	60.93784848			R2=	0.999421			
				R2=1-SSE/SST				

TABLE XIX

P45-5-0 RHEOLOGICAL CALCULATIONS

0.45 wc 5% SAP sample 1							
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley
300	104.1309091	103.2271677	0.816748487	959.3821058		Yield Stress	to 4.907747386
250	91.88818182	92.7811056	0.797312876	350.8566047		Viscosity	eta 2.927731285
200	80.68663636	81.49434506	0.652393343	56.6951956		Flow Index	n 0.616081305
150	69.34518182	69.05533915	0.08400877	14.53007336			
100	55.81654545	54.87596106	0.88469901	300.6918893			Bingham
50	37.07463636	37.50904387	0.18870988	1301.938059			Yield Stress 27.673
			3.423872366	2984.093928			Viscosity 0.2599
	73.15701515			R2=	0.998853		
				R2=1-SSE/SST			
0.45 wc 5% SAP sample 2							
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley
300	101.6363636	100.7502687	0.785164317	923.9223426		Yield Stress	to 3.10113348
250	89.70490909	90.54137167	0.699669649	340.942796		Viscosity	eta 3.085817702
200	78.718	79.4876355	0.592338797	55.91640517		Flow Index	n 0.605661968
150	67.36845455	67.27319358	0.009074651	14.99097603			
100	54.38436364	53.30003375	1.175771294	284.1216713			Bingham
50	35.62954545	36.09033343	0.212325561	1268.123897			Yield Stress 26.506
			3.474344268	2888.018088			Viscosity 0.2556
	71.24027273			R2=	0.998797		
				R2=1-SSE/SST			
0.45 wc 5% SAP sample 3							
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley
300	97.17609091	96.29687986	0.77301206	781.3354799		Yield Stress	to 5.358950456
250	86.17627273	86.97853964	0.643632191	287.3893111		Viscosity	eta 3.089809647
200	76.04663636	76.86313275	0.666666342	46.55229522		Flow Index	n 0.592951731
150	65.75990909	65.64943918	0.012203602	11.99793143			
100	53.85645455	52.76515515	1.190934374	236.1526054			Bingham
50	36.32690909	36.78855599	0.213117858	1082.19965			Yield Stress 28.075
			3.499566428	2445.627273			Viscosity 0.2351
	69.22371212			R2=	0.998569		
				R2=1-SSE/SST			

TABLE XX

P45-10-0 RHEOLOGICAL CALCULATIONS

0.45 wc 10% SAP sample 1							
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley
300	97.73	96.94299169	0.619382074	703.469529	Yield Stress	to	0
250	87.63209091	88.39507683	0.582147513	269.7836114	Viscosity	eta	5.399892368
200	78.18954545	78.95214148	0.581552698	48.75594102	Flow Index	n	0.506285799
150	68.419	68.25102941	0.02821412	7.772944			
100	56.69427273	55.58488381	1.230743762	210.6192529		Bingham	
50	38.57709091	39.13357194	0.30967114	1064.710967		Yield Stress	31.372
			3.351711307	2305.112246		Viscosity	0.2276
	71.207			R2=	0.998546		
				R2=1-SSE/SST			
0.45 wc 10% SAP sample 2							
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley
300	106.6090909	105.6126604	0.992873748	969.1750091	Yield Stress	to	0
250	94.41127273	95.38505657	0.948254966	358.4871759	Viscosity	eta	4.363547619
200	83.25554545	84.2054677	0.902352267	60.49775539	Flow Index	n	0.55866311
150	71.89627273	71.70371038	0.037080256	12.8252973			
100	58.602	57.16970338	2.05147361	284.7830116		Bingham	
50	38.09090909	38.81428456	0.523272065	1397.758313		Yield Stress	29.34
			5.455306913	3083.526562		Viscosity	0.2636
	75.47751515			R2=	0.998231		
				R2=1-SSE/SST			
0.45 wc 10% SAP sample 3							
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley
300	100.7381818	100.059364	0.460793617	780.7968542	Yield Stress	to	0
250	90.102	90.9378129	0.698583208	299.51704	Viscosity	eta	5.029789485
200	80.30327273	80.89774462	0.353396833	56.36756136	Flow Index	n	0.52428113
150	69.84618182	69.57182438	0.075272006	8.698120248			
100	57.44181818	56.24864536	1.423661382	235.7336843		Bingham	
50	38.34118182	39.1099915	0.591068334	1187.095865		Yield Stress	30.753
			3.60277538	2568.209125		Viscosity	0.2402
	72.79543939			R2=	0.998597		
				R2=1-SSE/SST			

TABLE XXI

P45-15-0 RHEOLOGICAL CALCULATIONS

0.45 wc 15% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	114.8081818	114.0378131	0.593468023	1269.261537		Yield Stress	to	0
250	100.8045455	101.9414005	1.292439421	467.55675		Viscosity	eta	3.416350606
200	88.18772727	88.86867658	0.46369196	81.1124026		Flow Index	n	0.61502296
150	75.14490909	74.45751217	0.472514521	16.29394385				
100	59.438	58.0240921	1.999135536	389.805194			Bingham	
50	36.70554545	37.88506135	1.391257754	1804.205427			Yield Stress	26.416
			6.212507215	4028.235255			Viscosity	0.3015
	79.18148485			R2=	0.998458			
				R2=1-SSE/SST				
0.45 wc 15% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	114.4427273	113.5611204	0.77723068	1293.440901		Yield Stress	to	0
250	100.2844545	101.3368947	1.10763027	475.5089047		Viscosity	eta	3.219946044
200	87.27890909	88.15174271	0.761838533	77.45093372		Flow Index	n	0.624669088
150	74.16736364	73.65216813	0.26542641	18.58406782				
100	58.619	57.17244557	2.092519707	394.3913151			Bingham	
50	36.07727273	37.08024858	1.005960568	1797.846086			Yield Stress	25.485
			6.010606169	4057.222208			Viscosity	0.3028
	78.47828788			R2=	0.998519			
				R2=1-SSE/SST				
0.45 wc 15% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	115.2390909	114.604435	0.402788173	1302.565749		Yield Stress	to	0
250	101.18	102.2496721	1.144198301	485.4083564		Viscosity	eta	3.231455722
200	88.35527273	88.9263517	0.326131197	84.77359207		Flow Index	n	0.625646892
150	74.96509091	74.27846889	0.471449794	17.49685522				
100	59.141	57.63575599	2.265759532	400.2806553			Bingham	
50	36.00763636	37.35541046	1.816495011	1861.092282			Yield Stress	25.582
			6.426822008	4151.61749			Viscosity	0.3061
	79.14801515			R2=	0.998452			
				R2=1-SSE/SST				

TABLE XXII

P45-20-0 RHEOLOGICAL CALCULATIONS

0.45 wc 20% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2				
300	122.6854545	122.018853	0.44435759	1603.103322		Yield Stress	to	0
250	106.9054545	108.0899627	1.403059615	588.4880542		Viscosity	eta	2.75155342
200	92.46418182	93.18742062	0.523074362	96.38330625		Flow Index	n	0.664823729
150	77.969	76.96531552	1.007382541	21.88070719				
100	60.47436364	58.77943492	2.872783358	491.6116936			Bingham	
50	35.38163636	37.0760554	2.871055868	2233.984522			Yield Stress	23.616
			9.121713335	5035.451605			Viscosity	0.3373
	82.64668182			R2=	0.998189			
				R2=1-SSE/SST				
0.45 wc 20% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2				
300	120.2363636	119.6693611	0.321491924	1455.406315		Yield Stress	to	0
250	105.3227273	106.508879	1.406955915	539.9187372		Viscosity	eta	3.126740103
200	91.73618182	92.35489026	0.382800135	93.11489712		Flow Index	n	0.639004322
150	77.90636364	76.8463959	1.123531596	17.47417338				
100	61.04572727	59.30624512	3.025798154	442.717305			Bingham	
50	36.27209091	38.08385999	3.282507218	2098.967022			Yield Stress	25.438
			9.543084943	4647.59845			Viscosity	0.3237
	82.08657576			R2=	0.997947			
				R2=1-SSE/SST				
0.45 wc 20% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2				
300	116.8136364	116.2977323	0.26615702	1330.950696		Yield Stress	to	0
250	102.56	103.7752025	1.476717105	494.1089066		Viscosity	eta	3.293841967
200	89.74481818	90.26883374	0.274592303	88.6117002		Flow Index	n	0.624865854
150	76.442	75.41676183	1.051113314	15.1277388				
100	60.41790909	58.53753982	3.535788603	396.5486891			Bingham	
50	36.01027273	37.96042805	3.803105768	1964.365815			Yield Stress	25.957
			10.40747411	4289.713545			Viscosity	0.3107
	80.33143939			R2=	0.997574			
				R2=1-SSE/SST				

TABLE XXIII

P45-25-0 RHEOLOGICAL CALCULATIONS

0.45 wc 25% SAP sample 1							
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2		Herschel-Bulkley	
300	124.3945455	123.4430882	0.90527085	1714.612426	Yield Stress	to	0
250	107.5390909	109.0388388	2.249243828	602.8215362	Viscosity	eta	2.545075102
200	92.99790909	93.67649276	0.4604758	100.2249749	Flow Index	n	0.680534379
150	77.99	77.02035515	0.940211141	24.96667778			
100	59.90090909	58.44796047	2.111059687	532.9522028		Bingham	
50	35.09754545	36.46767703	1.877260536	2293.36793		Yield Stress	22.546
			8.543521842	5268.945748		Viscosity	0.3454
	82.98666667			R2=	0.998379		
				R2=1-SSE/SST			
0.45 wc 25% SAP sample 2							
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2		Herschel-Bulkley	
300	127.45	126.7348703	0.511410489	1903.9167	Yield Stress	to	0
250	109.9872727	111.2540684	1.604771294	684.9299647	Viscosity	eta	2.151937201
200	94.30909091	94.8565456	0.299706639	110.102731	Flow Index	n	0.714565962
150	78.27272727	77.23076494	1.085685493	30.72904839			
100	59.00509091	57.80448238	1.441460849	615.5864728		Bingham	
50	33.87245455	35.22538336	1.830416373	2494.368327		Yield Stress	20.129
			6.773451136	5839.633244		Viscosity	0.3639
	83.81610606			R2=	0.99884		
				R2=1-SSE/SST			
0.45 wc 25% SAP sample 3							
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2		Herschel-Bulkley	
300	118.4463636	117.8963337	0.302532891	1512.547594	Yield Stress	to	0
250	103.0609091	104.2947325	1.522320316	552.5334606	Viscosity	eta	2.546800114
200	89.27581818	89.76445952	0.238770361	94.4966627	Flow Index	n	0.672355233
150	75.10036364	73.97776509	1.260227492	19.84270524			
100	57.87554545	56.32553524	2.402531673	469.9934938		Bingham	
50	33.57027273	35.34322979	3.143376741	2114.583995		Yield Stress	22.144
			8.869759474	4763.997911		Viscosity	0.3281
	79.55487879			R2=	0.998138		
				R2=1-SSE/SST			

TABLE XXIV

P55-0-0 RHEOLOGICAL CALCULATIONS

0.55 wc 0% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	56.11609091	56.32059415	0.041821574	195.2379543		Yield Stress	to	0
250	51.53163636	51.68348481	0.02305795	88.14023379		Viscosity	eta	3.830750733
200	46.64918182	46.52446443	0.015554427	20.30267057		Flow Index	n	0.471266125
150	41.08309091	40.6258058	0.20910967	1.124113998				
100	33.76654545	33.5595511	0.042846665	70.17057517			Bingham	
50	23.71345455	24.20755367	0.244133947	339.6604321			Yield Stress	20.056
			0.576524232	714.6359799			Viscosity	0.1262
	42.14333333			R2=	0.999193			
				R2=1-SSE/SST				
0.55 wc 0% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	56.53445455	56.75862892	0.050254149	199.9978782		Yield Stress	to	0
250	51.90090909	52.05339292	0.023251319	90.41186039		Viscosity	eta	3.78689031
200	46.93245455	46.82214958	0.012167186	20.61215031		Flow Index	n	0.474643366
150	41.35218182	40.84604444	0.256175045	1.082041257				
100	33.94118182	33.6953101	0.0604529	71.42298632			Bingham	
50	23.69318182	24.24865012	0.308545034	349.660534			Yield Stress	38.054
			0.710845634	733.1874504			Viscosity	0.8785
	42.39239394			R2=	0.99903			
				R2=1-SSE/SST				
0.55 wc 0% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	51.24709091	51.60637713	0.129086589	133.692107		Yield Stress	to	0
250	47.71681818	47.79040259	0.005414665	64.51716176		Viscosity	eta	4.666366215
200	43.665	43.50188394	0.02660685	15.84389777		Flow Index	n	0.421345766
150	39.00563636	38.53591343	0.220639634	0.460938127				
100	32.89218182	32.48406353	0.166560534	46.1364096			Bingham	
50	23.58063636	24.25675139	0.457131529	259.336376			Yield Stress	20.938
			1.005439801	519.9868903			Viscosity	0.1071
	39.68456061			R2=	0.998066			
				R2=1-SSE/SST				

TABLE XXV

P55-5-0 RHEOLOGICAL CALCULATIONS

0.55 wc 5% SAP sample 1								
[1/s]	[Pa]	tao'	(tao-tao')^2	(yi-ybar)^2		Herschel-Bulkley		
300	67.07881818	67.17758596	0.009755075	325.6274932		Yield Stress	to	0
250	60.86109091	61.12568266	0.070008797	139.8879642		Viscosity	eta	3.503898833
200	54.54281818	54.45565132	0.007598062	30.35075042		Flow Index	n	0.517807852
150	47.39054545	46.91899468	0.222360133	2.699847318				
100	38.30427273	38.03358483	0.073271936	115.1198943			Bingham	
50	26.02445455	26.56388346	0.290983551	529.4238424			Yield Stress	21.024
			0.673977553	1143.109792			Viscosity	0.1601
	49.03366667			R2=	0.99941			
				R2=1-SSE/SST				
0.55 wc 5% SAP sample 2								
[1/s]	[Pa]	tao'	SSE	SST		Herschel-Bulkley		
			(tao-tao')^2	(yi-ybar)^2				
300	65.39763636	65.38329414	0.000205699	289.0556639		Yield Stress	to	0
250	59.42172727	59.77913976	0.127743687	121.5666619		Viscosity	eta	3.962558235
200	53.51909091	53.56966565	0.002557804	26.24606046		Flow Index	n	0.491494366
150	46.98209091	46.50634946	0.226329927	1.999138917				
100	38.56590909	38.10345783	0.213861169	96.63068728			Bingham	
50	26.48954545	27.10253053	0.375750699	479.8927508			Yield Stress	22.032
			0.946448986	1015.390938			Viscosity	0.1507
	48.396			R2=	0.999068			
				R2=1-SSE/SST				
0.55 wc 5% SAP sample 3								
[1/s]	[Pa]	tao'	SSE	SST		Herschel-Bulkley		
			(tao-tao')^2	(yi-ybar)^2				
300	69.39218182	69.30601873	0.007424077	364.886404		Yield Stress	to	0
250	62.56572727	62.93326987	0.135087561	150.6890162		Viscosity	eta	3.390437199
200	55.80563636	55.92555207	0.014379778	30.42023884		Flow Index	n	0.529047678
150	48.46236364	48.02990543	0.187020102	3.340919306				
100	39.24390909	38.75708093	0.237001657	122.0201412			Bingham	
50	26.27127273	26.85912372	0.345568791	576.9079939			Yield Stress	20.999
			0.926481965	1248.264713			Viscosity	0.1674
	50.29018182			R2=	0.999258			
				R2=1-SSE/SST				

TABLE XXVI

P55-10-0 RHEOLOGICAL CALCULATIONS

0.55 wc 10% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	66.48090909	66.42480807	0.003147325	301.3317248		Yield Stress	to	0
250	60.29818182	60.71339202	0.172399509	124.90704		Viscosity	eta	3.988537566
200	54.264	54.38714818	0.015165473	26.440164		Flow Index	n	0.49311943
150	47.628	47.19397611	0.188376741	2.232036				
100	39.41627273	38.64137279	0.600469905	94.20114189			Bingham	
50	26.64463636	27.45420088	0.655394711	505.231876		Yield Stress		22.276
			1.634953664	1054.343983		Viscosity		0.1534
	49.122			R2=	0.998449			
				R2=1-SSE/SST				
0.55 wc 10% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	67.94390909	67.85763665	0.007442935	323.0706674		Yield Stress	to	0
250	61.59245455	61.93249168	0.115625252	135.0874371		Viscosity	eta	3.892570444
200	55.18554545	55.38012623	0.037861679	27.20460125		Flow Index	n	0.501130999
150	48.27327273	47.94499387	0.107767008	2.878009433				
100	39.90809091	39.12897566	0.60702057	101.2368312			Bingham	
50	26.91518182	27.64668195	0.535092443	531.5127647		Yield Stress		22.259
			1.410809886	1120.990311		Viscosity		0.1583
	49.96974242			R2=	0.998741			
				R2=1-SSE/SST				
0.55 wc 10% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	63.04545455	63.00394974	0.001722649	252.8740859		Yield Stress	to	0
250	57.49554545	57.81622314	0.10283418	107.1660999		Viscosity	eta	4.284523133
200	51.863	52.04465159	0.032997301	22.27425231		Flow Index	n	0.471299208
150	45.82754545	45.44567706	0.145823474	1.73157686				
100	38.28063636	37.54057386	0.547692509	78.54927755			Bingham	
50	26.34845455	27.07856893	0.533067018	432.4313948		Yield Stress		22.427
			1.364137131	895.0266873		Viscosity		0.1412
	47.14343939			R2=	0.998476			
				R2=1-SSE/SST				

TABLE XXVII

P55-15-0 RHEOLOGICAL CALCULATIONS

0.55 wc 15% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	70.01136364	69.93189665	0.006315001	353.1831134		Yield Stress	to	0
250	63.26109091	63.70834996	0.200040661	145.0312944		Viscosity	eta	3.787250987
200	56.66536364	56.84000745	0.030500461	29.67162469		Flow Index	n	0.511218907
150	49.52190909	49.06627424	0.20760312	2.877392568				
100	40.79172727	39.88061995	0.830116549	108.7112703			Bingham	
50	27.05772727	27.98141519	0.853199369	583.728296			Yield Stress	22.286
			2.127775161	1223.202991			Viscosity	0.1653
	51.21819697			R2=	0.99826			
				R2=1-SSE/SST				
0.55 wc 15% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	69.64354545	69.60478881	0.001502078	347.093272		Yield Stress	to	0
250	63.01136364	63.4255498	0.171550177	143.9581849		Viscosity	eta	3.797901196
200	56.42927273	56.60429448	0.030632613	29.33486136		Flow Index	n	0.509904574
150	49.35209091	48.8812776	0.221665176	2.758971334				
100	40.694	39.75143491	0.888428954	106.4839499			Bingham	
50	26.94836364	27.91619597	0.93669942	579.1118279			Yield Stress	22.263
			2.250478417	1208.741067			Viscosity	0.1643
	51.01310606			R2=	0.998138			
				R2=1-SSE/SST				
0.55 wc 15% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	69.77818182	69.66241803	0.013401254	352.5979203		Yield Stress	to	0
250	62.96163636	63.45437516	0.242791519	143.0666084		Viscosity	eta	3.756921494
200	56.37972727	56.60415695	0.05036868	28.93510802		Flow Index	n	0.511951695
150	49.35690909	48.85238021	0.254549387	2.701689919				
100	40.65772727	39.69497292	0.92689595	106.9748282			Bingham	
50	26.86936364	27.83701692	0.93635288	582.3161297			Yield Stress	22.153
			2.424359672	1216.592285			Viscosity	0.1648
	51.00059091			R2=	0.998007			
				R2=1-SSE/SST				

TABLE XXVIII

P55-20-0 RHEOLOGICAL CALCULATIONS

0.55 wc 20% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	74.64463636	74.54167024	0.010602022	439.4931076		Yield Stress	to	0
250	66.92118182	67.51311229	0.350381681	175.3144513		Viscosity	eta	3.363837873
200	59.65190909	59.80629942	0.023836374	35.65718368		Flow Index	n	0.543196689
150	51.74336364	51.15412057	0.347207394	3.752673397				
100	42.10927273	41.04199224	1.139087649	133.8943525			Bingham	
50	27.01290909	28.16501176	1.327340565	711.1628292		Yield Stress		21.63
			3.198455686	1499.274598		Viscosity		0.1831
	53.68054545			R2=	0.997867			
				R2=1-SSE/SST				
0.55 wc 20% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	73.75709091	73.71694627	0.001611592	426.4325122		Yield Stress	to	0
250	66.23754545	66.77582701	0.289747037	172.4152029		Viscosity	eta	3.341734808
200	58.99409091	59.16366879	0.028756659	34.65962336		Flow Index	n	0.542401932
150	51.24836364	50.61603072	0.399844913	3.453965932				
100	41.73472727	40.62336042	1.235136285	129.3251409			Bingham	
50	26.66927273	27.89308786	1.497723475	698.9454119		Yield Stress		21.438
			3.45281996	1465.231857		Viscosity		0.181
	53.10684848			R2=	0.997643			
				R2=1-SSE/SST				
0.55 wc 20% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	73.34809091	73.51624226	0.028274877	410.1293891		Yield Stress	to	0
250	66.19781818	66.65509225	0.209099569	171.6461261		Viscosity	eta	3.42958844
200	59.14436364	59.12298923	0.000456865	36.57738764		Flow Index	n	0.537374297
150	51.34254545	50.65443993	0.473489214	3.076143951				
100	41.84318182	40.73714616	1.223314872	126.6358061			Bingham	
50	26.70263636	28.06886288	1.866574882	696.6328384		Yield Stress		21.687
			3.80121028	1444.697691		Viscosity		0.1795
	53.09643939			R2=	0.997369			
				R2=1-SSE/SST				

TABLE XXIX

P55-25-0 RHEOLOGICAL CALCULATIONS

0.55 wc 25% SAP sample 1								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	73.87445455	73.84390116	0.000933509	443.4802047		Yield Stress	to	0
250	66.209	66.72221427	0.263388887	179.3862481		Viscosity	eta	3.093342588
200	58.74345455	58.9338385	0.03624605	35.14082473		Flow Index	n	0.556245121
150	50.84009091	50.21901221	0.385738755	3.902181216				
100	41.24781818	40.07912784	1.365837105	133.8109121			Bingham	
50	25.97809091	27.25660723	1.634603991	720.2457135		Yield Stress		20.589
			3.686748298	1515.966084		Viscosity		0.1842
	52.81548485			R2=	0.997568			
				R2=1-SSE/SST				
0.55 wc 25% SAP sample 2								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	70.86245455	70.7336816	0.016582471	385.4493346		Yield Stress	to	0
250	63.58190909	64.19246377	0.372777019	152.5797645		Viscosity	eta	3.398138177
200	56.78072727	57.00410583	0.04989798	30.81511493		Flow Index	n	0.532224745
150	49.51118182	48.91146268	0.359663046	2.952929804				
100	40.59909091	39.41763148	1.395846378	113.0075303			Bingham	
50	26.04218182	27.2568028	1.475304141	634.4055767		Yield Stress		21.198
			3.670071035	1319.210251		Viscosity		0.1716
	51.22959091			R2=	0.997218			
				R2=1-SSE/SST				
0.55 wc 25% SAP sample 3								
[1/s]	[Pa]	tao'	SSE (tao-tao')^2	SST (yi-ybar)^2			Herschel-Bulkley	
300	74.25981818	74.25770342	4.47221E-06	446.6536411		Yield Stress	to	0
250	66.47636364	67.10485766	0.395004736	178.2419187		Viscosity	eta	3.1233917
200	59.12454545	59.28127616	0.024564514	35.98691028		Flow Index	n	0.555529956
150	51.29363636	50.52546666	0.590084701	3.356224				
100	41.68890909	40.33539961	1.831987906	130.7987307			Bingham	
50	25.91054545	27.4444912	2.352989552	740.6611732		Yield Stress		20.732
			5.194635882	1535.698598		Viscosity		0.1851
	53.12563636			R2=	0.996617			
				R2=1-SSE/SST				

TABLE XXX

SUMMARY OF RHEOLOGICAL VALUES

Specimen	Bingham Yield Stress (Pa)	Bingham Viscosity (Pa·s)	Herschel-Bulkley Flow Behavior Index
P35-0-0	36.3533	0.8870	0.9111
P35-5-0	42.7180	0.9552	0.9221
P35-10-0	47.3077	1.0656	0.9088
P35-15-0	46.3730	0.9791	0.8816
P35-20-0	48.7037	1.1083	0.9241
P35-25-0	46.4197	0.9845	0.9638
P35-0-SP	12.3810	0.5665	1.1750
P35-5-SP	11.5913	0.5688	1.1843
P35-10-SP	6.2129	0.5355	1.2574
P35-15-SP	1.1778	0.5748	1.1843
P35-20-SP	0.5537	0.5986	1.3278
P35-25-SP	4.6212	0.6256	1.3492
P45-0-0	27.5533	0.2088	0.5319
P45-5-0	27.4180	0.2502	0.6045
P45-10-0	30.4883	0.2438	0.5153
P45-15-0	25.8277	0.3035	0.6218
P45-20-0	25.0037	0.3239	0.6429
P45-25-0	21.6063	0.3458	0.6892
P55-0-0	12.3810	0.5665	0.4730
P55-5-0	11.5913	0.5688	0.5128
P55-10-0	6.2129	0.5355	0.4971
P55-15-0	1.1778	0.5748	0.5128
P55-20-0	0.5537	0.5986	0.5410
P55-25-0	4.6212	0.6256	0.5480

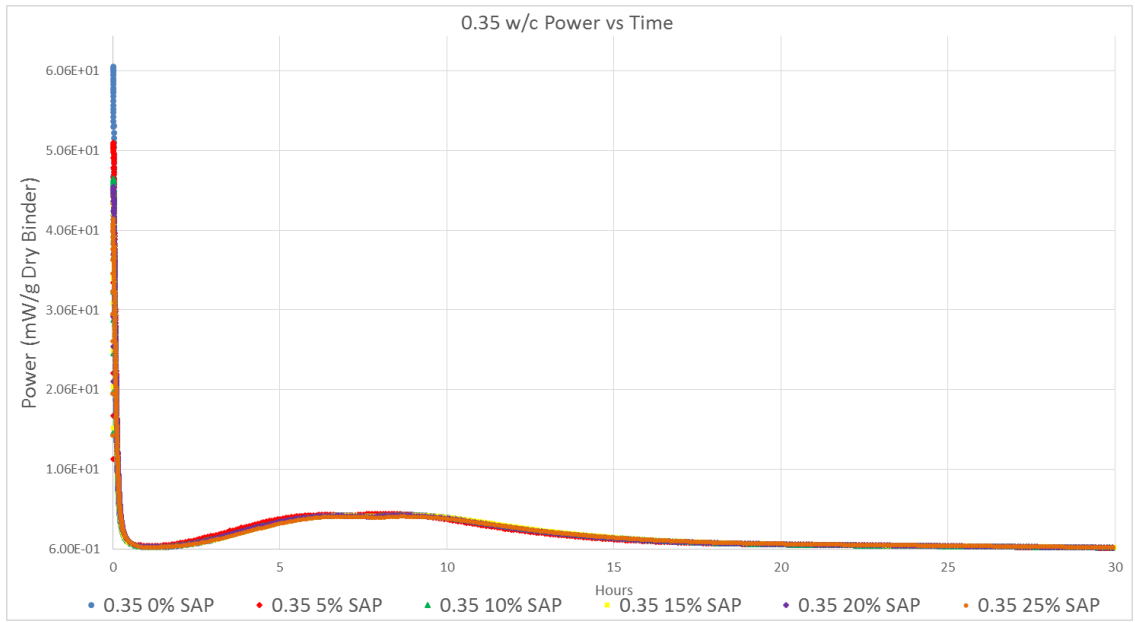


FIGURE 39 – POWER 0.35 W/C 0-30 HRS

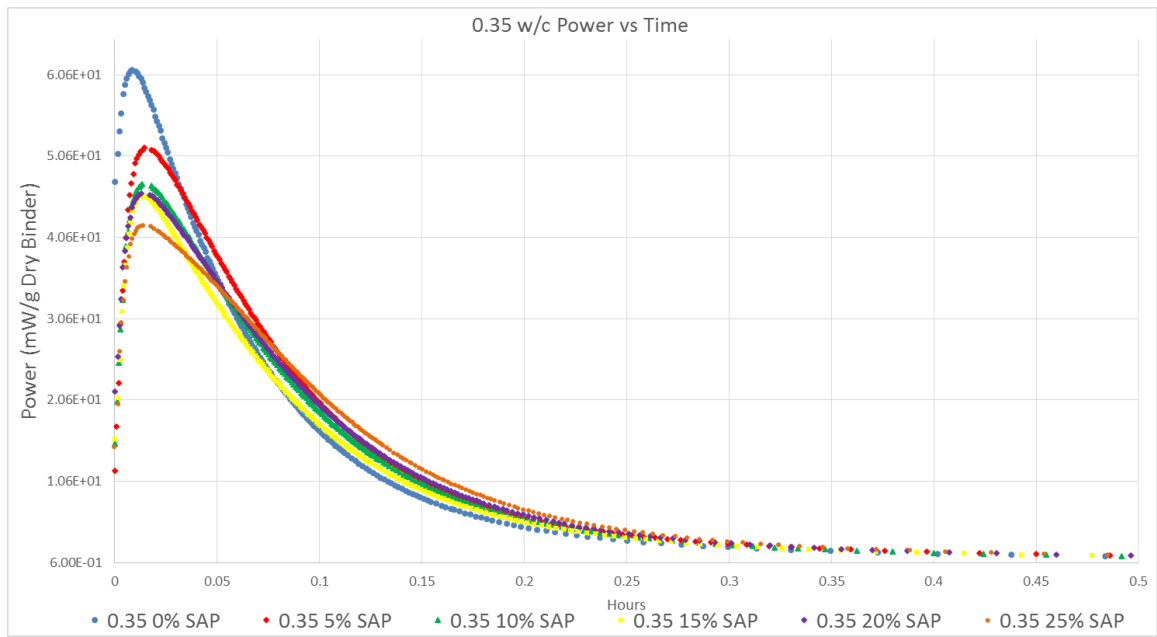


FIGURE 40 – POWER 0.35 W/C 0-0.5 HRS

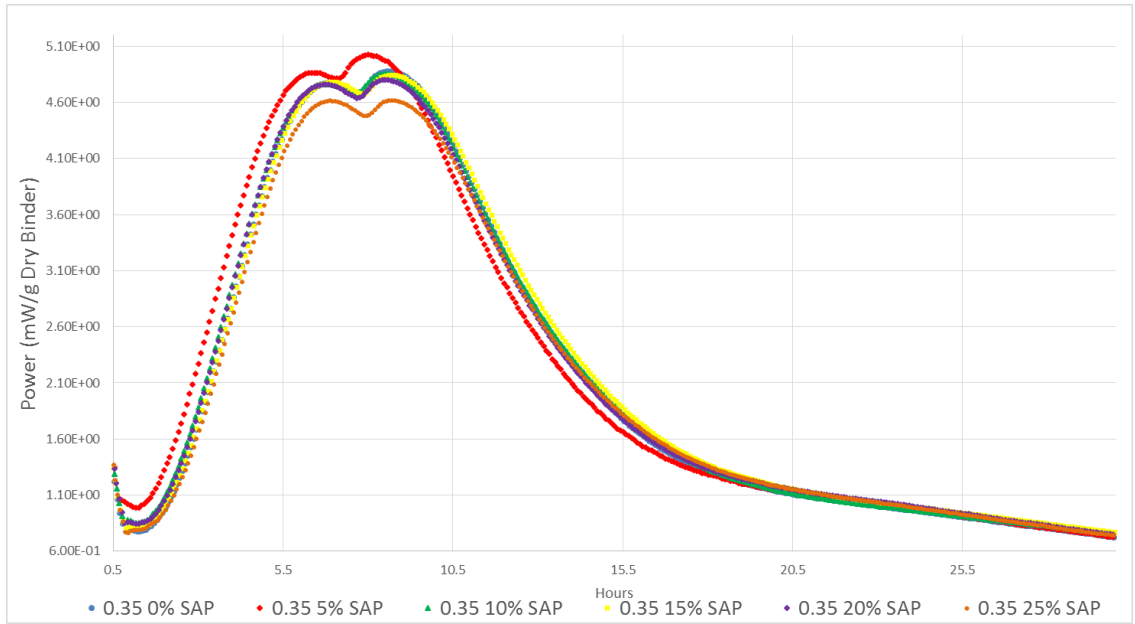


FIGURE 41 – POWER 0.35 W/C 0.5-30 HRS

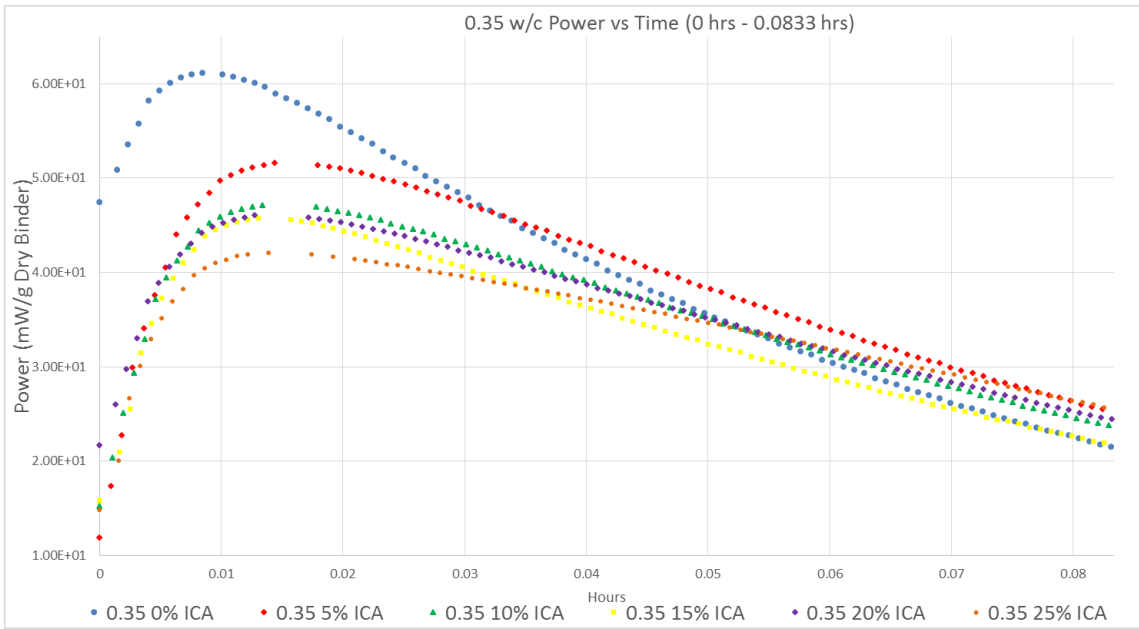


FIGURE 42 – POWER 0.35 W/C 0-0.0833 HRS

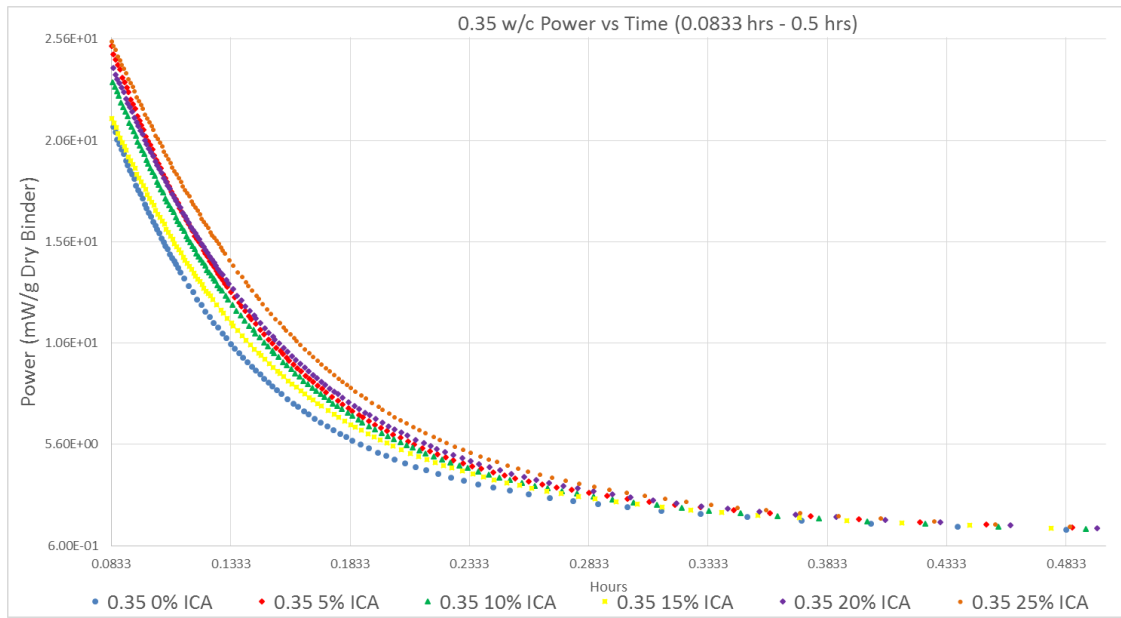


FIGURE 43 – POWER 0.35 W/C 0.0833-0.5 HRS

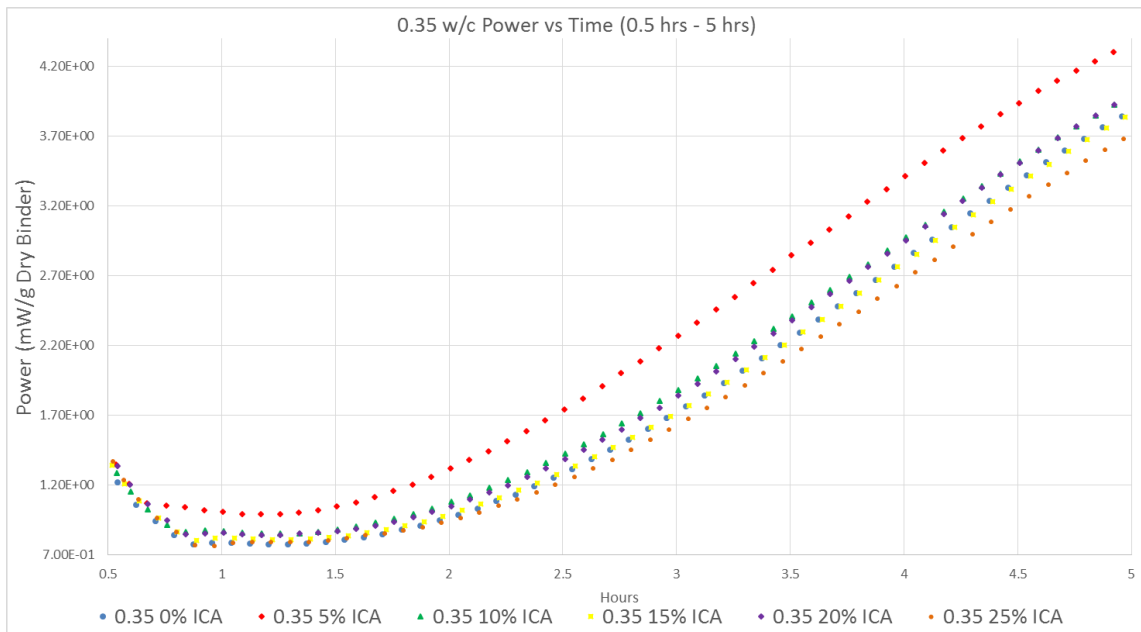


FIGURE 44 – POWER 0.35 W/C 0.5-5 HRS

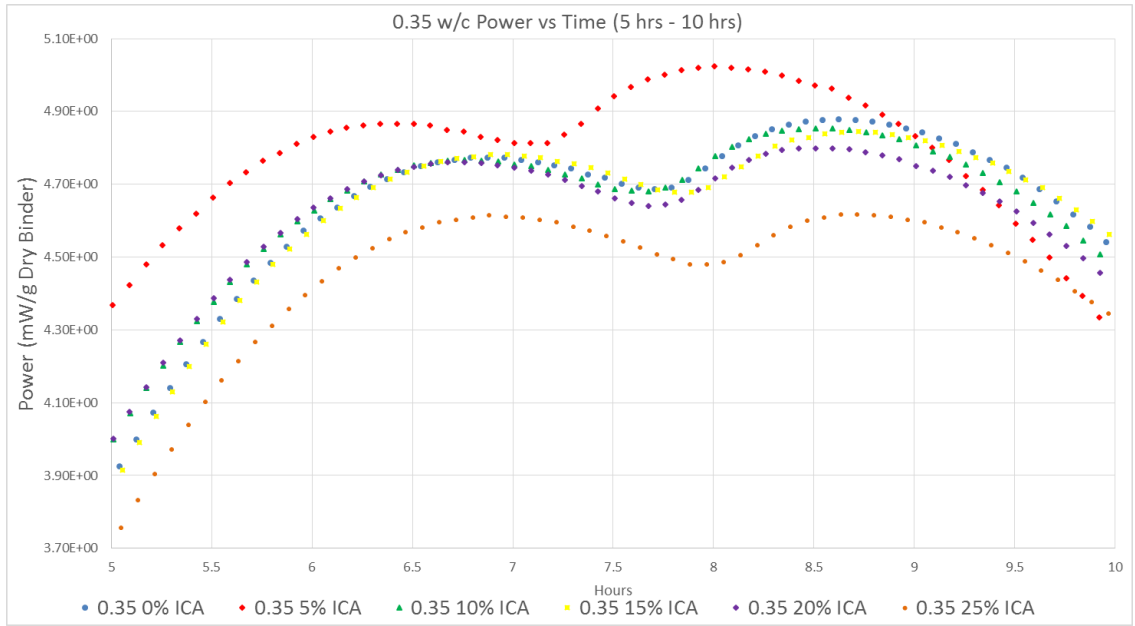


FIGURE 45 – POWER 0.35 W/C 5-10 HRS

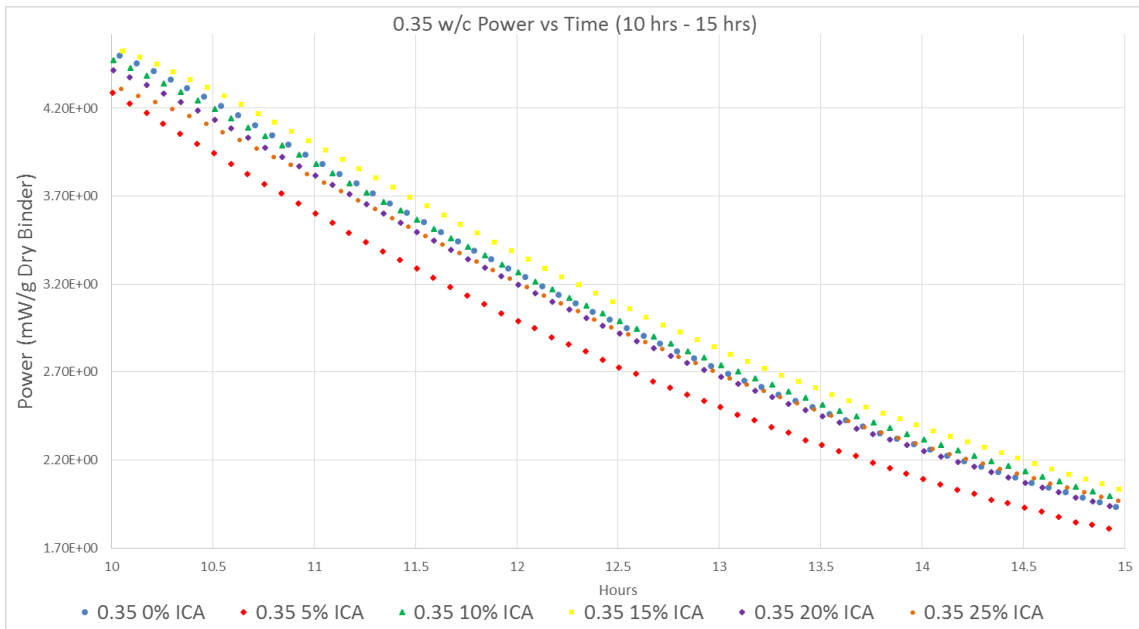


FIGURE 46 – POWER 0.35 W/C 10-15 HRS

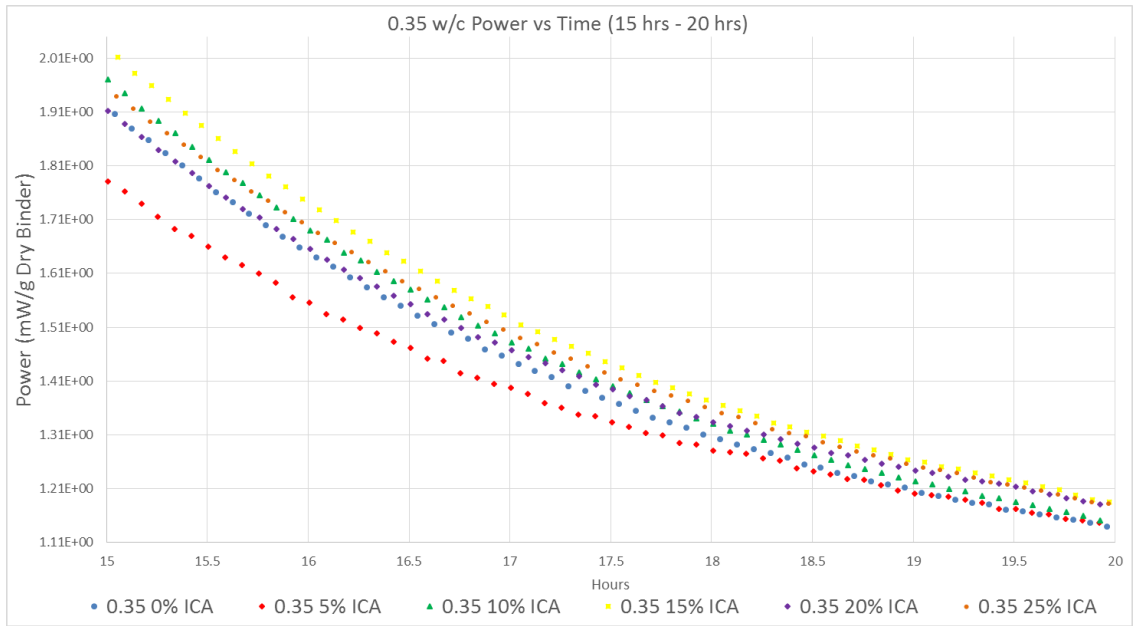


FIGURE 47 – POWER 0.35 W/C 15-20 HRS

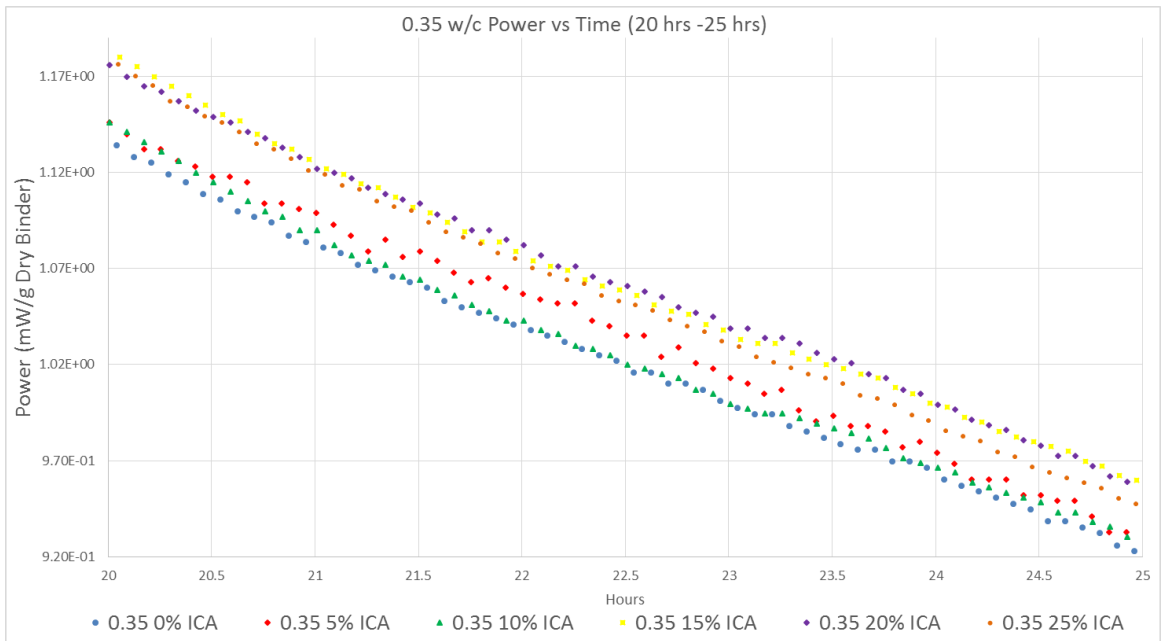


FIGURE 48 – POWER 0.35 W/C 20-25 HRS

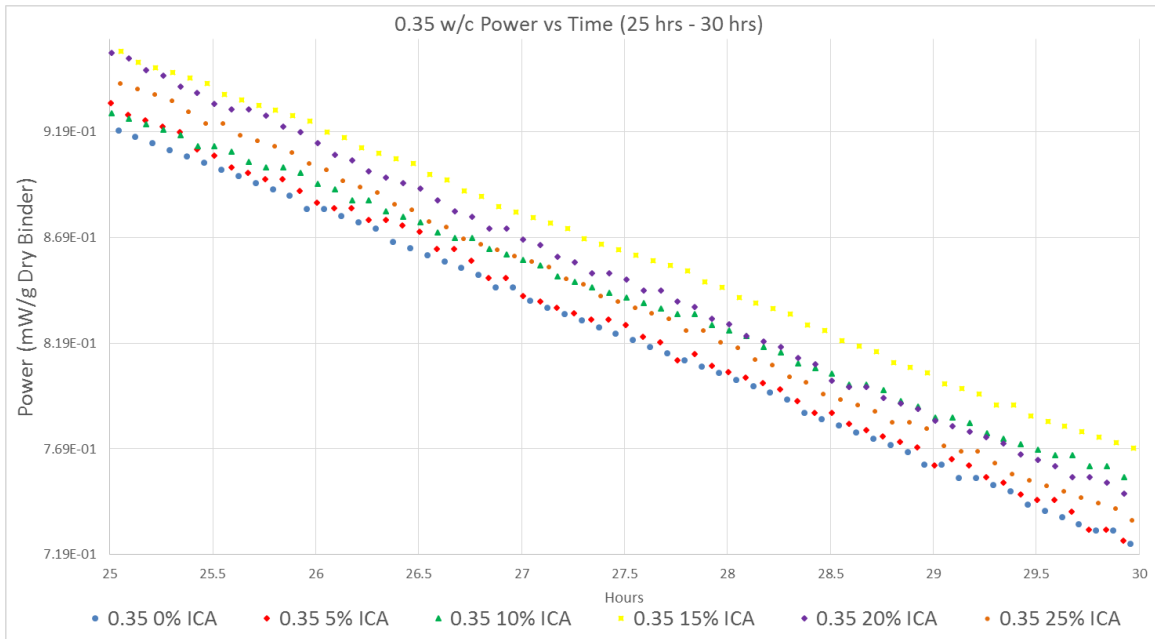


FIGURE 49 – POWER 0.35 W/C 25-30 HRS

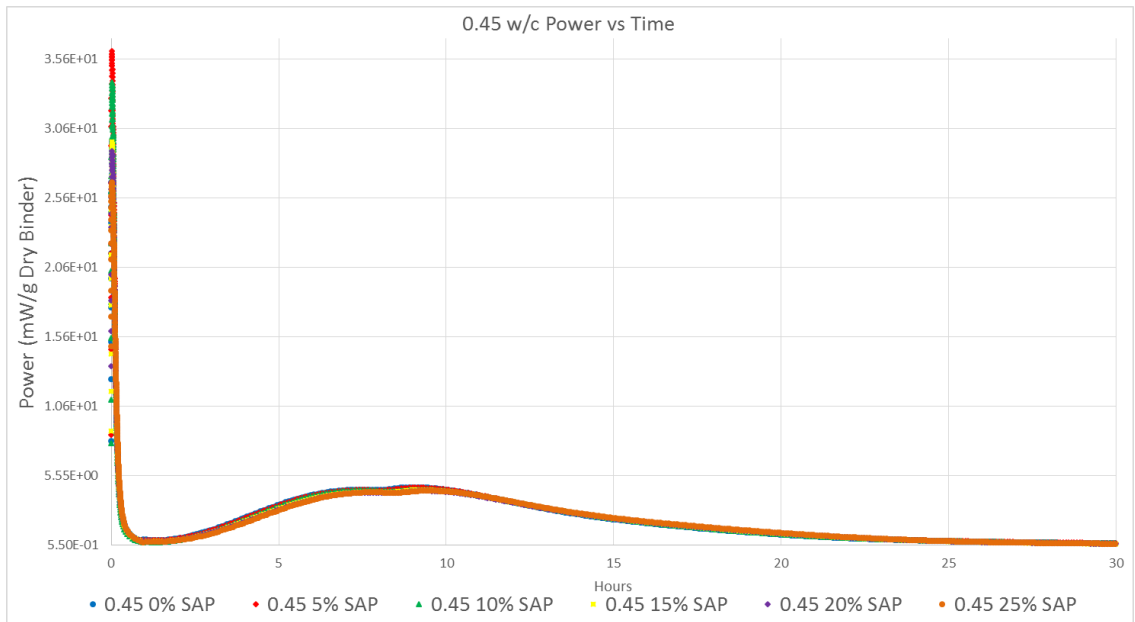


FIGURE 50 – POWER 0.45 W/C 0-30 HRS

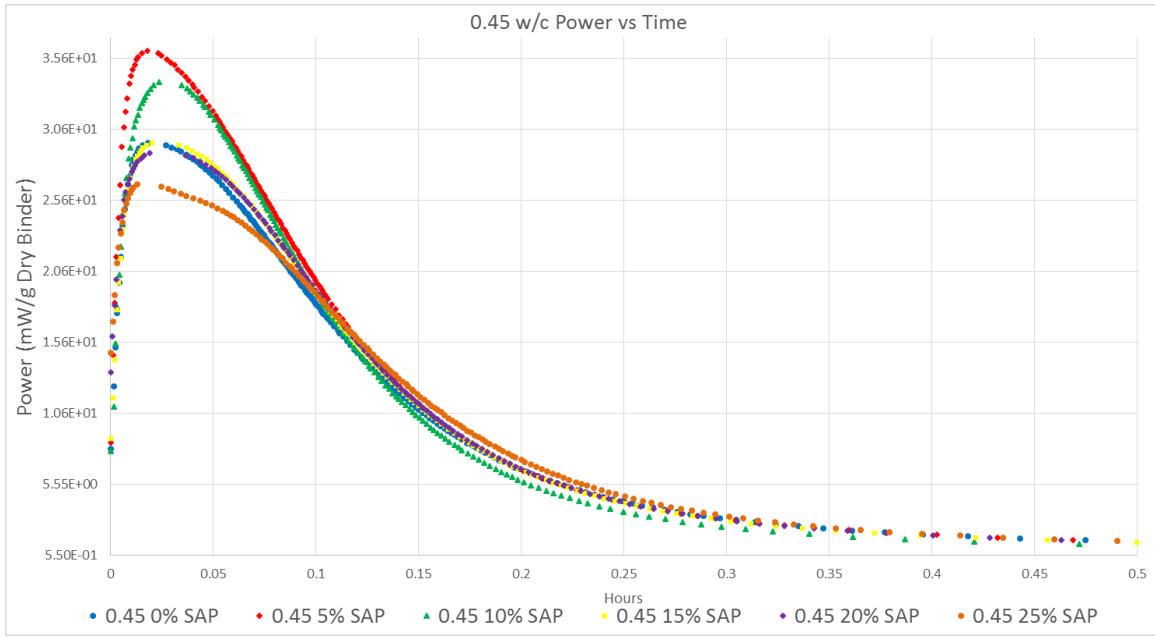


FIGURE 51 – POWER 0.45 W/C 0-0.5 HRS

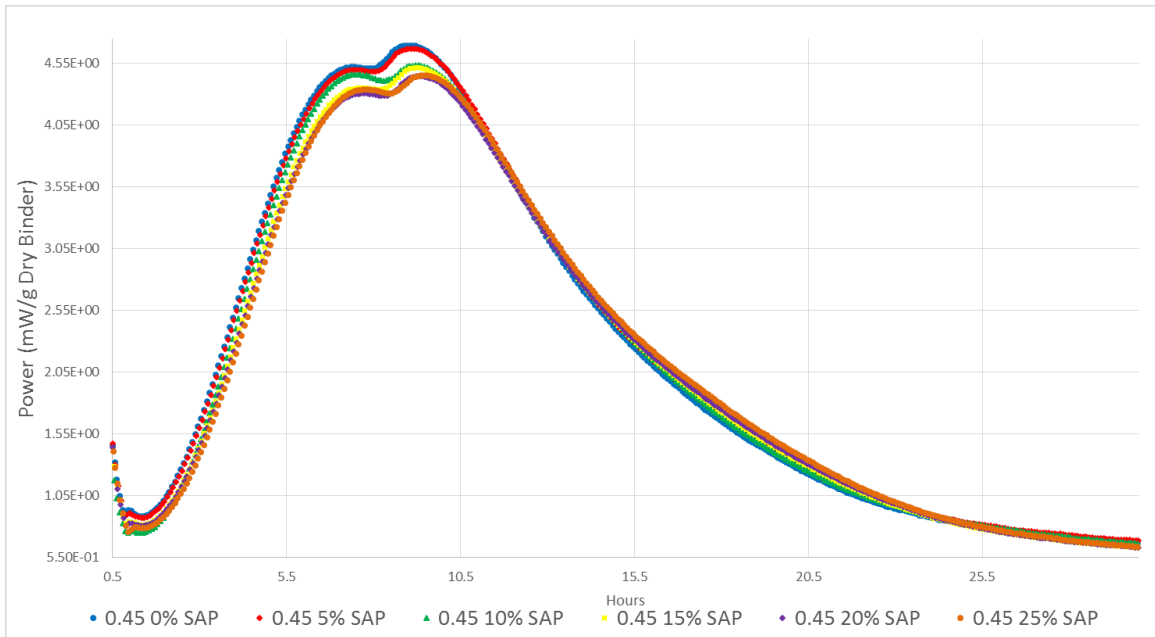


FIGURE 52 – POWER 0.45 W/C 0.5-30 HRS

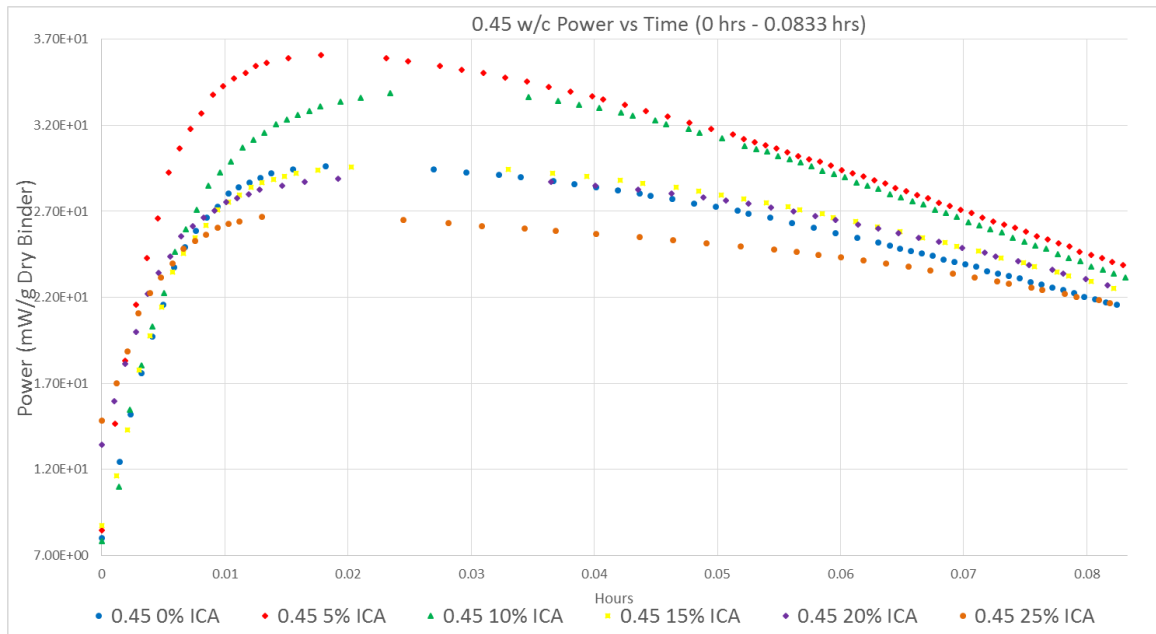


FIGURE 53 – POWER 0.45 W/C 0-0.0833 HRS

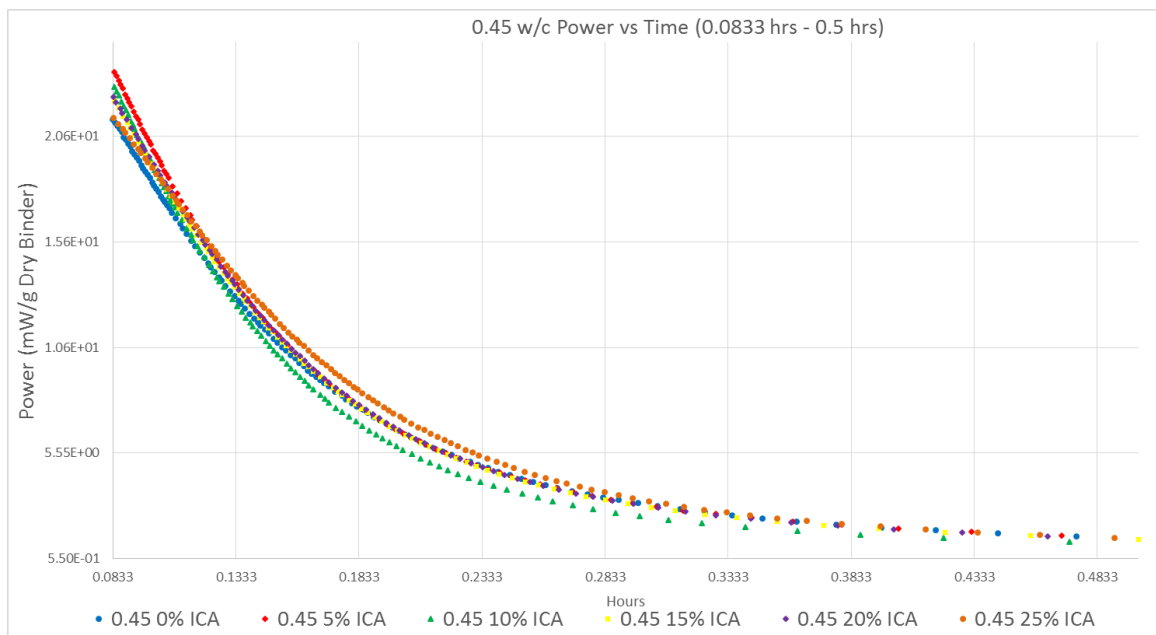


FIGURE 54 – POWER 0.45 W/C 0.0833-0.5 HRS

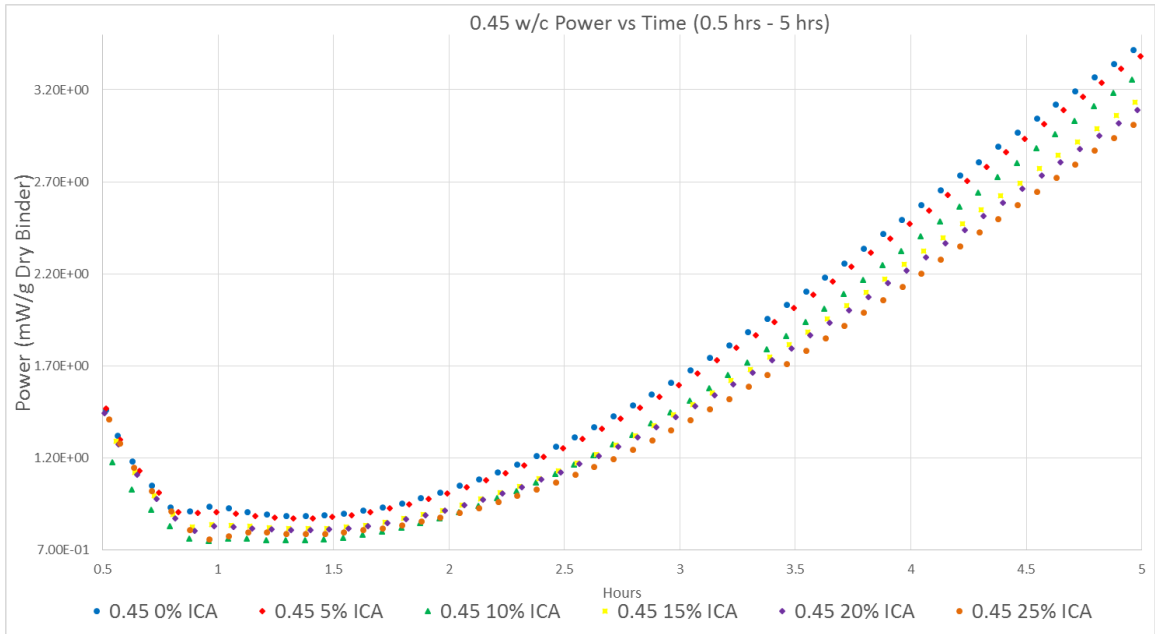


FIGURE 55 – POWER 0.45 W/C 0.5-5 HRS

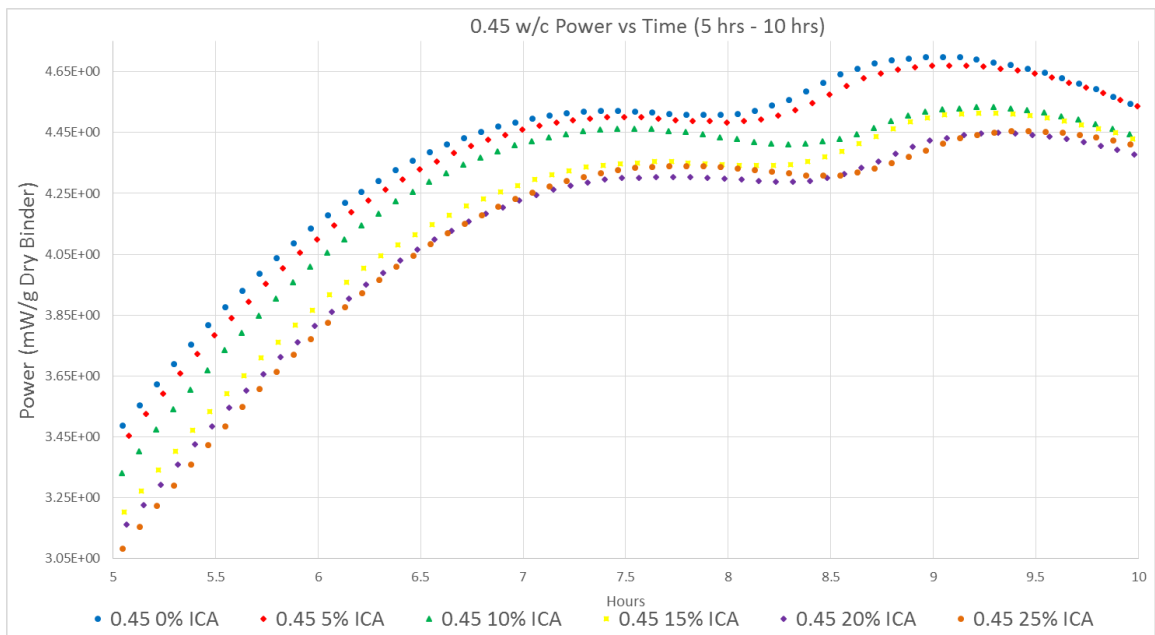


FIGURE 56 – POWER 0.45 W/C 5-10 HRS

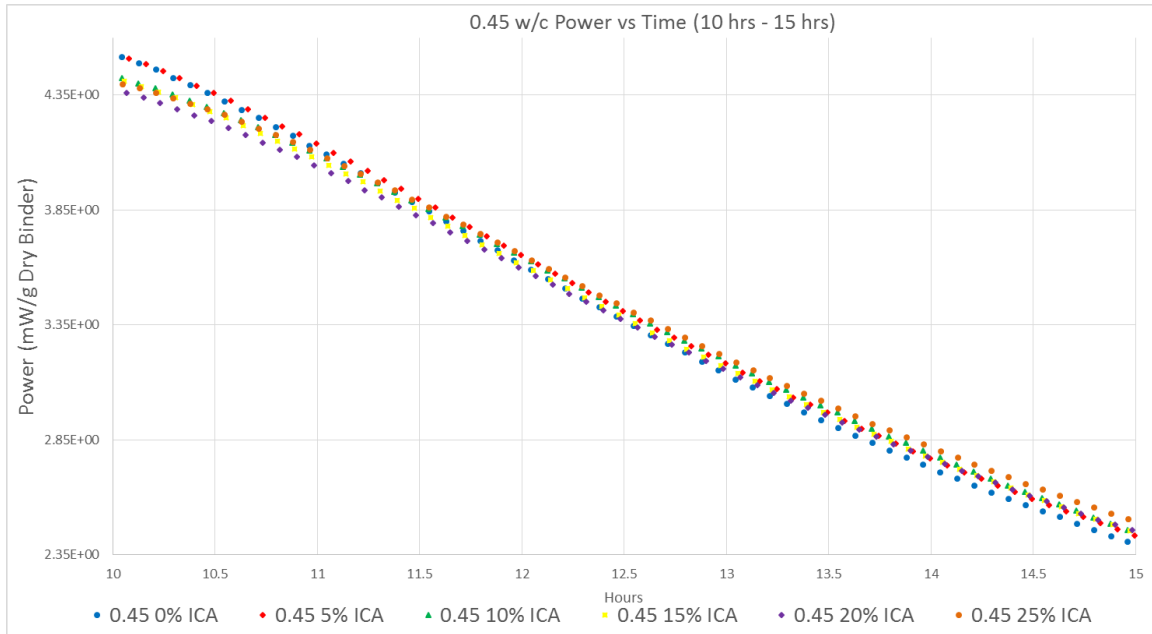


FIGURE 57 – POWER 0.45 W/C 10-15 HRS

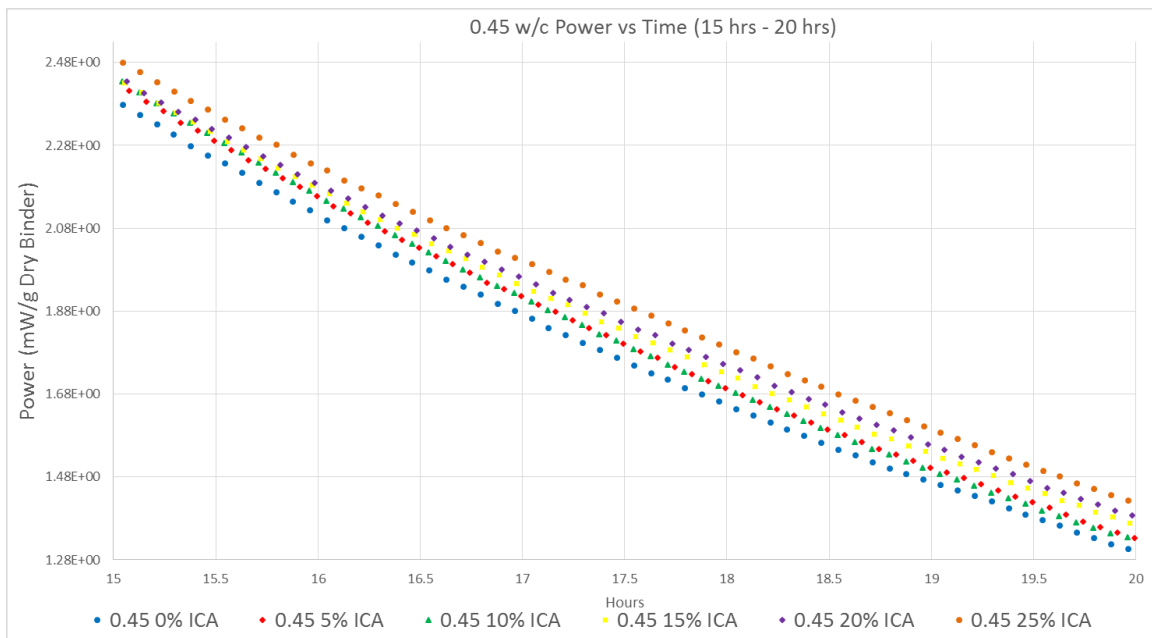


FIGURE 58 – POWER 0.45 W/C 15-20 HRS

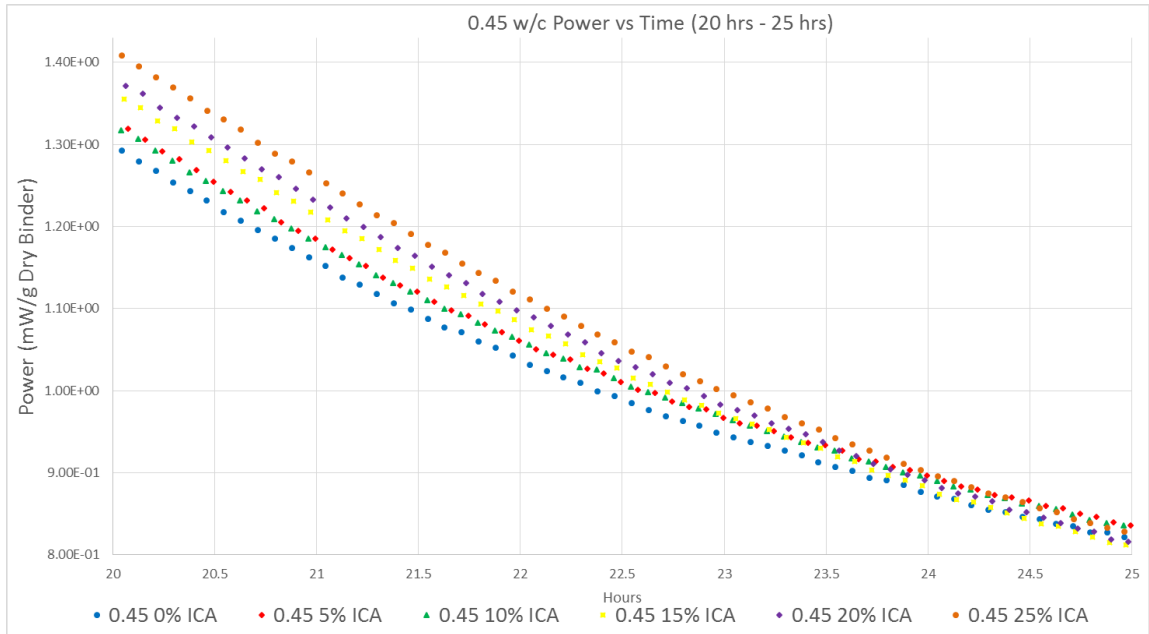


FIGURE 59 – POWER 0.45 W/C 20-25 HRS

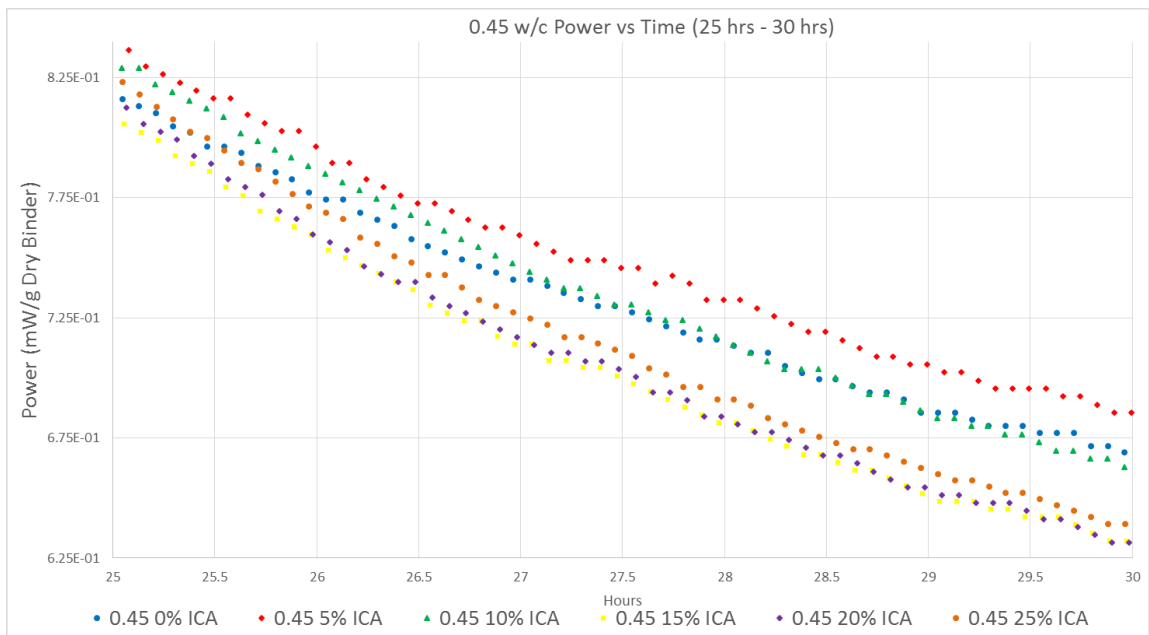


FIGURE 60 – POWER 0.45 W/C 25-30 HRS

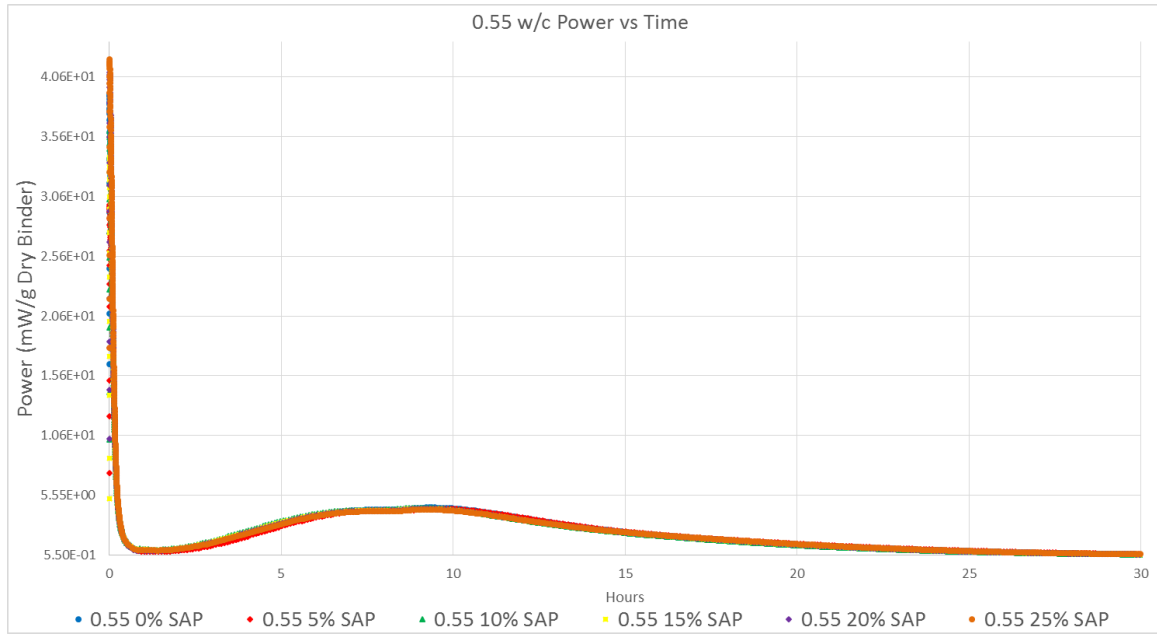


FIGURE 61 – POWER 0.55 W/C 0-30 HRS

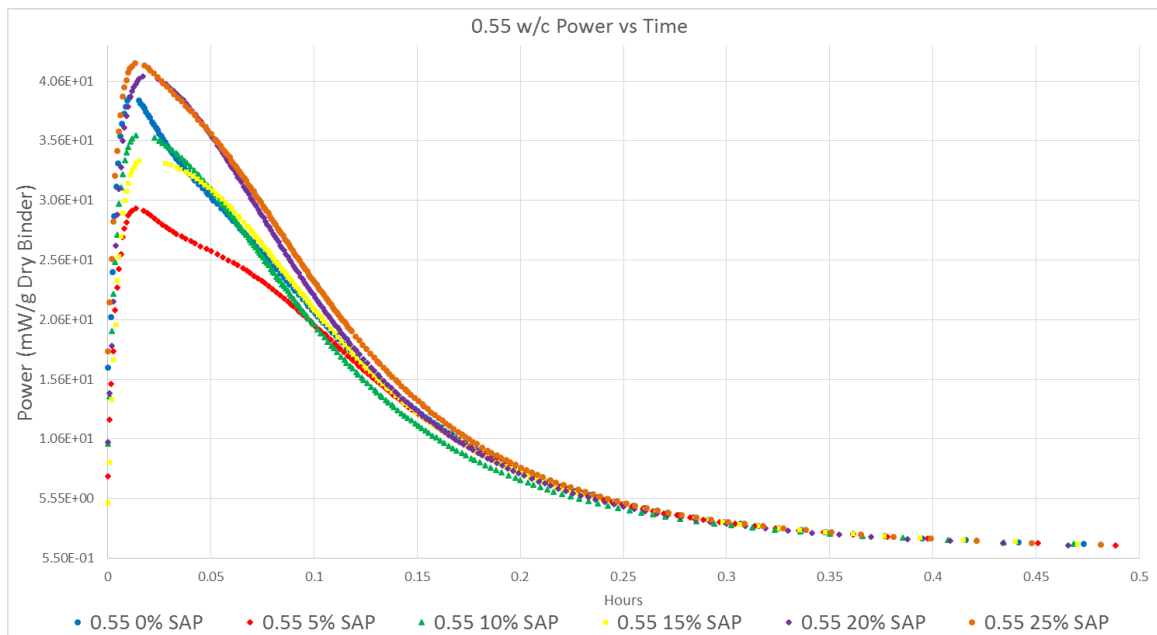


FIGURE 62 – POWER 0.55 W/C 0-0.5 HRS

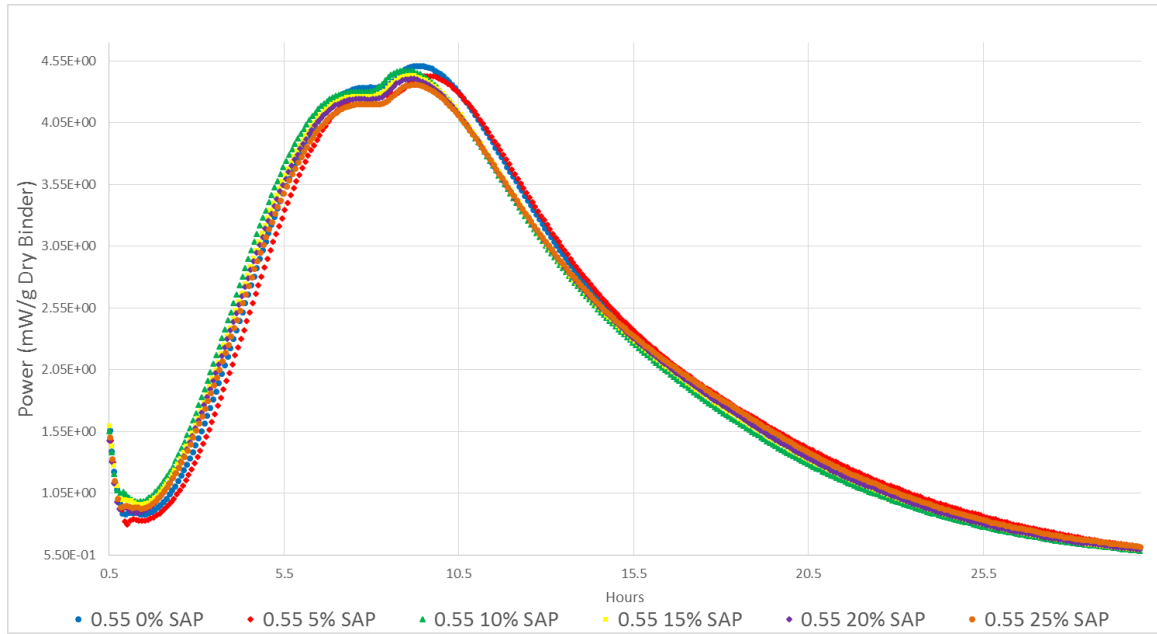


FIGURE 63 – POWER 0.55 W/C 0.5-30 HRS

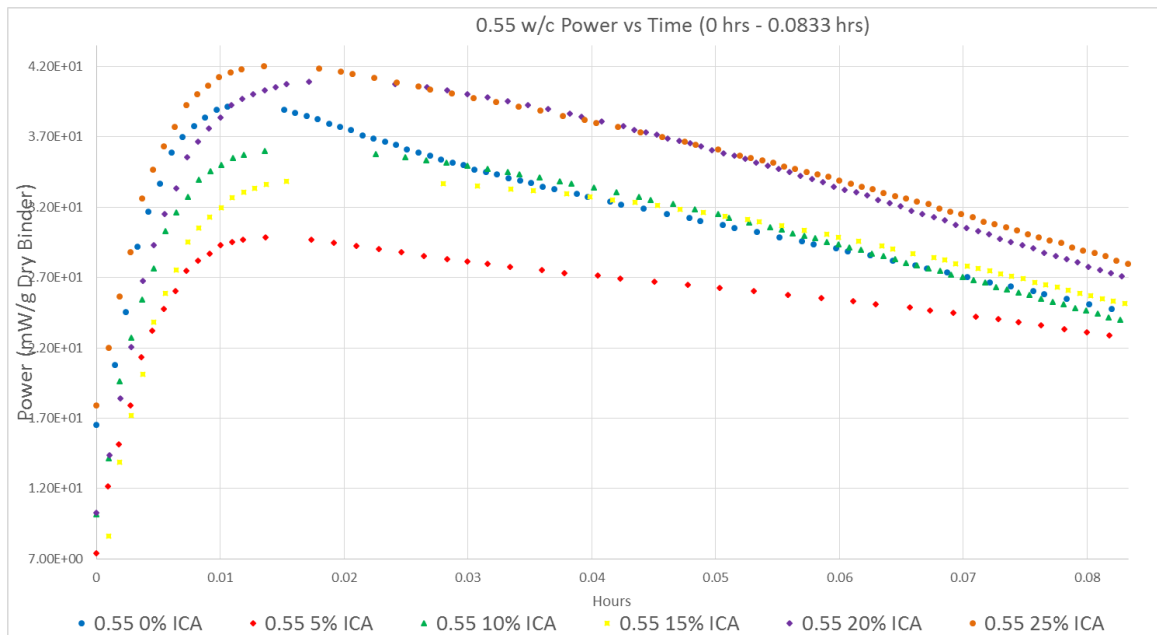


FIGURE 64 – POWER 0.55 W/C 0-0.0833 HRS

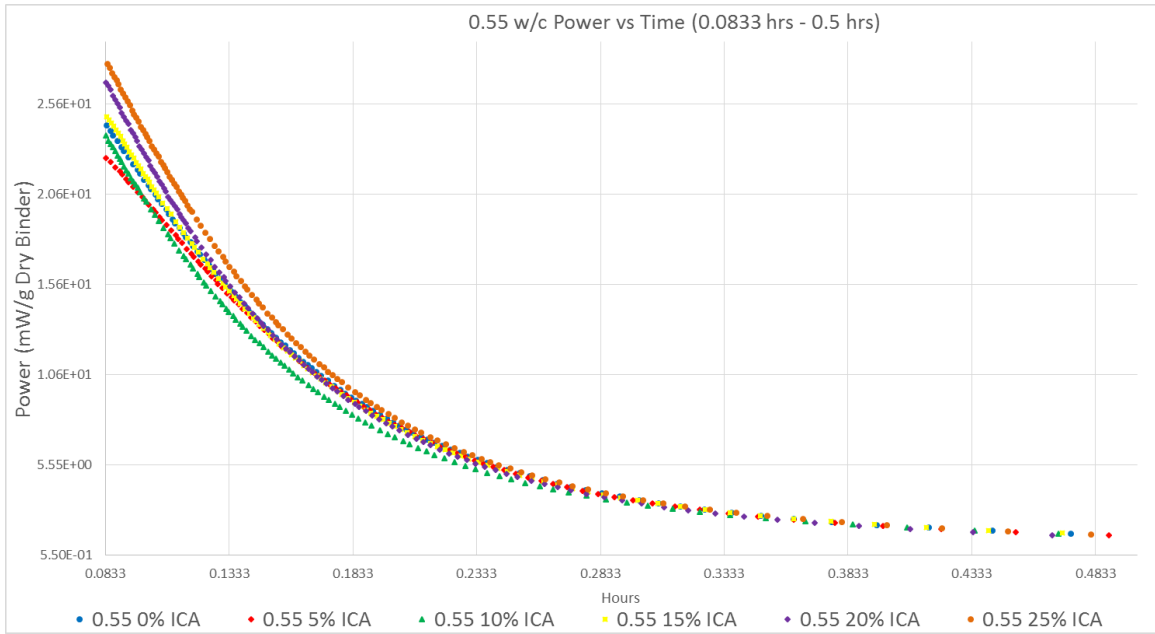


FIGURE 65 – POWER 0.55 W/C 0.0833-0.5 HRS

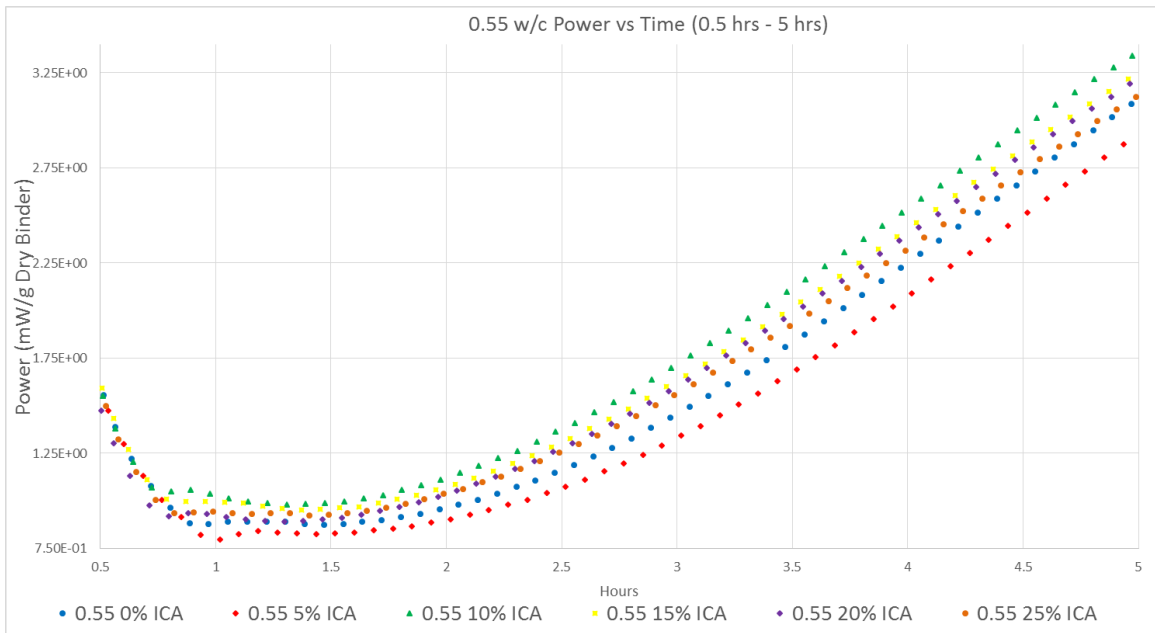


FIGURE 66 – POWER 0.55 W/C 0.5-5 HRS

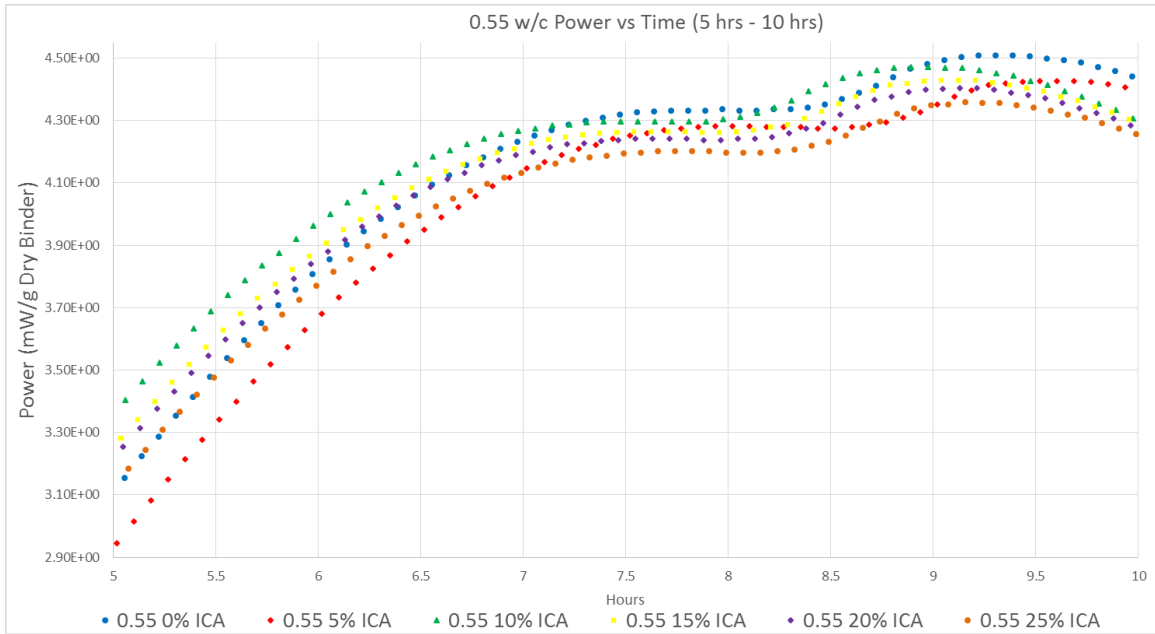


FIGURE 67 – POWER 0.55 W/C 5-10 HRS

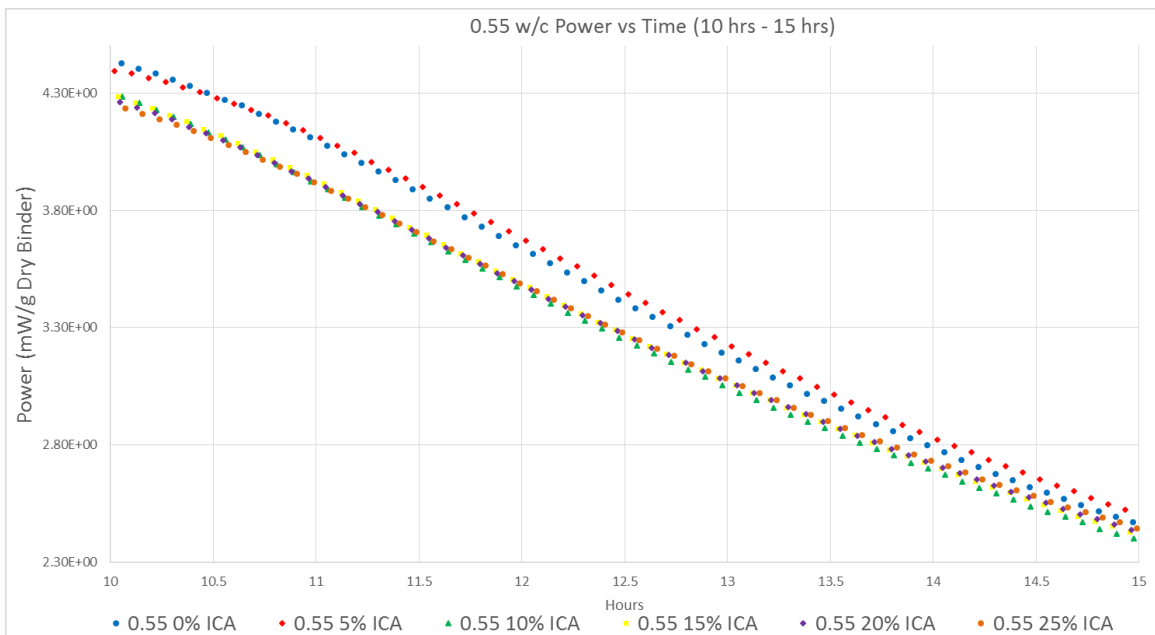


FIGURE 68 – POWER 0.55 W/C 10-15 HRS

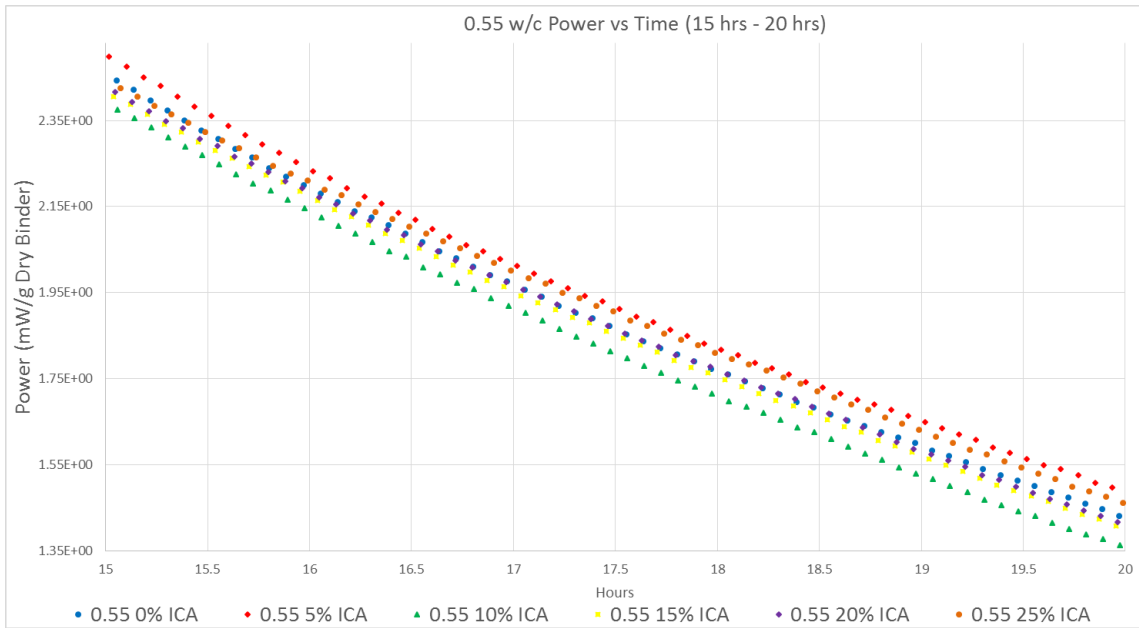


FIGURE 69 – POWER 0.55 W/C 15-20 HRS

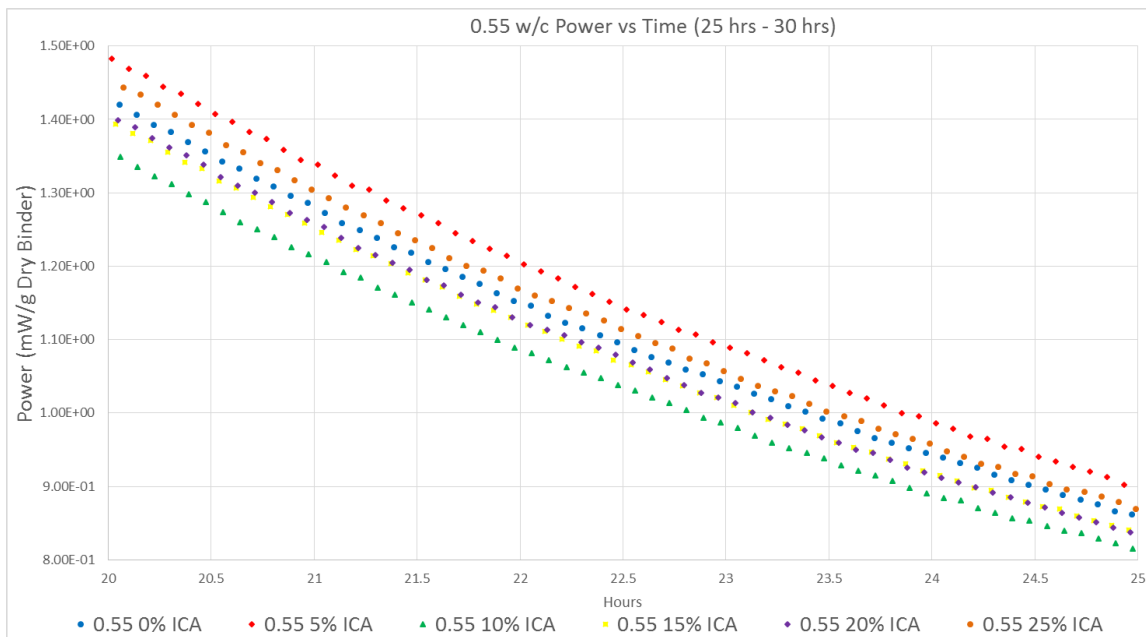


FIGURE 70 – POWER 0.55 W/C 20-25 HRS

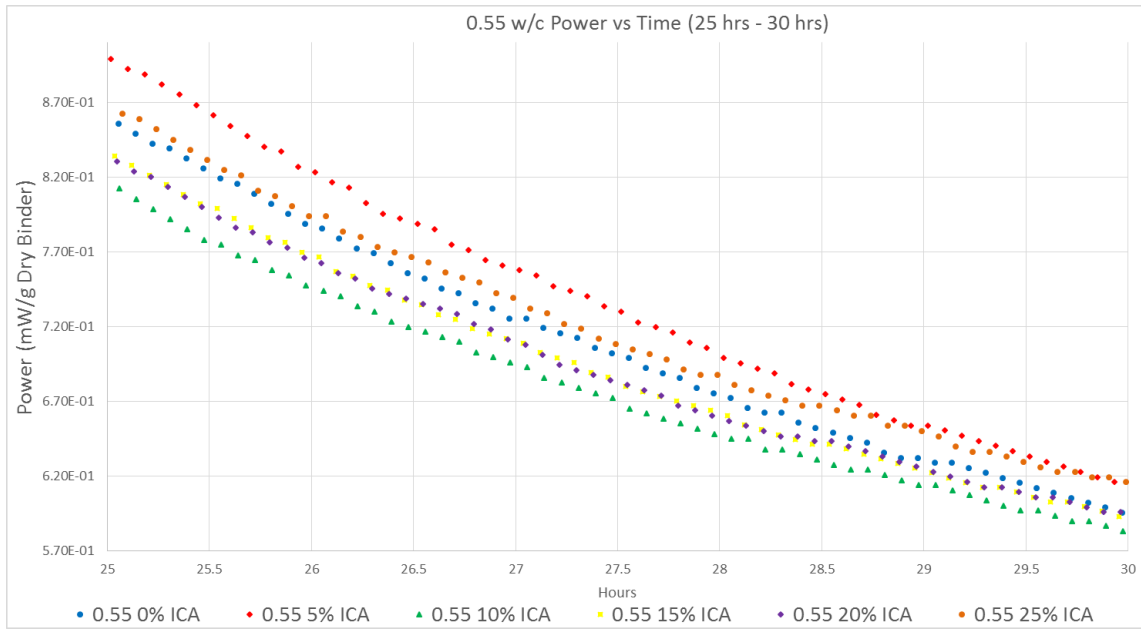


FIGURE 71 – POWER 0.55 W/C 25-30 HRS

NOMENCLATURE

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LWA = light weight aggregate

MK = metakaolin

NIST = National Institute of Standards and Technology

SAP = super absorbent polymer

SCC = self compacting concrete

SP = superplasticizer

SSE = sum of square error

SST = sum of square total

STAGAA = starch graft acrylamide-2-acrylamido-2-methyl propyl sulfonic acid

VEA = viscosity enhancing admixture

W/C = water-to-cement

τ = shear stress

τ_0 = yield stress

$\dot{\gamma}$ = shear rate

η = viscosity

η' = bingham plastic viscosity

K = consistency index

n = flow behavior index

VITA

James Wong was born in Louisville, Kentucky and is the first in his family to attend college and graduate with his Bachelor's of Science in Civil Engineering in 2015 from the University of Louisville. He will graduate in the spring of 2016 with a Master's of Engineering in Civil Engineering with a focus in structures. As an undergraduate he worked as Environmental Health and Safety intern at LLFLEX (previously Reynold Aluminum Packaging) from December 2011 to August 2014. While pursuing his Master's degree, he worked as a laboratory, teaching assistant and graduate research student in the Civil and Environmental Engineering department at the University of Louisville. He is also an active member of the ASCE student chapter. After graduation, he is expecting to utilize his education and research begin his career as a civil engineer.