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

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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.

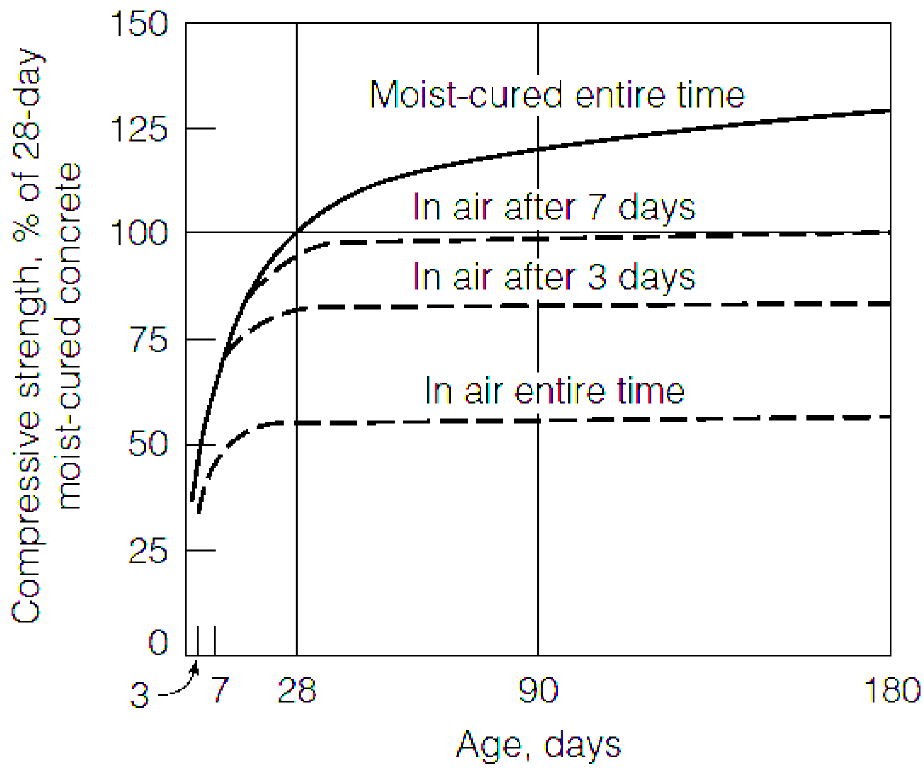


FIGURE 1 – COMPRESSIVE STRENGTH VS AGE (Mamlouk and Zaniewski 2011)

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.

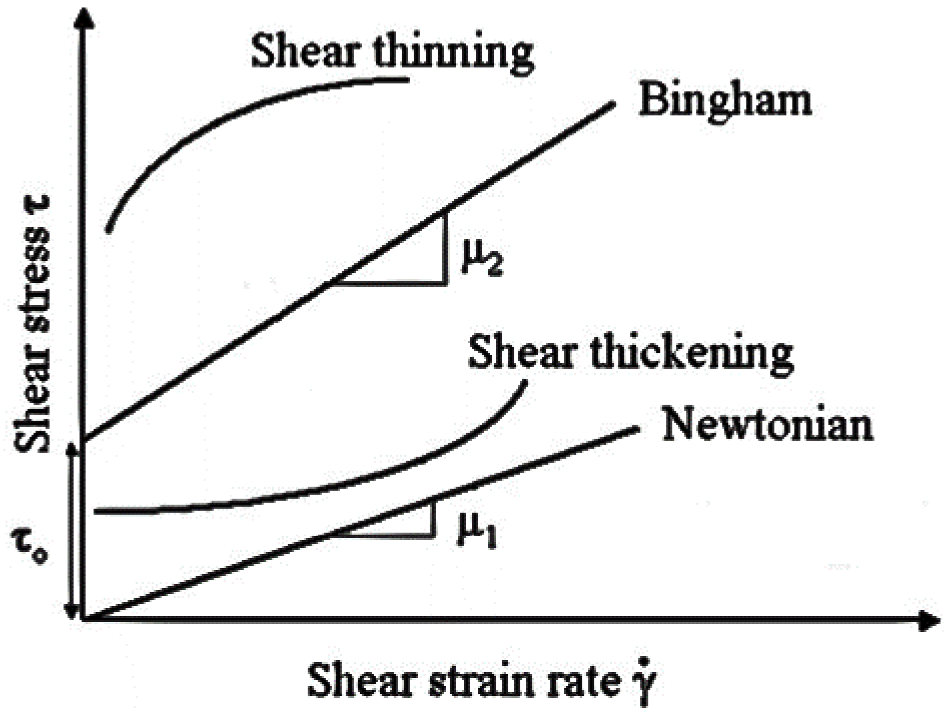


FIGURE 2 – FLOW BEHAVIORS (http://www.theconcreteportal.com/rheology.html)

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 $\tau$ (Pa) and shear rate $\dot{\gamma}$ ($s^{-1}$) are proportional. Viscosity $\eta$ (Pa·s), characterizes the slope of the linear line when plotting shear rate versus shear stress. The model is represented in the following equation.

$$\tau = \eta\dot{\gamma} \tag{1}$$

$\tau = \ shear\ stress$

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

$\eta = \ viscosity$

In the Bingham Model, Bingham plastic fluids exhibits a yield stress $\tau_0$ (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 $\tau_0$ (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.

$$\tau = \tau_0 + \eta' \dot{\gamma} \tag{2}$$

$$\tau = \ shear\ stress$$

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

$$\eta' = Bingham\ plastic\ viscosity$$

$$\tau_0 = \ yield\ stress$$

The Herschel-Bulkley model is applied when a material behaves non-linearly. Stress $\tau$ (Pa), shear rate $\dot{\gamma}$ ($s^{-1}$), flow behavior index n, yield stress $\tau_0$ (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.

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

$$\tau = \ shear\ stress$$

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

$$n = \ flow\ behavior\ index$$

$$K = consistency\ index$$

$$\tau_0 = \ yield\ stress$$

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 rested 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 rated) 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 thed 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 15$s^{-1}$, 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 |

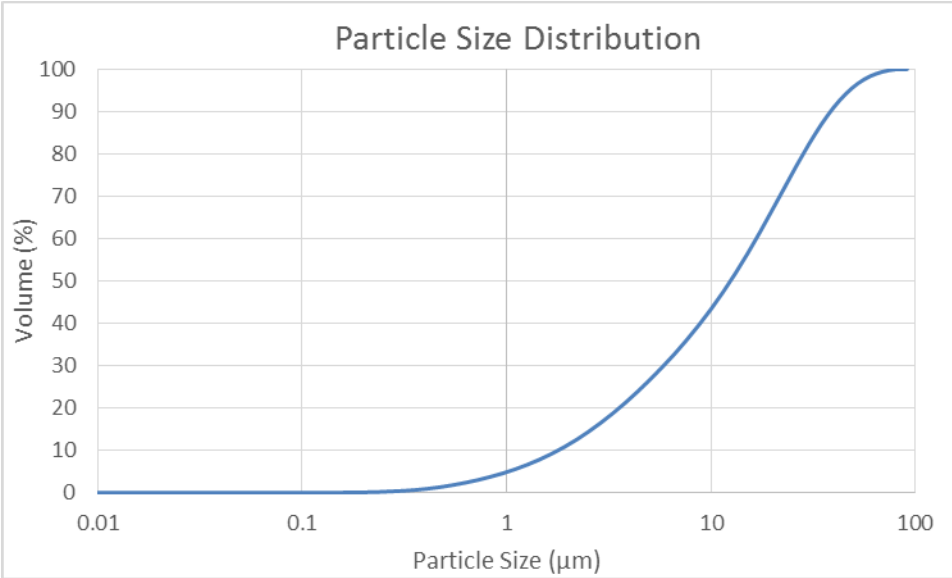


FIGURE 3 – PARTICLE SIZE DISTRIBUTION

**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-acrylamindo-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.

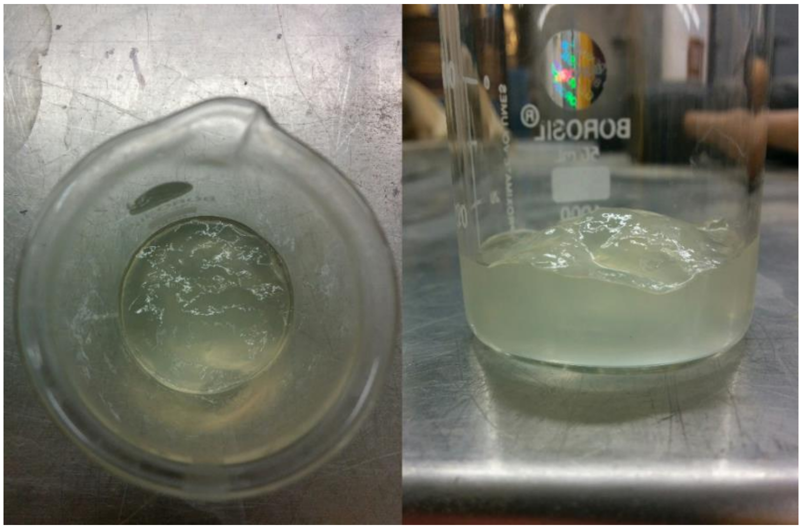


FIGURE 4 – STARCH GRAFT ACRYLAMIDE-2-ACRYLAMIDE-2-METHYL PROPYL SULFONIC ACID (STAGAA) GEL

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

### **C.** <u>Superplasticizer</u>

Superplastizier (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 show in Figure 6.

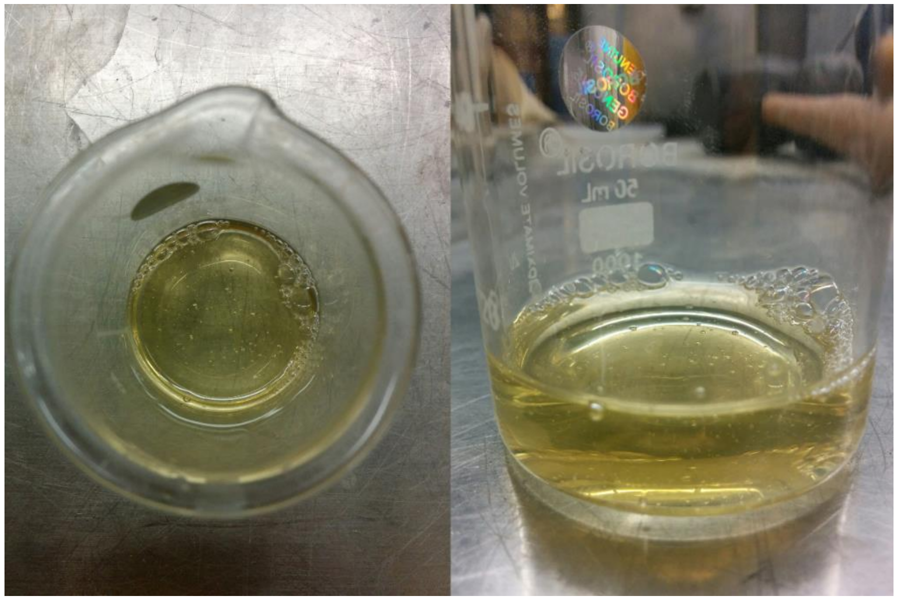

FIGURE 6 – SUPERPLASTICIZER (SP)

# 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 DUTIY 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 an 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 a 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 $\tau$, x = shear rate $\dot{\gamma}$, 26.636 = yield stress $\tau_0$ 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

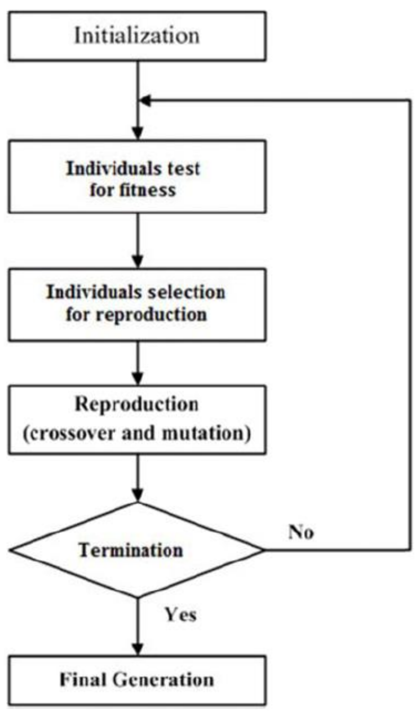


FIGURE 12 – GENETIC ALGORITHMS METHOD FLOW CHART (Rooki, Reza, et al. 2012)

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 |
|---|---|---|---|---|---|
| | | | SSE | SST | $R^2$ |
| $\dot{\gamma}$ | $\tau$ | $\tau'$ | $(\tau-\tau')^2$ | $(\tau-\Sigma\tau)^2$ | 1-[(ΣSSE)/(ΣSST)] |
| 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 |
| $\tau_0$ | K | n |
| 5.6045 | 2.7498 | 0.6092 |

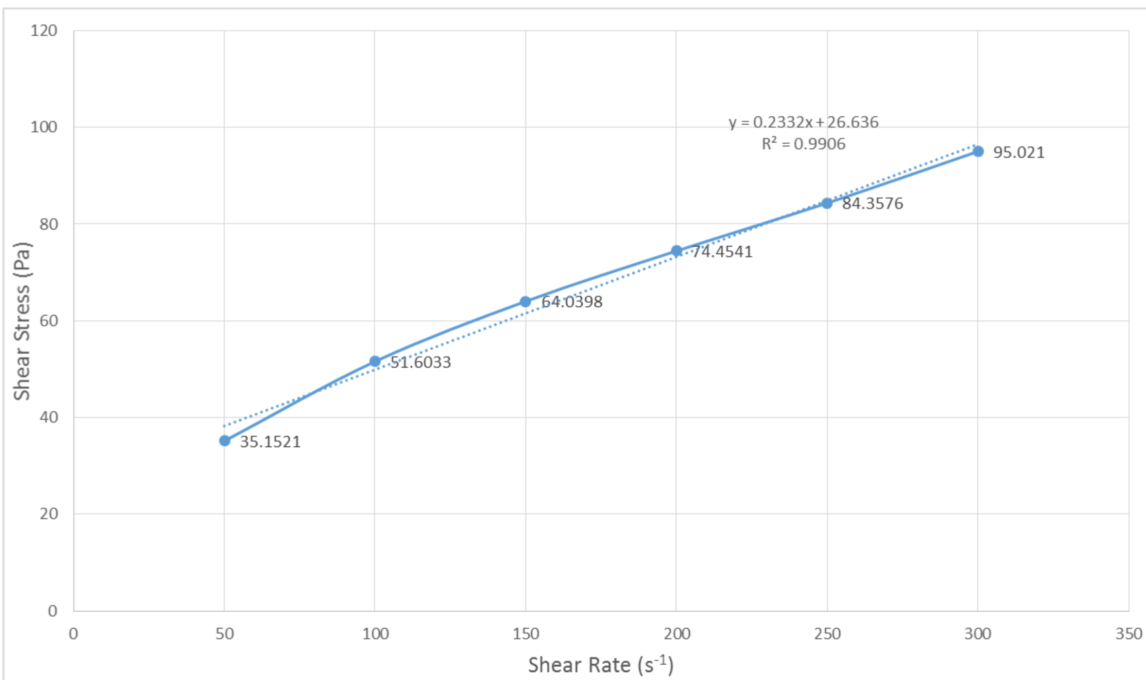


FIGURE 13 – SHEAR STRESS VS SHEAR RATE FOR P45-0-0 BINGHAM EQUATION PARAMETERS

## 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.

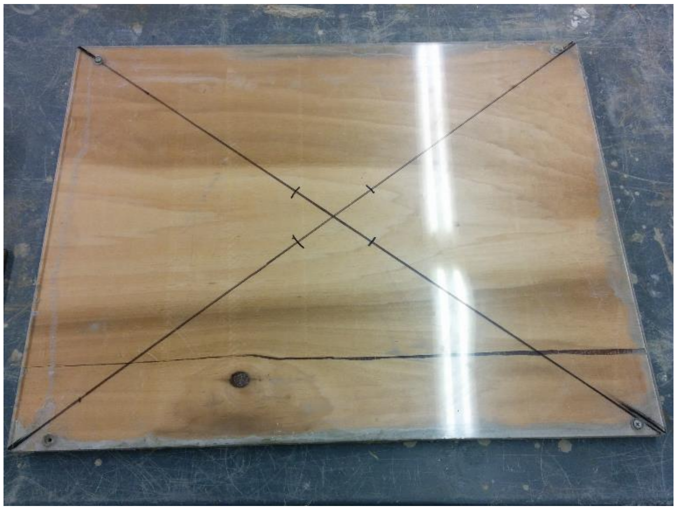

FIGURE 14 – FLOW TABLE

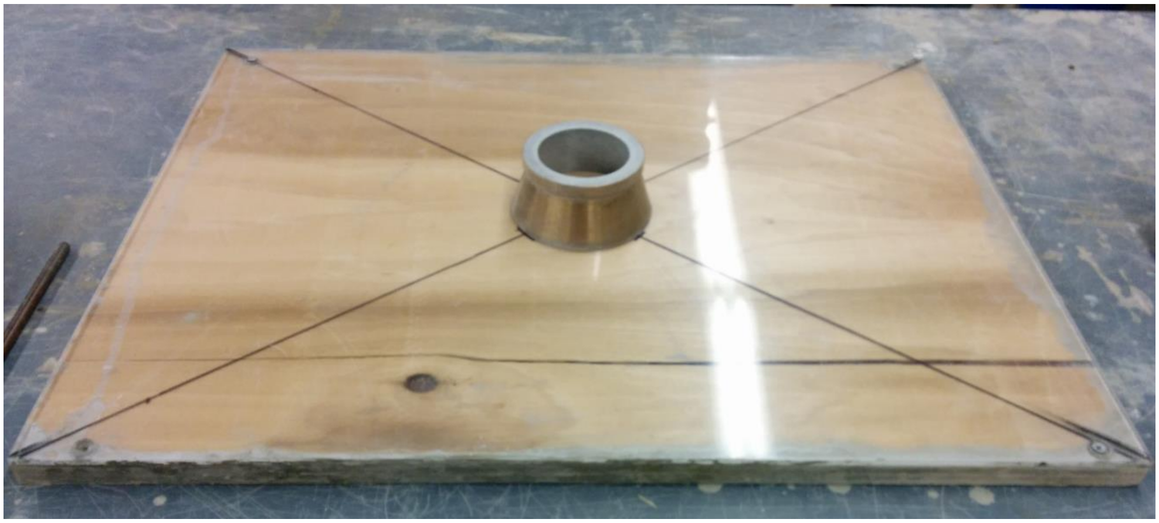

FIGURE 15 – SLUMP MINI-CONE

FIGURE 16 – STEEL ROD AND STRAIGHT EDGE

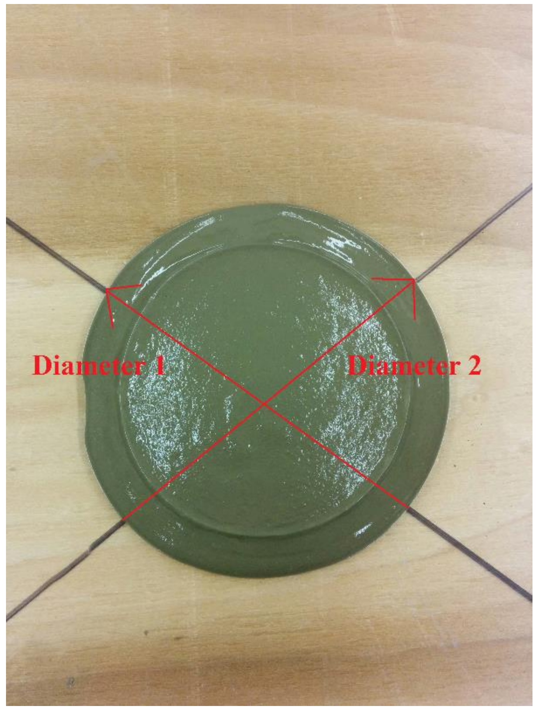


FIGURE 17 – MEASUREMENT EXAMPLE

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.

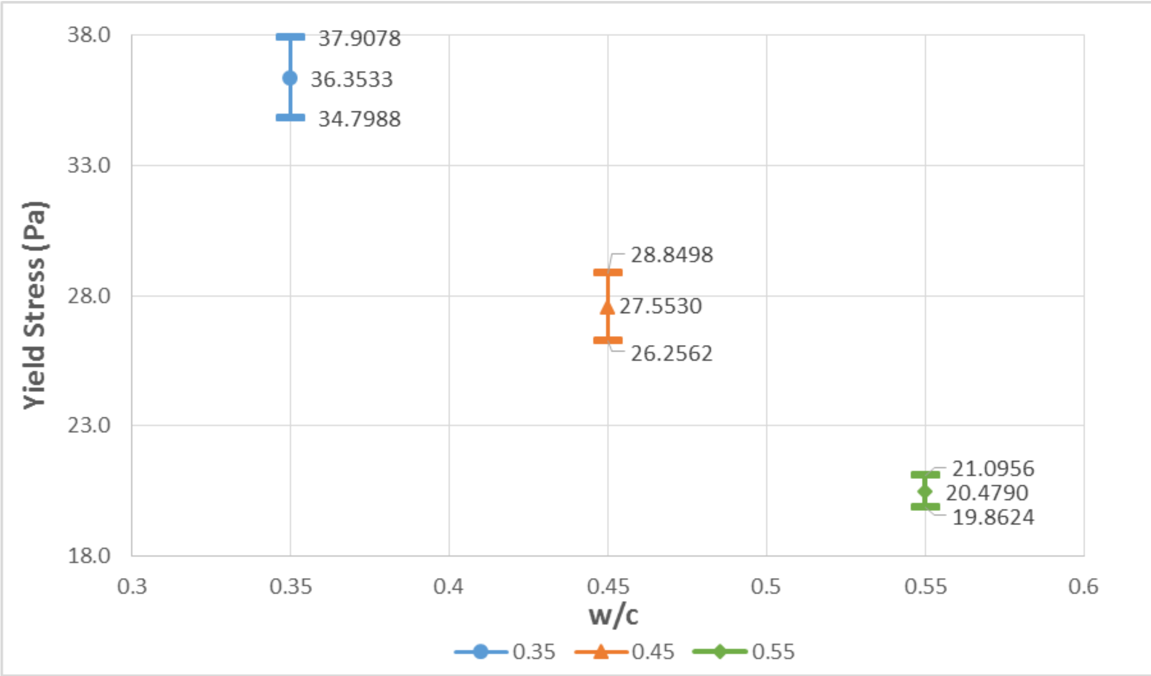


FIGURE 19 - BINGHAM YIELD STRESS VS W/C

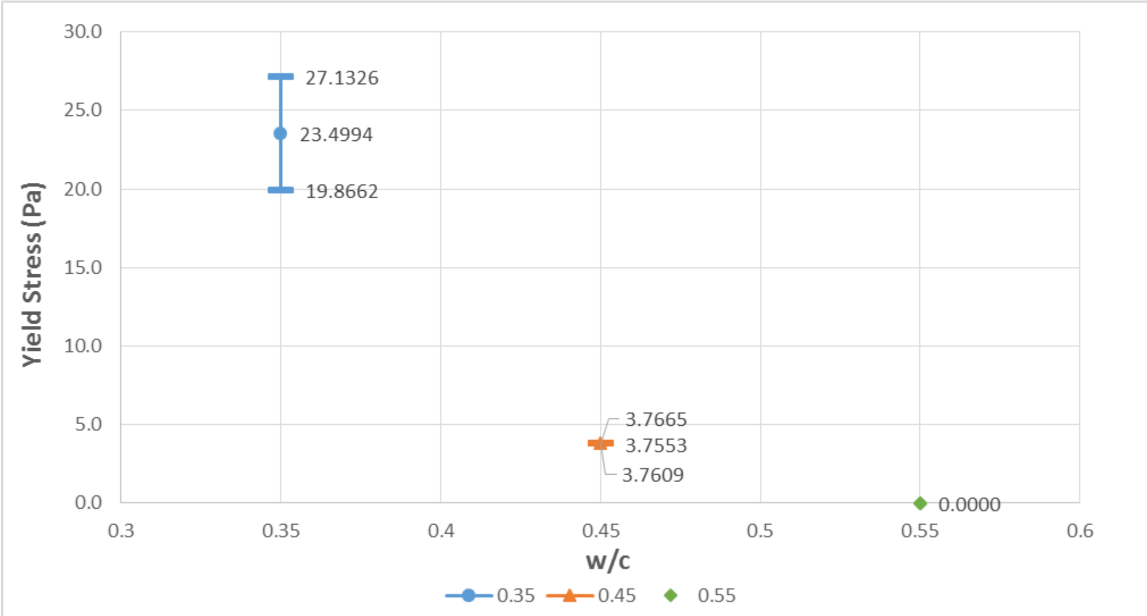


FIGURE 20 - HERSCHEL-BULKLEY YIELD STRESS VS W/C

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.

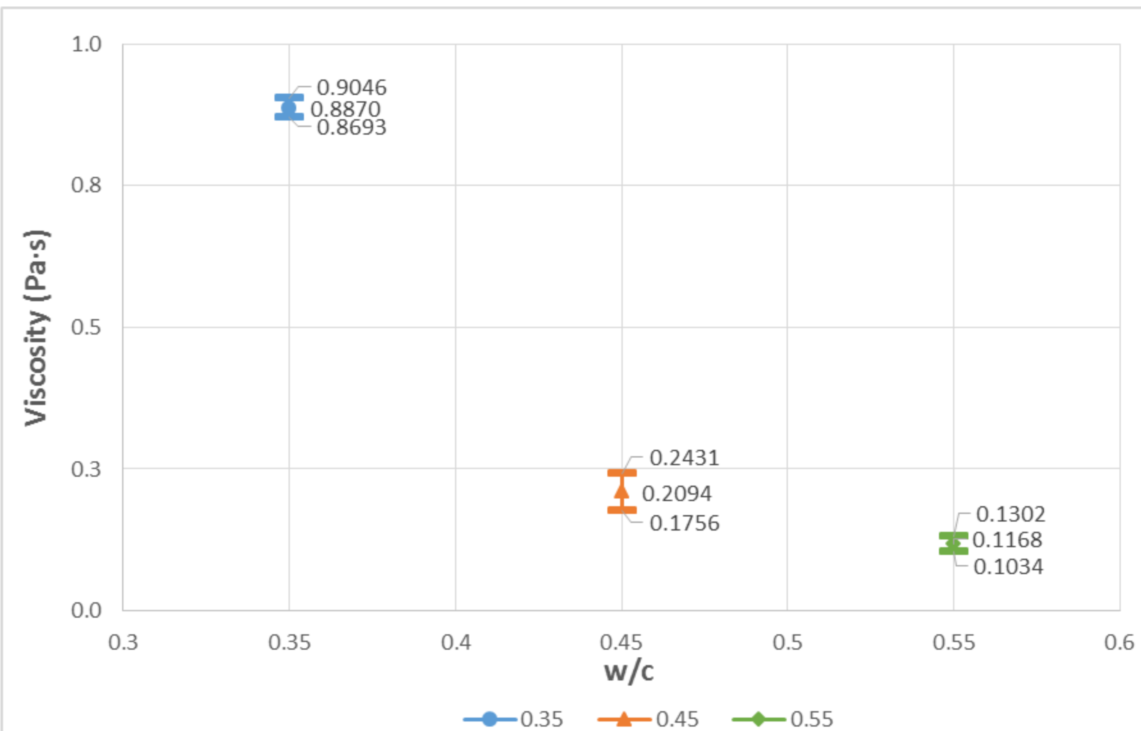


FIGURE 21 - BINGHAM VISCOSITY VS W/C

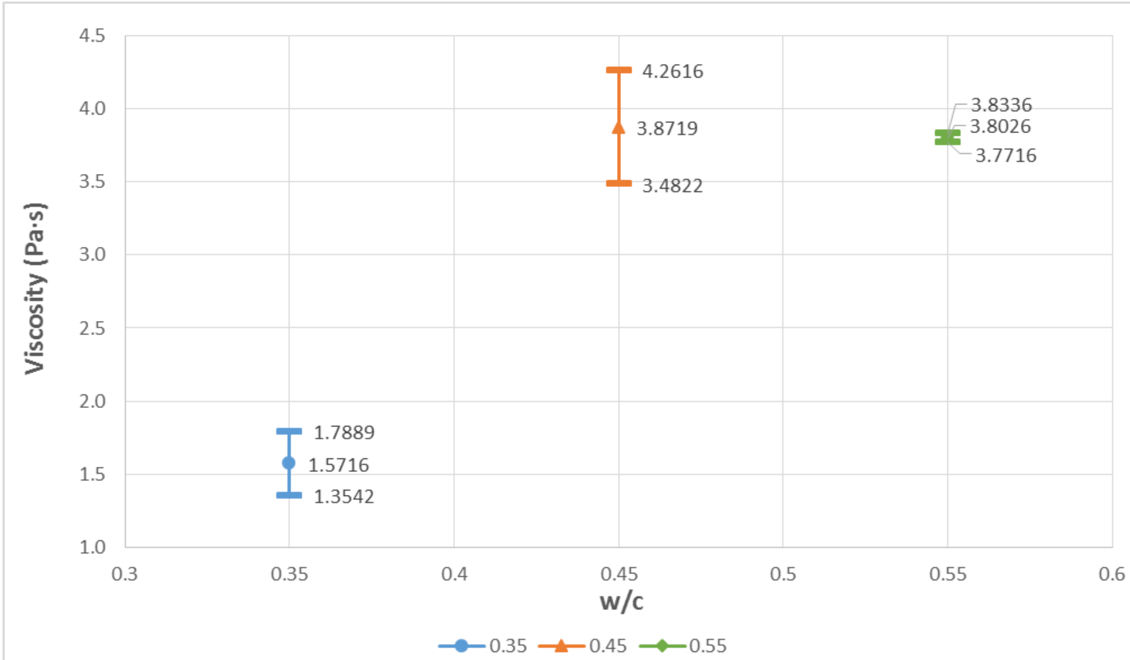


FIGURE 22 - HERSCHEL-BULKLEY VISCOSITY VS W/C

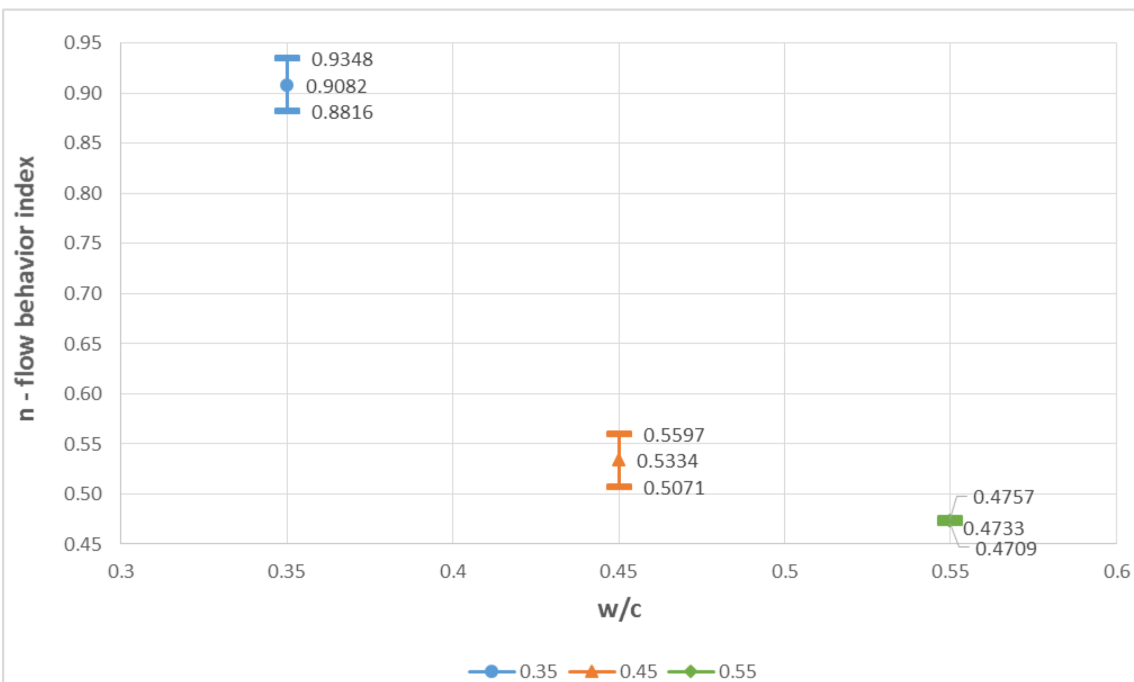


FIGURE 23 - HERSCHEL-BULKLEY FLOW BEHAVIOR INDEX VS W/C

## 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 contradicts 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.

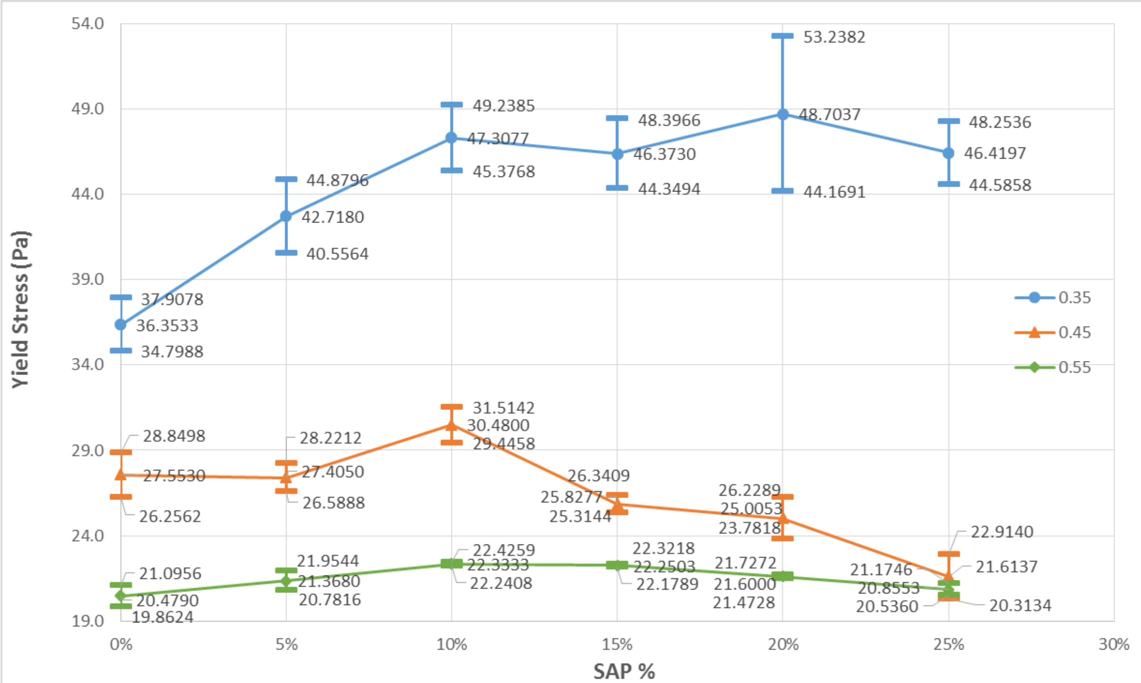


FIGURE 24 – BINGHAM YIELD STRESS VS SAP %

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.

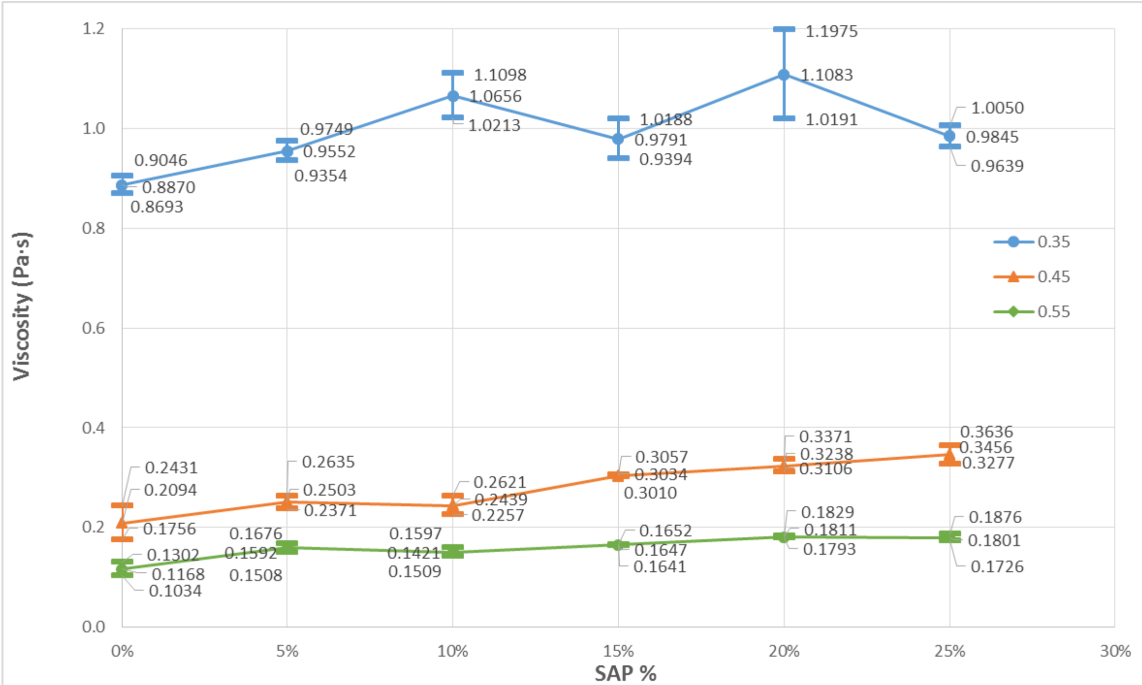


FIGURE 25 – BINGHAM VISCOSITY VS SAP %

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.

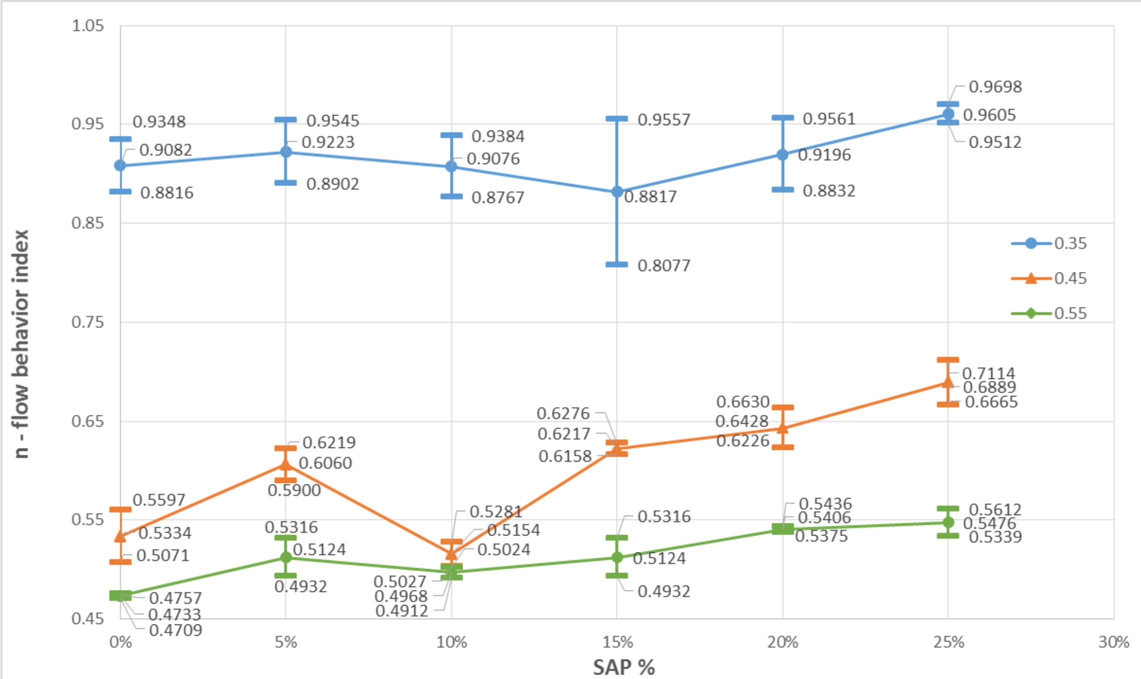


FIGURE 26 – HERSCHEL-BULKLEY FLOW BEHAVIOR INDEX VS SAP%

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.

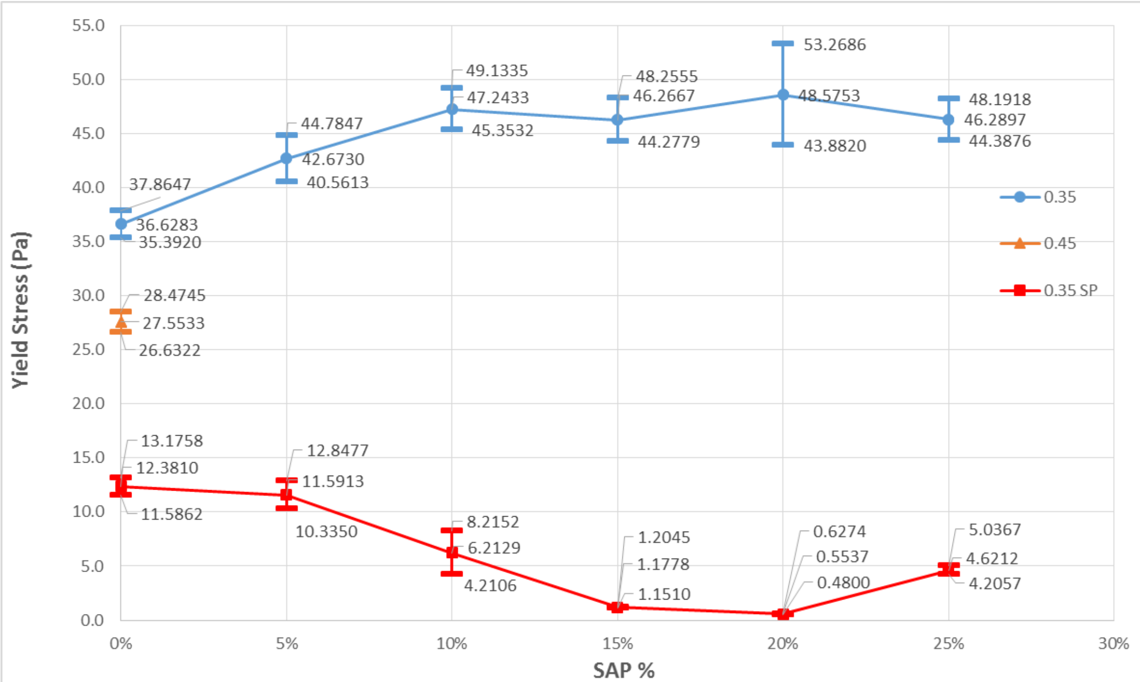


FIGURE 30 – ADDITION OF SP: BINGHAM YIELD STRESS VS SAP %

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.

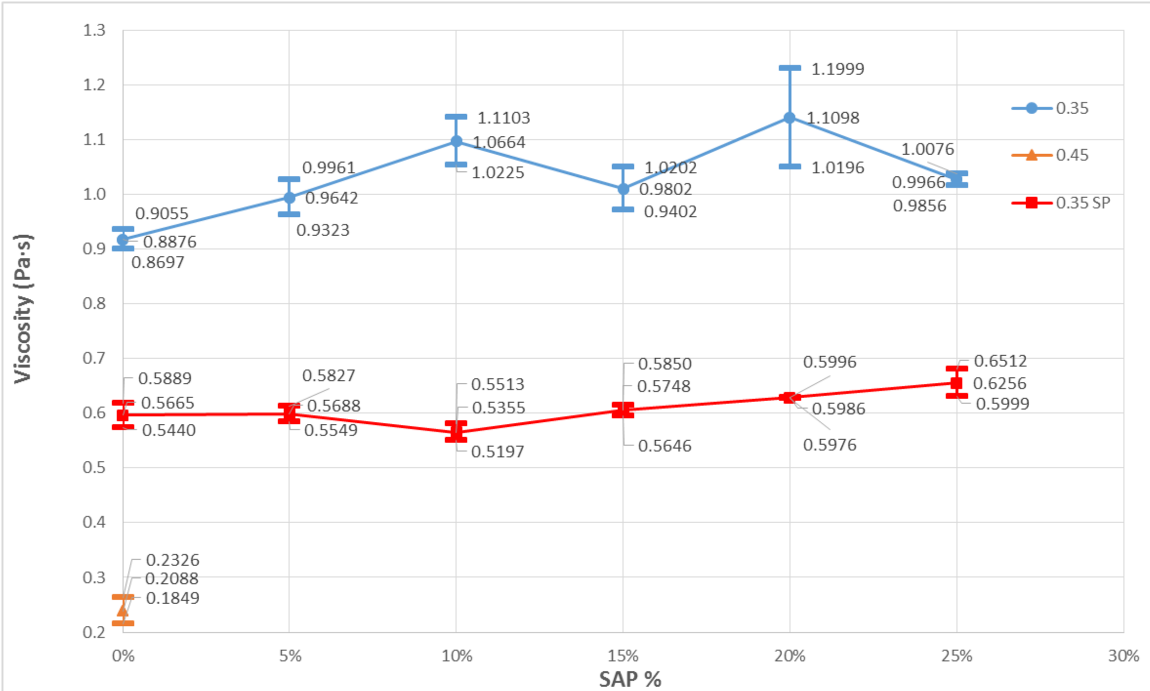


FIGURE 31 – ADDITION OF SP: VISCOSITY VS SAP %

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.

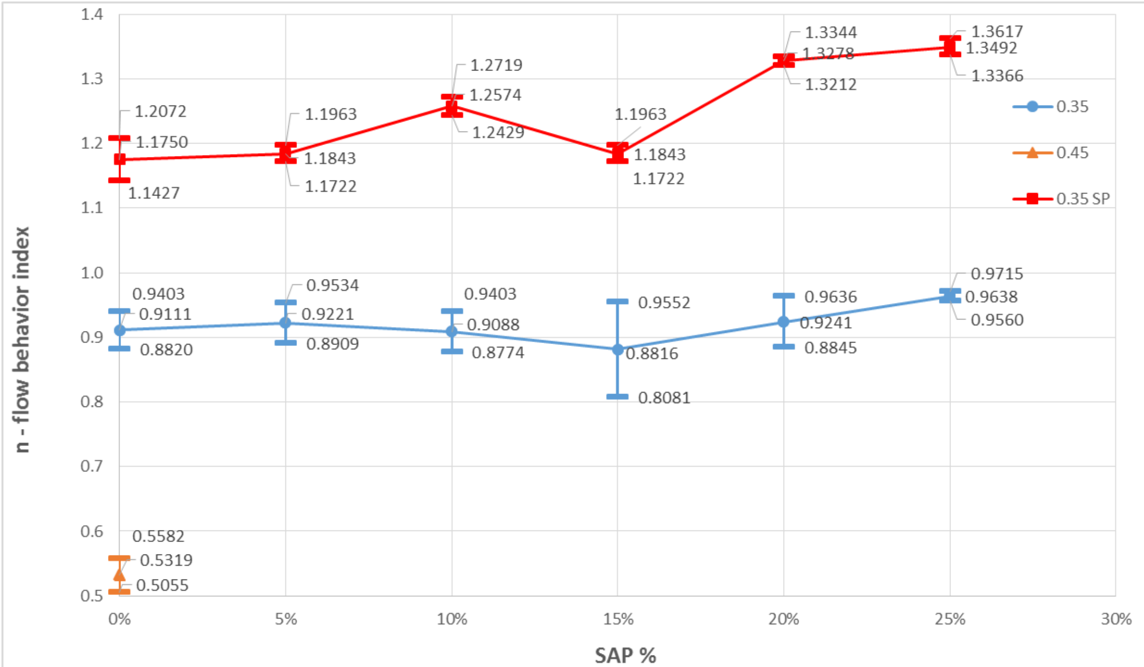


FIGURE 32 – ADDITION OF SP: FLOW BEHAVIOR INDEX VS SAP %

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 is 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.

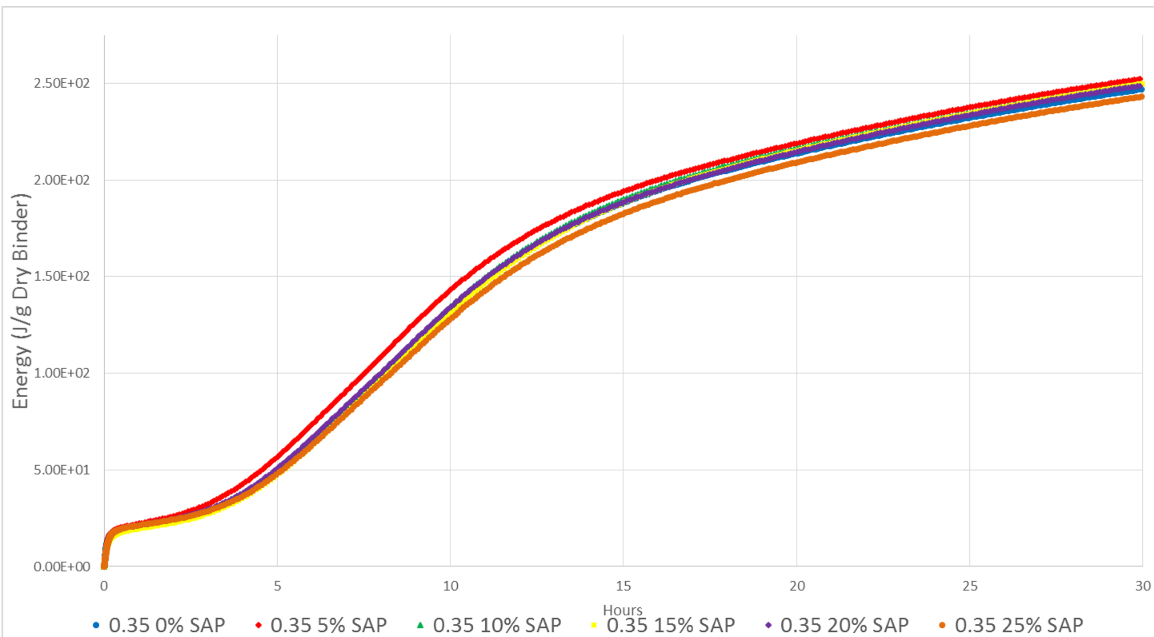


FIGURE 33 – ENERGY 0.35 W/C 0-30 HRS

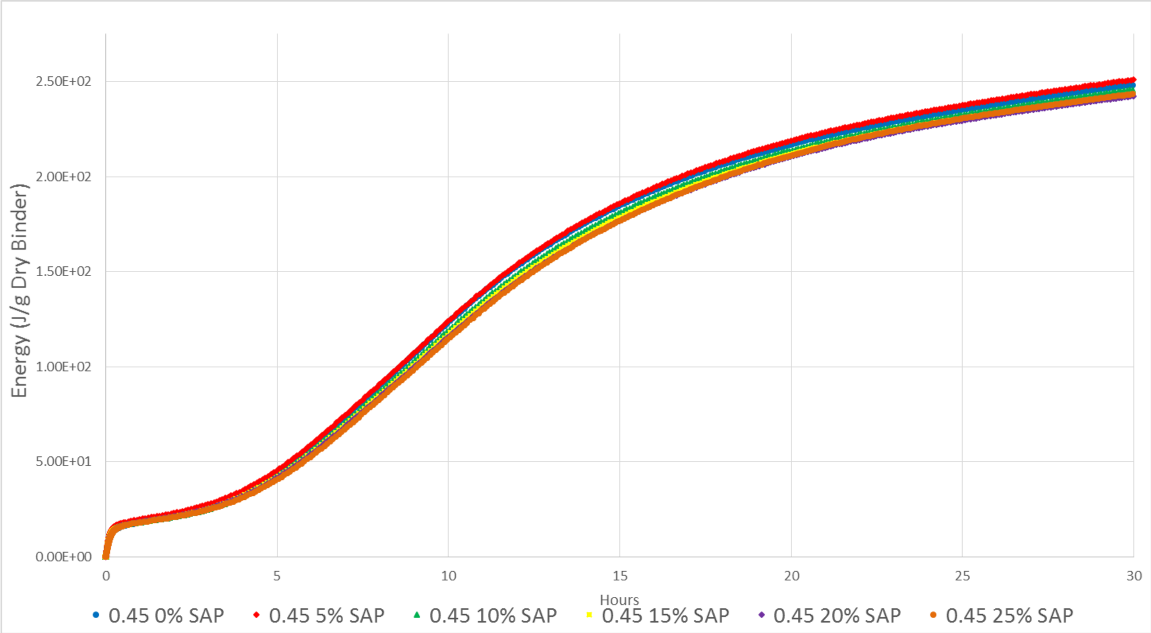


FIGURE 34 – ENERGY 0.45 W/C 0-30 HRS

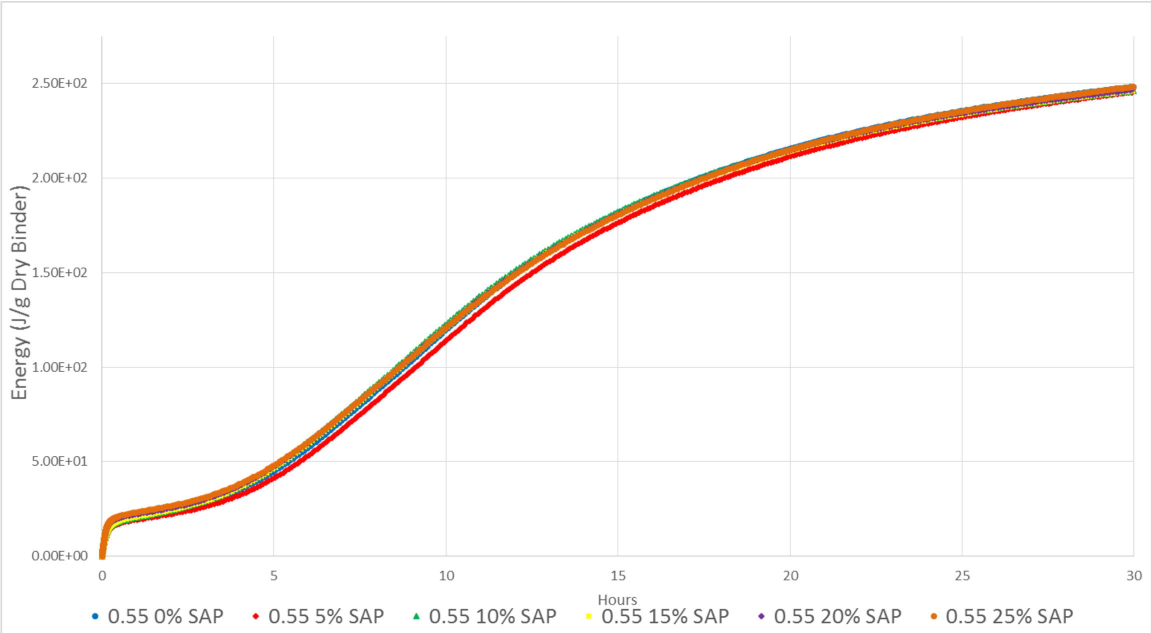


FIGURE 35 – ENERGY 0.55 W/C 0-30 HRS

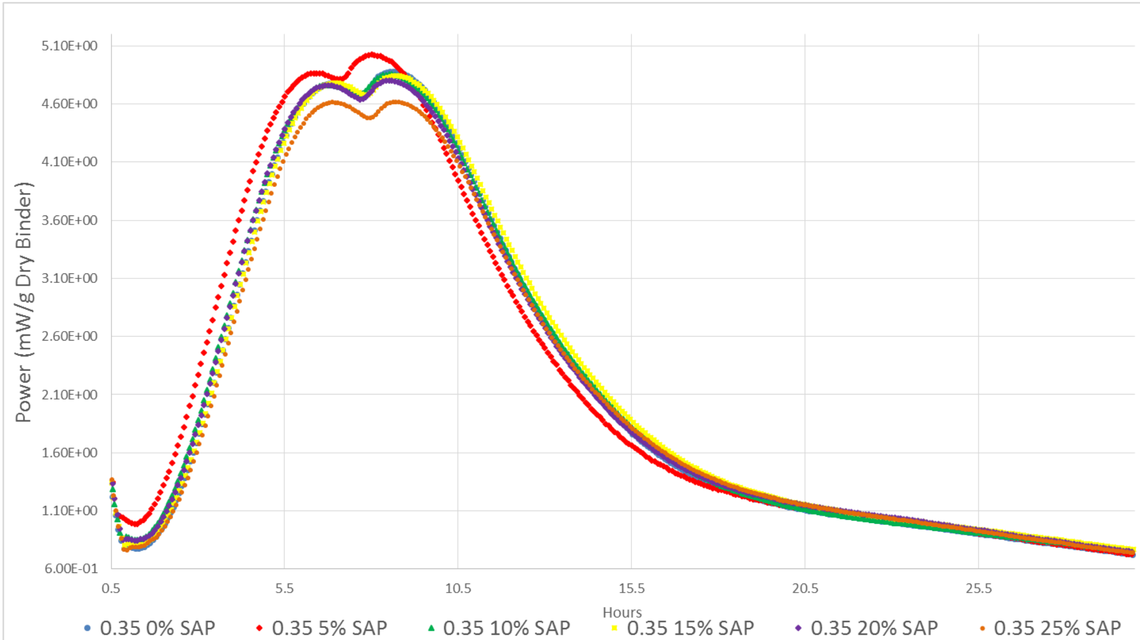


FIGURE 36 – POWER 0.35 W/C 0.5-30 HRS

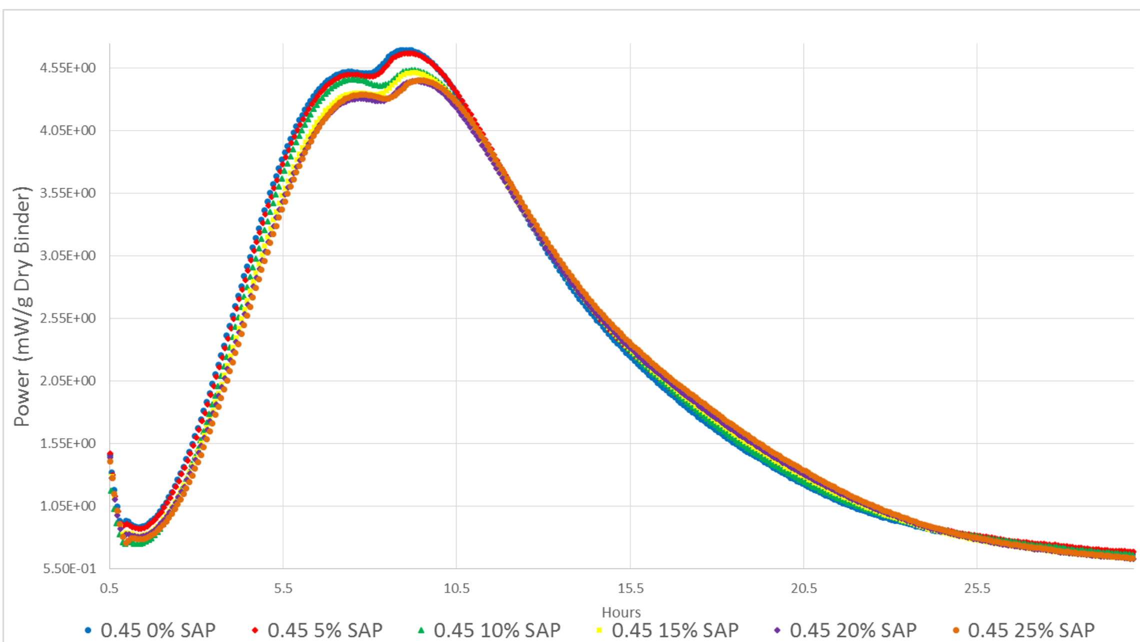


FIGURE 37 – POWER 0.45 W/C 0.5-30 HRS

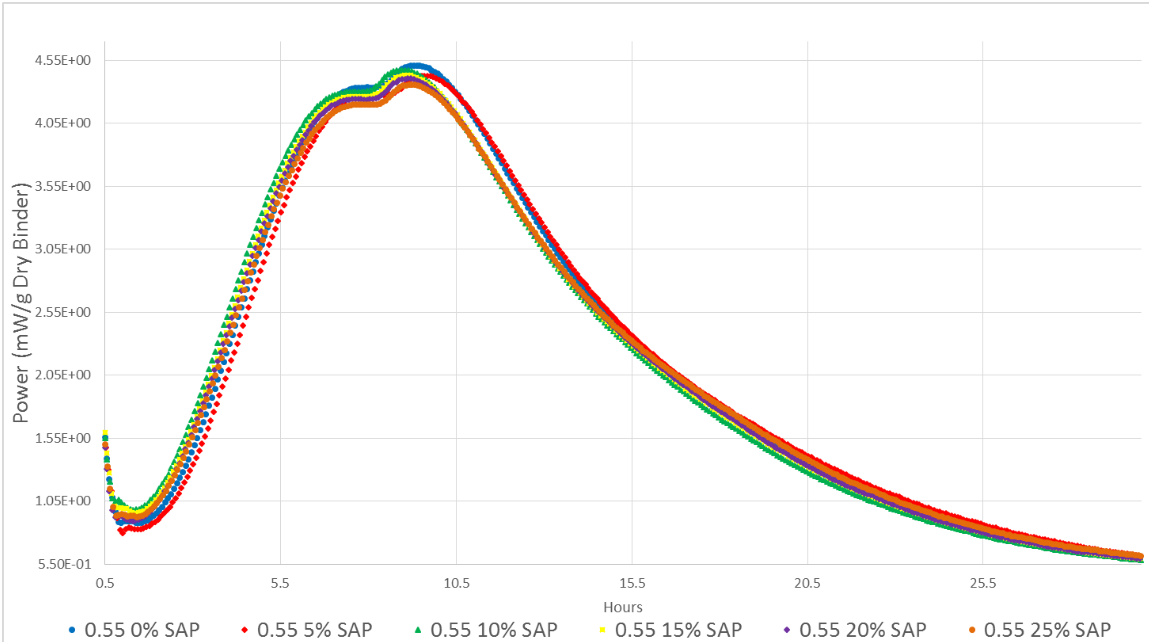


FIGURE 38 – POWER 0.55 W/C 0.5-30 HRS

# 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 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 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 | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 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 | | | | | | | | | |
| | | | SSE | SST | | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 300 | 65.39763636 | 65.38329414 | 0.000205699 | 289.055639 | | 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 | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (yi-ybar)^2 | | | Herschel–Bulkley | |
| 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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | SSE | SST | | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 | | | | | | | | |
| | | | SSE | SST | | | | |
| [1/s] | [Pa] | tao' | (tao-tao')^2 | (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 |

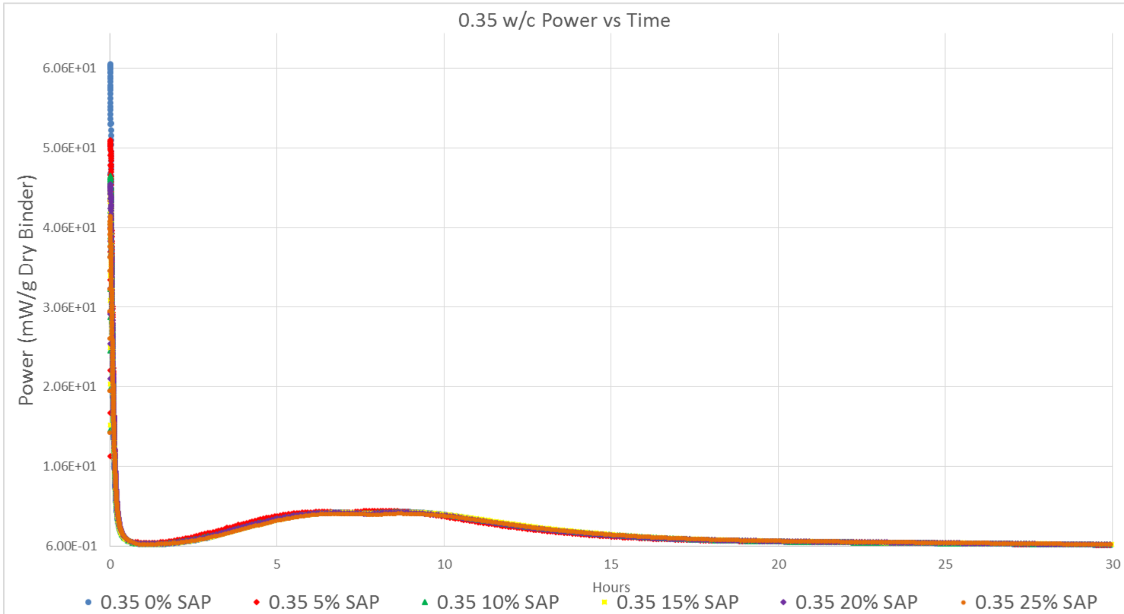


FIGURE 39 – POWER 0.35 W/C 0-30 HRS

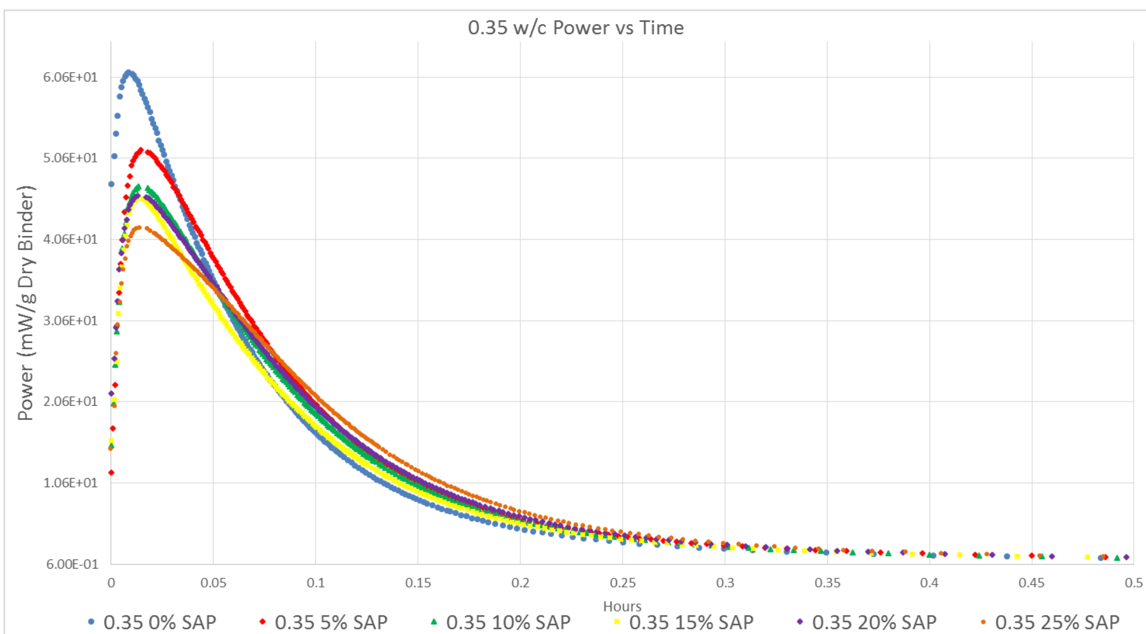


FIGURE 40 – POWER 0.35 W/C 0-0.5 HRS

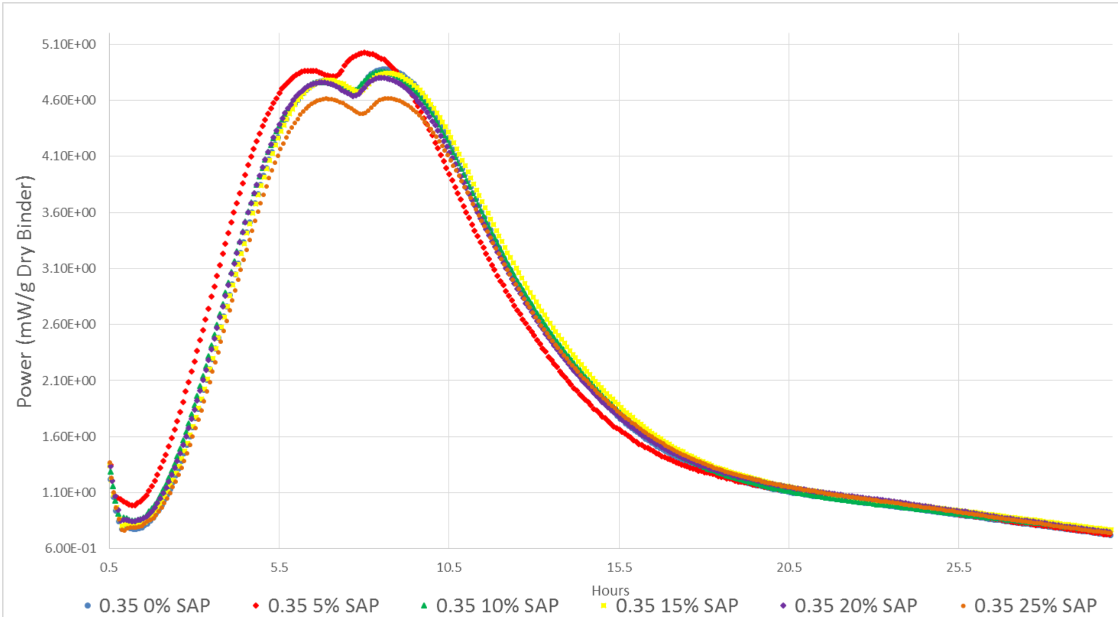


FIGURE 41 – POWER 0.35 W/C 0.5-30 HRS

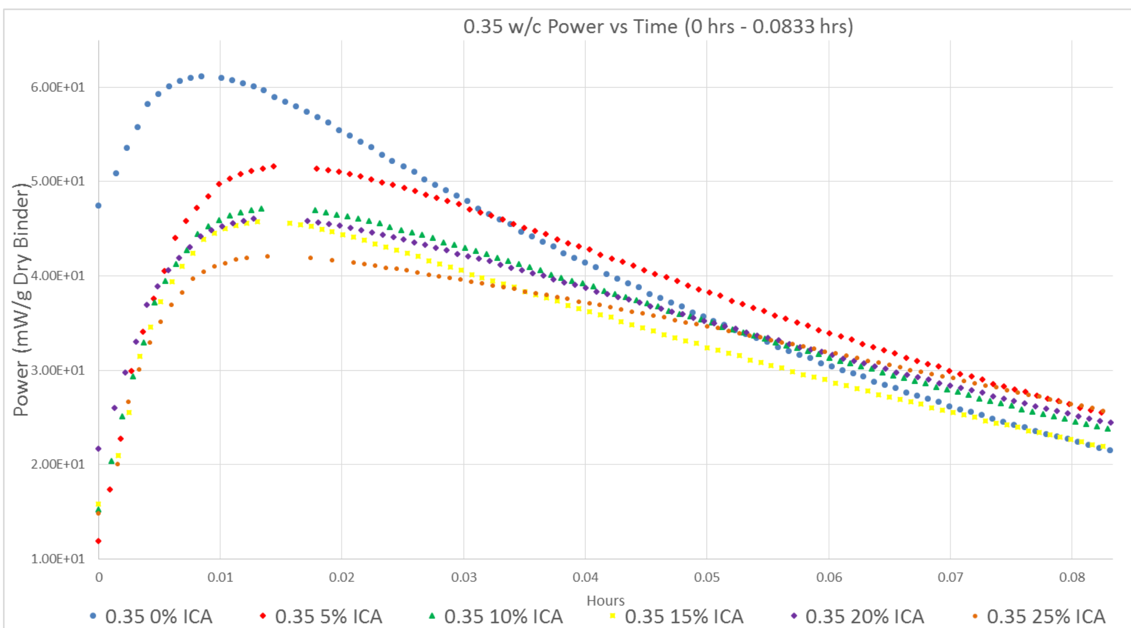


FIGURE 42 – POWER 0.35 W/C 0-0.0833 HRS

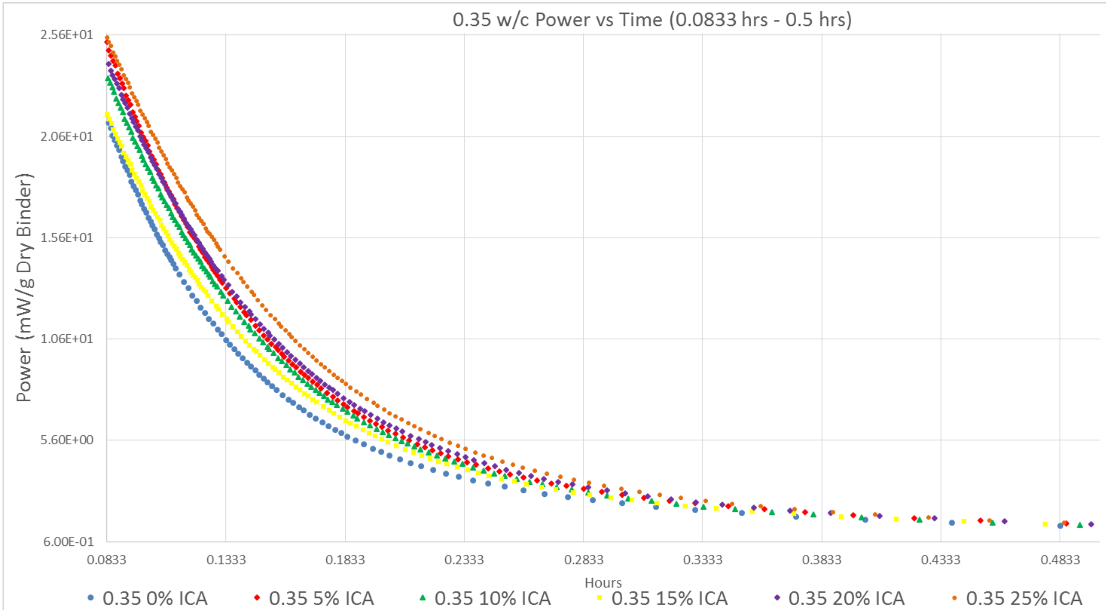


FIGURE 43 – POWER 0.35 W/C 0.0833-0.5 HRS

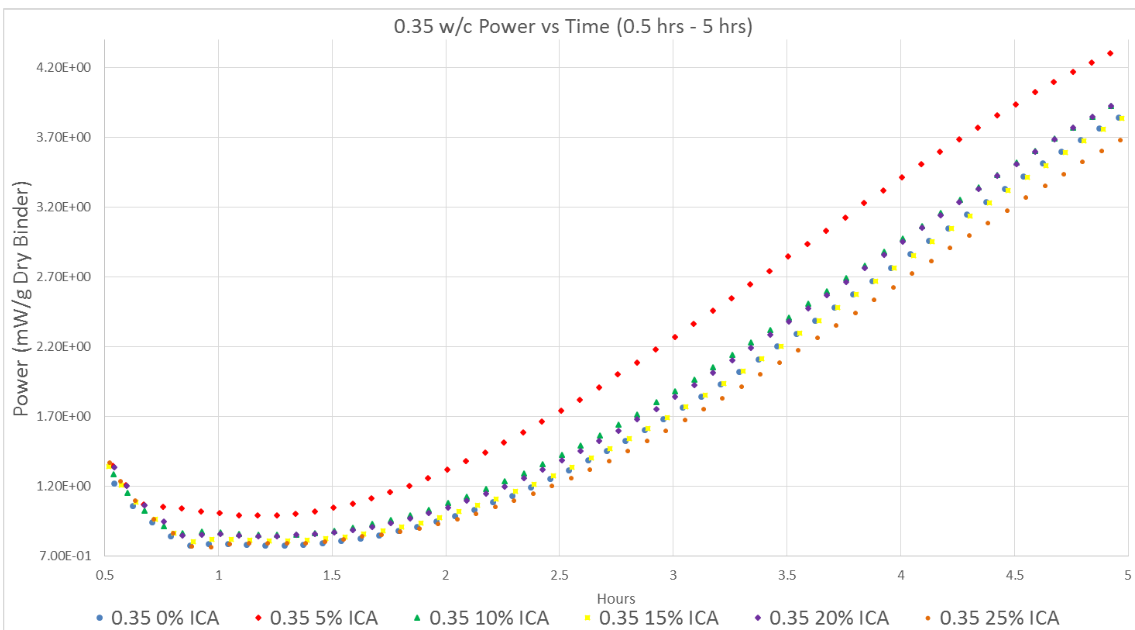


FIGURE 44 – POWER 0.35 W/C 0.5-5 HRS

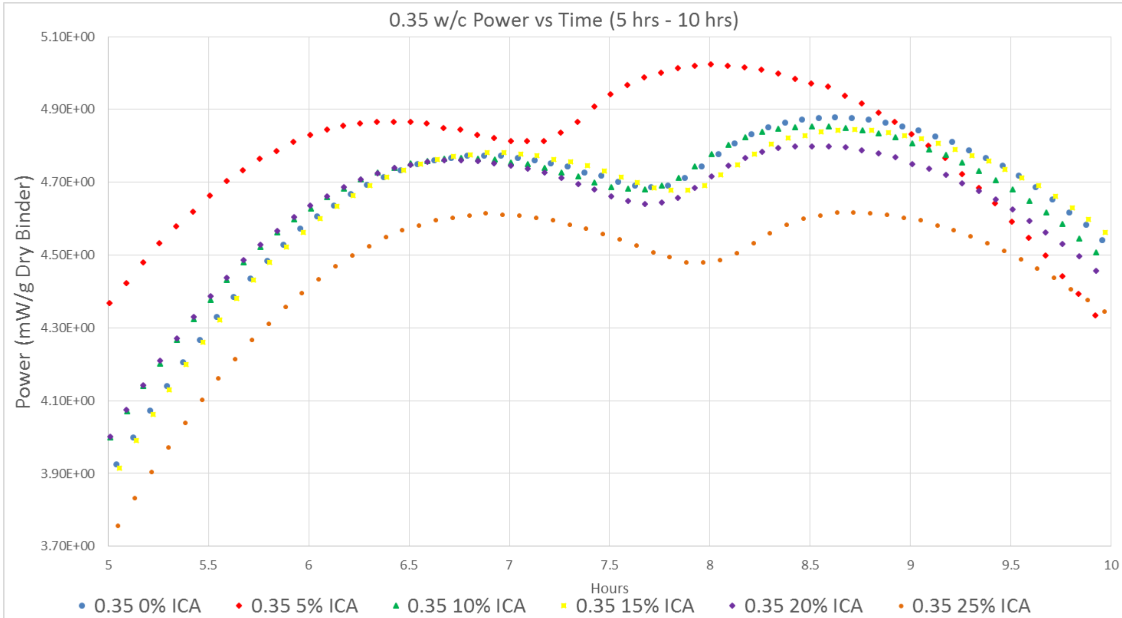


FIGURE 45 – POWER 0.35 W/C 5-10 HRS

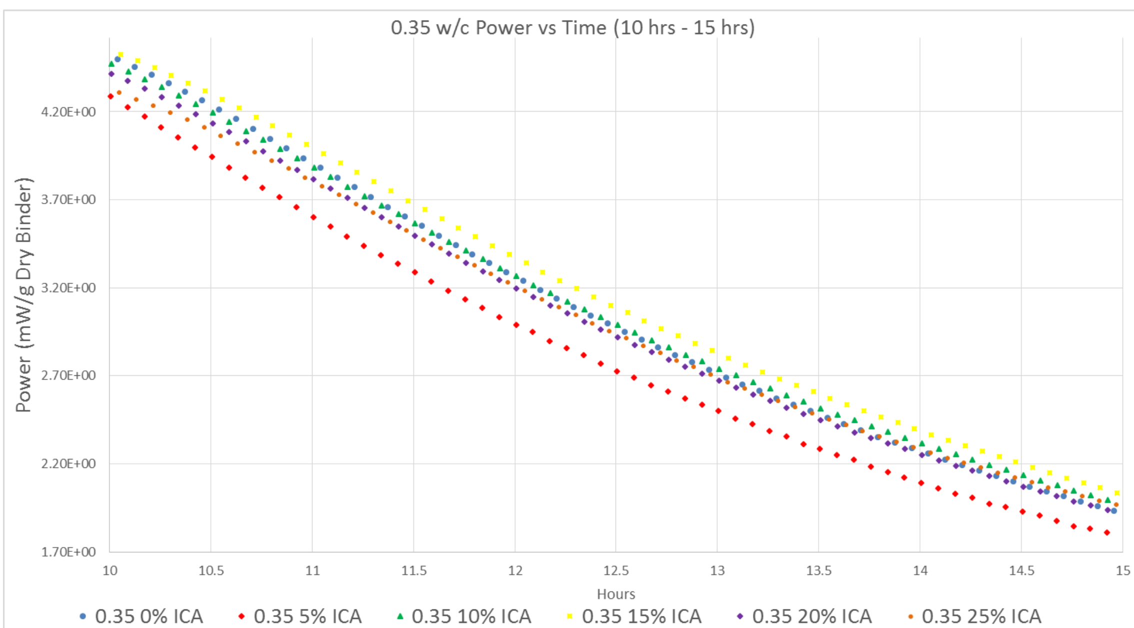


FIGURE 46 – POWER 0.35 W/C 10-15 HRS

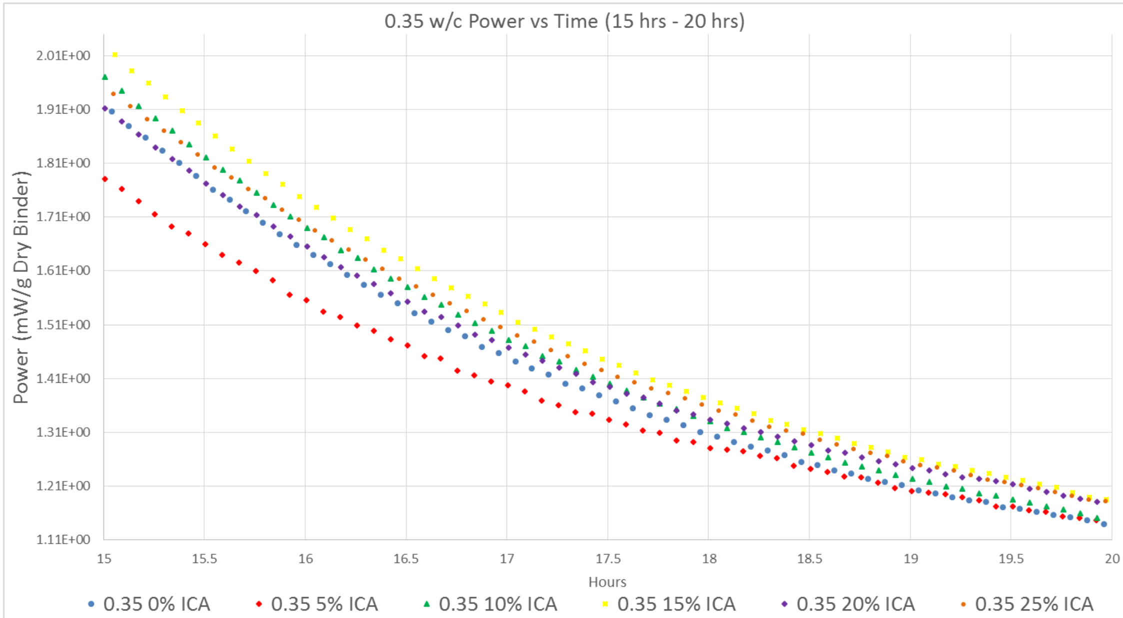


FIGURE 47 – POWER 0.35 W/C 15-20 HRS

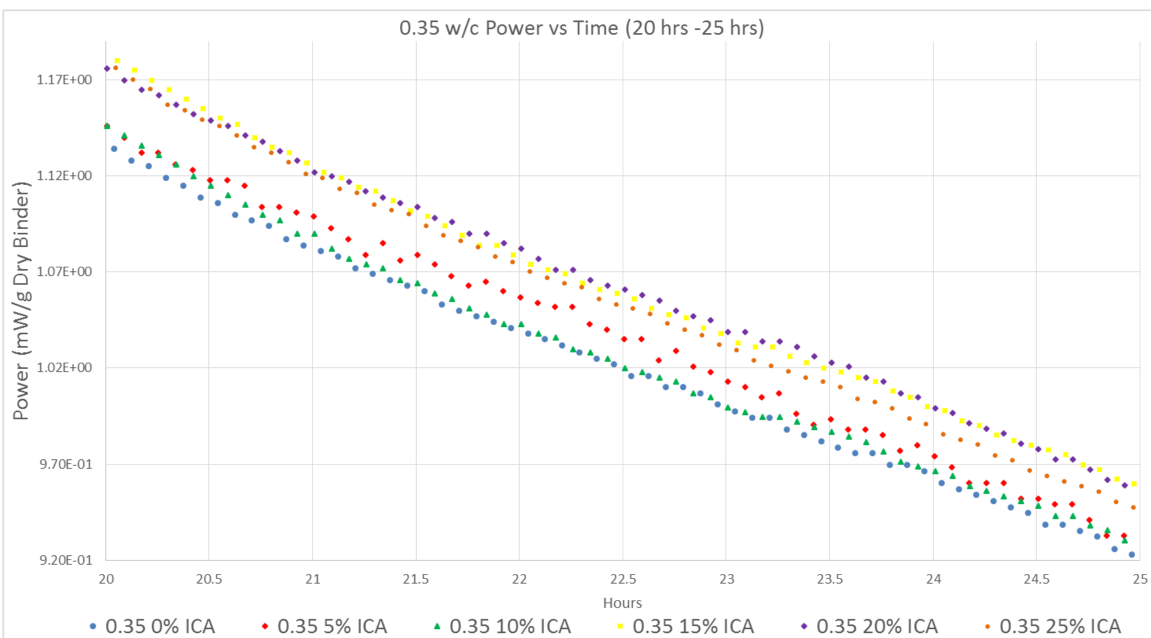


FIGURE 48 – POWER 0.35 W/C 20-25 HRS

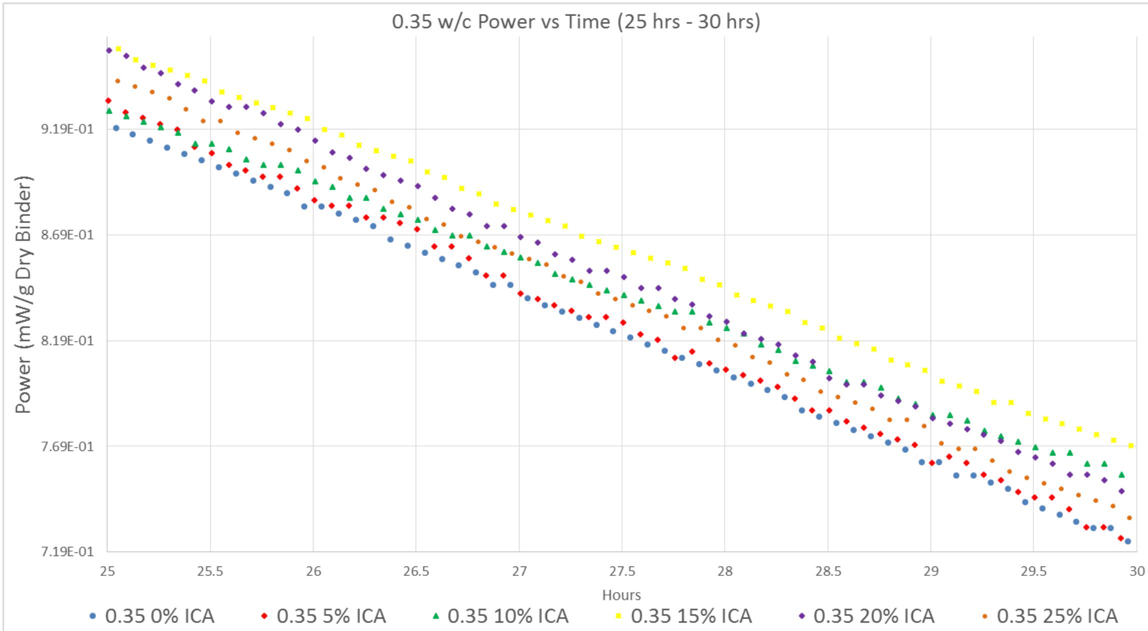


FIGURE 49 – POWER 0.35 W/C 25-30 HRS

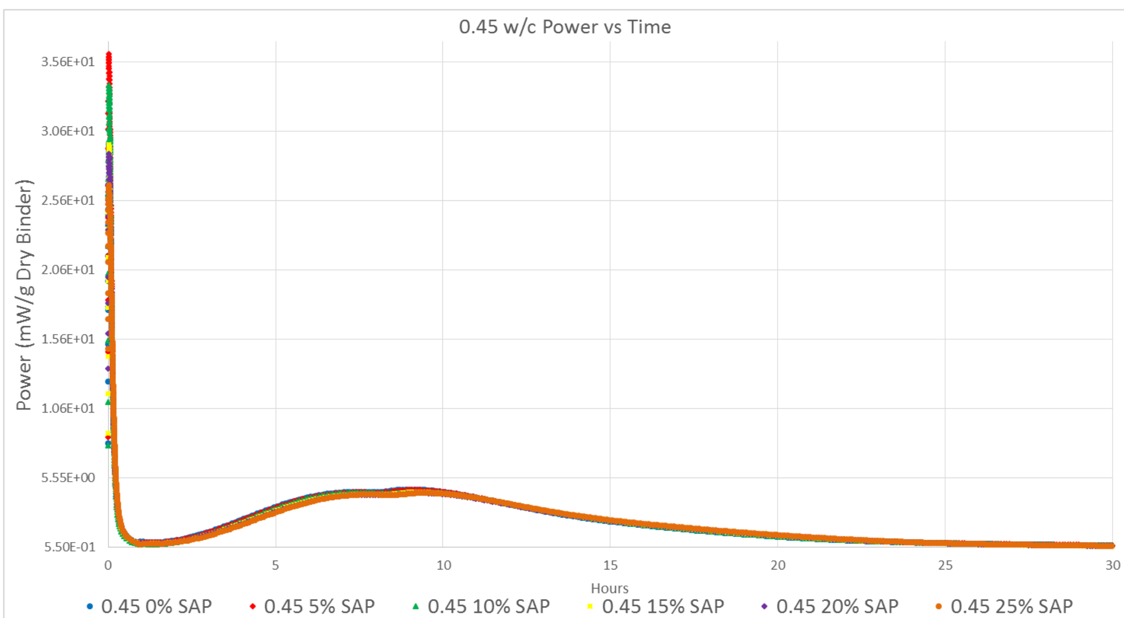


FIGURE 50 – POWER 0.45 W/C 0-30 HRS

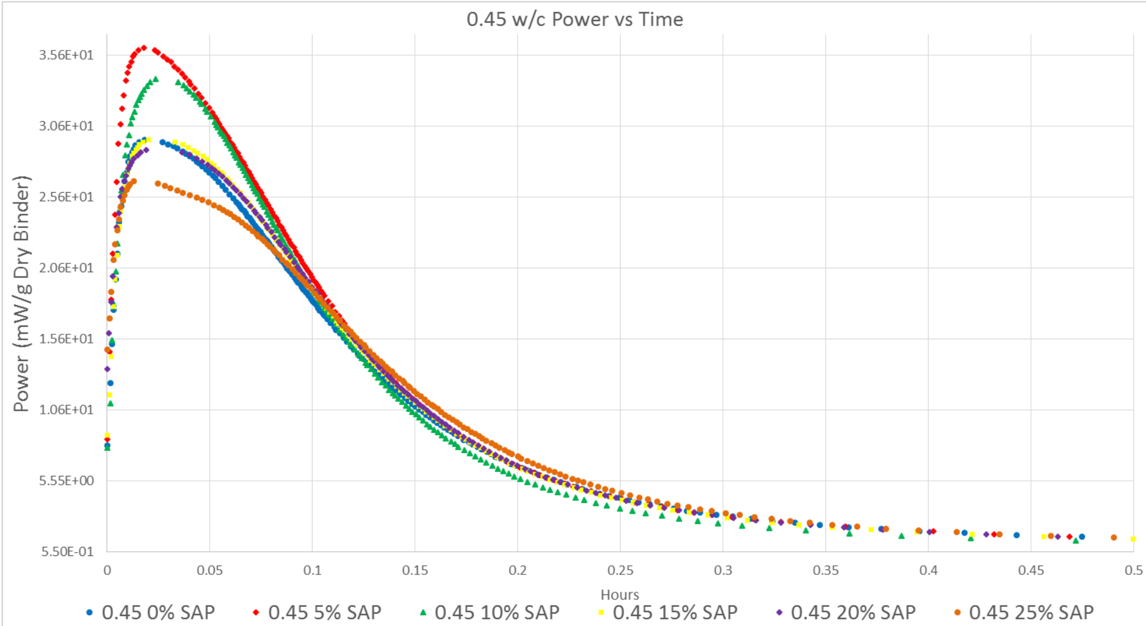


FIGURE 51 – POWER 0.45 W/C 0-0.5 HRS

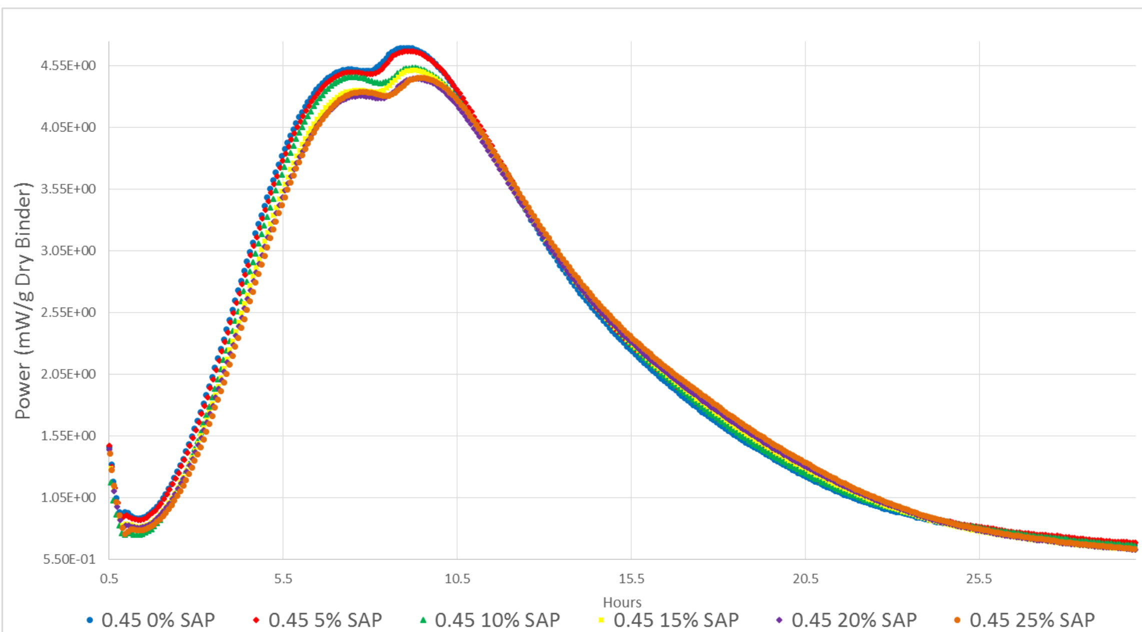


FIGURE 52 – POWER 0.45 W/C 0.5-30 HRS

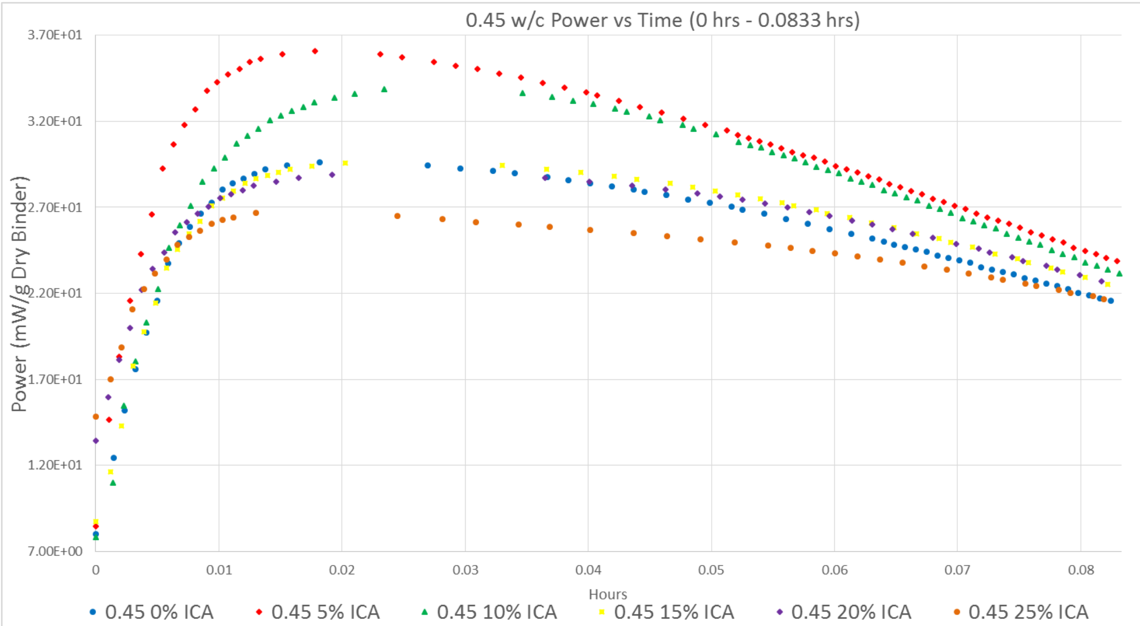


FIGURE 53 – POWER 0.45 W/C 0-0.0833 HRS

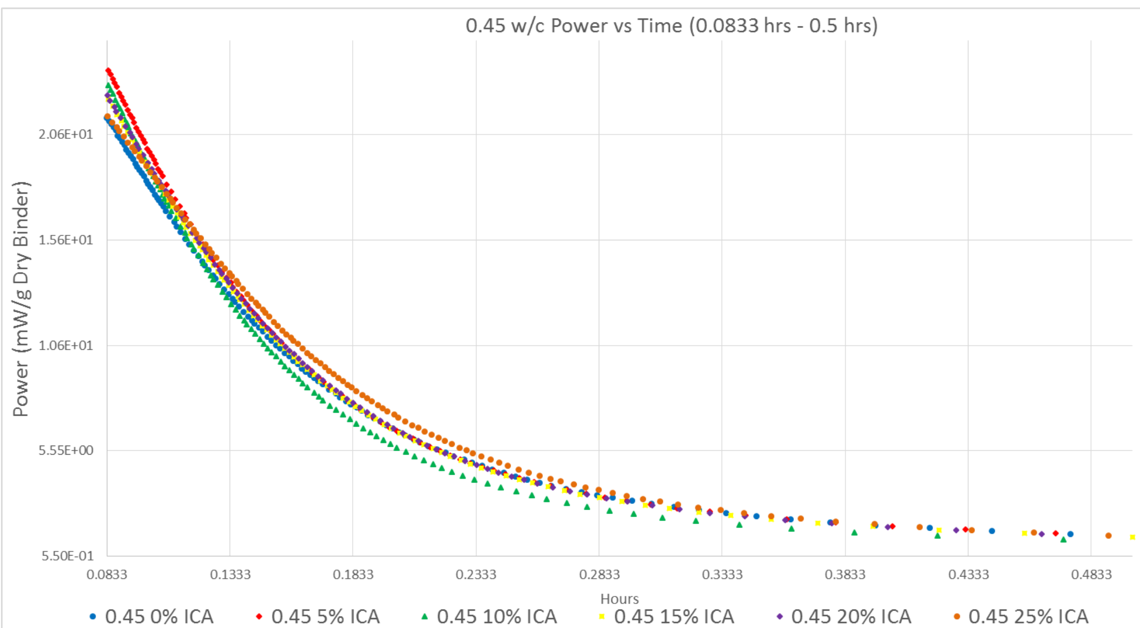


FIGURE 54 – POWER 0.45 W/C 0.0833-0.5 HRS

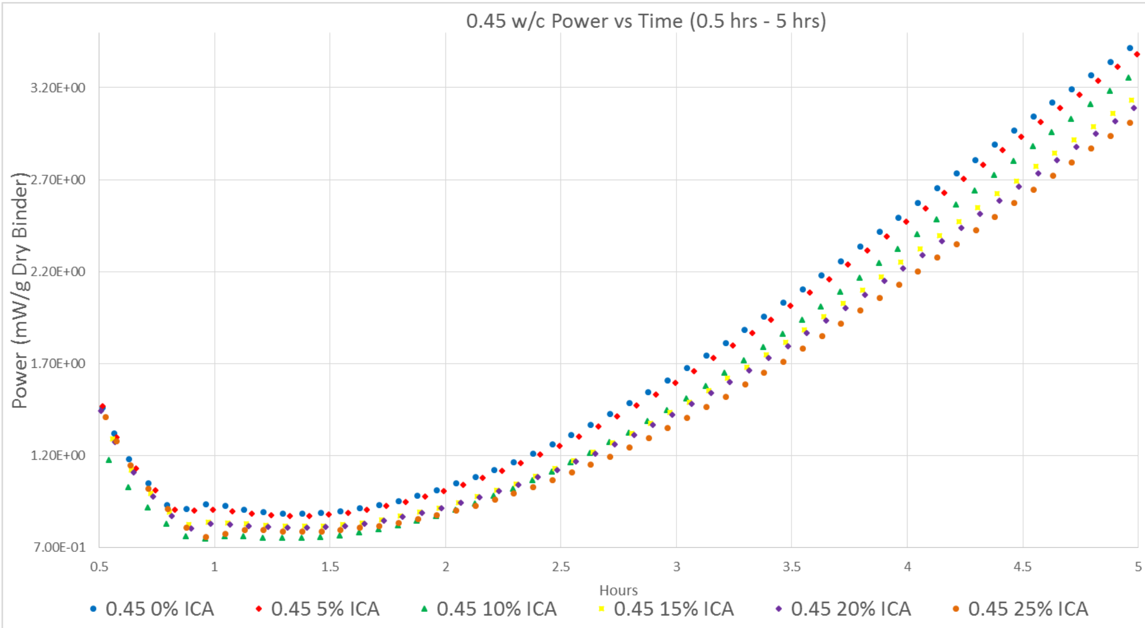


FIGURE 55 – POWER 0.45 W/C 0.5-5 HRS

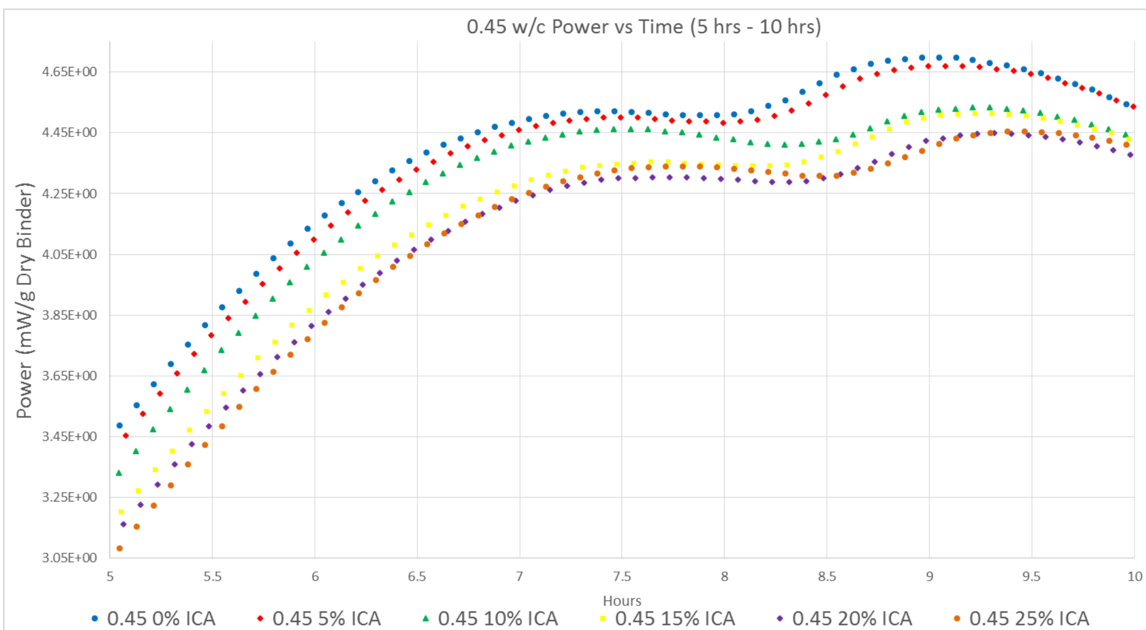


FIGURE 56 – POWER 0.45 W/C 5-10 HRS

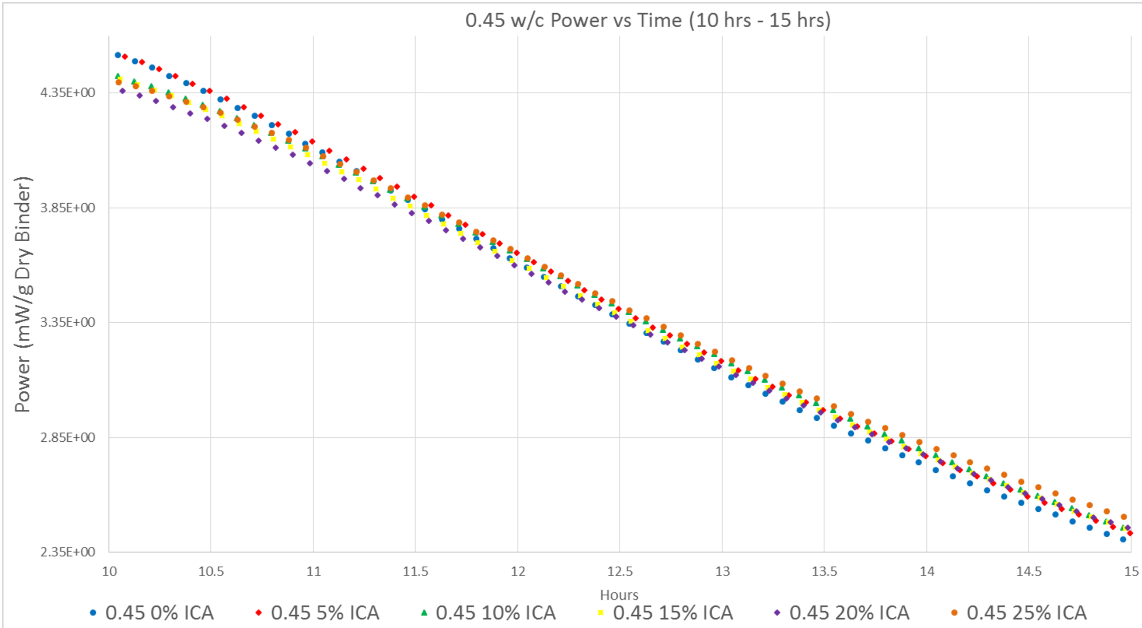


FIGURE 57 – POWER 0.45 W/C 10-15 HRS

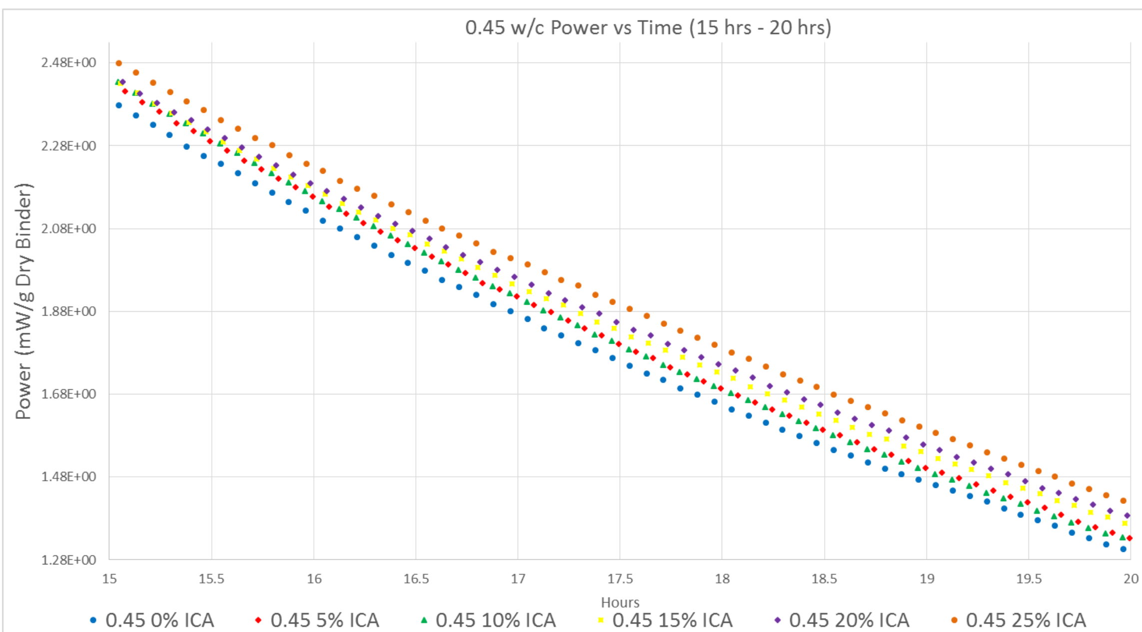


FIGURE 58 – POWER 0.45 W/C 15-20 HRS

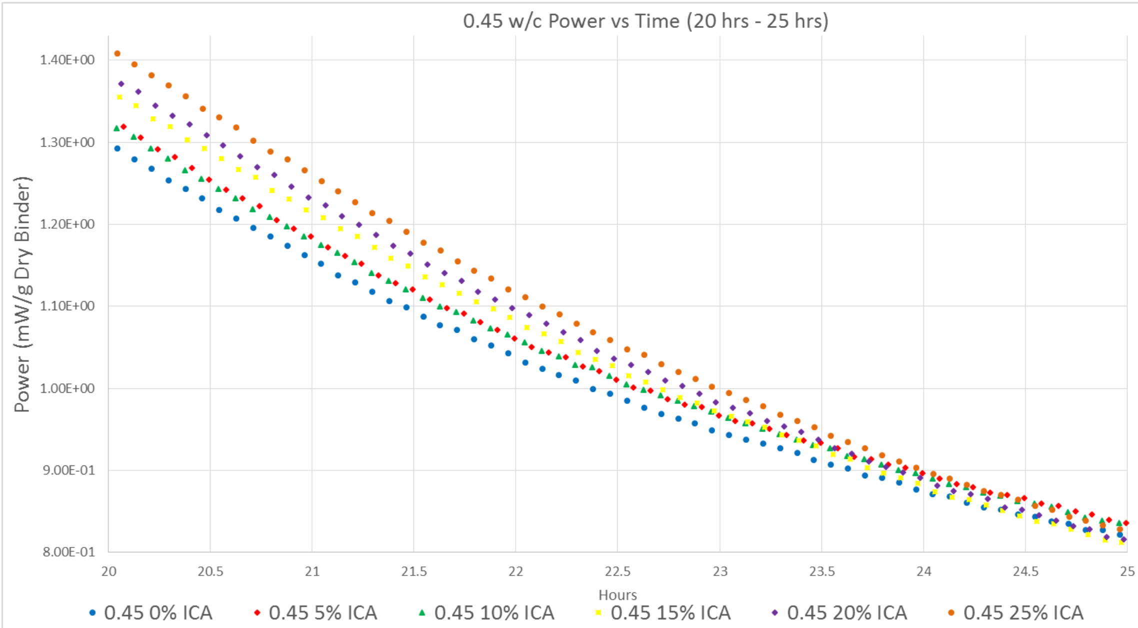


FIGURE 59 – POWER 0.45 W/C 20-25 HRS

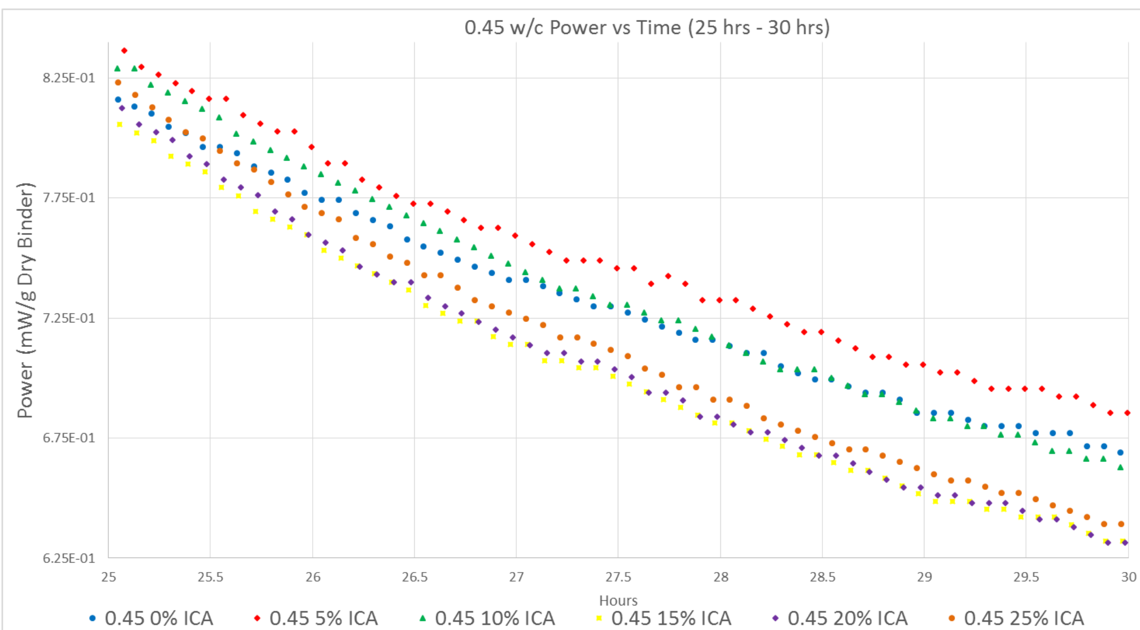


FIGURE 60 – POWER 0.45 W/C 25-30 HRS

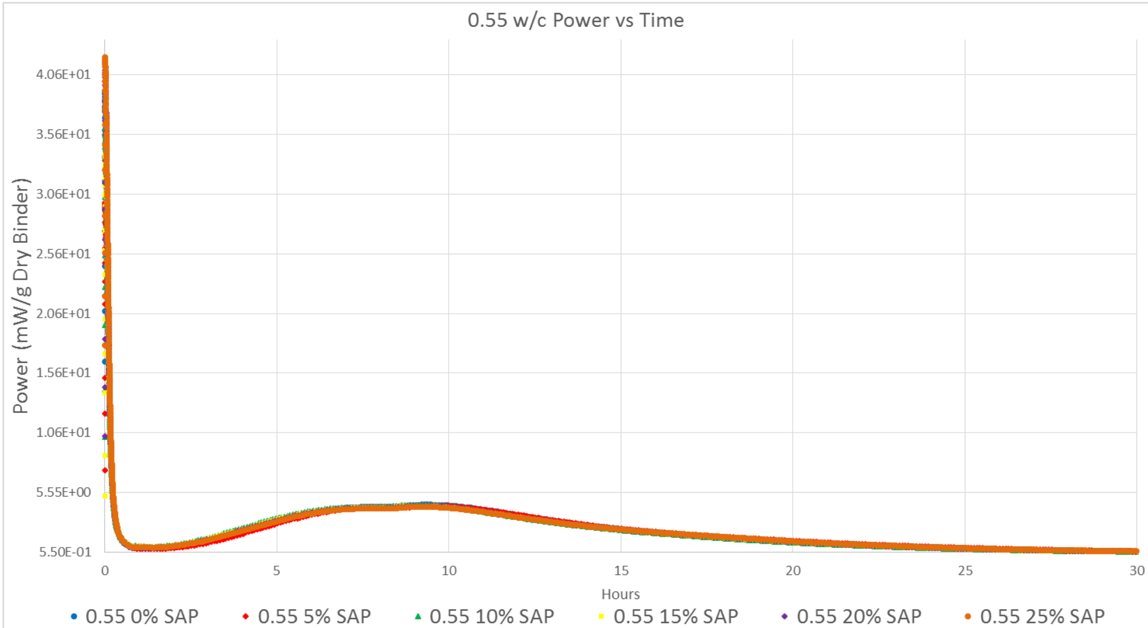


FIGURE 61 – POWER 0.55 W/C 0-30 HRS

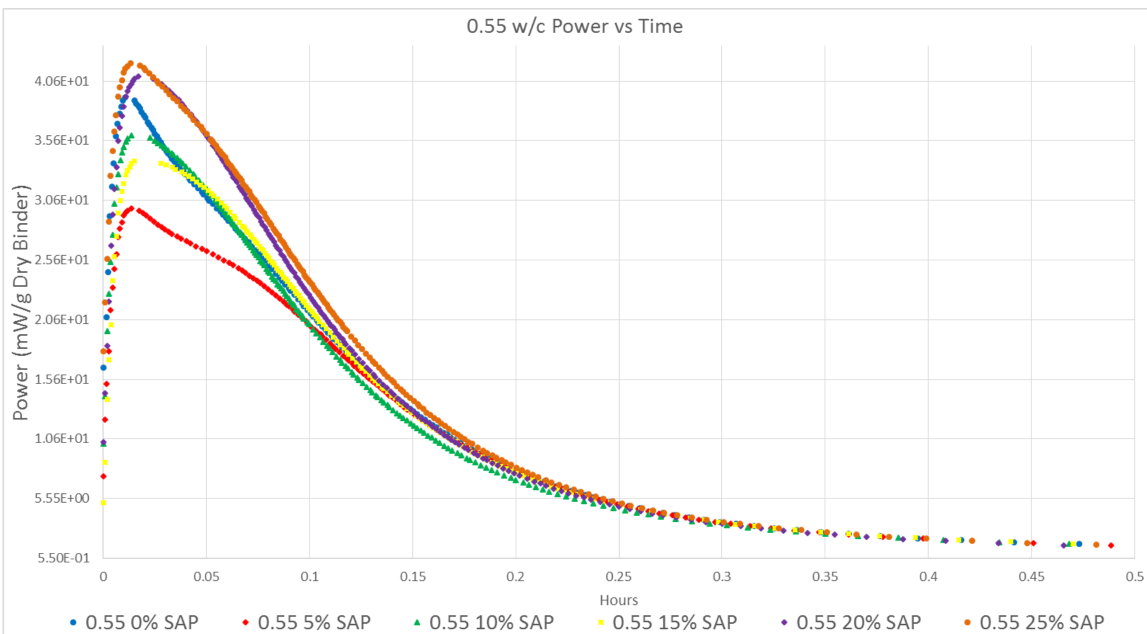


FIGURE 62 – POWER 0.55 W/C 0-0.5 HRS

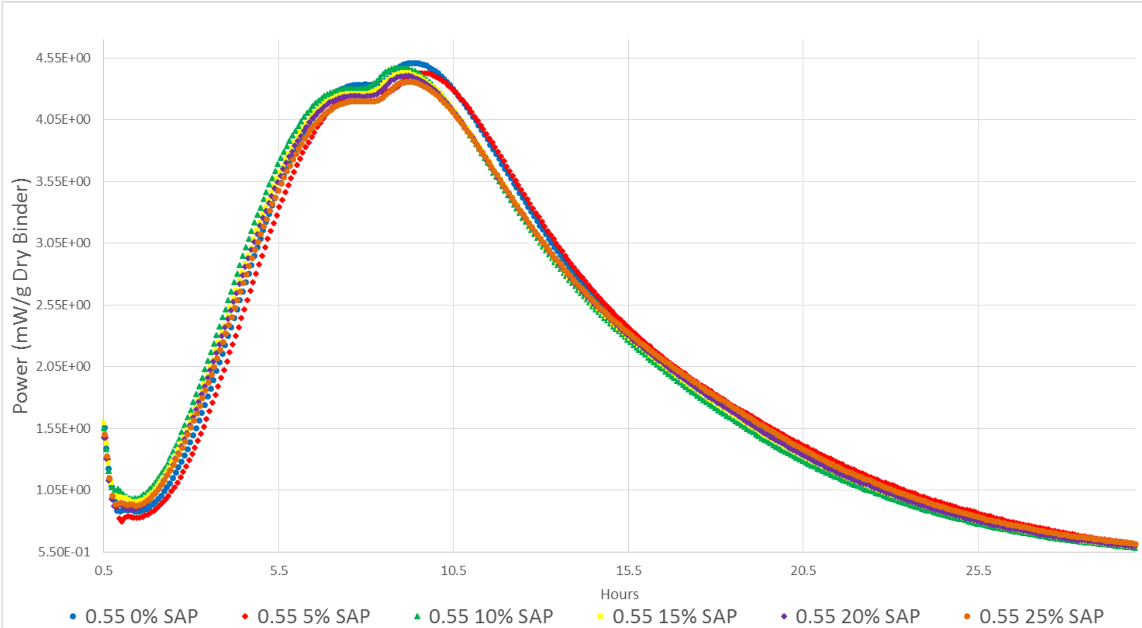


FIGURE 63 – POWER 0.55 W/C 0.5-30 HRS

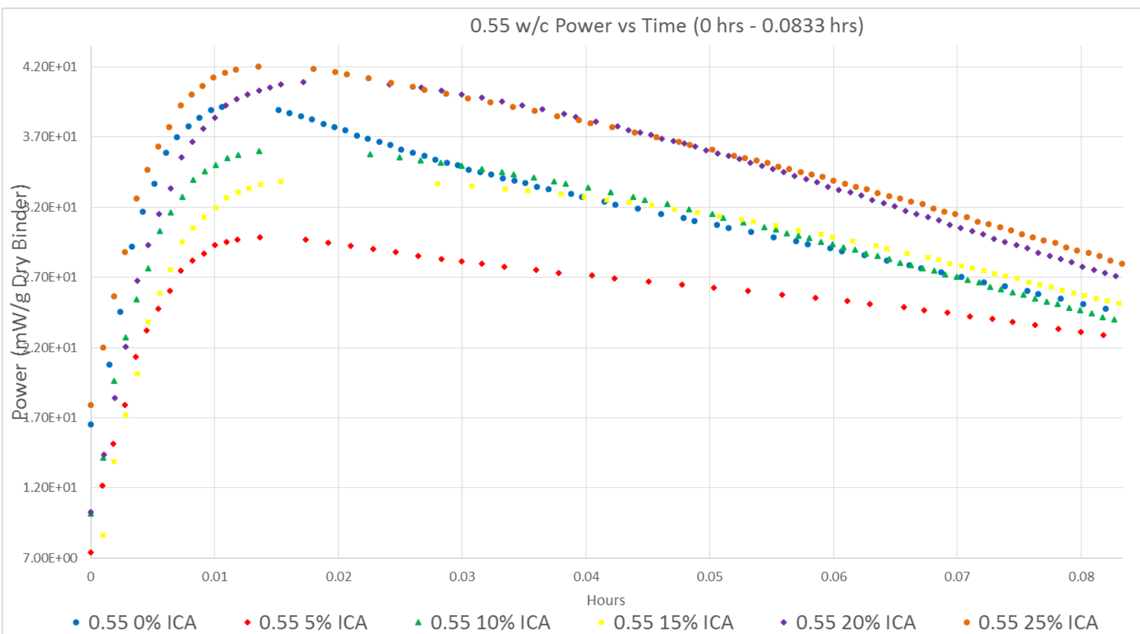


FIGURE 64 – POWER 0.55 W/C 0-0.0833 HRS

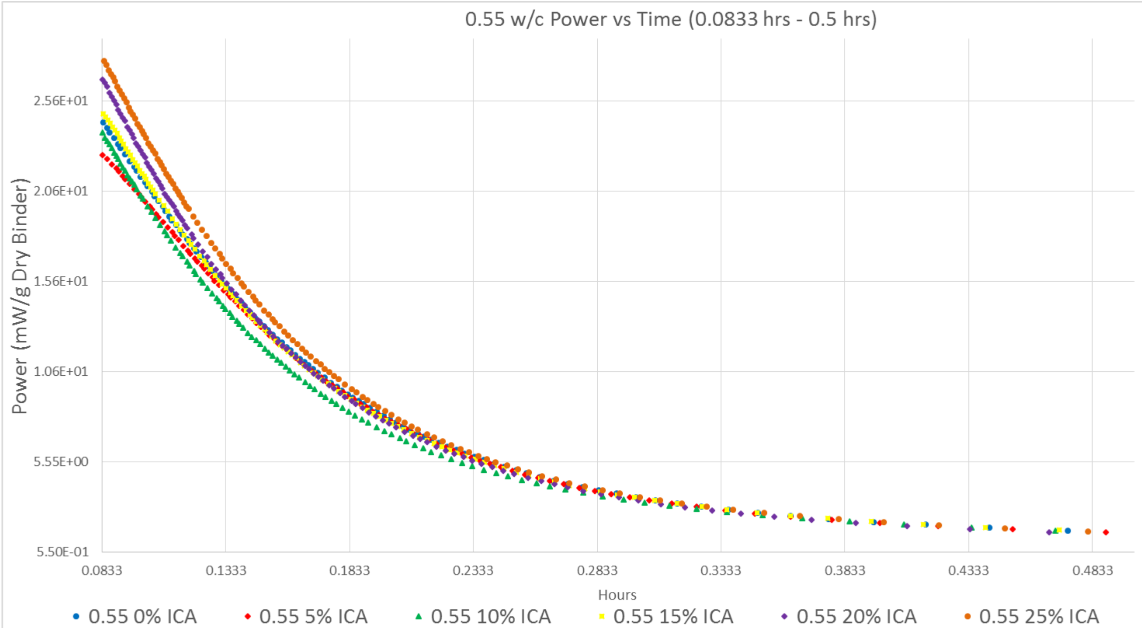


FIGURE 65 – POWER 0.55 W/C 0.0833-0.5 HRS

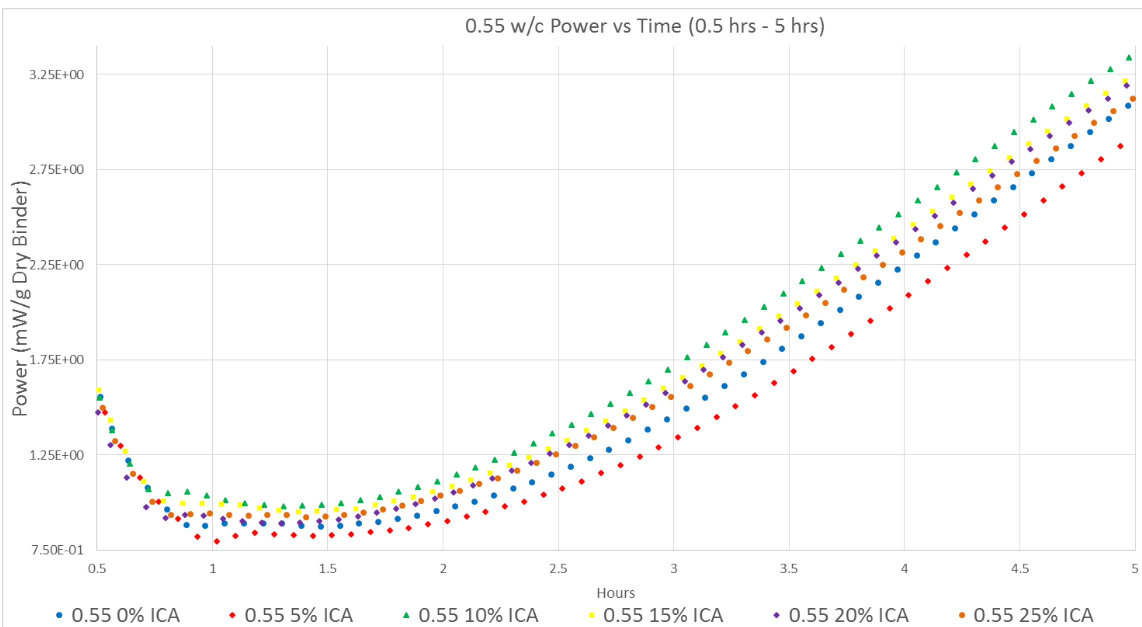


FIGURE 66 – POWER 0.55 W/C 0.5-5 HRS

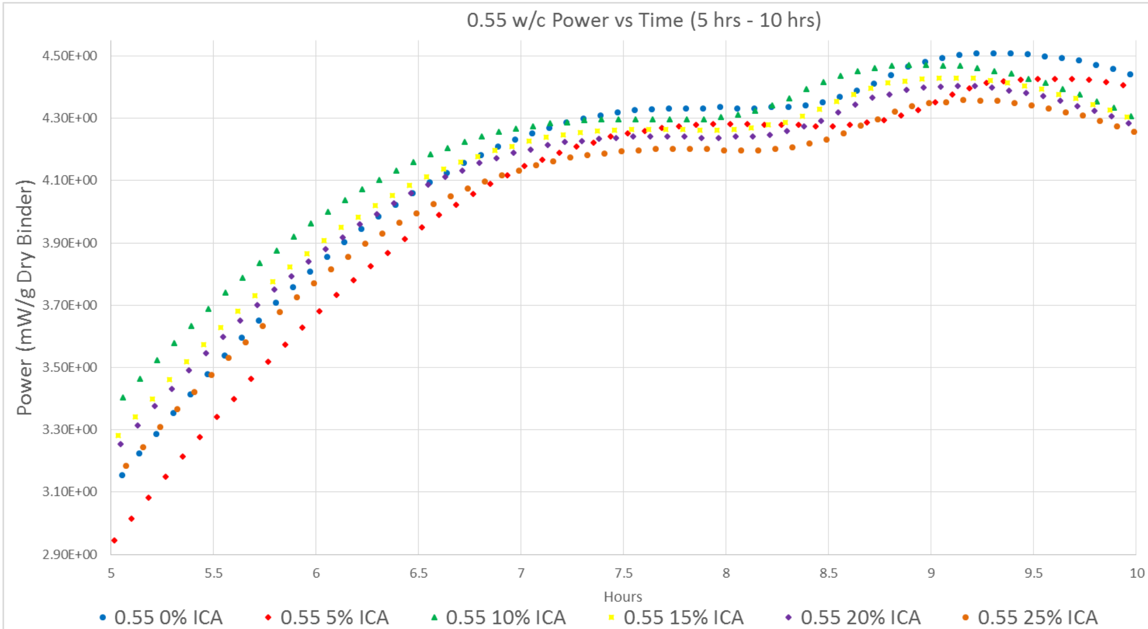


FIGURE 67 – POWER 0.55 W/C 5-10 HRS

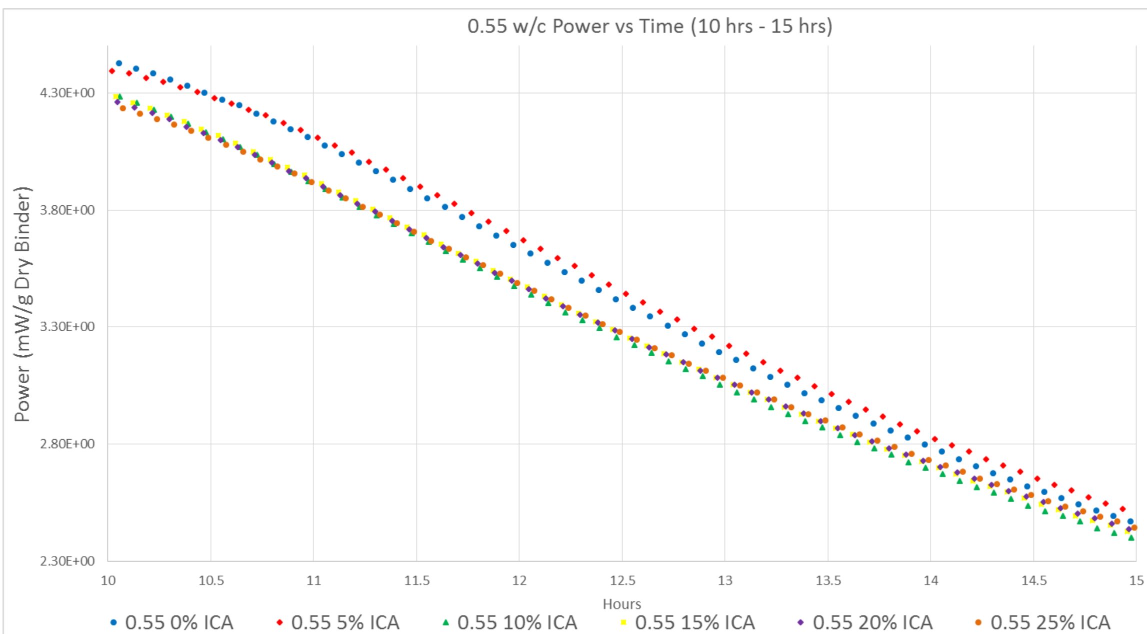


FIGURE 68 – POWER 0.55 W/C 10-15 HRS

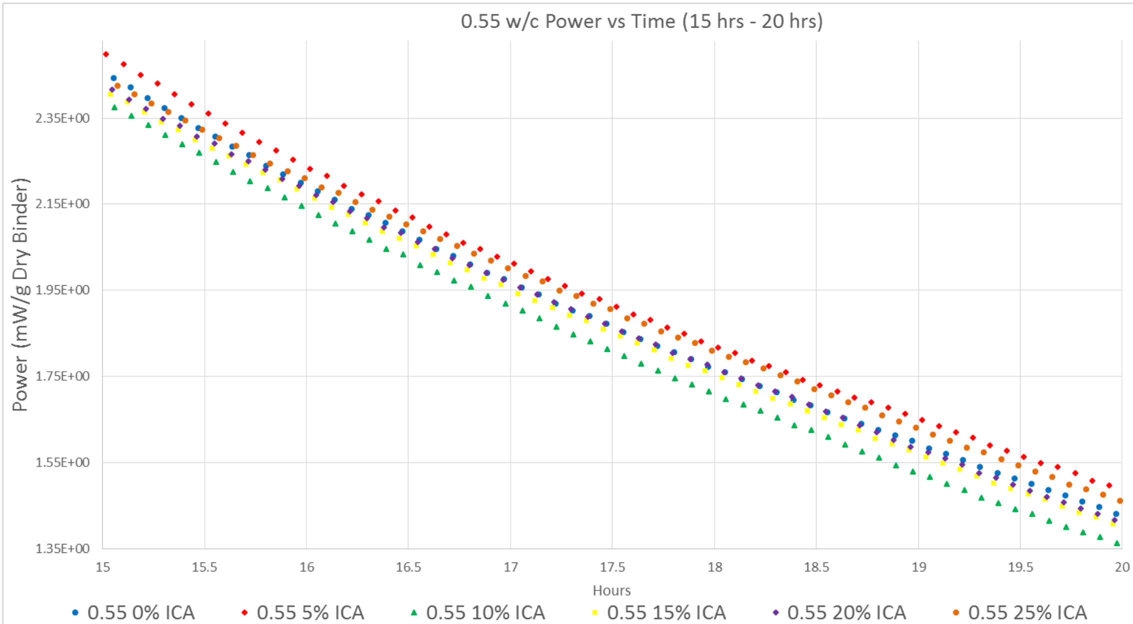


FIGURE 69 – POWER 0.55 W/C 15-20 HRS

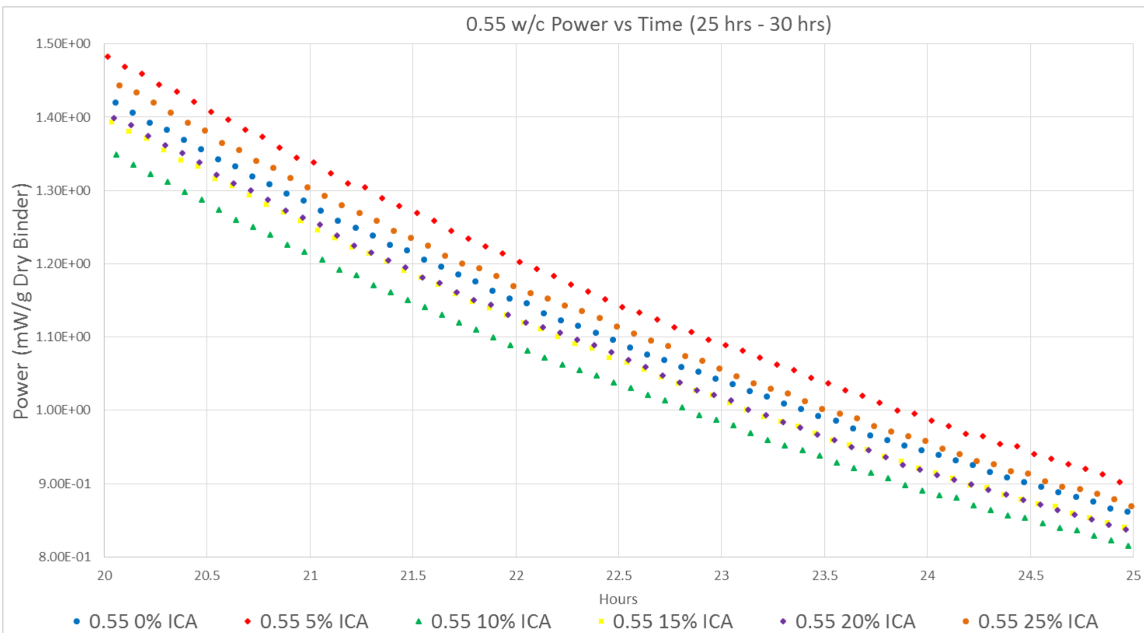


FIGURE 70 – POWER 0.55 W/C 20-25 HRS

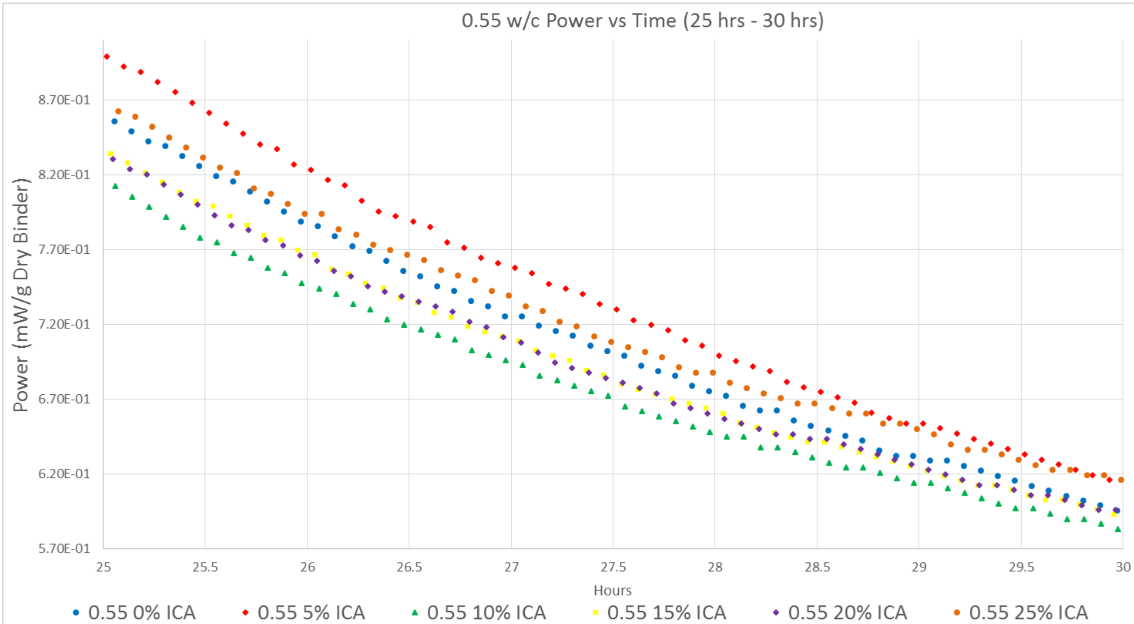


FIGURE 71 – POWER 0.55 W/C 25-30 HRS

# NOMENCLATURE

NOMENCLATURE

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

$\tau$ = shear stress

$\tau_0$ = yield stress

$\dot{\gamma}$ = shear rate

$\eta$ = viscosity

$\eta'$ = 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.